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Numerical quantification of shock absorber degradation using a fault severity index in a 4-DOF half-car model

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ABSTRACT

Shock absorber degradation alters vehicle suspension dynamics and may compromise ride and road-holding performance. This study proposes a 4-DOF half-car numerical framework to quantify degradation-induced response changes using a normalized Fault Severity Index (FSI) based on suspension travel. Shock absorber degradation is represented by a 0–90% reduction in damping capability, while a filtered stochastic road profile is used as the excitation. Model robustness is examined through parameter sensitivity, time-step convergence, and Monte Carlo simulations. Results show that 90% degradation increases RMS body displacement, combined suspension travel, and dynamic tire load by 269.75%, 196.35%, and 138.32%, respectively. The corresponding FSI increases to 196.35%, with a quadratic degradation–FSI relationship yielding R2=0.9578. Under stochastic road realizations, the Monte Carlo model achieves R2=0.9591, with an FSI of 155.53 ± 30.22% at 90% degradation. The proposed framework provides a compact quantitative indicator for assessing degradation-induced suspension response and establishes a basis for simulation-assisted shock absorber condition assessment. Experimental validation remains necessary before diagnostic application.

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1. INTRODUCTION

Shock absorbers are critical components of vehicle suspension systems because their damping characteristics strongly influence ride comfort, suspension travel, tire-load variation, and vehicle stability. Degradation of damping capability can therefore increase suspension motion and dynamic tire-load fluctuation. Vehicle suspension behavior has been widely investigated using quarter-car and half-car models under deterministic and stochastic road excitation, including passive and semi-active configurations (Abdelfattah & Ibrahim, 2021; Burdzik, 2022; Rajesh et al., 2025; Satyanarayana et al., 2021; Yang et al., 2022).

The half-car model offers a practical compromise between computational efficiency and dynamic representation because it captures both vehicle-body bounce and pitch responses. Previous studies have demonstrated that suspension responses are influenced by damping, suspension stiffness, vehicle mass, vehicle speed, and road excitation characteristics (An-Nizhami et al., 2023; An-Nizhami et al., 2025; Rajesh et al., 2025;

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Satyanarayana et al., 2021; Yang et al, 2022; Sai et al., 2023). Under stochastic road excitation, response variability may further complicate the assessment of degradation, making evaluation based on a single deterministic road profile potentially insufficient.

Suspension condition monitoring has consequently received increasing attention using vibration measurements, model-based parameter estimation, signal processing, and machine-learning techniques (Ata & Salem, 2025; Burdzik, 2022; Ott et al., 2024; Rajesh et al., 2025; Schramm et al., 2026; Transfer learning..., 2023; Zwosta et al., 2023; Zwosta et al., 2024). These studies demonstrate that changes in vehicle dynamic responses can be associated with suspension degradation. However, many existing approaches focus primarily on fault detection or classification, whereas a simple quantitative indicator describing the severity of degradation-induced suspension-response deviation remains less explored. Experimental investigations have also demonstrated that damper degradation can result from mechanisms such as oil loss, pressure reduction, friction, and changes in damper characteristics (Ata and Salem, 2025; Ott et al., 2024; Schramm et al., 2026; Zwosta et al., 2023; Zwosta et al., 2024).

A key gap in the existing literature is the limited use of a simple quantitative index to represent the severity of degradation-induced suspension-response deviation relative to a healthy reference condition. Most existing studies emphasize fault detection, classification, parameter estimation, or physical characterization of degraded dampers, rather than expressing progressive degradation through a single normalized response-based indicator. In contrast, the present study introduces a normalized Fault Severity Index (FSI) based on the combined front–rear suspension travel response. The proposed FSI is intended to quantify the relative deviation of the degraded suspension response from the healthy condition and to provide a continuous severity measure for progressive damping-capability loss. Thus, the novelty of the proposed approach lies not in introducing a new physical damper degradation mechanism, but in providing a simple, normalized, and simulation-based metric for quantifying degradation-induced suspension-response deviation under stochastic road excitation.

