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## A Review of Air Suspension Systems for Improving Ride Comfort in Passenger Buses

Ma Thi Huyen Trang<sup>1\*</sup>, Luong Chinh Long<sup>2</sup>, Nguyen Khac Minh<sup>3</sup>, Nguyen Trong Hieu<sup>4</sup>

<sup>1, 2, 3, 4</sup>Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Thai Nguyen, Vietnam.

\*Corresponding Author

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### Abstract

*This paper reviews the role of air suspension systems in improving the ride comfort of passenger buses. The review brings together recent and representative studies on bus suspension dynamics, heavy-vehicle air suspension, air spring modelling, pneumatic vibration isolation, and intelligent suspension control. The literature shows that ride comfort is mainly governed by vehicle speed, load condition, road roughness, suspension configuration, air spring parameters, and the way the suspension is controlled. Compared with conventional leaf spring suspension, air suspension generally provides lower body acceleration, better load adaptability, and improved vibration isolation. Recent bus studies also show that full-vehicle modelling, GENSYS-based air spring models, genetic-algorithm optimisation, and active or semi-active control can further improve ride comfort while maintaining road-holding requirements. However, the reported improvement is not constant across all studies because it depends on the vehicle model, excitation profile, evaluation index, and validation method. This review indicates that future work should move from simplified simulation models toward experimentally validated full-bus models, including seat locations, passenger load distribution, road profile estimation, and chassis-seat-human vibration transmission. The paper provides a concise basis for selecting and developing air suspension systems for modern passenger buses.*

**Keywords:** Air suspension systems; Passenger bus; Ride comfort; RMS acceleration; Air spring; Vibration isolation; Intelligent control

### INTRODUCTION

Ride comfort is a major performance requirement in passenger buses, particularly in long-distance coaches and urban buses operating repeatedly on uneven road surfaces. Passengers are exposed to vibration transmitted from the tire-road contact through the axle, suspension, chassis, floor, and seat. When this vibration is not properly isolated, it can reduce comfort, increase fatigue, and accelerate damage to vehicle components. For this reason, ride comfort is commonly assessed using vibration-based indices, including the root-mean-square (RMS) or frequency-weighted RMS acceleration defined in whole-body vibration standards (ISO 2631-1, 1997). Road excitation is often described using road-profile classes such as those specified in ISO 8608 (2016).

Conventional buses have widely used leaf spring suspension systems because they are simple, robust, inexpensive, and suitable for carrying high loads. Their main limitation is that the spring stiffness is essentially fixed. When the vehicle load

changes from empty to full load, the suspension cannot maintain the same natural frequency or vibration isolation performance. In practical service, this limitation becomes more visible at higher speeds, on rough roads, and at rear seating positions where pitch and roll responses may contribute to discomfort.

Air suspension systems offer a more flexible solution. By using compressed air as the elastic medium, an air spring can provide nonlinear stiffness, height regulation, and better adaptability to load variation. These features have made air suspension increasingly common in coaches, heavy-duty vehicles, and premium buses. Recent studies on bus models and heavy vehicles have shown that air suspension can reduce body acceleration and dynamic wheel load compared with conventional leaf spring systems (Ha *et al.*, 2022; Hung, 2022; Le, 2017; Long *et al.*, 2018; Nguyen *et al.*, 2020a, 2020b; Tan *et al.*, 2021). At the same time, new studies have moved beyond passive systems and have considered air spring parameter optimisation, neural-network PID control,

fuzzy PID control, and active air suspension (Do *et al.*, 2025; Hung, 2022; Jiang and Cheng, 2023; Zhang *et al.*, 2024).

Although many studies have reported the advantages of air suspension, the magnitude of ride-comfort improvement is not uniform. The reported benefit depends on the air spring model, vehicle speed, road profile, vehicle load, seat location, control method, and whether the study is based on simulation or road testing. Therefore, a focused review is needed to clarify the main findings reported in the literature and to identify the issues that still require further validation. This paper reviews recent and representative studies on air suspension systems for passenger buses and heavy vehicles, with emphasis on ride comfort, modelling approaches, optimisation methods, and future research directions.

