EFFECTS OF SUSPENSION AND AXLE MODIFICATIONS ON THE VEHICLE DYNAMICS OF AN EXTENDED MIDIBUS WITH A NARROW AXLE

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ABSTRACT: *In this study, the effects of rear axle and suspension modifications on the dynamic behavior of an extended midibus were analyzed. Modifications included an increased rear track width, achieved using a patented distancer system, and the integration of additional air and leaf springs. These changes were designed to enhance lateral stability, load distribution, and handling performance. A rigid-body vehicle dynamics model, validated through experimental testing, was used to evaluate the impact of these modifications under steady-state cornering conditions. The results demonstrated that the wider rear track and improved suspension geometry significantly reduced roll angle, enhanced yaw stability, and improved maneuverability. These findings provide a practical framework for optimizing stability and handling in extended vehicle configurations, contributing to safer and more dynamically robust midibus designs.*

KEYWORDS: *Vehicle Dynamics, Rear Axle Modification, Suspension, Extended Midibus, Lateral Dynamics*

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1. INTRODUCTION

The structural design of vehicle bodies varies widely depending on market demands and specific application requirements. Modifications to the vehicle body, particularly those that affect load and passenger capacities or alter dimensional attributes, can have a profound impact on dynamic performance, especially in terms of stability and handling. This study aims to investigate these effects using rigid body modelling in MATLAB, focusing specifically on a midibus-type vehicle's dynamics across several modified configurations.

In recent years, the influence of dimensional variations in vehicle design on dynamic behavior has garnered significant attention, particularly in cases where modifications to the vehicle's body structure, such as extending or widening for increased passenger capacity, impact handling and stability. For example, Botosso and Vilela [1] examined the effects of manufacturing-induced dimensional tolerances on suspension systems. Their analysis revealed that even small variations in key attachment points and suspension components can significantly alter the vehicle's dynamic response, particularly in terms of camber and toe angles. While their study focuses on suspension tolerances, similar principles apply to body modifications, as changes in vehicle dimensions can shift weight distribution and suspension loads, thus affecting handling and stability. Through simulations such as Kinematic and Compliance (K&C) tests and constant-radius maneuver evaluations, their work identifies critical points in vehicle dynamics that inform tolerance control criteria aimed at improving handling and stability.

Modifications to the chassis, such as increasing payload and shifting the center of gravity (CG), have also been shown to affect vehicle dynamics, particularly in handling and stability performance. As Pandurengan [2] highlighted, these changes necessitated objective testing to accurately assess stability concerns, including rollover propensity. Their research demonstrated the need for further design adjustments, particularly to the suspension system, in response to increased payload and altered CG, underlining the importance of understanding the dynamic consequences of such vehicle modifications.

Additional studies, like those by Arndt et al. [3], have investigated how varying loading conditions affect vehicle dynamics, demonstrating that increased cargo and occupant loadings can alter steering behavior, transient response, and the propensity for wheel lift during high-demand maneuvers. These findings underscore the significance of physical modifications, whether in load distribution or dimensional changes, and their substantial impact on vehicle stability and handling performance.

Garbin and Neto [4] provided further insights through their study on the addition of leaf springs to heavy trucks. Primarily aimed at increasing stiffness and lifting the rear axle to comply with legal weight limits, their modifications altered the vehicle's CG and inertial properties, which in turn affected roll dynamics, lateral stability, and rollover thresholds. Using computer simulations, they compared the performance of original and modified vehicles, concluding that while lateral dynamics improved under full-load conditions, performance in other scenarios was compromised. These findings point to the trade-offs inherent in structural modifications and their varying effects on vehicle dynamics.

Building on these studies, this research investigates the effects of extending and widening a midibus-type vehicle to increase passenger capacity. The baseline vehicle model, provided by the original equipment manufacturer (OEM), serves as the reference point. A modified version, developed through dimensional changes such as width and track adjustments, is evaluated to assess the impact of these alterations on vehicle stability and handling performance. The research integrates a patented distancer system to increase track width and improve lateral stability.

