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Dynamic Analysis of Micromobility In-Wheel Suspension System – Enhancing Safety in Urban Environments

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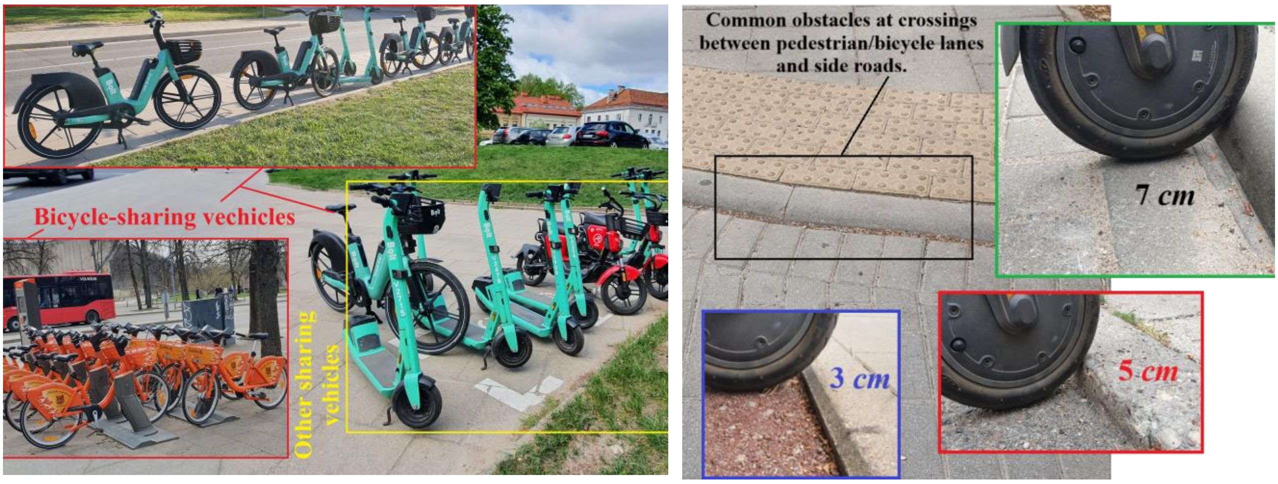
ABSTRACT
Micromobility has emerged as a major global trend in urban transportation. However, it has also led to a rise in accidents, largely attributed to improper usage and inadequate safety precautions. This paper presents a model developed for the dynamic analysis of an in-wheel suspension system for micromobility vehicles, along with proposals for its improvement. The model accounts for challenges related to urban infrastructure, particularly variation in various obstacle types and heights on cycle road pavement, using the city of Vilnius (Lithuania) as a case study. The research paper additionally evaluates factors affecting rider safety and risk, with a primary focus on in-plane dynamics. The dynamic analysis demonstrates that the in-wheel suspension system enhances riding safety across simulated variations. These findings help identify critical vertical dynamic risks for micromobility in urban area and offer insights for future city's road infrastructure planning.

KEYWORDS
micromobility; suspension; in-wheel; dynamic; city infrastructure; risk; safety.

1. INTRODUCTION: MICROMOBILITY IN URBAN ENVIRONMENTS

Around the world, urban transit is being transformed by the rise of micromobility platforms featuring bicycles and electric scooters, which represent a noteworthy advancement in personal transport [1]. Shared micromobility is defined as a cost-effective vehicle designed for short-distance travel in densely populated urban zones [2] (*Figure 1a*). These options are not only quicker than walking but also offer a way to mitigate common city issues like air pollution, traffic congestion and parking scarcity. However, significant safety concerns have emerged. A combination of improper handling and inadequate infrastructure has led to a high number of accidents with these vehicles [3]. The World Health Organization has identified this as a growing concern for road safety within its 2021–2030 Global Plan [4]. Therefore, addressing this problem effectively requires a comprehensive analysis of the specific risks associated with micromobility. While prior research has investigated injury patterns involving micromobility vehicles, fatal outcomes are infrequent and, as a result, have received limited attention in academic publications. To gain a deeper insight into the safe use of these vehicles, it is crucial to explore technical elements like vehicle dynamics and simulation, a point emphasised in references [3, 5].

Analysis of micromobility accidents reveals that a significant portion (86%) involves collisions with motor vehicles, often compounded by hit-and-runs (28%), low visibility (81%) and poor weather (43%) [3, 6, 7, 8]. The majority of fatal outcomes are traced back to two scenarios: being rear-ended by a motor vehicle or the rider losing control due to road hazards [3, 5, 9]. From an infrastructure perspective, while major intersections and traffic flows pose obvious risks, some of the most immediate and frequent dangers in an urban area are the small-scale physical obstacles present on road surfaces. Elements such as curbs, ledges and other protrusions along travel paths represent a critical and often underestimated threat, particularly for the growing number of micro-mobility users (*Figure 1b*). For a city to be truly safe for modern, mixed forms of transportation, planners and engineers must focus on the micro-details of the ground itself. The quality and maintenance of surface materials are essential to ensuring smooth, predictable and obstacle-free pathways. Since creating and maintaining perfectly smooth urban infrastructure is practically impossible, the focus of innovation has shifted from the environment to the vehicle. Consequently, the industry is now prioritising advancements like better suspension and more robust designs to ensure vehicles can safely and comfortably handle the reality of imperfect city surfaces.



