The influence of the suspension system on the energy efficiency of an autonomous public transport vehicle

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Abstract. In the dynamic and constantly evolving field of autonomous transportation, prioritising energy efficiency is of utmost importance in order to facilitate the sustainable implementation of public transportation systems. The present study investigates the significant influence of suspension systems on the energy economy of autonomous public transport vehicles. This study employs sophisticated simulations to examine the effects of various suspension systems on energy consumption, ride comfort, and stability across various road conditions. The results highlight the importance of optimised suspension systems, as they not only improve the comfort of passengers but also significantly decrease energy consumption. The study highlights the necessity of intelligent and adaptable systems that can dynamically modify suspension characteristics, hence facilitating the development of environmentally sustainable and economically feasible autonomous public transportation systems.

1. Introduction

Within the context of urban transportation, the incorporation of autonomous technology marks a significant and transformative change, signalling the advent of a fresh era characterised by enhanced effectiveness, safety, and environmental responsibility. The emerging domain of autonomous public transit vehicles is at the convergence of advanced robotics, artificial intelligence, and transportation engineering. The exploration of this scientific frontier not only presents a challenge to the established standards of public transport, but also has the potential to fundamentally reshape our urban environments [1].

The fundamental principle underlying autonomous public transport vehicles involves the complicated integration of sensor technology, machine learning algorithms, and real-time data processing. These transportation vehicles, which vary in size from buses to shuttles, are outfitted with highly advanced assistance systems. This enables them to accurately sense and understand their surrounding environment with remarkable precision. Optimal algorithms are employed to analyse the sensor data, enabling the ability to make real-time decisions in navigating intricate urban settings, predicting pedestrian actions, and adjusting to constantly shifting traffic conditions [2].

The Society of Automotive Engineers (SAE) has established a classification system consisting of six levels to classify autonomous driving technology. In Level 0, automation is absent, necessitating the complete reliance on the human driver for vehicle control. Level 1 encompasses driver assistance systems, whilst Level 2 entails partial automation wherein certain functions might be mechanised concurrently. Level 3 signifies the implementation of conditional automation, wherein the vehicle possesses the capability to independently execute a majority of driving activities under predetermined circumstances. However, human intervention becomes necessary when the vehicle confronts a problem outside its operational capabilities. Level 4 vehicles possess the capability to function autonomously within predetermined parameters, whereas Level 5 vehicles represent a state of complete automation, wherein they are capable of executing all driving activities without the need for human intervention, regardless of the prevailing conditions. The advancement of the industry across these stages signifies a significant transformative process towards a future in which the transportation landscape is redefined by completely autonomous cars. However, it is important to acknowledge that the evolution is accompanied by crucial considerations pertaining to legislation, safety, and ethics [2], [3].

The field of vehicle dynamics holds a central position in the development of autonomous driving technologies, exerting significant influence on the trajectory of transportation advancements. The fundamental aspect consists of comprehending the manner in which a vehicle reacts to various stimuli and exterior variables, as this plays an essential role in guaranteeing the comfort of occupant. Autonomous systems depend on this knowledge in order to uphold stability, manage emergency scenarios, and optimise driving patterns to enhance fuel efficiency. Through a comprehensive understanding of vehicle dynamics, autonomous vehicles possess the ability to effortlessly traverse intricate settings, while simultaneously ensuring a comfortable and secure ride. This capability fosters a sense of confidence among both passengers and authorities. Furthermore, this comprehension facilitates the ability to make predictions, hence enabling timely decision-making and accurate trajectory planning. Moreover, it aids in the assimilation of data originating from diverse sensors, so ensuring precise comprehension of the vehicle's environment and augmenting the overall level of situational awareness [4].

Vehicle dynamics play a crucial role not only in ensuring safety and efficiency but also in meeting regulatory requirements and assessing responsibility. The ability to meet rigorous legislative criteria requires a comprehensive understanding of the behaviour of autonomous vehicles across a wide range of scenarios. Engineers, legislators, and regulators depend on this knowledge to assess adherence, guaranteeing the safe and responsible use of these vehicles on roadways. In essence, the acquisition of expertise in vehicle dynamics serves as a catalyst for the technological advancement of autonomous driving, while simultaneously establishing the foundation for the trust and responsibility required for the broad adoption of self-driving technology [5], [6].