Rigid body modelling with defined degrees of freedom (DOF) is employed to simulate and analyze the behavior of both baseline and modified vehicles under various driving conditions. This methodology allows for a precise evaluation of how geometric modifications affect CG, load distribution, and dynamic response to external forces, all of which contribute to the overall stability of the vehicle. By exploring these aspects, this study provides valuable insights into vehicle dynamics, offering guidance for better design practices tailored to specific market applications.

2. METHODOLOGY

2.1. Vehicle Modifications

To accommodate the extended configuration and increased passenger capacity of the midibus, significant modifications were made to the rear axle and suspension system, as outlined in Table 1. These changes aimed to enhance lateral stability, load distribution, and overall handling performance under dynamic conditions.

Table 1: *Comparative dimensions of baseline and modified vehicle*

Parameter	Baseline	Modified/Final
Width	2020 mm	2320 mm
Length	7367 mm	8096 mm
Track Width	1732 mm	1732 mm / 1852 mm
Curb Weight	2245 kg	4940 kg

2.1.1. Integration of the Distancer

One of the primary modifications involved the integration of a patented system, the "distancer", which increases the rear axle track width [5]. This component, shown in Figure 1, manufactured from high-strength steel, acts as an intermediary connection between the axle and the wheel, extending the track width from 1732 mm to 1852 mm. The design features circular profiles on both axle- and wheel-facing surfaces, along with precision bolt holes to ensure secure alignment and attachment.

The track width extension directly improves lateral stability by reducing roll moments during cornering and minimizing the risk of rollover. Additionally, the distancer helps distribute dynamic forces more evenly, addressing stress concentrations that can arise in extended vehicle configurations.

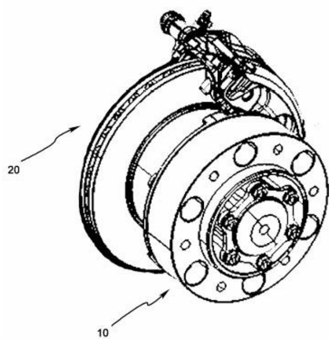


Figure 1. *Patented Distancer system for track width extension [5]*

2.1.2. Suspension adjustments

To support the increased load and stabilize the extended structure, the rear suspension system was redesigned with two key enhancements:

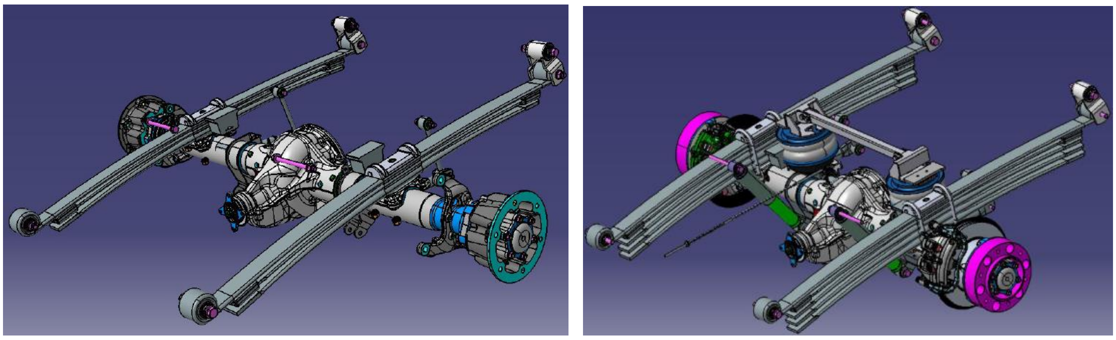
2.1.2.1. Integration of Air Springs:

Two air springs were added symmetrically to the left and right sides of the rear axle. These air springs provide additional support for the increased passenger and cargo loads, contributing to better load distribution and enhanced ride comfort. They also improve pitch control by reducing oscillations under varying dynamic conditions.