(a) *(b)*

Figure 1 – Photos for research introduction in Vilnius (Lithuania) city case (author's photos): a) Micro-mobility shared applications; b) Obstacles view on city micromobility infrastructure

The recent popularity of micromobility means that well-established dynamic models are not yet available. These models are crucial for advancing vehicle safety and design [10, 11]. Computer based simulation is a widely adopted industry approach that accelerates this process safely and affordably for machine dynamic analyses [11, 12]. However, the inherent instability of two-wheeled vehicles makes them more difficult to simulate than four-wheeled vehicles, precluding the use of open-loop maneuverer models [13, 14]. Research shows that the simulation methods for bicycles and electric scooters are fundamentally different from those used for automobiles or even motorcycles. This is mainly because the rider has a dominant effect, typically representing as much as 90% of the combined mass of the system [13]. This high mass ratio heavily influences the vehicle's overall dynamic response, a conclusion supported by other comparable bicycle studies. Evidence shows that a rider's posture affects not only their comfort but also substantially changes the dynamic properties of the system [15]. Over the years, various techniques have been used to model the human body for these simulations, such as complex multibody systems that mimic biomechanics with detailed joint and muscle models [16]. Furthermore, tire modelling is a crucial aspect of vehicle dynamics simulations, as tires provide the sole connection to the ground where forces for movement are generated. While tire models have already been well created in research cycle [17, 18 and 19] for various transport vehicles, they are also suitable for, and readily adaptable to, micro-mobility applications. Despite the well-documented advantages of frames with suspension systems, manufacturers in the bike-sharing industry generally avoid them for two key reasons. First, incorporating suspension requires more complex and costly bicycle frame designs. Second, it creates significant maintenance challenges; while a common issue can be fixed on the street, a damaged suspension system requires the entire bicycle to be removed from service and transported to a workshop for specialised repair.

This paper investigates a novel in-wheel suspension solution, which serves as a middle ground between previously mentioned approaches. While this technology was recently introduced to the market primarily for wheelchairs [20], our study explores its application for micro-mobility. Research paper presents a simulation model that uses a bicycle as a representative example to analyse the vertical dynamic response of these vehicles with requirements improve for suspension. Additionally, the findings highlight the significant potential of in-wheel suspension technology to improve the performance and safety of micro-mobility vehicles, offering valuable insights for the future design of specialised micromobility suspension systems.

2. DYNAMIC MODEL AND SIMULATION DETAILS

This section details a model of a bicycle featuring an in-wheel suspension system analysis with a different amount of shock-absorber. The model is designed with a dual purpose: first, to measure how the suspension affects the bike's dynamic performance, and second, to contrast its behaviour with an identical, non-suspended bicycle frame. The developed dynamic model details a computational model that applies the principles of multi-body dynamics to analyse the vertical operational behaviour of a two-wheel micromobility vehicle, exemplified by a bicycle. A key feature of this model is its inclusion of the in-wheel suspension analysis and the evaluation of potential control-loss risks. In developing the two-mass vertical dynamic model, the following simplifying assumptions are adopted: (1) the wheel-road interaction is represented by a linear stiffness element without damping, valid for small displacements; (2) the suspension system is modelled using the Kelvin-Voigt viscoelastic formulation, which captures combined spring and damper behaviour; (3) equal static load distribution between the front and rear wheels is assumed; and (4) the motion is restricted to the vertical plane, neglecting lateral and steering effects.

2.1 Initial model and analytical framework for bicycle suspension requirements

The initial model integrates three core models: the bicycle structure, the rider's body and the tire's interaction with the ground. Particular emphasis was placed on modelling the tire's dynamic contact behaviour. To replicate authentic riding conditions, the model must incorporate road surface imperfections as an input. Therefore, in this model, road roughness is modelled and characterised according to the ISO 8608 standard [21], which outlines eight surface classes based on their power spectral density [22, 23]. A single-point contact model represents the tire, applying the road's influence as a set displacement where the front and rear wheels make contact (refer to model scheme on *Figure 2*). To model the tire's material dynamics, a mathematical formulation was used based on the rheological framework from prior studies [18, 24].

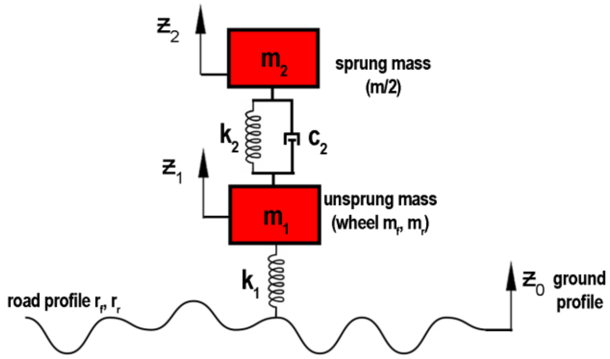
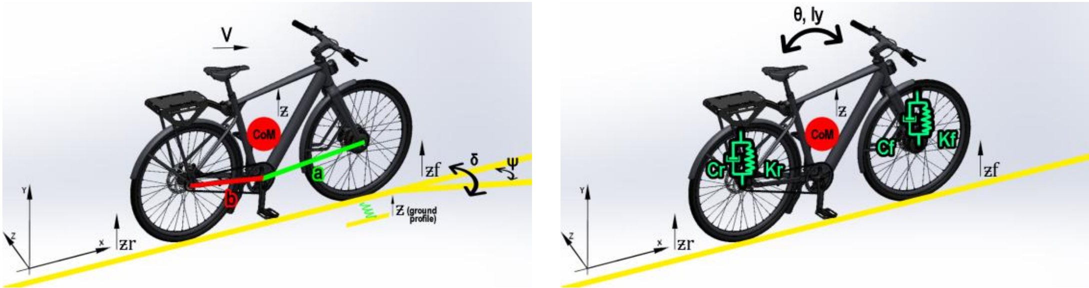


Figure 2 – Formulation for single wheel of two-wheel vehicle in vertical dynamics

The vertical dynamic response of micro-mobility vehicles is a key factor in ensuring both rider safety and overall handling performance. These dynamics affect not only the vibration transmitted to the rider but also the level of tire-road traction. Vibrations are particularly significant, as they may negatively impact human health [5, 25, 26] and accelerate wear or failure of mechanical components [27, 28]. To investigate these effects, a simplified lumped-parameter model is employed. This modelling approach, widely used in vehicle dynamics studies [29, 30], provides an effective compromise between computational efficiency and physical accuracy. Ultimately, this modelling framework can support the assessment of safety when using micro-mobility vehicles in urban environments, particularly for simulating driver and pedestrian behaviour [31] and guiding the development of micro-mobility infrastructure [32].