The development of suspension systems in automobiles is a significant milestone in the field of automotive engineering, bringing about a paradigm shift in our perception of road travel. The evolution of suspension systems, ranging from basic leaf springs to complex adaptive air suspensions, has been a truly outstanding progression. Modern suspension systems, incorporating advanced features such as magnetic dampers and adjustable ride height mechanisms, have revolutionised the automotive driving encounter. These technological advancements have not only considerably improved the level of comfort, enabling seamless transportation experiences even on irregular surfaces, but have also brought about a transformative impact on the safety and manoeuvrability of vehicles. By dynamically adapting to varying road conditions and driver inputs, these systems effectively optimise tyre contact with the road surface, thereby augmenting both traction and stability. Additionally, the use of electronic sensors and artificial intelligence algorithms has introduced a new era in which suspension systems are capable of dynamically adjusting in real-time, providing an optimal equilibrium between comfort and performance. Nevertheless, within the domain of autonomous vehicles, when human intervention is eliminated and thus unable to predict and respond to road conditions, the suspension system assumes an even greater level of importance [7], [8].

The aim of the research is to thoroughly replicate and evaluate various suspension system setups in autonomous public transport vehicles. The primary objective of the study is to enhance energy efficiency while simultaneously maintaining ride quality and ensuring safety. In order to optimize the design and functionality of autonomous public transport vehicles, manufacturers, transportation planners and policymakers will greatly benefit from the research's findings. Moreover, public transport operators can increase overall operational efficiency, extend the range of the vehicle and reduce the frequency of charging by choosing the proper suspension setup. This study supports ongoing initiatives to develop sustainable and energy-efficient urban transportation systems, paving the way for a more environmentally friendly future.

2. Methods

In order to emphasize the importance of the suspension system in energy efficiency and its influence on the dynamic behavior of an autonomous public transport vehicle, a simulation software called CarMaker, created by IPG Automotive GmbH was used. It is specifically designed for the virtual testing and development of commercial and non-commercial vehicles, including cars, trucks, buses and trailers.

Table 1. Technical characteristics of Navya ARMA [9]

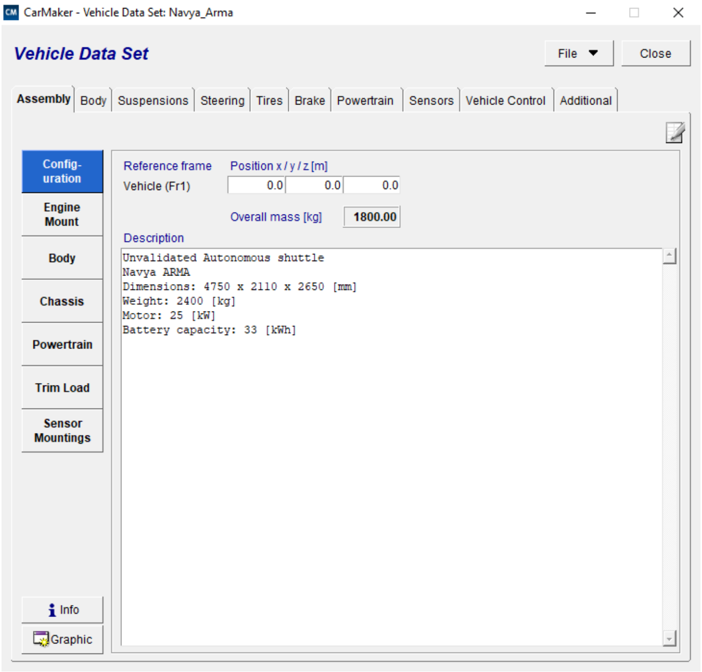
Specification type	Value
Length	4750 mm
Width	2110 mm
Height	2650 mm
Weight	2400 kg
Maximum authorized weight	3450 kg
Passenger capacity	11 seating + 4 standing
Motor	25 kW peak
Battery	33 kWh
Autonomous technologies	Two 360° multi-layer LIDARs Six 180° single-layer LIDARs Front & Rear cameras Wheel encoders + Intertial sensor for Odometry Real-time kinematic (RTK) navigation using GNSS

With the help of this software, engineers and researchers can precisely model the dynamics and behavior of commercial vehicles in a highly realistic simulation environment. Advanced vehicle physics models, including precise representations of suspension systems, powertrains, brakes and aerodynamics, are incorporated into the software.