2.1.2.2. Revised Suspension Geometry:

The geometry of the suspension was adapted to ensure effective load management during acceleration, braking, and cornering. This included recalibrating the suspension stiffness to account for the increased vehicle weight and modified center of gravity.

The integration of the distancer and air springs, along with adjustments to the suspension geometry, collectively enhance the vehicle's dynamic behavior. Figures 2a and 2b illustrate the original and modified rear axle and suspension configurations, highlighting the structural and functional changes introduced to achieve the desired performance improvements.



(a) ***(b)***

Figure 2. *Rear axle arrangements both for original vehicle (a) and modified vehicle (b)*

2.2. Vehicle Model

The vehicle model was developed to evaluate the effects of rear axle and suspension modifications on lateral dynamics, with a particular focus on handling performance and stability. The model assumes constant longitudinal velocity, as longitudinal dynamics are not significantly affected by the modifications under investigation. This simplification enables a detailed analysis of lateral forces, moments, and their impact on vehicle stability. The model incorporates five degrees of freedom (DOF): lateral slip, yaw, vertical motion, roll, and pitch. Tire dynamics were modelled using the Wade Allen STI tire model [6, 7], incorporating data from Heydinger et al. [8]. The model calculates lateral and longitudinal forces for a range of longitudinal slip (S) and lateral slip angles (α), expressed in a normalized form with respect to μF_z, as shown in Equations (1) and (2).

$$\frac{F_y}{\mu F_z} = \frac{f(\sigma) K_s \tan\alpha}{\sqrt{K_s^2 \tan^2\alpha + K'^2_c S^2}} + Y_\gamma \gamma \qquad (1)$$

$$\frac{F_x}{\mu F_z} = \frac{f(\sigma) K'_c S}{\sqrt{K_s^2 \tan^2\alpha + K'^2_c S^2}} \qquad (2)$$

Where, μ represents the friction coefficient of the tire, σ denotes the composite slip function, f(σ) is the force saturation function, Ks is the lateral stiffness coefficient, and K'c refers to the modified longitudinal stiffness coefficient.

The vertical load distribution on each wheel (F_z), is critical for evaluating roll stability and load transfer during cornering. Equations (3) and (4) describe how the vertical forces are distributed between the front and rear wheels, considering static load, lateral acceleration, and roll effects. Longitudinal load transfer is excluded based on the assumptions of level road and constant longitudinal velocity. In these equations, m represents the total mass of the vehicle, h is the height of the center of gravity for the sprung mass, M_ϕ roll moment caused by lateral forces acting on the suspension system, t refers to the track width, and subscripts f, l, r indicates front, left, right, or rear, respectively.

$$F_{Zf(l,r)} = \frac{m_f \cdot g}{2} - \frac{a_y \cdot m_f \cdot h}{2 \cdot t_r} \pm \frac{M_{\phi f}}{t_r} \qquad (3)$$

$$F_{Zr(l,r)} = \frac{m_r \cdot g}{2} + \frac{a_y \cdot m_r \cdot h}{2 \cdot t_r} \pm \frac{M_{\phi r}}{t_r} \qquad (4)$$

Equations (5) and (6) define the slip angles (α) for the front and rear wheels, which are essential for calculating lateral forces during cornering. These angles represent the difference between the tire's actual travel direction and its alignment, capturing the vehicle's steering dynamics.

$$\alpha_{f(l,r)} = \delta_{f(l,r)} - tan^{-1}\left(\frac{v + a.r}{U \pm \frac{t_f}{2}.r}\right) \qquad (5)$$

$$\alpha_{r(l,r)} = tan^{-1}\left(\frac{v - b.r}{U \pm \frac{t_r}{2}.r}\right) \qquad (6)$$

The dynamic behavior of the vehicle is described by Equations (7) through (11), which model the forces and moments acting on the vehicle during lateral motion. These include the equations of motion for lateral acceleration, yaw rate, and roll dynamics, as well as the effects of suspension stiffness K_φ and damping C_φ. The roll angle equation, for instance, accounts for the influence of roll stiffness and damping on vehicle stability during cornering maneuvers.