## REVIEW SCOPE AND SELECTION OF LITERATURE

This paper is a focused narrative review rather than a statistical meta-analysis. The reviewed literature was selected to cover four groups of work that are directly related to passenger bus ride comfort. The first group includes studies on bus suspension dynamics and air suspension performance. The second group includes heavy-vehicle and semi-trailer studies, because these vehicles have operating characteristics similar to buses: large sprung mass, strong load variation, multi-axle configuration, and strict requirements on both comfort and road friendliness. The third group includes air spring modelling and pneumatic vibration isolation studies. The fourth group includes recent studies on active, semi-active, and intelligent suspension control.

Priority was given to studies published from 2021 to 2025, while several classical references were retained because they provide the theoretical basis for vehicle dynamics, air spring modelling, and comfort assessment. To strengthen the relevance to Vietnamese bus and heavy-vehicle applications, several studies from the Thai Nguyen University of Technology research group were also considered, especially those dealing with bus suspension parameters and heavy-vehicle air suspension optimisation (Le, 2017; Long *et al.*, 2018; Nguyen *et al.*, 2020a, 2020b).

## FUNDAMENTALS OF RIDE COMFORT AND AIR SUSPENSION

Ride comfort is affected by the level, frequency content, and direction of vibration transmitted to the human body. In bus applications, vertical acceleration is usually the primary index, but pitch, roll, and seat vibration can also affect passenger perception. A full evaluation should therefore consider not only the vertical body acceleration but also vibration at different seat positions, suspension working space, dynamic tire load, and vehicle attitude responses.

The suspension system is the main path through which road-induced vibration reaches the bus body. A leaf spring performs both load-carrying and guidance functions. This structure is mechanically simple, but its vibration isolation ability is limited when the load changes. In contrast, an air suspension system separates the load-carrying function from the air pressure and volume characteristics of the air spring. The effective stiffness can be adjusted through air pressure,

and in more advanced systems, the air chamber, auxiliary reservoir, orifice, damping element, levelling valve, and controller can be designed together to achieve a better compromise between comfort and road holding.

The physical behaviour of an air spring is nonlinear. Its response depends on the thermodynamic process inside the air chamber, pressure variation, volume change, air mass flow, orifice damping, rubber bellow deformation, and friction. Therefore, simple linear models may be useful for early analysis but can miss important dynamic characteristics. More detailed models, such as three-dimensional air spring models, auxiliary-reservoir models, and GENSYS-based models, have been used to improve the accuracy of simulation and optimisation (Berg, 1999; Eskandary *et al.*, 2016; Hung, 2022; Quaglia and Sorli, 2001).

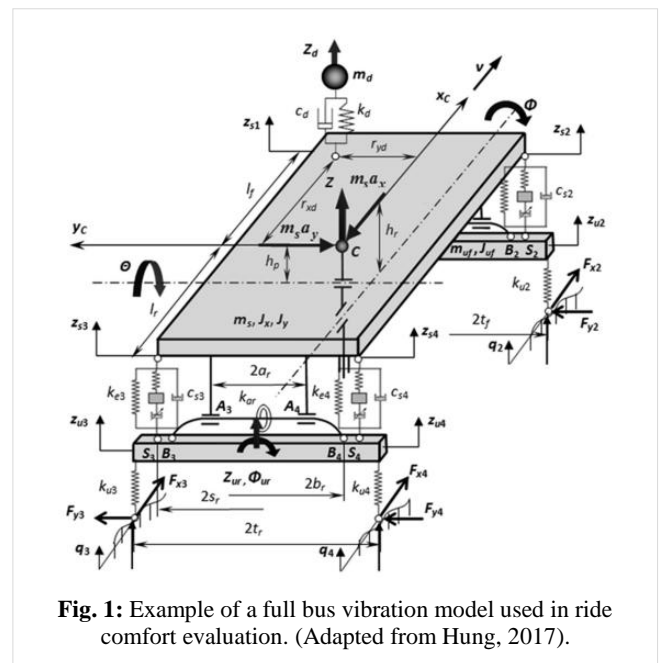


Fig. 1: Example of a full bus vibration model used in ride comfort evaluation. (Adapted from Hung, 2017).

