

# Integrated Suspension Engineering for Enhanced Vehicle Ride and Handling Performance

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**Abstract** - Study focuses on enhancing the ride comfort of passenger vehicles by optimizing floor level vibrations via using optimized suspension parameters during various driving conditions like straight-line, steady state, transient handling, accelerations, cornering and braking. This research study showcases the controlling measures for the objective of reducing transmissibility, which governs and reflects the transfer mechanism of the road vibrations from tyre to the floor and passenger Floor. The study focuses on reduction of transmitted vibrations to floor by addressing and limiting the transmitted accelerations at the floor during various common driving conditions.

The study reveals the parameters which are responsible for vibration transfer mechanism and highlights the real time relationship of these parameters for acceleration levels at floor. These parameters are like sprung, unsprung masses, frequency ratio along with spring stiffness, damping coefficient and suspension bushing compliances. The frequency ratio defined as the ratio of the unsprung mass frequency to the sprung mass frequency. The shift of frequency ratio in higher frequency ratio zones enhances the ride quality of vehicle and leads to reduction in transmitted vibrations at floor level, results in enhanced passenger comfort. This is due to the characteristics of frequency ratio helps to shift the zone away from the resonance marked in transmissibility trend.

Enhanced suspension design process with development strategies are employed to achieve the lower vibrations and transmissibility by studying the effect of suspension parameters. The analytical study verified and validated with simulation for vehicle physical level driving scenarios, ensuring the floor accelerations remain within targeted limits. The findings shows a significant enhancement in ride comfort and also provides a robust framework for designing high-performance suspension systems which leads to minimize discomfort during dynamic driving conditions. Experimental trails with no. of iterations performed to explore the relationship and change impact of parameters on transmissibility and transferred accelerations at floor. The results compared and shown the 88% correlation and helped in establishing the proven methodology approach for advanced suspension design.

## 1. INTRODUCTION

The comfortable ride is main aspect of designing suspension for passenger vehicles. This is due to the direct linkage of better ride with passenger satisfaction and passenger comfort zones related to health as well. The better ride is measured in the vibrations transmitted and perceived at floor level. Transmissibility is the factor which describes the vibration transmission mechanism from road to floor level including the vibration transmission from road to tyre to suspension to floor. These vibrations should be reduced by using effective damping and springing characteristics of suspension system otherwise it can cause passenger discomfort, uneasiness and fatigue. Suspension system and its characteristics to be defined and designed in such a way that vibrations should be reduced and along with comfort it should raise the confidence during vehicle handling at different driving conditions.

The identification of suspension parameters responsible for vibrations transmission has been done and also studied there effects and relationship to reduce floor level accelerations has been done. This detailed study reveals the iterations performed to measure the impact and relationship of identified suspension parameters to reduce floor accelerations. Study showcases the parameters and their contributions to enhance the ride comfort by lowering transmitted vibrations in passenger cars. This study has also considered handling aspects like vehicle handling in different scenarios includes cornering, braking, and straight-line motion. Vibrations generated and transmitted during vehicle maneuvering are considered in this study with transfer mechanism and there effects. Transmissibility factor plays a major role in suspension design by using vehicle dynamics. Transmissibility is defined as the functions of excitation frequency described as ratio of vibrations amplitude at output to the input. This is reflected as the quantitative measure of transfer vibrations from output to input locations. Transmissibility is dependent on frequency response and also defined the way of vibrations transfer and propagates through mechanical components like suspension, chassis and floor level.

During design of suspension for passenger vehicle, transmissibility plays an important role to evaluate ride comfort. As the transmissibility defined the transfer mechanism from road to tyre to suspension to floor and ability of suspension system to filter these vibrations before