In the present study, degradation is represented by an equivalent reduction in damping capability, rather than by explicitly modelling individual physical failure mechanisms. This simplification allows progressive degradation to be systematically evaluated from 0% to 90% while maintaining a computationally tractable half-car model. The assumed degradation percentage therefore represents a numerical damping-loss parameter, not a direct measurement of physical damper damage.

To improve numerical credibility, the proposed framework incorporates time-step convergence, parameter sensitivity, and Monte Carlo stochastic-road analysis. These analyses examine whether the predicted degradation response remains stable with respect to numerical discretization, vehicle parameters, and road-profile variability. Nevertheless, the resulting indicator is considered a simulation-based metric and requires experimental validation before practical diagnostic implementation.

Accordingly, this study develops a 4-DOF half-car model with a normalized Fault Severity Index (FSI) based on combined front–rear suspension travel. The FSI quantifies the relative deviation of degraded suspension response from the healthy condition. The principal objective is to determine whether the proposed FSI can provide a consistent quantitative representation of progressive damping degradation under stochastic road excitation.

The main contributions are: (i) development of a computationally efficient 4-DOF half-car degradation mode; (ii) formulation of a normalized FSI for quantifying degradation-induced suspension-response deviation; and (iii) evaluation of FSI robustness using regression, sensitivity, time-step convergence, and Monte Carlo uncertainty analyses. The proposed FSI is intended as a simulation-based severity indicator, rather than a validated diagnostic threshold.

2. RESEARCH METHODS

A four-degree-of-freedom half-car model was developed to represent the vertical and pitch dynamics of the vehicle body together with the front and rear unsprung masses.

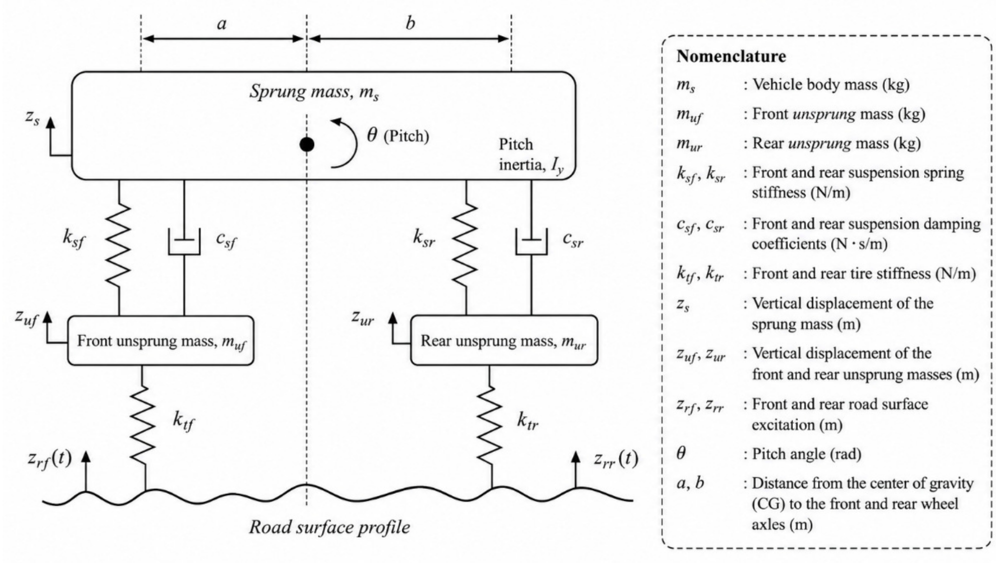

Figure 1. Four-degree-of-freedom half-car dynamic model with shock absorber degradation.

The generalized coordinates were the sprung-mass vertical displacement z_s, body pitch angle θ, and front and rear wheel displacements z_{uf} and z_{ur}. The suspension forces were formulated using linear spring–damper elements,

$$F_{sf} = k_{sf}\left(z_s + a\theta - z_{uf}\right) \quad (1)$$

$$F_{sr} = k_{sr}\left(z_s - b\theta - z_{ur}\right) \quad (2)$$

while the tire forces were defined as

$$F_{tf} = k_{tf}\left(z_{uf} - z_{rf}\right) \quad (3)$$

$$F_{tr} = k_{tr}\left(z_{ur} - z_{rr}\right) \quad (4)$$

where z_{rf} and z_{rr} denote the front and rear road elevations. The resulting coupled equations were solved numerically using MATLAB/ODE45. Half-car formulations are appropriate when both bounce and pitch responses are required, while recent studies have also demonstrated their relevance for suspension degradation and damper characterization (An-Nizhami et al., 2023, 2025).
The parameters used in the half-car suspension model are summarized in Table 1.