## SYNTHESIS OF RECENT STUDIES

### Bus-level Studies

For passenger buses, the most relevant studies are those using bus-specific dynamic models and air suspension configurations. Long *et al.* (2018) developed a three-dimensional bus model and showed that suspension stiffness and damping parameters have a direct influence on weighted RMS acceleration at the driver, middle-passenger, and rear-overhang positions. This point is important because passenger buses do not have a uniform vibration level along the body. A model that includes only one seat or one vertical degree of freedom may underestimate the variation in comfort between seating positions.

Tan *et al.* (2021) investigated the ride comfort of buses equipped with an air suspension system. Their work is useful because it connects air suspension performance with realistic bus operating conditions. Hung (2022) further developed this direction by optimising air spring parameters for a full bus model using a genetic algorithm. In that study, a GENSYS-based air spring model was used, and the optimisation

**Table 1:** Synthesis of reviewed studies related to air suspension and ride comfort.

Study group	Representative references	Main focus	Relevance to passenger buses
Bus ride comfort	Long <i>et al.</i> (2018), Tan <i>et al.</i> (2021), Hung (2022)	Full or bus-specific models; seat-position comfort; air spring optimisation	Most directly applicable to passenger bus suspension design
Heavy-vehicle air suspension	Le (2017), Nguyen <i>et al.</i> (2020a, 2020b), Ha <i>et al.</i> (2022)	Dynamic load coefficient, multi-axle response, load and speed effects	Useful because buses and heavy vehicles share large mass and load variation
Air spring modelling	Atindana <i>et al.</i> (2023), Eskandary (2016), Quaglia and Sorli (2001)	Nonlinear stiffness, auxiliary reservoir, friction, orifice damping, dynamic air spring behaviour	Provides the modelling basis for realistic prediction of ride comfort
Pneumatic isolation review	Atindana <i>et al.</i> (2023)	Classification, modelling methods, control options, and future directions	Clarifies strengths and limitations of pneumatic suspension
Intelligent and active control	Jiang and Cheng (2023), Zhang <i>et al.</i> (2024), Do <i>et al.</i> (2025)	BP neural-network PID, fuzzy PID, GA optimisation, active air suspension	Shows the likely development direction for modern bus suspension systems

considered both ride comfort and road safety. The reported results show that the optimal air spring parameters can improve ride comfort while keeping road-holding performance within an acceptable range. This supports the view that air suspension should not be evaluated only as a replacement for a leaf spring, but as a tunable subsystem whose parameters need to be selected for the vehicle and operating condition.

**Air Spring Modelling and Pneumatic Isolation**

Pneumatic vibration isolation has been reviewed in detail by Atindana *et al.* (2023). Their review shows that air suspension systems are used not only in chassis suspension but also in cabin and seat suspension. The main advantages are variable stiffness, load adaptability, and flexible control possibilities. However, the same review also points out practical issues such as modelling complexity, nonlinear behaviour, air supply requirements, and the need for reliable control.

Classical modelling studies remain important. Atindana *et al.* (2023) proposed a three-dimensional air spring model with friction and orifice damping. Quaglia and Sorli (2001) presented a dimensionless analysis and design procedure for pneumatic suspension with an auxiliary reservoir. Eskandary *et al.* (2016) analysed an air suspension system with independent height and stiffness tuning, showing that air pressure and chamber configuration can be used to adapt the suspension to load and road conditions. These works explain why a realistic air spring model is necessary before drawing strong conclusions about ride comfort.

**Recent Control Trends**

Recent research has moved toward controlled air suspension systems. Jiang and Cheng (2023) designed a BP neural-network PID controller for an air suspension system while considering the stiffness of rubber bellows. Their results indicate that intelligent PID tuning can improve suspension response when nonlinear air spring behaviour is included. Zhang *et al.* (2024) developed a genetic-algorithm-optimised fuzzy PID control strategy and reported reductions in RMS vertical body acceleration, suspension deflection, and wheel dynamic load compared with passive suspension. Do *et al.* (2025) recently addressed PID controller design for an active

air suspension system on a passenger bus, which is directly aligned with the future development of bus suspension control.