In this work, the modelling framework illustrated in *Figure 3* is adopted. The system is divided into subsystems to enable multibody dynamic analysis of a two-wheeled micro-mobility vehicle, with the bicycle both suspended and unsuspended, serving as the case study. Since both the rider and the bicycle undergo vertical motion as well as pitch rotation, an additional horizontal degree of freedom is incorporated to capture the relative displacement between the vehicle and the rider's body mass. To better represent biomechanical interaction, rheological models of the rider's arms and ankles are included, with parameter values taken from the data reported in [33].



(a) (b)

Figure 3 – Multibody dynamic modelling of a two-wheeled micromobility vehicle (bicycle case study): a) Rigid bicycle; b) Bicycle with suspension

Schemes variables describing: z – vertical displacement of vehicle body (CoM – centre of mass); θ – pitch angle (rotation around z-axis); I_z – pitch moment of inertia; K_f, K_r – suspension stiffness of front and rear; C_f, C_r – suspension damping front and rear; Z_f, Z_r – vertical displacement of front and rear suspensions relative to ground.

The system's equations of motion are derived using the Lagrangian mechanics formulation, expressed as follows:

$$\frac{d}{dt}\frac{\partial L(r_j,\dot{r}_j)}{\partial \dot{r}_j}-\frac{\partial L(r_j,\dot{r}_j)}{\partial r_j}=F_{r_j}. \quad (1)$$

The Lagrange function can be displayed in the form of kinetic (T) and protentional energies (P) form:

$$L(r_j,\dot{r}_j)=T(r_j,\dot{r}_j)-V(r_j). \quad (2)$$

They are all expressed in the terms of generalised coordinates $r_j=(x_j;y_j;z_j)$.

The vertical dynamic model in this case is constructed to be simple in form, while retaining the capacity to describe all dynamics relevant to two-wheeled vehicles:

$$[M]\{\ddot{q}\}_t+[C]\{\dot{q}\}_t+[K]\{q\}_t=\{F\}_t, \quad (3)$$

where $\{F\}_t$ are vectors of external forces; $\{\ddot{q}\}_t$, $\{\dot{q}\}_t$, $\{q\}_t$ are the acceleration, velocity and displacement vectors of system elements at solution time (t); [M], [C] and [K] are matrices of masses, damping and stiffness, respectively.

In more detail form with adaptation for previously displayed scheme, the motion equations have a form of vertical force balance (*Equation 4*) and pitch torque balance (*Equation 5*):

$$m\cdot\ddot{z}=-K_z\cdot(z+a\theta-z_f)-C_f\cdot(z_f+a\theta-\dot{z}_f)-K_r\cdot(z-b\theta-z_r)-C_r\cdot(\dot{z}-b\dot{\theta}-\dot{z}_r)+mg. \quad (4)$$

$$I_y\ddot{\theta}=-a[K_f\cdot(z+a\theta-z_f)+C_f\cdot(\dot{z}+a\theta-\dot{z}_f]+b\cdot[K_r\cdot(z-b\theta-z_r)++C_r\cdot(\dot{z}-b\dot{\theta}-\dot{z}_r)]. \quad (5)$$

where m – mass; K_z – stiffness of contact wheel-road; z – vertical displacement of vehicle body (CoM – centre of mass); θ – pitch angle (rotation around z-axis); I_z – pitch moment of inertia; K_f, K_r – suspension stiffness of front and rear; C_f, C_r – suspension damping front and rear; z_f, z_r – vertical displacement of front and rear suspensions relative to ground; a, b – distance from CoM to front and rear wheel centre, respectively; g – gravitational acceleration.

The vertical dynamic model is expressed as a nonlinear system of ordinary differential equations, governed by the combined effects of the front and rear lateral forces together with the longitudinal motion of the two-wheeled vehicle. While the longitudinal dynamics are not analysed in depth here, their interaction with the vertical dynamics, as described in [9], is incorporated into the present formulation. The coupling between the two domains arises through the longitudinal velocities at the tire-road contact points, where the external traction forces are applied.

The simulation results, performed in MATLAB R2022a, presented curves for driving bicycles case study. *Figure 4* illustrates that the inclusion of suspension markedly enhances the bicycle's performance. With suspension, vertical displacements are smaller and decay rapidly, reflecting effective shock absorption and vibration attenuation. In contrast, the unsuspended bicycle exhibits larger, sustained oscillations, indicating poor capability in handling vertical disturbances. *Figure 5* depicts the variation in tire-road contact force. An initial sharp rise in force corresponds to the system's immediate reaction to the disturbance, followed by oscillatory behaviour. The most pronounced force peaks occur shortly after 0.5 second, coinciding with programmed obstacle contact. Subsequently, the force amplitude gradually decreases, demonstrating the suspension system's ability to dissipate energy and return to equilibrium, thereby enhancing ride stability.

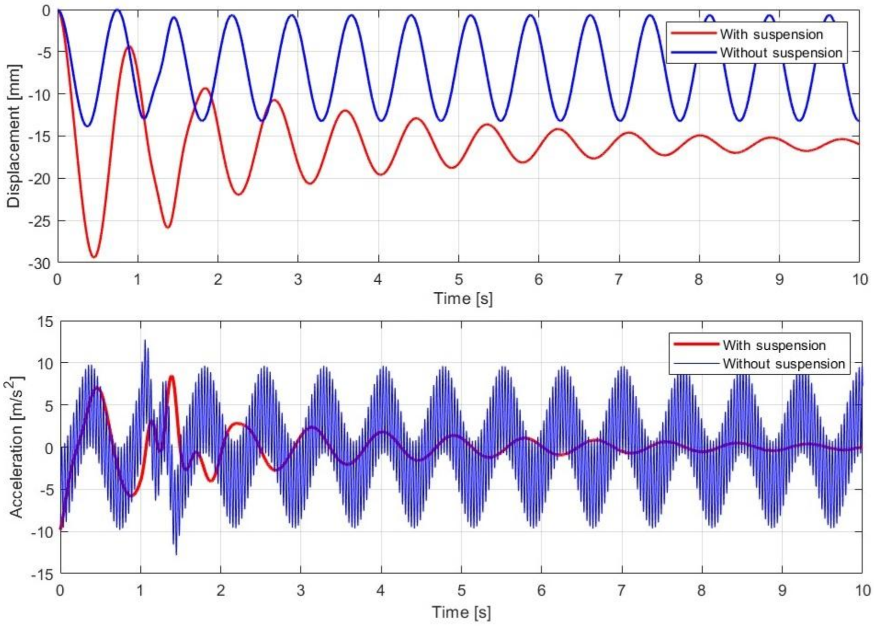


Figure 4 – Vertical bicycle dynamics analysis: sprung mass displacement (top) and acceleration (bottom) for suspended and unsuspended configurations