For this study, an autonomous shuttle has been modeled using technical data from Navya company. Their shuttle model ARMA is one of the solutions used around the world for this type of vehicles. The technical specifications of Navya ARMA are presented in Table 1.

Additional information regarding suspension, steering, braking and different powertrain components has been incorporated following the generation of the vehicle model. In the CarMaker simulation environment, the expanded dataset enables detailed configuration and offers a thorough overview of the vehicle's characteristics. In order to fine-tune the simulation parameters in CarMaker, the introduced collection of vehicle data is presented visually in Figure. 1.

Figure 1. Vehicle data set preview in CarMaker



Reference frame Position x / y / z [m]
Vehicle (Fr1) 0.0 0.0 0.0
Overall mass [kg] 1800.00

Description

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Unvalidated Autonomous shuttle
Navya ARMA
Dimensions: 4750 x 2110 x 2650 [mm]
Weight: 2400 [kg]
Motor: 25 [kW]
Battery capacity: 33 [kWh]
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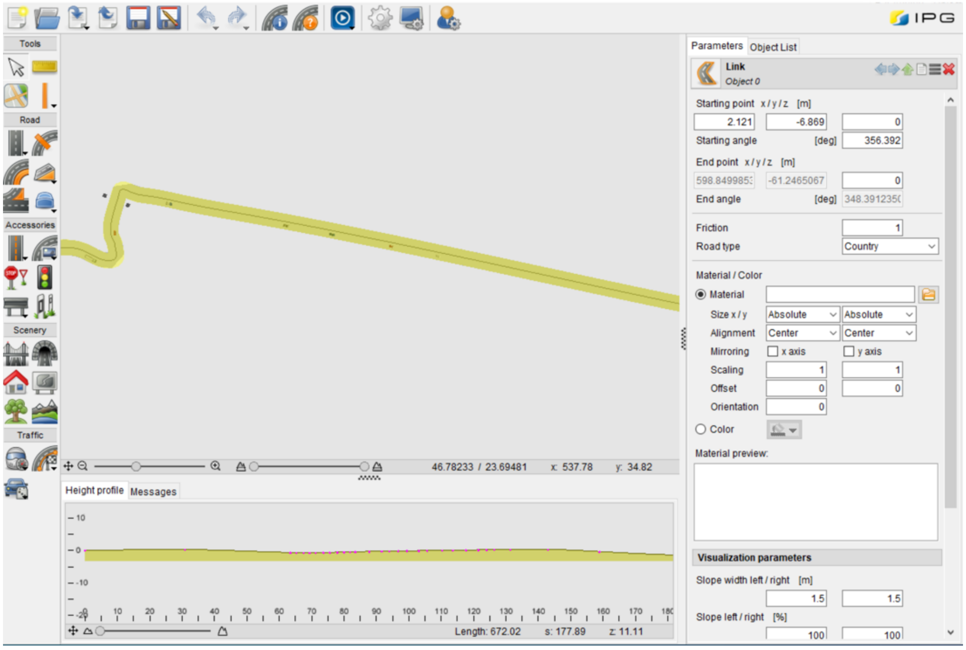
The accurate representation of the vehicle's suspension system, including the springs, shock absorbers, anti-roll bars and other related parts, is made possible by the inclusion of suspension data. This data is essential for capturing the vehicle's dynamic behavior and enables simulation runs to evaluate the ride quality, handling and stability. Furthermore, a dataset for powertrain has been included. This information includes specifics about the electric motor, battery system, transmission and drivetrain of the vehicle. These characteristics enable a thorough evaluation of the vehicle's powertrain performance, energy usage, regenerative braking abilities and other essential propulsion-related factors.

The following step in the simulation process was setting up the route for the shuttle by creating a virtual route. A virtual road is a computer-modelled or digitized simulation of a road or circuit that resembles a real course or is created expressly for testing. The road can be created in one of two ways with CarMaker: by merging individual road segments or by using digitized data from a previously acquired route.