These studies also show a clear development trend from passive air suspension toward semi-active, active, and intelligent control strategies. For passenger buses, this shift is technically attractive but must be evaluated carefully. Actuators, compressors, valves, sensors, and controllers introduce cost, delay, energy consumption, and reliability constraints. A control method that performs well in simulation may not be suitable for bus operation unless actuator bandwidth, air supply dynamics, sensor noise, and fail-safe behaviour are considered.

Table 1 summarizes the main groups of reviewed studies and their relevance to passenger bus ride comfort. The table is intended to show the direction of evidence rather than to combine the results into a single percentage improvement, because the models, road inputs, and evaluation indices differ among the studies.

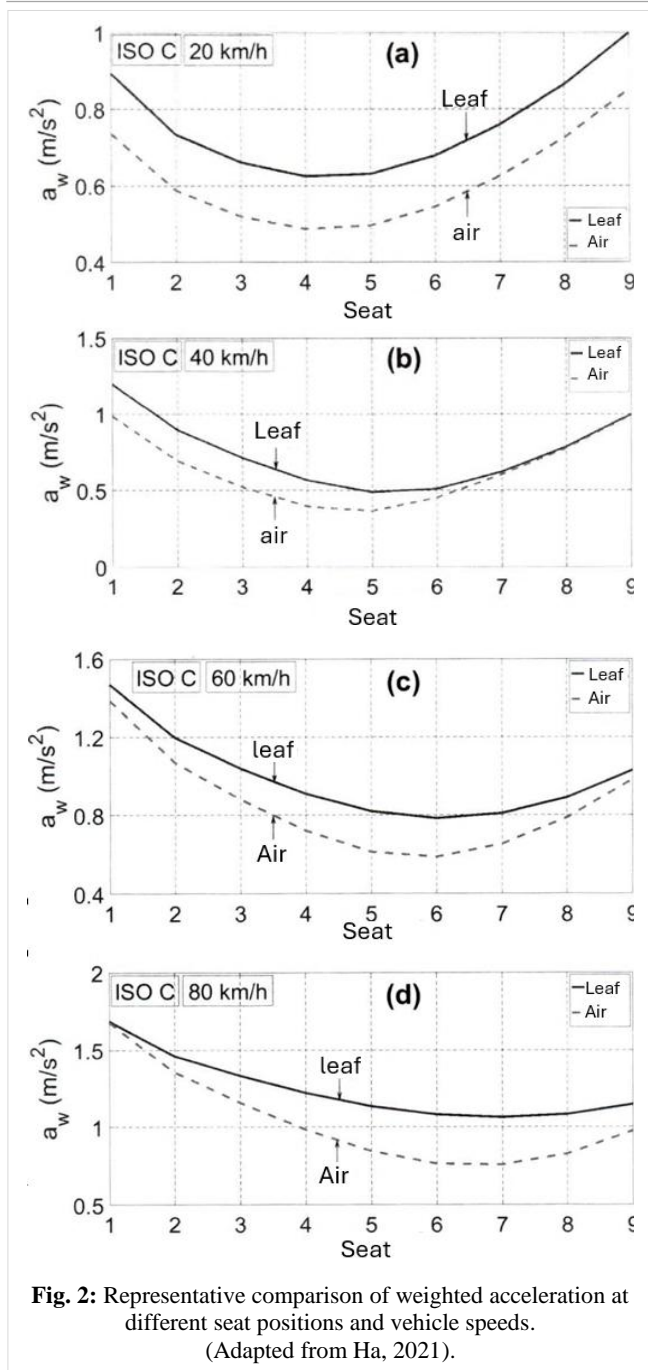
**Effect of Vehicle Speed**

Vehicle speed is one of the clearest factors affecting ride comfort. As speed increases, the frequency and amplitude of road-induced excitation transmitted to the suspension also increase. The reviewed bus studies show that air suspension generally maintains lower RMS acceleration than leaf spring suspension at different speeds (Hung, 2022; Tan *et al.*, 2021). This trend is consistent with basic vehicle dynamics: when excitation becomes stronger, a suspension with better vibration isolation and more suitable effective stiffness becomes more beneficial (Gillespie, 1992).