$$m(\dot{W} - qV) = [F_{spring} + F_{damper} + F_{tire} + \Delta F_z] \qquad (7)$$

$$m(\dot{V} + rU) = \left[F_{yrL} + F_{yrR} + \left(F_{yfL} + F_{yfR}\right) \cos\delta + \left(F_{xfL} + F_{xfR}\right) \sin\delta - \left(F_{bfL} + F_{bfR}\right) \sin\delta\right] \quad (8)$$

$$I_{xx}\dot{p} = \left[m_s \cdot (\dot{V} + r \cdot U)(h_{cg} - h_{rc}) + m_s g(h_{cg} - h_{rc})\varphi - C_\varphi \dot{\varphi} - K_\varphi \varphi\right] \quad (9)$$

$$I_{zz}\dot{r} = \begin{bmatrix} a\left(F_{yfL} + F_{yfR}\right) \cos\delta + \frac{t_f}{2}\left(F_{yfL} - F_{yfR}\right) \sin\delta + \cdots \\ \ldots + a\left(F_{xfL} + F_{xfR}\right) \sin\delta + \frac{t_r}{2}\left(F_{brL} - F_{brR} - F_{xrL} + F_{xrR}\right) - \cdots \\ \ldots - b\left(F_{yrL} + F_{yrR}\right) - \frac{t_f}{2}\left(F_{xfL} + F_{bfR} - F_{xfR} - F_{bfL}\right) \cos\delta - a\left(F_{bfR} + F_{bfL}\right) \sin\delta \end{bmatrix} \quad (10)$$

$$I_{yy}\dot{q} = \begin{bmatrix} m\left(\dot{\dot{V}} + rU\right) d.p - 2(K_{sf}a - K_{sr}b)w - 2(K_{sf}a^2 + K_{sr}b^2)q - 2(C_f a - C_r b)\dot{w} - \cdots \\ \ldots - 2(C_f a^2 + C_r b^2)\dot{q} + F_x h_{cg} w \\ \end{bmatrix} \quad (11)$$

The vehicle dynamics model used in this study was previously validated in [7], demonstrating its accuracy under operating conditions comparable to those in the present analysis. In the meantime, a steady state turning road test at a constant speed was also performed to ensure that the model can accurately presents the vehicle body’s lateral behavior under dynamic conditions. For the reason, body lateral acceleration response was analyzed.

3. FINDINGS AND DISCUSSION

3.1. Testing

The real-world data were collected from the modified vehicle. A series of steady state turning tests were performed at constant 20 km/h vehicle longitudinal velocity and 20° steering wheel inputs. Data acquisition was achieved using a 3-axis IEPE accelerometer mounted at the vehicle’s center of gravity, with a sampling rate of 20,000 Hz. The accelerometer was rigidly fixed to the vehicle using a specially designed mounting platform to ensure accurate measurement of lateral accelerations. Data collection was handled by a DEWE 43A data acquisition system [9], which continuously recorded the vehicle's dynamic responses during testing. Figure 3 shows the comparison between simulation and experimental data for the 20 km/h, 20° steering input test case. According to the Figure, the simulation and experimental curves show a reasonable agreement, particularly in the steady-state regions where lateral acceleration stabilizes.