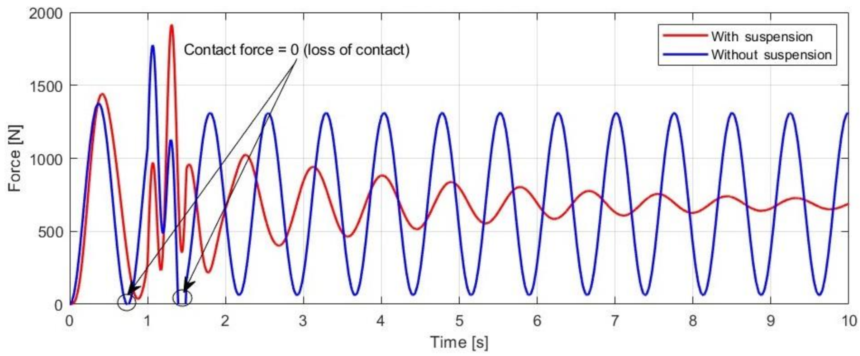


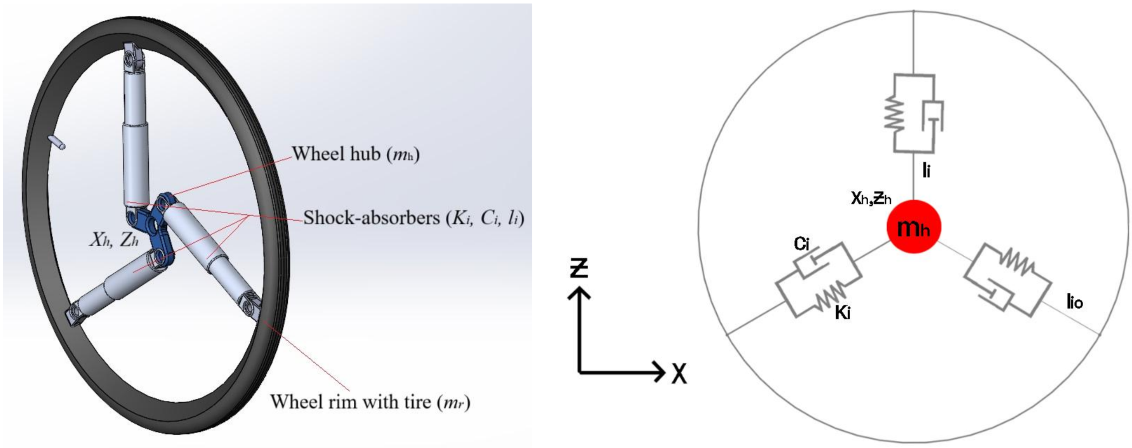
Figure 5 – Graphs of variation in tire–road contact force

With suspension, the tires experience more stable and uniform forces, ensuring consistent traction and enhanced vehicle stability. In contrast, the unsuspended bicycle exhibits large oscillations in tire-road contact forces, including near-zero values that indicate temporary loss of ground contact. This behaviour adversely affects traction, rider control and overall safety. The modelling also shows that the suspended bicycle undergoes smaller and smoother acceleration variations, resulting in a more comfortable and stable ride. Without suspension, the system experiences high-frequency, high-amplitude acceleration spikes, which can cause discomfort and reduce control.

Overall, these results indicate that a suspension system provides significant benefits in terms of both comfort and safety. It reduces vertical displacements, rapidly damps oscillations and stabilises tire contact forces, thereby improving traction and ride stability. In situations where modifying the chassis or frame to accommodate a suspension system is not feasible, an alternative approach could be to integrate the suspension directly within the wheel assembly.

2.2 In-wheel suspension dynamic model

In-wheel suspension systems consist of multiple suspension elements evenly distributed around the wheel (see *Figure 6a*). Each shock absorber connects at one end to the outer rim and at the other end to the central hub. *Figure 6b* shows schematic analysis how such system looks like when using three shock absorbers for numerical simulation. This section proposes a novel analysis approach that bridges the gap between previously explored in-wheel suspension concepts for bicycles [34] and recently commercialised systems [20], which have mainly been developed for wheelchairs, with the main comparison focusing on different shock-absorber configurations and formulations as a basis for identifying potential improvements.



(a) *(b)*

Figure 6 – In-wheel suspension dynamic model view: a) In-wheel suspension 3D model; b) In-wheel suspension scheme for numerical model

$X_h, Ƶ_h$ – position of hub relative to the rim centre (global or wheel frame); m_h – mass of hub (including part of bicycle); m_r – effective mass of rim; K_i, C_i – stiffness and damping of i-th suspension arm (i =3, 4, 5 etc.); θ_i – angle of the i-th damper relative to the wheel vertical (0°, 120°, 240°,... etc.); l_i – instanteneous length of the i-th damper; l_{io} – rest length of the i-th damper.

In-wheel suspension can consist of a different number of shock absorbers arranged at equal distance and angle from one another. *Figure 7* provides a visual representation of how such a system could look and how it is used for the current dynamic analysis.