However, speed should not be interpreted alone. A comfort result obtained at 60 km/h on an ISO Class C road cannot be directly compared with a result at 80 km/h on another road class if the vehicle load, seat position, and evaluation index are different. For this reason, future studies should report vehicle speed together with road roughness, load condition, seat position, and frequency weighting method.

**Effect of Load Condition**

Load variation is another important issue in passenger buses. During service, a bus may operate with only a few



**Fig. 2:** Representative comparison of weighted acceleration at different seat positions and vehicle speeds. (Adapted from Ha, 2021).

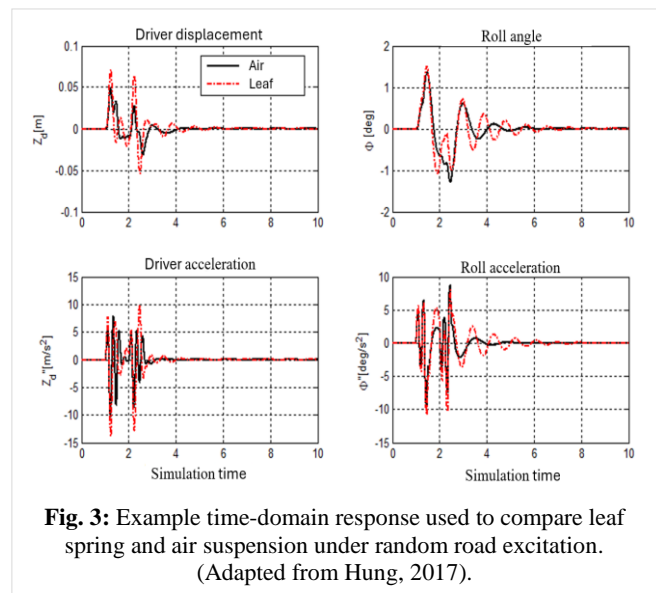
passengers, at nominal full load, or under temporarily high load. A leaf spring system cannot adjust its stiffness to the actual passenger load, whereas an air suspension can regulate pressure and ride height. This explains why air suspension tends to show more stable comfort performance over different load cases.

The benefit of air suspension under load variation has also been observed in heavy-vehicle studies (Ha *et al.*, 2022; Le, 2017; Nguyen *et al.*, 2020a, 2020b). For buses, this finding should be extended to include passenger distribution. A full-load case with passengers evenly distributed along the bus body may produce a different pitch and rear-overhang response than a case where passengers are concentrated near the rear. Therefore, passenger distribution should be reported when ride comfort is evaluated experimentally.

### Effect of Road Roughness and Seat Location

Road roughness determines the input energy transmitted into the suspension. Air suspension is expected to be more beneficial on rougher roads, but the improvement is limited by suspension travel, damping, tire dynamics, and the excitation frequency range. If the road profile contains strong low-frequency components close to the vehicle body mode, an improperly selected air spring may still generate resonance amplification. This is why air spring parameters and damping should be selected together rather than independently.

Seat location is particularly important in buses. The driver, middle passengers, and rear passengers do not experience the same vibration level. Previous bus modelling has shown that suspension parameters can affect different locations differently (Long *et al.*, 2018). A review conclusion based only on the vehicle body centre of gravity may therefore be incomplete. A more convincing bus comfort study should measure or simulate vibration at multiple seat locations and should combine chassis response with seat transmissibility.



**Fig. 3:** Example time-domain response used to compare leaf spring and air suspension under random road excitation. (Adapted from Hung, 2017).