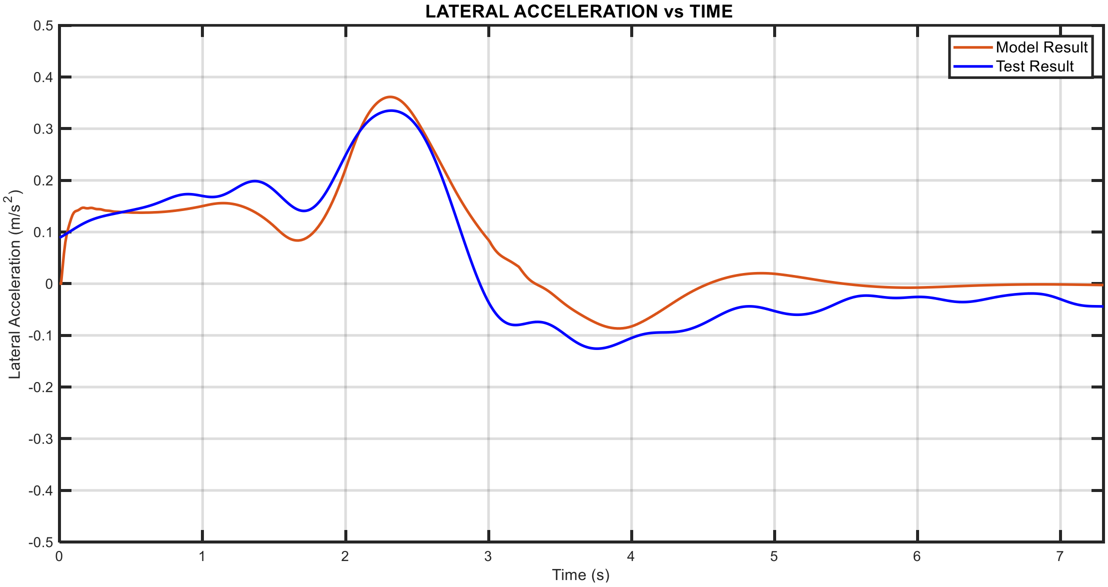


Figure 3. *Simulated and experimental lateral acceleration responses for a steady-state turning test at 20 km/h and 20° steering input*

The experimental tests were conducted on a road surface that may not have been perfectly smooth or consistent. Minor irregularities, such as uneven pavement or small inclinations, could introduce variations in the vehicle's dynamic response that are not reflected in the idealized model. Despite these deviations, the model successfully captures the overall trends and steady-state behavior of the vehicle's lateral dynamics. This validates its applicability for evaluating the effects of dimensional modifications on vehicle stability and handling.

3.2. Effects of Rear Axle Modifications

The Figures from 4a to 4d illustrate key motion parameters and the vehicle's path under various dynamic scenarios. These parameters, including vehicle's trajectory, yaw rate, roll angle and roll rate, were analyzed to evaluate the impact of dimensional modifications on the vehicle's handling and stability.

According to the figures, the observed increase in yaw rate for the modified configuration (Figure 4b), particularly during transient maneuvers, is attributed to the wider rear track enabled by the distancer. This enhanced maneuverability is also evidenced by the improved vehicle path and reduced turning radius (Figure 4a). This increased track width enhances lateral stability, allowing the vehicle to respond more dynamically to steering inputs without compromising stability. Meanwhile, a noticeable reduction in roll angle, given in Figure 4c, was observed for the modified vehicle under steady-state cornering conditions. This reduction is primarily due to the increased rear track width achieved through the distancer, which reduces the roll moment arm. Additionally, the integration of air springs and increased leaf numbers, contributes to greater vertical stiffness, further minimizing body roll during cornering. These combined effects enhance the vehicle's lateral stability, even at low speeds, where roll tendencies are primarily governed by geometry and suspension characteristics rather than inertial effects.