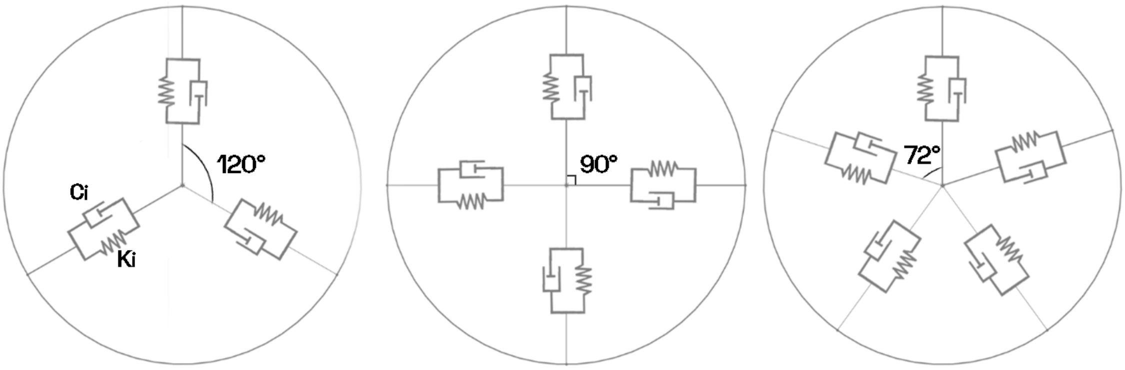


Figure 7 – In-wheel suspension models with 3, 4 and 5 shock absorbers used for dynamic analysis

Model the in-plane motion (X-Ƶ) plane of the wheel hub relative to the rim where the rim rotates with the wheel and the hub (attached to the bicycle frame) is suspended by 3, 4 and 5 shock-absorbers arranged symmetrically. *Figure 8a* shows a visual representation of how the wheel hub moves during the operation of the suspension system. During the movement, some shock absorbers compress while others extend depending on the angle of impact. Additionally, *Figure 8b* shows the in-wheel suspension motion scheme with road interaction.

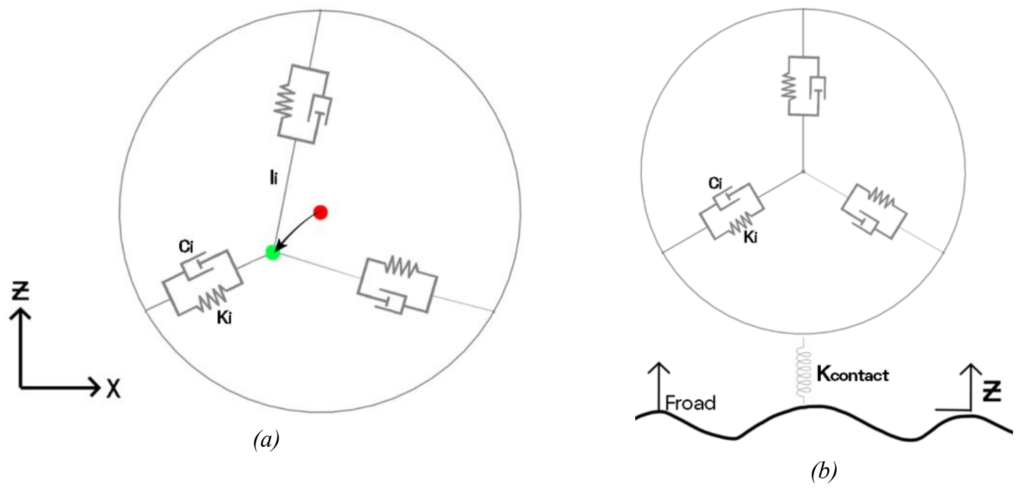


Figure 8 – In-wheel suspension dynamic model view: a) Representation of wheel hub location before road bump (red) and during (green); b) In-wheel suspension motion scheme with road interaction

For modelling, it is necessary to determine damper position vectors. This vector can determine it from rim centre to damper connection points:

$$r_i = R \cdot \begin{bmatrix} \cos\theta_i \\ \sin\theta_i \end{bmatrix}, \tag{6}$$

where, R – radius of rim. The displacement vector of each damper is:

$$\triangle l_i = r_h - r_i, \tag{7}$$

where:

$$r_h = \begin{bmatrix} X_n \\ z_h \end{bmatrix}, \tag{8}$$

The length l_i and rate i_i:

$$l_i = \|\triangle l_i\|. \tag{9}$$

$$i_i = \frac{\triangle l_i^T \cdot \dot{r_n}}{\|l_i\|}. \tag{10}$$

Each spring in damper applies a force on the hub along its direction:

$$F_i = -[K_i \cdot (l_i - l_{io}) + c_i \cdot i_i] \cdot \frac{\triangle l_i}{l_i}. \tag{11}$$

The total force on the wheel hub is:

$$F_{total} = \sum_{i=1}^{n} F_i + F_g + F_{road}. \tag{12}$$

$$F_g = \begin{bmatrix} 0 \\ -m_n g \end{bmatrix}. \tag{13}$$

where, F_g – gravity force; F_{road} – contact force from ground (related to model in-wheel suspension motion scheme with road interaction based on $K_{contact}$).

Finally, it should include two systems that are calculated simultaneously and depend on each other.

First, hub motion hub (in three variations):

$$m_h \ddot{r_h} = F_{total};. \quad (14)$$

$$m_h \ddot{r_h} = \sum_{i=1}^{n} F_{ix}\,; \quad (15)$$

$$m_h \ddot{r_h} = \sum_{i=1}^{n} F_{iz} - m_{hg}. \quad (16)$$

where, F_{ix}, F_{iz} – components of F_i.

Second, rim dynamics (vertical input):

$$r_{rim} = \begin{bmatrix} X_r \\ z_r(t) \end{bmatrix}. \quad (17)$$

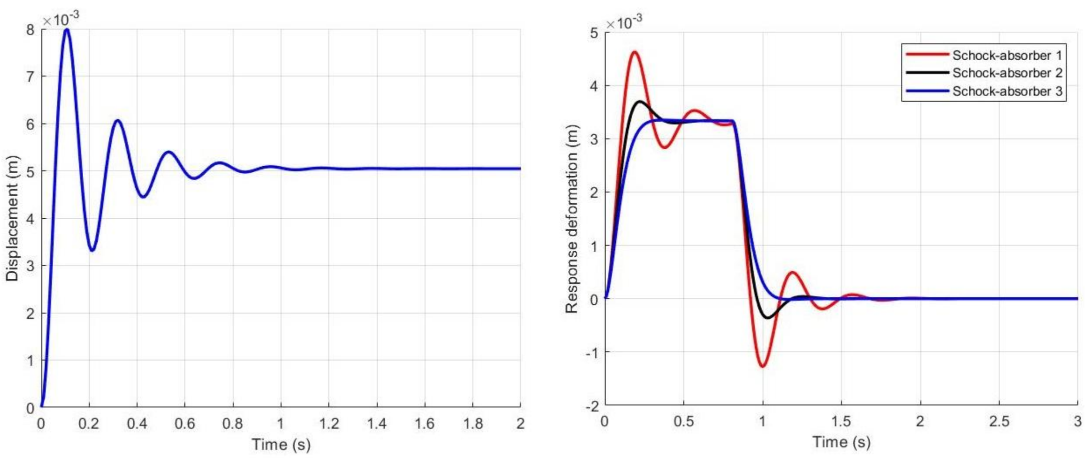
Define state vector:

$$X = [x_n, z_n, \dot{x_n}, \dot{z_n}]^T. \quad (18)$$

The preceding analysis indicates that incorporating in-wheel suspensions results in a certain reduction in overall mechanical efficiency when compared to a conventional bicycle without suspension elements. This loss primarily arises from the additional damping and spring mechanisms that dissipate part of the input energy. Nevertheless, this drawback is expected to be offset by significant gains in ride comfort, stability and safety, especially under uneven road conditions or dynamic loading scenarios.

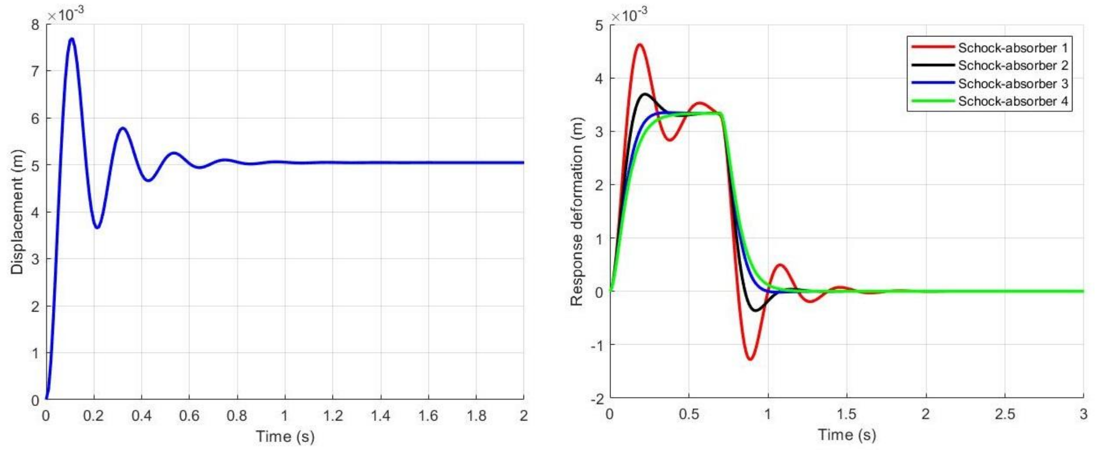
3. RESULTS FROM THE IN-WHEEL SUSPENSION DYNAMIC ANALYSIS

The primary objective of this analysis is to evaluate the trade-offs between mechanical efficiency and ride performance, as introduced in the previous chapter. The simulations focus on quantifying the suspension's influence on wheel-ground dynamic contact, for future overall ride comfort under various operating conditions. A series of comparative studies were conducted to examine how different configurations of shock absorbers affect the vertical dynamics of the in-wheel system. Specifically, models with varying numbers of dampers were analysed to assess their influence on the wheel's response to road irregularities and dynamic load transfer. *Figures 9–11* show the main results from dynamic analysis. Simulations were performed for systems incorporating three, four and five shock absorbers, with identical boundary conditions and road input characterised by a vertical obstacle of 5 cm height. The results presented below summarise the time-domain responses of the wheel's vertical motion and the corresponding damper stroke displacements. These results provide a foundation for understanding the dynamic behaviour of in-wheel suspension systems and their potential advantages for enhancing comfort and safety in bicycle applications.



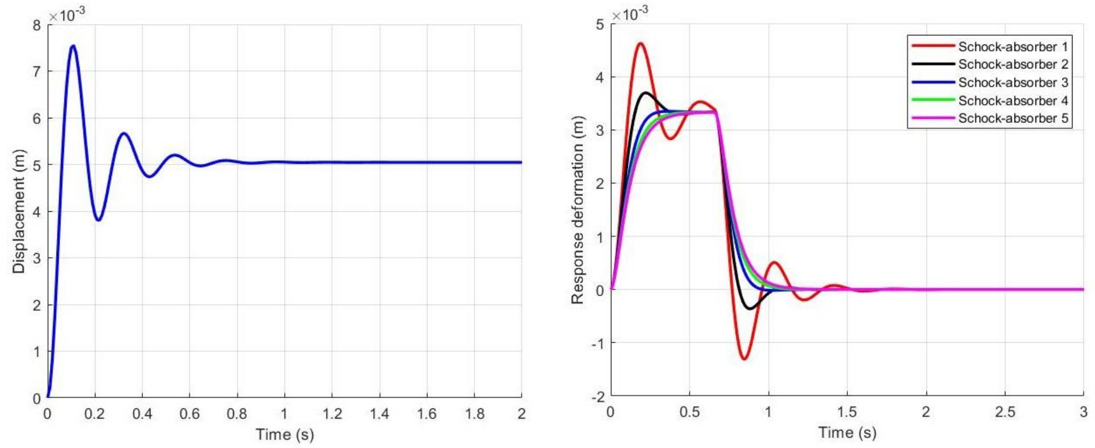
(a) *(b)*

Figure 9 – In-wheel suspension dynamic modelling results (with 3 shock-absorbers): a) Wheel vertical dynamics; b) Shock-absorbers response



(a) *(b)*

Figure 10 – In-wheel suspension dynamic modelling results (with 4 shock-absorbers): a) Wheel vertical dynamics; b) Shock-absorbers response