### Passive, Semi-active, and Active Air Suspension

Passive air suspension already improves ride comfort because of its nonlinear stiffness and load adaptability. Semi-active and active air suspension can potentially improve performance further by adjusting the system response in real time. Control methods such as PID, fuzzy PID, neural-network PID, adaptive control, and optimisation-based tuning have been investigated in recent studies (Do *et al.*, 2025; Ha, 2021; Hu *et al.*, 2025; Zhang *et al.*, 2024).

Nevertheless, active control should be assessed with practical constraints. The controller must operate within the limits of the pneumatic actuator, valve flow rate, compressor capacity, air tank pressure, sensor accuracy, and computational delay. In bus applications, reliability and maintenance cost are also important. Therefore, a practical development path may be to start from passive air suspension with well-optimised air spring parameters, then move to semi-active or active control only where the expected comfort benefit justifies the added system complexity.

## DISCUSSION AND FUTURE RESEARCH DIRECTIONS

The reviewed studies show a clear tendency: when properly designed, air suspension can reduce the vibration transmitted to the bus body more effectively than a conventional leaf-spring suspension. This benefit is mainly related to lower effective stiffness, load-dependent adjustment, ride-height regulation, and the nonlinear behaviour of air springs. In bus applications, full-vehicle modelling and optimisation-based studies provide stronger evidence than simple quarter-car models, because passenger buses are strongly affected by axle layout, mass distribution, pitch and roll motion, and seat location (Ha *et al.*, 2022; Hung, 2022).

However, the improvement should not be reported as a universal percentage. The values found in the literature differ because the studies use different road classes, speeds, load cases, air spring models, damping assumptions, seat positions, and comfort indices. Therefore, a statement such as "air suspension improves ride comfort by 20-30%" is only meaningful when the tested vehicle, road condition, load condition, evaluation index, and reference suspension are clearly defined.

Another point that should not be overlooked is the trade-off between ride comfort, suspension working space, and road holding. A softer suspension may reduce body acceleration, but it can also increase suspension deflection or dynamic tire load. For this reason, RMS acceleration alone is not sufficient to judge suspension performance. A more reliable assessment should consider body acceleration, suspension deflection, dynamic tire load, pitch and roll responses, and passenger-seat vibration at the same time. This multi-index view is consistent with recent optimisation studies (Hung, 2022; Nguyen *et al.*, 2020b; Zhang *et al.*, 2024).

From this comparison, several research directions deserve priority. First, more full-bus experimental validation is needed, especially road tests under clearly defined road classes, speed ranges, and loading conditions. Second, comfort should be evaluated at several seat positions, because vibration at the driver seat, middle seats, and rear overhang can be quite different. Third, future models should link chassis suspension, seat suspension, and human-body response, since passengers feel the final vibration transmitted through the seat rather than the acceleration of the bus body alone. Recent seat-level air spring studies also show that friction damping and seat suspension characteristics can strongly influence the final comfort response (Hu *et al.*, 2025).

Finally, semi-active and active air suspension should be assessed together with practical implementation constraints, including valve dynamics, actuator bandwidth, compressor capacity, reservoir pressure, energy consumption, sensor noise, reliability, and maintenance cost. Future papers should also report the vehicle model, road profile, speed, load condition, seat position, evaluation index, filtering or frequency-weighting method, and validation method in a consistent way. Such details would make future comparisons more reliable and would provide a stronger technical basis for applying air suspension systems in modern passenger buses.

## CONCLUSION

Overall, the literature reviewed in this paper shows that air suspension is a suitable technical solution for improving ride comfort in passenger buses, particularly when the vehicle operates under varying load and road conditions. Its main advantages come from load-adaptive stiffness, ride-height control, and better vibration isolation than conventional leaf-spring suspension. Recent modelling, optimisation, and control studies further indicate that the benefit can be increased when air spring parameters and control strategies are properly selected.

However, the reported improvement should not be treated as a fixed value. It depends on the bus model, road profile, vehicle speed, load condition, seat position, comfort index, and validation method. For practical application, air suspension should therefore be evaluated as part of an integrated chassis-seat comfort system rather than as an isolated component. Full-bus road tests, standardised reporting, and validation at several passenger positions are needed to support more reliable design recommendations for modern buses.

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## Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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