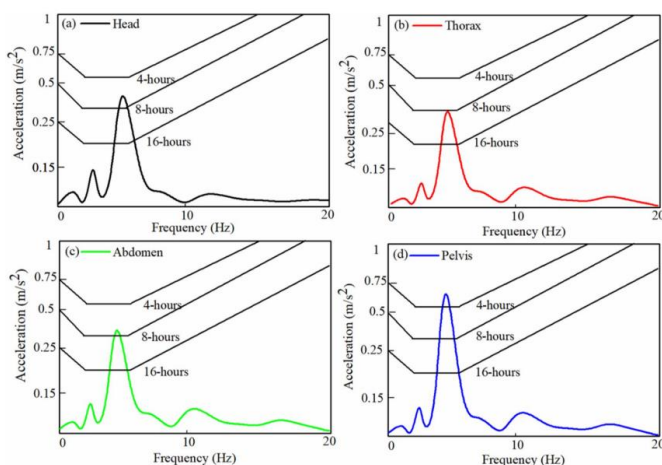
reaching to passenger. During study of transmissibility characteristics, design improvements and enhancements can be done to minimize the transfer of vibration so that suspension design can be optimized in most sensitive frequency zone to human feel (typically 4–8 Hz). Optimized suspension design governs a way of controlling of the transmissibility leads to better ride comfort and overall vehicle maneuvering.

Ride comfort analysis is done using segmental vibration transmissibility [1] which describes how the transmitted vibrations affects to different body segments of a passenger. This method helps to figure out on vibrations level and impacts on critical body parts (e.g., pelvis, spine, and head) which experience the most discomfort. It enables targeted vibration level so that design improvements or enhancements can be done in suspension and Floor design for enhanced ride comfort.

**Segmental Vibration Transmissibility (SVT)** is a vibro-biomechanical measure of how vibration transfers from the Floor to various body parts [1]. It's critical for:

- Occupant targeted comfort and safety.
- Improving suspension design.
- Identifying body segment specific risks, especially in frequencies that resonate with human tissue or organs.

The human body is a complex physical and biological system consisting of critical organs. Each organ has its own inherent limiting frequency under which it performs precisely. From Figure 1 it may observe that all the critical organs (head, thorax, abdomen, and pelvis) represent maximum vibration transmissibility between 4–6 Hz. Upon comparison Figure 1 it may observe that the input vibration has maximum influence on the head and least on the abdomen at the resonance frequency.



**Figure 1.** Transmissibility ratio at critical segments. [1]

Ride comfort and handling are fundamental to suspension system design and development [1,5], while the importance of a cost effective and most efficient design cannot be

overlooked. Conventional suspension design involves complex designs, multiple prototypes, and iterative tuning, all of which contribute to increased time and involves cost. Therefore, fine -tuning of suspension systems not only for dynamic performance but also for manufacturability, simplified design and cost -efficiency is essential considering mass production of passenger vehicles. Performance and practicality is to be considered during suspension design so that the balance in ride and handling can be maintained at optimum level. To achieve the vehicle level targets along with optimized ride and handling can be done by using lightweight materials and advanced damping technologies will be the key aspect.

Macpherson strut suspension system is commonly considered in modern passenger vehicle design due to its benefits related to compact geometry, less space requirement and proven design. Macpherson strut suspension system design helps to reduce unsprung mass, resulting improving ride comfort and handling. In addition MacPherson strut offers improved anti-dive characteristics during braking and provides robust and high structural stiffness, which contributes to both vehicle stability and steering precision.

In the first section of this study, MATLAB is used to predict the damping forces and vehicle behavior for given vehicle inputs as initial design parameter. Suspension parameters like spring stiffness, damping ratio, unsprung mass, and sprung mass are adjusted by performing no. of iterations analyzing vehicle characteristics. [3,4]. This experimental ride comfort predictions is performed using acceleration data measured at the floor level, in reference to the ISO standards [6].

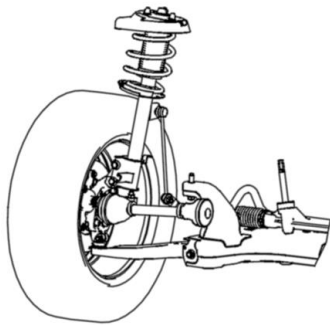
Ride comfort analysis is performed in the early design phase by adjusting suspension parameters, followed by a series of DOE in virtual domain. This approach enhances the design robustness and reduces development costs by minimizing the number of physical iterations. Optimized design is later manufactured and taken up for physical testing.