Table 1. Vehicle and suspension parameters used in the numerical model

Parameter	Symbol	Value	Unit
Sprung mass	m_s	1200	kg
Pitch moment of inertia	I_{yy}	2200	kg·m²
Front unsprung mass	m_{uf}	60	kg
Rear unsprung mass	m_{ur}	60	kg
CG-to-front axle distance	A	1.20	m
CG-to-rear axle distance	B	1.40	M
Wheelbase	$L = a + b$	2.60	M
Front suspension stiffness	k_{sf}	25,000	N/m
Rear suspension stiffness	k_{sr}	25,000	N/m
Nominal front damping coefficient	$c_{sf,0}$	2,500	Ns/m
Nominal rear damping coefficient	$c_{sr,0}$	2,500	Ns/m
Front tire stiffness	k_{tf}	200,000	N/m
Rear tire stiffness	k_{tr}	200,000	N/m
Vehicle speed	V	20	km/h

The vehicle parameters were selected to represent a conventional passenger-car half-car suspension while maintaining consistency with commonly reported ranges in vehicle-dynamics studies. The sprung mass, front

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and rear suspension stiffness, tire stiffness, wheelbase, and nominal damping coefficient were selected within physically plausible ranges for a passenger vehicle rather than being treated as vehicle-specific measured parameters. Accordingly, the model should be interpreted as a representative numerical half-car model, and the subsequent sensitivity analysis was used to assess whether the identified degradation trend remained stable under parameter variations.

Shock-absorber degradation was represented by a reduction in the effective damping capability,

$$c_D = (1 - D)\, c_0 \tag{5}$$

where c_0=2500 Ns/m is the nominal damping coefficient and D is the degradation fraction. Five conditions were considered: 0%, 25%, 50%, 75%, and 90% degradation, corresponding to damping coefficients of 2500, 1875, 1250, 625, and 250 Ns/m, respectively.

The degradation levels of 0%, 25%, 50%, 75%, and 90% were selected to provide a progressive representation from the healthy condition to severe damping-capability loss. The 25% increments enable the response trend to be examined at moderate degradation levels, while the 90% case represents an intentionally severe limiting condition with only 10% of the nominal damping retained. These levels are therefore numerical severity scenarios rather than direct representations of specific physical failure mechanisms.

This representation is intentionally defined as an equivalent damping-capability loss, rather than a detailed physical model of hydraulic leakage, valve degradation, friction, or temperature dependence. Such a distinction is important because recent suspension-diagnosis studies have treated degradation through changes in damping parameters (Abdelfattah & Ibrahim, 2021; Burdzik, 2022; Rajesh et al., 2025), while more advanced studies estimate suspension parameters directly from measured vehicle states (Pham, 2024; Yang et al., 2022).

The vehicle was simulated at 20 km/h over a reproducible filtered stochastic road profile with an amplitude of 5 mm. A low-pass autoregressive filtering procedure was applied to Gaussian white noise to generate the spatially varying road excitation. The rear-wheel excitation was obtained by introducing the kinematic delay:

$$z_{rr}(t) = z_r[Vt - (a + b)] \tag{6}$$

where $L = a + b = 2.6\text{m}$ is the wheelbase and $V - 5.556\, m/s$ the vehicle velocity. The corresponding kinematic delay is given by Eq.

$$\tau = \frac{L}{V} = \frac{2.6}{5.556} = 0.468\ \text{s}$$

Thus, the rear-wheel excitation is applied with a delay of 0.468s relative to the front-wheel excitation. This approach avoids claiming that the generated profile is a calibrated ISO 8608 road class unless an explicit ISO PSD fitting procedure is performed. The use of stochastic road excitation is consistent with recent suspension studies investigating ride response and degradation under random road disturbances (Rajesh et al., 2025; Satyanarayana et al., 2021; Yang et al., 2022).