(a) *(b)*

Figure 11 – In-wheel suspension dynamic modelling results (with 5 shock-absorbers): a) Wheel vertical dynamics; b) Shock-absorbers response

From the simulation results presented in *Figures 9–11*, a clear trend can be observed regarding the dynamic response of the in-wheel suspension system under road excitation. The three-damper configuration exhibited a balanced dynamic behaviour, providing a stable compromise between structural stiffness and damping efficiency. The wheel experienced a maximum vertical displacement of approximately 80 mm immediately after impact with the obstacle, followed by a gradual decay in oscillation amplitude. The system achieved stabilisation within approximately 1 s, indicating an effective energy dissipation rate. Introducing a fourth damper slightly altered the dynamic characteristics of the system. The wheel's peak displacement was reduced to approximately 77 mm, representing a decrease of about 4% compared to the three-damper model. However, the additional shock-absorber increased the system's mass significantly. The damping stabilisation time improved marginally by 10%, but this gain did not translate into a proportional improvement in ride control, comfort and safety. The system equipped with five shock absorbers demonstrated the highest theoretical damping capacity but also introduced excessive stiffness and mass into the wheel assembly. The maximum vertical displacement decreased further to 76 mm (an additional reduction of 5% relative to the three-damper system). Despite this, the overall dynamic response became more linear, with a shorter stabilisation time of approximately 0.65 s.

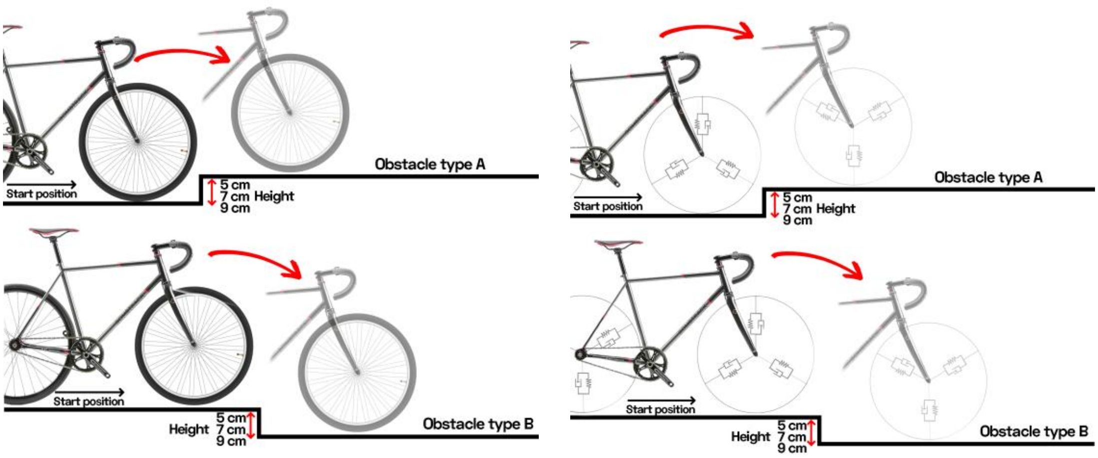
Finally, the three-damper system demonstrates an optimal balance between structural stiffness and damping efficiency, allowing the wheel to maintain better contact with the road surface while minimising vertical oscillations. In contrast, configurations incorporating four- and five- shock absorbers exhibit diminishing returns in performance. The additional dampers beyond the third unit do not contribute significantly to absorbing the transmitted energy from the road bump. Instead, they reach their preload positions without participating in the energy dissipation process, effectively acting as passive constraints rather than functional damping elements. The relative motion analysis shows that, for the three-shock-absorber configuration, the phase lag and amplitude ratio between the wheel's vertical displacement and the corresponding damper stroke remain within an optimal range (exact values to be inserted later). This indicates efficient energy transfer from the wheel to the suspension system, leading to effective vibration isolation. Conversely, in the four- and five-damper configurations, this relationship becomes increasingly nonlinear and less efficient, suggesting mechanical redundancy and reduced damping effectiveness.

4. SAFETY EVALUATION

The research focuses on evaluating the safety implications of various geometric characteristics of road obstacles to regular and in-wheel suspension tires using (refer to *Figure 12*). Based on the obtained vertical dynamic results, a stability analysis of the system was carried out. Considering that micromobility vehicle with its rider can be treated as a holonomic mechanical system (the two-wheel vehicle) coupled with a subsystem (the rider), stability characteristics can be determined by combining system trajectory stability with an assessment of human control behaviour. In this study, the rider subsystem was analysed separately using homogeneous polynomial Lyapunov functions, which provide a sufficient condition for global asymptotic stability of the rider model under a dwell-time constraint, following the approach described in [34, 35 and 36]. The subsystem for the rider control model uses a homogeneous polynomial Lyapunov function ($V(x)$) ensuring global asymptotic stability under dwell-time constraints:

$$V(x) > 0; \dot{V}(x) = \frac{\dot{\partial V}}{\partial x}\dot{x} \leq 0; \quad (19)$$

where, x – state vector of the rider control subsystem.



(a) (b)

Figure 12 – Schemes for safety evaluation modelling: a) Regular non-suspension case; b) In-wheel suspension case

The human control behaviour analysis was performed with reference to decision-making in both stable and unstable dynamic control environments [9, 37, 38, 39]. In such environments, individuals tend to be sensitive to the inherent stability of the system they are required to control, particularly when the controllability of the outcome varies from easy to difficult. In other words, by maintaining all system parameters constant while modifying only the internal system properties, the control task can be perceived as either "Stable" or "Unstable" depending on the value of the objective function. Objective function (J) describes the rider-to-two-wheel vehicle affecting stability and is used to classify risk zones:

$$Risk\ Level = \begin{cases} Stable, if\ J \approx 1 \\ Transient, if\ 0.9(9) < J < 1 \\ Unstable, if\ J \ll or\ J \gg 1 \end{cases} \quad (20)$$

The summarised results used to assess the rider's risk and safety evaluation when manoeuvring an micromobility vehicle with in-wheel suspension and without suspension through an obstacle are presented in *Table 1*. Additionally, a transient state was identified separately, corresponding to the condition where the objective function approached the boundary between the stable and unstable regions.