CarMaker allows building highly complex road networks for vehicle and driving simulation. The front end of the road building module is the Scenario Editor, while the backend module, IPG Road, is a software library used to build roads and scenery in CarMaker. One notable benefit of the Scenario Editor is the ability to create realistic situations, incorporating road altitude, traffic data, intersections, road signs, traffic lights, etc. [10]

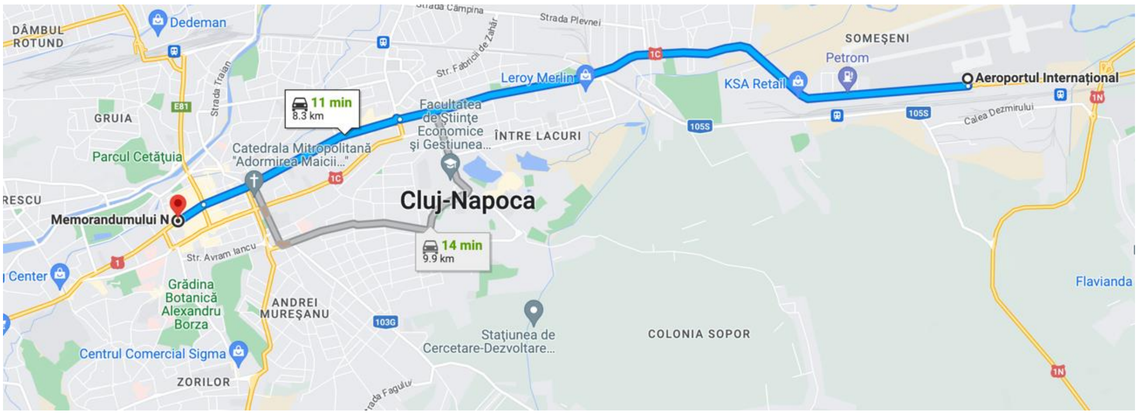
Figure 2. Illustration of the road in Scenario Editor



Starting point x / y / z [m]: 2.121 | -6.869 | 0
Starting angle [deg]: 356.392
End point x / y / z [m]: 598.849985 | -61.2465067 | 0
End angle [deg]: 348.391235
Friction: 1
Road type: Country
Material / Color
● Material
Size x / y: Absolute | Absolute
Alignment: Center | Center
Mirroring: ☐ x axis ☐ y axis
Scaling: 1 | 1
Offset: 0 | 0
Orientation: 0
○ Color
Material preview:
Visualization parameters
Slope width left / right [m]: 1.5 | 1.5
Slope left / right [%]: 100 | 100
46.78233 / 23.69481 x: 537.78 y: 34.82
Length: 672.02 s: 177.89 z: 11.11

Moreover, the Scenario Editor allows the import of Keyhole Markup Language (KML) files. These files are digitized road data obtained from specific geographic software such as Google Earth or Google Maps. For the simulation of the electric bus, the route illustrated in Figure. 3 has been used. This route starts from the Arrivals Terminal of Cluj "Avram Iancu" International Airport ending at Memorandumului street, in the center of Cluj-Napoca, with a total distance of 8.3 km.

Figure 3. Route in Google Maps from Arrivals Terminal of Cluj "Avram Iancu"



International Airport to Memorandumului street [11]

The route in this study has been segmented into several sections to precisely simulate the currently existing bus stops in order to ensure more accurate and realistic results. Thus, the simulations can capture the distinct dynamics and characteristics linked to each bus stop.

A thorough analysis of the energy efficiency and performance during the boarding and disembarking processes can be done by simulating each bus stop separately. The simulations allow accurate representation and accounting of factors like passenger flow, dwell time, acceleration and deceleration at each stop.

The existence of a designated bus lane and its effect on the study's findings are other crucial factors to be considered in the analysis. The safety, energy efficiency and overall performance of an autonomous public transport vehicle can be significantly impacted by the presence of a designated lane, especially in relation to traffic conditions from Cluj-Napoca.

The traffic light system was not considered in the simulations run for this study, instead, the ideal green light path for the electric bus was taken into account. The main goal of this analysis is to investigate the energy efficiency under ideal circumstances, presuming that all the traffic lights along the route are synchronized to give the bus a steady stream of green lights.