The principal response variables were body acceleration, body displacement, pitch acceleration, suspension travel, and dynamic tire load. The combined suspension-travel amplitude was defined as

$$RMS_{ST} = \sqrt{\frac{RMS_{STF}^2 + RMS_{STR}^2}{2}}. \tag{7}$$

A normalized Fault Severity Index (FSI) was subsequently introduced to quantify the deviation from the healthy suspension condition:

$$\text{FSI} = \frac{RMS_{ST,D} - RMS_{ST,H}}{RMS_{ST,H}} \times 100\% \tag{8}$$

The healthy condition therefore gives FSI=0%, while increasing values represent increasing deviation in suspension response. Importantly, the proposed FSI bands are treated as simulation-based severity indicators rather than experimentally validated diagnostic thresholds. This distinction is consistent with current suspension-health research, where vibration response, odal changes, transmissibility, and parameter estimation are increasingly used for fault identification (Burdzik, 2022; Rajesh et al., 2025; Sai et al. (2023; Ata and Salem, 2025).

Three additional analyses were performed to evaluate the robustness of the proposed FSI. First, linear and quadratic regressions were used to quantify the relationship between damping degradation and FSI. Second, a parameter sensitivity analysis was conducted at 50% degradation by varying sprung mass, suspension stiffness, nominal damping, vehicle speed, and tire stiffness. Third, numerical convergence was evaluated using time steps of 0.002, 0.001, and 0.0005 s.

Finally, 30 independent stochastic road realizations were simulated for each degradation level. The resulting FSI distributions were summarized using mean, standard deviation, 95% confidence interval, and coefficient of variation. This Monte Carlo procedure was introduced to distinguish the degradation trend from a response obtained from only one particular road realization. Sch uncertainty-aware approaches are particularly relevant because suspension response is strongly dependent on road excitation and operating conditions (Satyanarayana et al., 2021; Yang et al., 2022; Rajesh et al., 2025).

The overall simulation procedure consisted of vehicle parameter definition, stochastic road generation, healthy-condition simulation, degraded-damping simulation, transient removal, response extraction, FSI calculation, regression analysis, sensitivity analysis, time-step convergence analysis, and Monte Carlo uncertainty analysis.

This framework combines a physics-based vehicle model with response-based degradation quantification. Unlike approaches that directly classify measured vibration signals using machine learning, the present method focuses on establishing a physically interpretable relationship between damping-capability loss and suspension-response deviation. Recent studies have demonstrated both model-based parameter estimation and vibration-based fault classification, supporting the relevance of this direction while leaving room for experimentally validated extension (Burdzik, 2022; Pham, 2024; Rajesh et al., 2025; Yang et al., 2022).

3. RESULTS AND DISCUSSION

The simulation results demonstrate a nonlinear influence of shock absorber degradation on vehicle suspension response. Reducing the damping coefficient from 2500 to 250 N·s/m increased the combined RMS suspension travel from 1.659 to 4.915 mm, corresponding to a 196.35% increase. RMS body displacement increased from 0.773 to 2.857 mm, while the combined dynamic tire load increased from 223.76 to 533.27 N. The RMS body displacements are presented in figure 2. These changes indicate that severe damping degradation substantially increases suspension motion and tire-load variation, consistent with the established influence of damper characteristics on vehicle dynamic behavior behavior (Abdelfattah & Ibrahim, 2021; Burdzik, 2022; Rajesh et al., 2025; Satyanarayana et al., 2021; Yang et al., 2022).

An important observation is that RMS acceleration does not increase monotonically with degradation. It decreases from 0.157 m/s² in the healthy condition to 0.105 m/s² at 75% degradation before increasing to 0.130 m/s² at 90%. In contrast, combined suspension travel increases consistently from 1.659 to 4.915 mm. This difference indicates that acceleration alone may not provide a robust monotonic indicator of progressive damper degradation, whereas suspension travel provides a clearer response measure (An-Nizhami et al., 2023, 2025; Ata & Salem, 2025; Schramm et al., 2026; Sai et al., 2023).