In the second part of the study, vehicle-level tests were conducted using sensors to measure vibrations with the design intended components in place. Accelerometers were mounted at designated locations on the floor to capture real-time acceleration data. This study helps to analyses how vibration are transmitted to floor.

The simulation results showed better correlation with the experimental data, demonstrating the validity of the proposed suspension design.

The design philosophy proposed in this paper starts with damping force estimation using MATLAB and concludes with meeting the target floor acceleration criteria. This approach enables design optimization with fewer physical iterations by leveraging digital simulations, making it an effective and

most efficient method for modern suspension design and development.



**Figure.2** Macpherson Strut

## 2. DESIGN APPROACH FOR OPTIMIZED PROPOSAL

The design methodology was performed through the following steps:

**1. Estimation of damping forces using MATLAB** - MATLAB is used to estimate damping force, where the damping coefficients are determined. This helps to understand the vehicle level dynamic responses with body heave and body pitch motions taken in account.

- Key parameters considered are as below:
  - Sprung and unsprung masses to understand vehicle weight distribution.
  - Suspension spring stiffness and tyre stiffness.
  - Body mass, rotational inertia, center of gravity (COG) height and location.
- Methodology: The system dynamics were modeled in MATLAB to simulate vehicle motion, the damping coefficients were adjusted to understand and achieve the desired behavior of the vehicle.

This MATLAB simulation based approach allows for the rapid identification of critical damping parameters which reduces the dependency on physical prototype and rig level iterations in early stage of the product life cycle.

**2. Calculation Floor-Level Accelerations** - To assist suspension tuning at the concept stage, floor-level accelerations were calculated.

- Objective: To identify critical suspension tuning parameters which assists to meet the floor level acceleration.
- Approach: MATLAB simulation is done to analyze results to understand the trends of suspension parameters which helps to fine tune the parameters in order to meet the target floor-level acceleration values.

**3. Verification and Validation of proposed suspension design parameters** - Iterations were done in MATLAB to understand the trends -

- Objective: To confirm that the proposed suspension parameters effectively reduce floor accelerations.
- Validation Criteria: Simulated vertical accelerations at both the floor levels were evaluated to ensure floor level acceleration to meet the acceptance value.
- Approach: The dynamic model was subjected to road excitation inputs and the responses were analyzed to validate that the design meets required ride comfort requirements and in line with the MATLAB simulation prediction.

**4. Vehicle Level Measurements** - Vehicle level measurements done to measure real-time floor level acceleration data at key designated locations.

- Objective: Acceleration measured at floor level under actual driving conditions.
- Instrumentation: At designated location, accelerometers were installed.
- Purpose: Further this data was used to evaluate ride comfort and validate the effectiveness of the suspension parameters determined through MATLAB simulation.

**5. Correlation Analysis between Measured and MATLAB Data** - An analysis is conducted to compare the results of vertical acceleration at the floor levels.

- Objective: To evaluate the accuracy and reliability of the MATLAB simulation model by quantifying its alignment with experimental data.
- Method: Time and frequency domain comparisons were performed for correlations and model validation is done.
- Outcome: A strong correlation between simulated and measured values validated the proposed suspension design and simulation model, demonstrating its effectiveness in achieving ride comfort and handling targets.

**Estimation of damping forces using MATLAB** Damping force is estimated using MATLAB which involves simulating the suspension dynamics to compute the forces to get the desired ride comfort and handling characteristics. Vehicle condition with sprung mass, unsprung mass, suspension stiffness, suspension travel etc. are considered for analysis. MATLAB coding has been established to facilitate prediction of the force-velocity relationship based on studying vehicle behavior like body pitch and body heave motions and body roll, which serves as a basis for initial damper tuning.

Pitch motion is one of the critical aspect of vehicle dynamics, referring to the oscillatory motion of the vehicle body about its lateral axis. This motion typically occurs during acceleration, braking, or when the vehicle traverses on uneven road surfaces. Resulting in the front and rear ends of the vehicle move in opposite vertical directions, producing a nose-up or down nature. This vibrations have a considerable impact on ride comfort, vehicle stability and occupant comfort. Therefore, it must be carefully addressed during the design and tuning of the suspension system.