Table 2. Road segments definition

Road segment number	**Road segment using existing bus stop names**	**Road length**
1	Cluj Airport, Arrivals Terminal – Traian Vuia Nord	0.7 km
2	Traian Vuia Nord – Planoarelor	0.85 km
3	Planoarelor – Vlad Țepeș	0.65 km
4	Vlad Țepeș – Cămin Someșeni	0.7 km
5	Cămin Someșeni – Branului	0.6 km
6	Branului – EXPO Transilvania	0.75 km
7	EXPO Transilvania – Aurel Vlaicu	0.65 km
8	Aurel Vlaicu – Arte Plastice	0.85 km
9	Arte Plastice – Crinului	0.45 km
10	Crinului – Someș	0.6 km
11	Someș – Constanța	0.6 km
12	Constanța – Sora	0.45 km
13	Sora – Memorandumului Nord	0.45 km
Total distance		8.3 km

IPG Driver allows the integration of a human driver's control actions to the vehicle simulation. Steering, braking, throttle position, gear shifting and clutch function are all examples of these actions. However, one can utilize IPG Driver to control simply the path and not the speed, or vice versa. In order to run the defined routes, the manoeuvers that the driver needs to make must be specified. In CarMaker, these instructions can be specified in TestRun manoeuver. A series of directions for the test driver can be defined, such as: "Accelerate to a top speed of 50 km/h, maintain this speed for 10 seconds and then brake until the vehicle is completely stopped". Giving these commands, one can accurately emulate an autonomous driving controller which would take into account all the information received from the sensors in order to run the vehicle safely [10].

To adhere to the study's particular emphasis, the conducted simulations incorporated two separate suspension configurations: one that utilised standard steel springs and traditional dampers, and another that integrated air springs with electronically controlled dampers. The strategic selection of these suspension systems enabled a comprehensive analysis of the energy efficiency characteristics of standard and advanced suspension systems in autonomous vehicles, providing useful insights. Through the utilisation of these specific configurations, the research aims to offer objective and evidence-based observations, thus enhancing the comprehension of energy dynamics within the field of autonomous driving.

3. Results and discussions

Users are given the ability to generate visual representations of the simulated bus operations using IPG Movie. These representations can include the driver's maneuvers as well as the trajectory of the bus along its route. This function improves the analysis process by providing a visual context that makes it easier to comprehend the interactions that occur between the actions of the driver, traffic and the behavior of the vehicle.

Figure 4. Visual representation of the driving scenario in IPG Movie

During the simulations, several vehicle parameters, performance metrics and system data were gathered through IPG Control, the data acquisition tool of CarMaker. The main parameters that were analyzed are high-voltage battery state of charge and energy consumption.

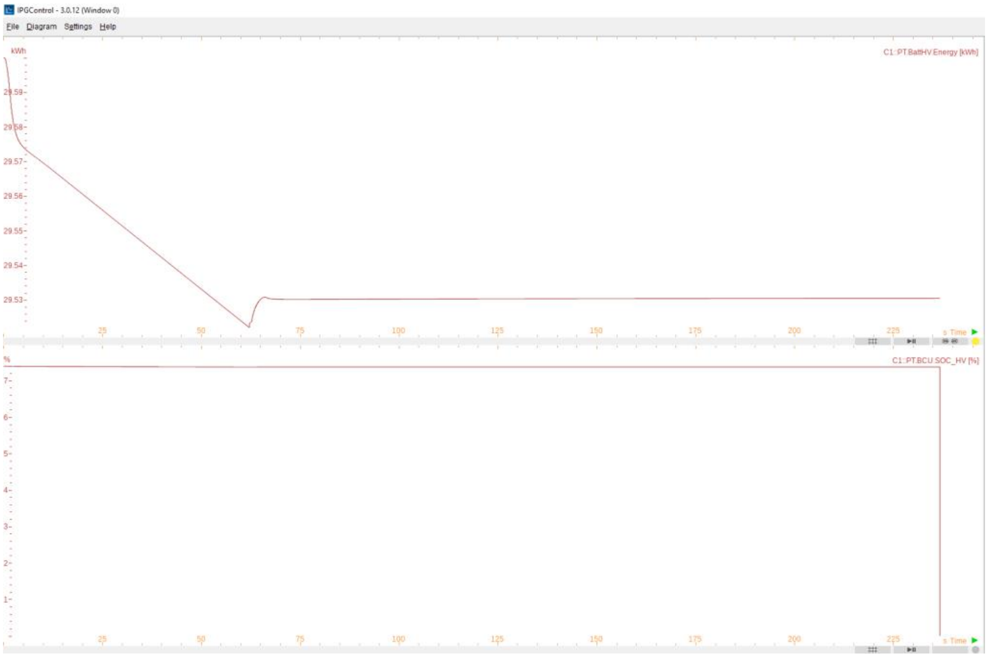


Figure 5. Graphic example of High-Voltage battery energy consumption and State-Of-Charge from IPG Control