The proposed Fault Severity Index (FSI) quantifies the relative deviation of combined suspension travel from the healthy condition. The FSI increases from 0% in the healthy condition to 12.83%, 35.27%, 88.37%, and 196.35% at 25%, 50%, 75%, and 90% damping degradation, respectively.

The degradation–FSI relationship shows a nonlinear trend and is represented by the quadratic model: $FSI(D) = -0.95948D + 0.0329466D^2$, where D denotes the damping degradation percentage. The model gives R^2=0.9555, adjusted R^2=0.9111, and RMSE =15.09%. At D=90%, the predicted FSI is 196.35%, consistent with the direct simulation.

The positive quadratic coefficient indicates that response severity increases progressively at high degradation levels. This behavior is associated with the decreasing capability of the damper to dissipate road-induced vibration energy as damping capability is lost (An-Nizhami et al., 2023, 2025; Ata & Salem, 2025; Schramm et al., 2026; Sai et al., 2023). Consequently, suspension travel provides a more consistent degradation-sensitive metric than RMS body acceleration.

The principal novelty of the present study lies in converting this degradation-induced suspension-response change into a normalized FSI and subsequently establishing its nonlinear relationship with equivalent damping loss. Unlike approaches that primarily classify suspension faults or estimate individual suspension parameters (Ata and Salem, 2025; Dai et al., 2024; Ott et al., 2024; Schramm et al., 2026; Zwosta et al., 2023, 2024), the proposed framework provides a directly interpretable quantitative measure of response deviation relative to the healthy state. The FSI therefore links the physical degradation parameter to an observable system-level response, while maintaining a computationally simple 4-DOF half-car formulation.

Based on the simulated responses, the FSI is classified into four simulation-based severity bands: low response deviation for 0–25% degradation, mild response deviation at 50%, moderate response deviation at 75%, and high response deviation at 90%. These bands are proposed only for numerical interpretation and should not be regarded as experimentally validated diagnostic thresholds.

A further contribution of this study is the incorporation of stochastic-road uncertainty into the proposed FSI assessment. To examine whether the degradation trend was dependent on a single road realization, 30 independent stochastic road profiles were generated for each degradation level. The mean FSI increased from 11.31% at 25% degradation to 155.53% at 90% degradation, while the standard deviation increased from 1.17% to 30.22%.

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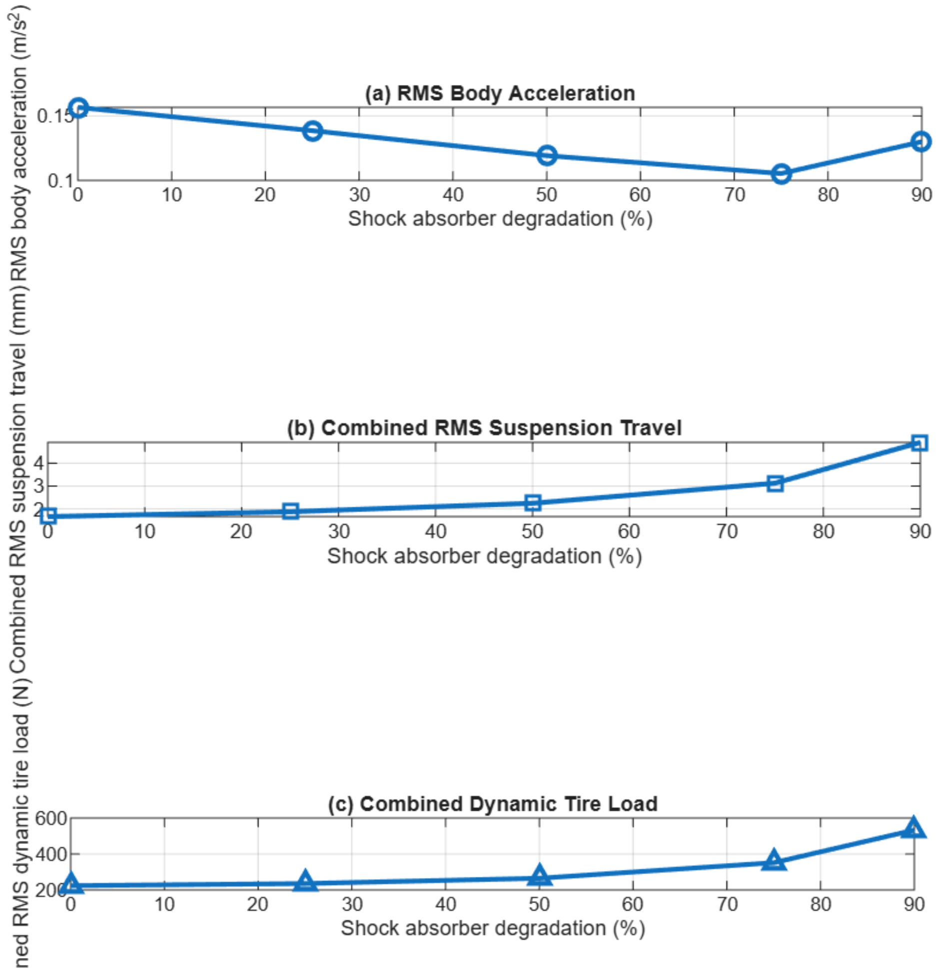