Table 1 – Risk and safety analysis result

Type of bicycle tire	Infrastructural type	Height of obstacle	Risk evaluation	Safety evaluation
Regular/ Non-suspension	Type "A"	5	Moderate	Transient / Acceptable
		7	High	Unsafe – instability likely
		9	Very High	Critical – high fall risk
	Type "B"	5	Low	Stable / Safe
		7	Moderate	Transient / Acceptable
		9	High	Unsafe – instability likely
In-wheel suspension	Type "A"	5	Low	Stable / Safe
		7	Moderate	Transient / Acceptable
		9	Moderate	Marginally Safe
	Type "B"	5	Very Low	Stable / Safe
		7	Low	Stable / Safe
		9	Moderate	Transient / Acceptable

The summarised data indicate that the in-wheel suspension configuration consistently improves vehicle stability and rider safety compared to the regular non-suspension setup. For regular tires, the risk level escalates rapidly with obstacle height, especially on Type A surfaces, where obstacles above 5 cm generate high dynamic loads and instability. The in-wheel suspension effectively mitigates these effects, maintaining lower risk levels even at 7–9 cm obstacle heights. Type B infrastructure produces generally safer outcomes due to opposite geometry type, though transient states appear near the 7–9 cm range for non-suspension cases. Overall, the in-wheel suspension demonstrates superior vertical dynamic performance by reducing acceleration peaks and improving vertical controllability, validating its potential to enhance micro-mobility safety in typical urban environments.

5. DISCUSSION AND CONCEPT PROPOSAL

Based on the analysis of the modelling results, it can be concluded that the return phase of the suspension system should be smoother to further enhance ride comfort and stability. The simulations revealed that while the three-shock-absorber configuration performs optimally in energy absorption, the return motion following compression could benefit from improved smoothness to minimise rebound-induced vibrations. This insight motivated the development of a novel smooth-return in-wheel suspension shock-absorber concept, for which a patent application has been prepared and submitted. The main structural elements of this proposed in-wheel suspension system for micro-mobility vehicles are shock absorbers of a specific design, installed between the wheel rim and the rotatable wheel hub. The system can include a variable number of shock absorbers, a minimum of three, distributed evenly at equal angular intervals depending on the required load absorption capacity dictated by the vehicle's mass. A distinctive feature of the proposed shock absorber design is the inclusion of a floating washer positioned between the piston and the coil spring, which is free to move along the piston rod. The drainage holes in the floating washer are deliberately designed with smaller diameters than those in the piston, introducing a controlled hydraulic restriction during rebound. This configuration results in a smoother and more precise return motion of the piston rod. The floating washer, responding to inertial forces, regulates the fluid flow between the internal chambers of the shock absorber during the rebound phase, effectively reducing the rate of hydraulic fluid transfer and thus achieving the desired smooth-return effect.

This behaviour ensures a high level of motion precision and significantly enhances the comfort and safety of micro-mobility vehicles by minimising sudden rebound shocks after impact. Moreover, recognising that the structural frames of many existing micro-mobility vehicles, such as electric scooters, cannot easily accommodate conventional suspension systems, the proposed integrated in-wheel suspension concept provides a practical and scalable solution. By embedding the suspension mechanism directly within the wheel hub assembly, this approach enables effective vibration damping and shock absorption without requiring modifications to the vehicle frame.

The unique floating washer mechanism not only facilitates a more controlled rebound but also improves stability on uneven urban surfaces, contributing to a smoother, safer and more comfortable riding experience. Furthermore, integrating this mechanism with airless tire technology offers additional structural flexibility, making the system particularly suited for compact and lightweight micro-mobility platforms where traditional suspension architectures are infeasible.

In summary, the proposed smooth-return in-wheel suspension system represents a significant advancement in micro-mobility vehicle design, combining mechanical simplicity with functional efficiency. It effectively addresses a key limitation in current small vehicle platforms by providing localised, hub-integrated damping capability, thereby improving both ride quality and operational safety.

6. CONCLUSIONS

Research presented a dynamic analysis of a novel in-wheel suspension concept for micromobility vehicles, focusing on improving ride stability, comfort and safety in urban environments characterised by variable infrastructure quality. Using a multibody simulation framework, the research compared the vertical dynamic behaviour of bicycles with and without in-wheel suspension, examining configurations with 3-, 4- and 5 shock absorbers. The results demonstrated that integrating an in-wheel suspension significantly enhances ride dynamics by reducing vertical acceleration peaks, improving tire-road contact consistency and shortening stabilisation times after impact. Among the configurations analysed, the three-shock-absorber layout exhibited the most favourable performance, achieving a maximum vertical wheel displacement of approximately 80 mm after a 5 cm obstacle impact, with rapid damping and stable tire-road contact. Adding a fourth or fifth shock absorber provided only marginal improvements reducing displacement to 77 mm and 76 mm, respectively, but introduced unnecessary mass and stiffness, thus lowering overall efficiency.

The safety evaluation results further demonstrated that bicycles equipped with in-wheel suspensions maintained stable or marginally safe conditions even when traversing 7–9 cm obstacles, while non-suspended configurations became unstable or unsafe beyond 7 cm. The in-wheel system effectively mitigated vertical load spikes and maintained traction continuity, lowering the rider's risk of loss of control and fall events.

In addition, the study introduced a novel "smooth-return" in-wheel shock-absorber design featuring a floating washer for controlled hydraulic rebound. This concept minimises rebound-induced vibration and improves motion precision, providing a practical solution for micro-vehicles where traditional suspension integration is infeasible. Future work should experimentally validate this design, incorporate nonlinear damping and tire models, and extend the analysis to include longitudinal-pitch coupling and rider posture effects.

Overall, the proposed in-wheel suspension framework represents an efficient and scalable advancement for next-generation micromobility systems, bridging mechanical innovation with urban safety needs. It also provides guidance for future infrastructure planning and standardisation efforts aimed at enhancing the safe coexistence of micro-vehicles within mixed urban traffic networks.

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