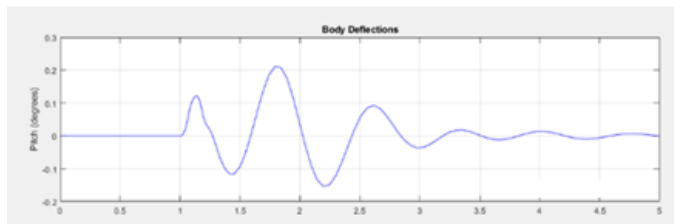


Figure 3. Pitch

Heave motion refers to the vertical translational motion of the vehicle body, in which the entire vehicle moves upward and downward as a complete rigid mass. Heave vibrations influence ride comfort due to vertical acceleration felt by occupants which are induced by road instabilities.

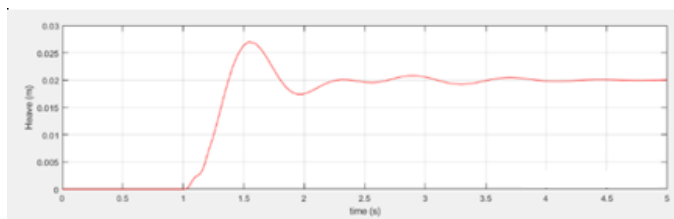


Figure 4. Heave

Body roll is the rotational motion of the vehicle body around its longitudinal axis, when running from front to rear which typically occurs during cornering and lateral maneuvers. This causes the vehicle to lean outward from the turn due to lateral motion of the vehicle. Roll is influenced by suspension geometry, roll centre height, and anti-roll stiffness. It plays a critical role in determining vehicle handling, stability, and occupant comfort during turns.

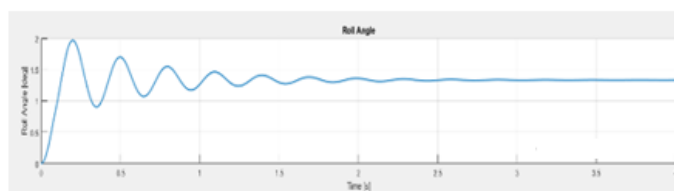


Figure 5. Body Roll

**Calculation of floor-level accelerations** – Steps to achieve improved performance:-

**Step 1:** Calculation of Natural Frequency for Sprung and Unsprung Mass - The natural frequency for the sprung mass ( $f_{n-s}$ ) and unsprung mass ( $f_{n-us}$ ).

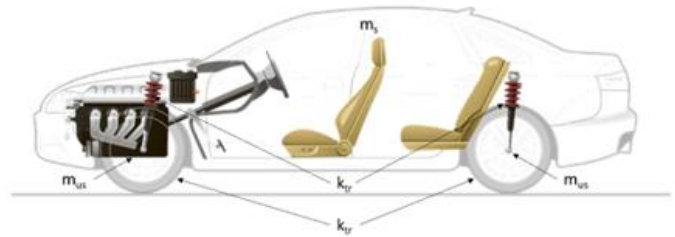


Figure 6. Road Vibration to Floor Transmission

**Step 2 - Frequency ratio:** - It's ratio of unsprung frequency ( $f_{n-us}$ ) to sprung frequency ( $f_{n-s}$ ). For better occupant comfort, higher frequency ratio is ideal condition. Lower frequency ratios are considered undesirable, as they lead to higher peaks in the transmissibility ratio and require increased damping, indicating the need for suspension design improvements.

**Step 3 - Damping Ratio:** Critical damping coefficient is the value of damping at which a system moves from oscillatory to non-oscillatory motion. This represents the minimum damping needed to prevent oscillations after a disturbance i.e., the system returns to equilibrium as quickly as possible without oscillating.

Force transmissibility ( $T_s$ ) is effectiveness of vibration isolation. A lower  $T_s$  indicates better isolation, which means less force is transmitted through the system. For a passenger car, Floor-floor transmissibility is a widely used measure to evaluate the effectiveness of vibration isolation between the vehicle chassis and the occupant. This ratio helps determine how much of the road-induced vibration, originating from tyre-road interaction and transmitted through the suspension and body structure, ultimately reaches the passenger through the floor.