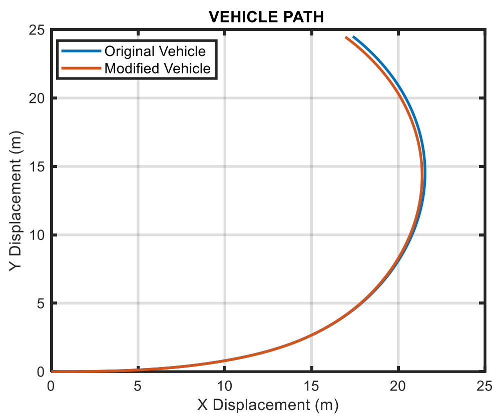


__Figure 4a.__ Trajectory of the vehicles

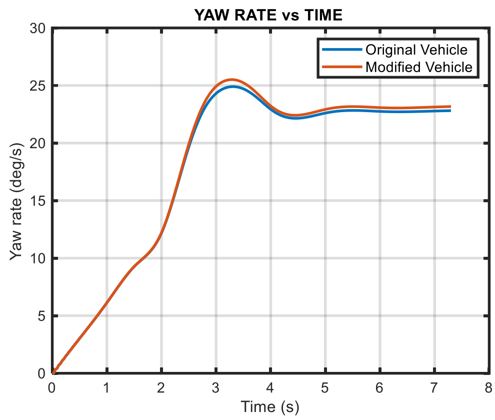
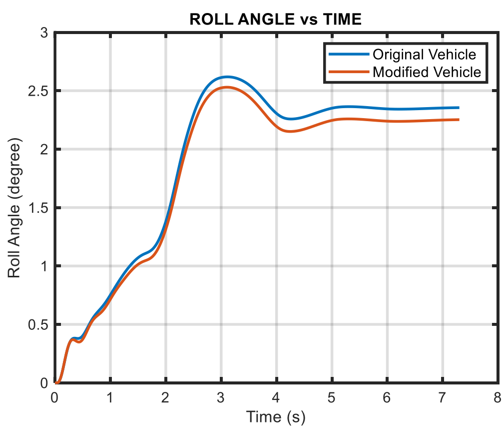


__Figure 4b__. Yaw rate responses of the vehicles



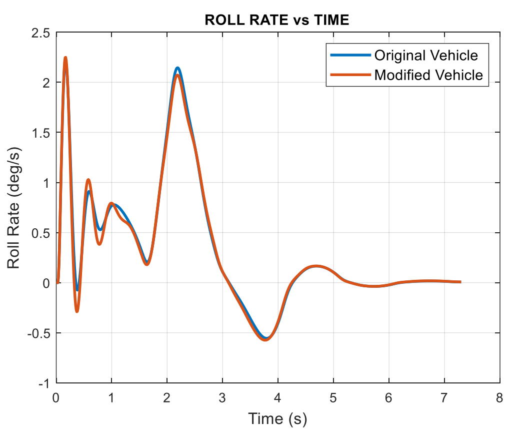


Figure 4c. *Roll angle responses of the vehicles* ***Figure 4d.*** *Roll rate responses of the vehicles*

For the roll rate presented in Figure 4d, the modified vehicle initially exhibits slightly higher peaks, likely due to the changes in mass distribution and increased suspension stiffness. The higher initial peaks reflect a more pronounced dynamic response during transient maneuvers. However, as the motion stabilizes, the roll rate values of both configurations converge, indicating that the modifications do not adversely affect the vehicle's roll dynamics during steady-state conditions.

4. CONCLUSION

This study investigated the effects of rear axle and suspension modifications on the dynamic behavior of an extended midibus. By integrating a patented distancer system to increase rear track width and incorporating additional air and leaf springs to the suspension, the modified configuration demonstrated notable improvements in lateral stability, roll angle reduction, and overall handling performance under steady-state cornering conditions. The findings provide valuable insights for designing safer and more dynamically robust passenger vehicles, particularly those with extended configurations. The results highlight the importance of targeted structural and suspension modifications in addressing the challenges associated with increased load capacities and altered vehicle geometries. Specifically, the use of track widening and optimized suspension setups offers a practical framework for enhancing stability and handling without compromising ride comfort.

Future work could expand on this research by exploring additional vehicle operating scenarios, such as higher speeds and dynamic maneuvers like lane changes or obstacle avoidance. Incorporating advanced tire models or real-time suspension control systems could further refine the analysis and optimize vehicle performance. Moreover, the implications of these modifications on ride comfort, fuel efficiency, and long-term durability warrant further investigation to ensure comprehensive design optimization for extended vehicle platforms.

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