Figure 2. Effect of shock absorber degradation on (a) RMS body acceleration, (b) combined RMS suspension travel, and (c) combined dynamic tire load.

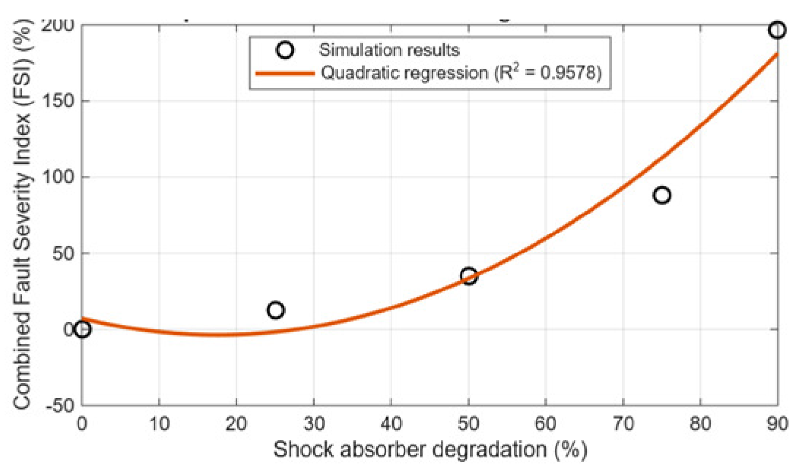

Figure 3. Relationship between shock absorber degradation and combined Fault Severity Index (FSI) with quadratic regression.

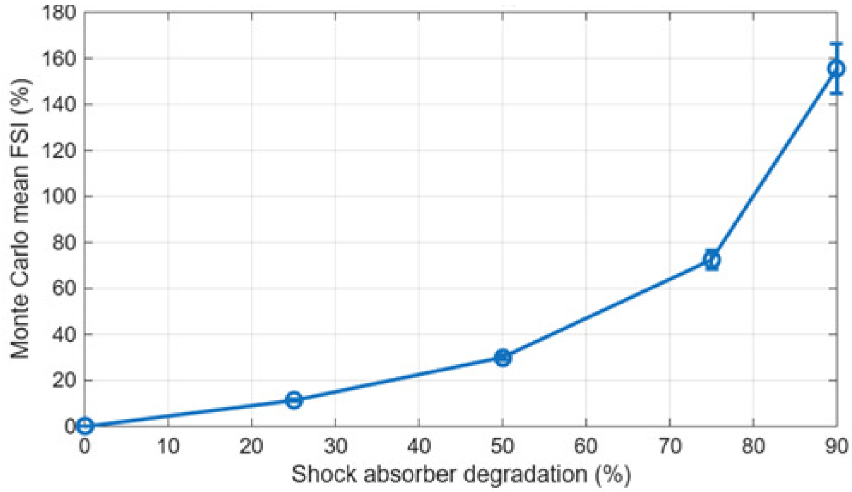

Figure 4. Monte Carlo mean FSI and 95% confidence intervals for different shock absorber degradation levels.