Excessive vibrations results in fatigue, discomfort, and even long-term health concerns. Hence, minimizing floor accelerations is essential for ensuring a smooth and comfortable ride. To ensure this, design iterations has been performed out to optimize suspension design parameters. This iterations is done across a range of driving conditions such as straight-line travel, cornering, and braking. Design iteration for suspension parameters are done basis on required vehicle's dynamic response from the road vibration for better passenger comfort. To summarize, transmissibility is an important parameter to design optimized suspension and Flooring systems for the passenger cars, which directly influences the occupant ride comfort and overall driving experience.

Graph shows the transmissibility ratio as a function of the frequency ratio ( $r$ ) for a damped vibrating system, with different curves representing varying damping ratios.

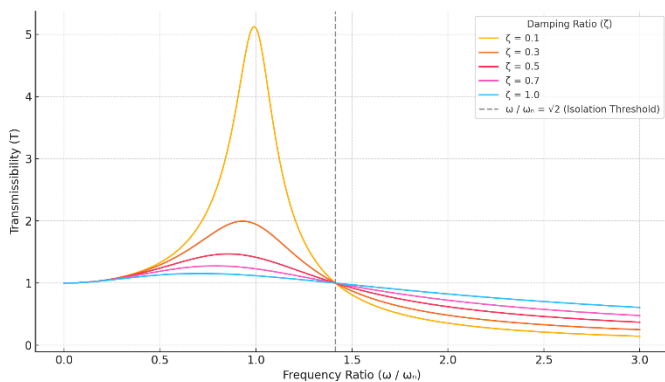


Figure 7. Transmissibility [7]

Step 4:- Floor level acceleration: - Floor level acceleration are derived by using the relation with transmitted force from road contact to the floor.

A design-of-experiments (DOE) simulations were performed by varying suspension parameters such as spring stiffness, damping coefficient, and unsprung mass, along with braking and cornering conditions.

### 3. DESIGN OPTIMIZATION PARAMETERS

**Spring Stiffness** – Spring stiffness directly effects system's natural frequency as it enhances vibration transmissibility to the passenger. Higher the spring stiffness results in increase the suspension's natural frequency, leading to shift of the peak transmissibility to a higher frequency band. This shift results in increased floor level accelerations, potentially worsening vertical vibrations. Below table summarizes the effect of spring stiffness on floor and Floor level acceleration.

Table 1 – Spring Stiffness - DOE Table for Floor level Accelerations

	Iteration 1	Iteration 2	Iteration 3
Spring Stiffness (Kg/mm)	1.5	2.5	3.5
Floor level acceleration (m/s <sup>2</sup> )	0.62	0.64	0.66

**Damping ratio** - The damping ratio in Floor-level vibration is a critical parameter influencing how vibrations are absorbed and transmitted to the occupant. A fine-tuned damping ratio helps to reduce the floor level accelerations by minimizing vibration in the range of system's natural frequency. However, excessive damping can introduce ride harshness, while insufficient damping may allow excessive oscillations.

Table 2 –Damping ratio - DOE Table for Floor level Accelerations

	Iteration 1	Iteration 2	Iteration 3
Damping Ratio	0.25	0.3	0.35
Floor level acceleration (m/s <sup>2</sup> )	0.53	0.62	0.73

**Sprung and Unsprung mass** – Balancing of sprung and unsprung masses is crucial, as it ensures optimal mass distribution resulting in frequency shift and reduces transmissibility. This balancing of mass distribution results in better suspension performance in terms of ride and passenger comfort. Suspension design with a lower transmissibility ratio has better isolation from road disturbances, resulting in the enhanced occupant comfort and better overall vehicle dynamics.