Table 3. Results with conventional suspension system

Road segment number	Initial state of charge [%]	Destination state of charge [%]	Energy consumption [kWh/km]
1	98	96.8	0.42
2	96.8	94.2	0.44
3	94.2	92.7	0.52
4	92.7	90.9	0.41
5	90.9	88.7	0.43
6	88.7	87.9	0.47
7	87.9	86.1	0.45
8	86.1	84.8	0.44
9	84.8	83.3	0.5
10	83.3	81.5	0.42
11	81.5	80.0	0.46
12	80.0	78.9	0.44
13	78.9	76.8	0.54

Table 4. Results with air spring and electronically controlled dampers suspension system

Road segment number	Initial state of charge [%]	Destination state of charge [%]	Energy consumption [kWh/km]
1	98	96.9	0.4
2	96.9	94.5	0.41
3	94.5	93.2	0.48
4	93.2	92.0	0.39
5	92.0	89.5	0.42
6	89.5	88.3	0.46
7	88.3	87.8	0.44
8	87.8	86.9	0.42
9	86.9	85.7	0.49
10	85.7	84.6	0.4
11	84.6	83.2	0.44
12	83.2	81.4	0.41
13	81.4	80.1	0.53

As a result of the substantial quantity of data gathered, the results have been organized into tables to facilitate the process of analysis. This methodology facilitates a methodical and thorough analysis of the collected data, enhancing comprehension of the findings of the research.

The research findings clearly highlight the significant advantages of adaptive suspension systems over conventional alternatives, with a particular focus on their superior energy efficiency. The adaptive suspension system distinguishes itself by its capacity to optimise energy consumption by intelligently adjusting to various driving circumstances. The incorporation of this feature not only improves the overall comfort experienced during rides, but also plays a substantial role in enhancing fuel efficiency, thereby leading to a reduction in the environmental impact caused by automobiles. The objective research conducted in this study highlights the essential value of adaptive suspension systems in the continuous endeavour towards energy-efficient and ecologically conscientious transportation solutions.

Additionally, the air suspension controller utilised in our research was specifically calibrated to optimise energy economy rather than prioritise comfort. The intentional emphasis on this aspect resulted in a notable enhancement in the efficiency of energy recuperation from the regenerative braking system. The act of customising suspension settings serves to emphasise the versatility of these systems in relation to particular objectives, hence emphasising the possibility for customised solutions in enhancing energy economy for autonomous vehicles.

It is essential to acknowledge that the differences noticed between the two suspension systems may also arise from several other factors that influence the simulation. The findings can be considerably influenced by external variables, such as road conditions, vehicle weight, and driving behaviours. It is imperative to recognise these auxiliary factors in order to conduct a thorough assessment of the outcomes, facilitating an in-depth understanding of the distinctions between the adaptive and standard suspension systems within the framework of the simulation.

4. Conclusion

In conclusion, the analysis of an autonomous public transport vehicle's energy efficiency taking into consideration it suspension system setup, offers useful information for enhancing the effectiveness and sustainability of future public transportation. The examination of conventional and adaptive suspensions has demonstrated the notable capacity of the latter in augmenting both the driving encounter and energy saving. Nevertheless, it is imperative to recognise the complex interaction of numerous factors that impact simulation results. They emphasise the necessity of using a comprehensive strategy when assessing suspension systems.

This analysis reveals numerous potential areas for further enhancements and investigation. To increase the credibility and comprehensiveness of the simulation outcomes, it is imperative to perform testing scenarios in real-world conditions. This validation would yield invaluable insights into the practical efficacy and performance of adaptive suspension systems in autonomous public transport vehicles. Moreover, the investigation of using machine learning algorithms to augment the flexibility of suspension systems in real-time driving situations presents a potentially fruitful avenue for further research. In addition, conducting an examination into the possible ecological consequences associated with the extensive use of adaptive suspensions, encompassing their production methods and capacity for recycling, would enhance our holistic comprehension of their overall sustainability. By focusing on these specific areas, future research efforts can further progress the subject, ultimately resulting in the development of autonomous transportation systems that are not only safer and more energy-efficient but also environmentally conscientious.

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