The Monte Carlo quadratic relationship is $FSI_{MC} = -0.66861D + 0.0251518D^2$. The quadratic model adequately describes the degradation trend of FSI_{MC} with driving distance. The model achieved an R^2 of 0.9591, an adjusted R^2 of 0.9183, and an RMSE of 11.42%. These results indicate that the degradation trend remains well captured despite stochastic variability caused by different road conditions.

This uncertainty-aware extension differentiates the proposed framework from a single-profile degradation analysis. The deterministic FSI at 90% degradation is 196.35%, whereas the Monte Carlo mean is 155.53%, demonstrating that road variability can substantially influence the absolute severity response. Therefore, incorporating stochastic realizations provides a more robust interpretation of FSI and reduces the risk of associating a degradation level with a response obtained from only one particular road profile (Rajesh et al., 2025; Satyanarayana et al., 2021). The Monte Carlo results also show that response variability increases with degradation. The coefficient of variation rises from 10.36% at 25% degradation to 19.43% at 90% degradation. This finding suggests that severe damper degradation not only increases the mean suspension-response deviation but also makes the response more sensitive to road-excitation variability (Rajesh et al., 2025; Satyanarayana et al., 2021).

The numerical convergence analysis showed highly stable FSI predictions at 50% degradation. The calculated FSI values were 35.2693%, 35.2706%, and 35.2712% for time steps of 0.002, 0.001, and 0.0005 s, respectively. The maximum difference was below 0.01%, demonstrating that the selected time step of 0.001 s provides adequate numerical resolution. The sensitivity analysis identified vehicle speed and suspension stiffness as the dominant parameters, with normalized sensitivity coefficients of −0.4417 and 0.4415, respectively. Nominal damping showed a moderate influence with a coefficient of −0.2086, whereas sprung mass and tire stiffness showed smaller effects. These findings indicate that FSI interpretation should account for operating speed and suspension characteristics when comparing different vehicle conditions.

Collectively, the results establish three levels of contribution: (i) a physics-based FSI that quantitatively links equivalent damping loss to suspension-response deviation, (ii) a nonlinear degradation–FSI relationship that captures the increasing severity at high damping loss, and (iii) an uncertainty-aware extension demonstrating that the degradation trend remains identifiable under stochastic road variability. This combination provides a more robust simulation-based framework than a single deterministic response evaluation.

Nevertheless, the proposed FSI remains a simulation-based severity indicator. The equivalent damping-loss assumption does not explicitly reproduce hydraulic leakage, valve deterioration, friction, or temperature-dependent nonlinear damping. Therefore, the obtained FSI values and severity bands should not yet be interpreted as universal physical damage thresholds. Experimental damper characterization and real-vehicle road testing are required for calibration and validation before practical diagnostic implementation (Ata & Salem, 2025; Ott et al., 2024; Schramm et al., 2026; Zwosta et al., 2023, 2024).

4. CONCLUSION

A physics-based 4-DOF half-car model was developed to quantify shock-absorber degradation through a normalized Fault Severity Index (FSI) under stochastic road excitation. The results demonstrate that progressive damping loss produces a nonlinear increase in suspension response, while the quadratic degradation model provides a strong representation of the FSI response. Monte Carlo analysis further indicates that the degradation trend remains identifiable under stochastic road variability, supporting the robustness of the proposed indicator.

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The main scientific contribution is the development of a physics-based and uncertainty-aware framework that links equivalent damping loss to suspension-response deviation. This approach provides a more robust degradation indicator than relying on a single deterministic response and identifies vehicle speed and suspension stiffness as important parameters affecting diagnostic sensitivity.

However, the proposed FSI thresholds are currently derived from numerical simulations and have not yet been experimentally validated. Future work should therefore incorporate laboratory tests and real-vehicle measurements to calibrate the degradation thresholds and assess the applicability of the proposed framework for practical condition monitoring and shock-absorber fault diagnosis.

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