Table 3 – Sprung Mass - DOE Table for Floor level Accelerations

	Iteration 1	Iteration 2	Iteration 3
Sprung mass (Kg)	770	800	900
Floor level acceleration (m/s <sup>2</sup> )	0.9	0.66	0.51

**Cornering Conditions** – During cornering, the vehicle's weight shifts towards lateral side, causing a transfer of the sprung mass towards the outer wheel. To understand the effect during cornering condition, it's essential to evaluate the impact of suspension parameters on floor level acceleration under these conditions. Later the results are verified through simulation to ensure accuracy and to support the design optimization process.

The table below summarizes the effect of spring stiffness and damping ratio during cornering conditions.

Table 4 – Cornering - DOE Table for Floor level Accelerations

Cornering Conditions			
	Iteration 1	Iteration 2	Iteration 3
Spring Stiffness (Kg/mm)	1.5	2.5	3.5
Floor level acceleration (m/s <sup>2</sup> )	0.35	0.46	0.54
Damping Ratio	0.25	0.3	0.35
Floor level	0.35	0.43	0.47

acceleration (m/s <sup>2</sup> )			
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Effective suspension design as mentioned in above section enhances both ride comfort and vehicle stability.

#### 4. VERIFICATION AND VALIDATION OF THE SUSPENSION PARAMETERS

To verify the suspension design effectiveness with the optimized parameters, simulations are conducted in MATLAB to evaluate the model performance. MATLAB simulations done are to understand the acceleration levels at floor positions under various driving conditions. Model performance is checked with the optimized damping parameters and the suspension's ability to minimize vibration transmission is evaluated.

This verification step is crucial to confirm that the target ride acceleration levels are met before moving into part manufacturing which in turn reduces the physical iterations which involves lot of cost and ensuring alignment with real-world performance expectations.

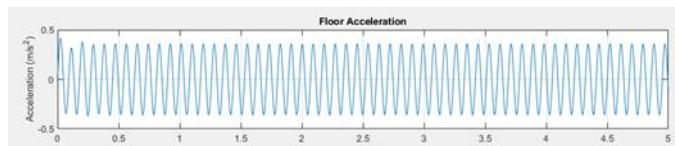


Figure 8. Floor Accelerations

**Vehicle-level measurements** - Vehicle-level measurements were carried out using the design intended suspension components to evaluate performance.

- Driving Conditions: Ride tests conducted under various driving scenarios across different road patches, which also includes uneven surfaces and urban conditions, assisting to simulate realistic operational conditions.
- Instrumentation: Accelerometers mountings done at the floor levels to capture acceleration data during this driving conditions.
- Results: Floor level acceleration as per above mentioned driving conditions were is in line to target.

Table 5 – Measured acceleration level –Floor level

	Metric	Target	Actual
<b>Floor level</b>	m/s <sup>2</sup> (RMS)	0.65	0.71

#### 5. CO-RELATION ANALYSIS

The finalized suspension design with the correct configuration was tested at the vehicle level to validate simulation accuracy.

- Approach: Vehicle test results were compared with simulation results for floor and Floor accelerations.
- Outcome: The correlation analysis demonstrated approximately 88% between the measured and simulated results, confirming the accuracy of the MATLAB model and the effectiveness of the design approach towards this optimization study.

Table 6 – Correlation

	Floor level
RMS acceleration (m/s <sup>2</sup> ) calculated	0.63
RMS acceleration (m/s <sup>2</sup> ) actual	0.71
Co-relation (%)	89%

#### 6. CONCLUSIONS

This research demonstrates that optimizing floor vibrations by tuning tire stiffness, spring stiffness, bush stiffness, damping coefficient, unsprung mass and sprung mass.

**Targeted Comfort Thresholds** - Achieving floor accelerations level within target across driving conditions like normal, cruising, cornering, and braking creates in high comfort benchmark.

**Effective Damping Strategies** - Implementing the optimized damper design along with tuned suspension parts reduces vibrations in the floor structure.

**High Correlation between Simulation and physical results**- This outcomes showed an 89% correlation with physical testing, underscoring the practical applicability of the methodology.

**Comprehensive Design Approach**- The combined use of stiffness tuning, mass ratio adjustment, and damping optimization offers a holistic framework for suspension design, moving beyond isolated component tweaks in physical world with first time right design and reducing number of iteration in physical world.

## 7. REFERENCES

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