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Investigation of Control Behavior via Active Suspension System Considering Time-Delay and Variable Masses

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ABSTRACT

The comfort and safety of drivers greatly depend on the design of the suspension system in road cars. The study presents modeling and control of an Active Suspension System (ASS) for a ¼ car with two degrees of freedom, considering unknown masses, time delay, and various types of road disturbances using the MATLAB/Simulink environment. The study examines the performance of the Model Predictive Control (MPC) scheme. Numerous controllers are utilized in literature, including Artificial Neural Networks (ANN), fuzzy logic controllers, Linear Quadratic Regulators (LQR), and Proportional Integral Derivative (PID) controllers. An MPC setup for the ASS model was presented in this paper. MPC is an optimal control strategy that predicts future output using a plant model. The performance of MPC was compared with that of an LQR control method. The results indicate The MPC can produce better road holding, and handling and ride quality are greatly improved by the LQR. The MPC control is 87% faster at eliminating oscillations compared to LQR which is 30%, The conclusion emphasizes that the effectiveness of the MPC scheme is far superior to LQR in all aspects. Despite certain challenges, such as reduced effectiveness under severe overload and increased energy consumption with larger loads.

Keywords: Active suspension system, Linear quadratic regulator, Model predictive control, Variable masses, Road disturbance.

1. INTRODUCTION

The most important goals of a vehicle's suspension system are to recover stability, driving safety, and ride comfort. Consequently, there is a contradiction between the criteria of ride quality and driving control **(Alzughaibi et al., 2019).** Road cars are built with suspension systems that minimize discomfort for both the driver and the passengers. The growing frequency of traffic accidents, which are one of the leading causes of death in the modern world, worries the World Health Organization greatly. A difficult problem and a highly

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sophisticated engineering undertaking is designing a suspension system **(Florea et al., 2023).** Vehicles may be exposed to a variety of external sources of disturbances, such as bumps and potholes. Prolonged body vibrations cause detrimental consequences on the human body's organs, including lumbar discomfort, early spine degeneration, fast heartbeat, pelvic osteoarthritis, visual abnormalities, shoulder and neck pain, and others **(Dridi et al., 2023).** Good isolation of the car's body from the wheel and superior isolation of the entire vehicle from road disturbances are made possible by a sturdy suspension system (**Matrood and Nassar, 2021)**. There are now three different kinds of suspension systems for vehicles: semi-active, active, and passive. Of these, the majority of automobiles employ the passive suspension system. While the car is in motion, its structural requirements cannot be changed in real-time, but they can be adjusted to improve the vehicle's comfort and handling stability. In terms of elastic qualities, the active suspension system performs better than the other two in terms of enhancing handling stability and driving comfort **(Yan et al., 2019)**. All the components of a passive suspension are present in an ASS, but an actuator plays a major role as well. Real-time suspension deflection manipulation is achieved by the actuator by injecting an independent force **(Yu et al., 2023)**. For this reason, research into ASS is crucial to both the growth of the automotive industry and the general public's need for comfort **(Chen et al., 2024)**. Consequently, a large number of academics have been studying active control to attain high performance. There have been several ASS proposed, such as optimum control, aimed at different performance objectives **(Boulaaras et al., 2024),** sliding mode control **(Bayar and Khaneghah, 2020),** fuzzy control **(Al-ashtari, 2023)**, H∞ control **(Fu and Dong, 2021),** adaptive control **(Wang, 2022),** And so forth. Since its complicated nature makes it difficult to use, the ASS means more research is needed to simplify the construction of the active suspension. Taking time delays in the control loop into account is one of the difficult problems **(Udwadia and Phohomsiri, 2006),** The authors develop a time delay compensation controller that greatly improves the vehicle's semi-active suspension performance by evaluating the time delay coming from the response of the Magneto-Rheological MR damper actuator and using Smith predictive control. **(Zhang and Chen, 2024)**. Research has indicated that the implementation of a suitable time delay in control can enhance the system's stability and damping properties **(Bououden et al., 2016),** A methodical and appealing approach to solving these difficult control problems is to combine hybrid modeling with Nonlinear Predictive Control (NPC). Due to its capacity to handle limited optimization control problems for Multiple-Input Multiple-Output (MIMO) systems as well as its ability to reject disruptions **(Findeisen, 2006),** LQR **(Ahmed, 2021)**, MPC, seems to be a useful method. Conversely, although predictive control methods consider actuator limits, their use is presently restricted due to the inadequacy of the necessary measurements in meeting reliability requirements and industrial costs, Time-domain advanced control strategies are designed via MPC. It differs from other controllers in that it may explicitly manage system constraints. At first, the difficulty of the computational requirements meant that the application of MPC was limited to slow processes in the petrochemical, paper, and pulp mill industries **(Yang et al., 2023)**.

This study's primary contribution is the enhanced ride comfort and vehicle stability brought about by the use of an advanced time-domain control approach called LQR in conjunction with MPC. After explaining the MPC control approach and comparing the ASS's performance with a LQR control technique using a plant model, it is clear that MPC is the best control method for projecting future output. The dynamic equations of motion and Newton's second law are provided for ASS based on the ¼ model. Modeling and control of an ASS by using MATLAB/Simulink software.

2. MATHEMATICAL MODELLING

2.1. Active Suspension System Model

ASS can enhance suspension performance using a force actuator and a closed-loop control system. The force actuator is a mechanical component installed inside the system that is controlled by a controller. The controller can increase or decrease the system's energy output, using sensors as a source of input. Sensors will provide information about the road. Newton's second law will be used for each mass **(Aljarbouh and Fayaz, 2020).** The system consists of two masses, two springs one damper, and one actuator. The first mass is the Body mass Mb (kg), the second mass is the wheel mass Mw (kg), the two masses are connected with a spring with a stiffness factor. K_1 (N/m), a damper with a damping coefficient C_1 (N.s/m) and a hydraulic actuator with force Fa (N), the tire has a stiffness factor K_2 (N/m) and a damping coefficient C_2 (N.s/m) as Presentation as shown in **Fig. 1(a)** for the quarter vehicle model of the ASS and **Fig.1(b)** for the free body diagram active suspension system model **(Xue et al., 2019).**

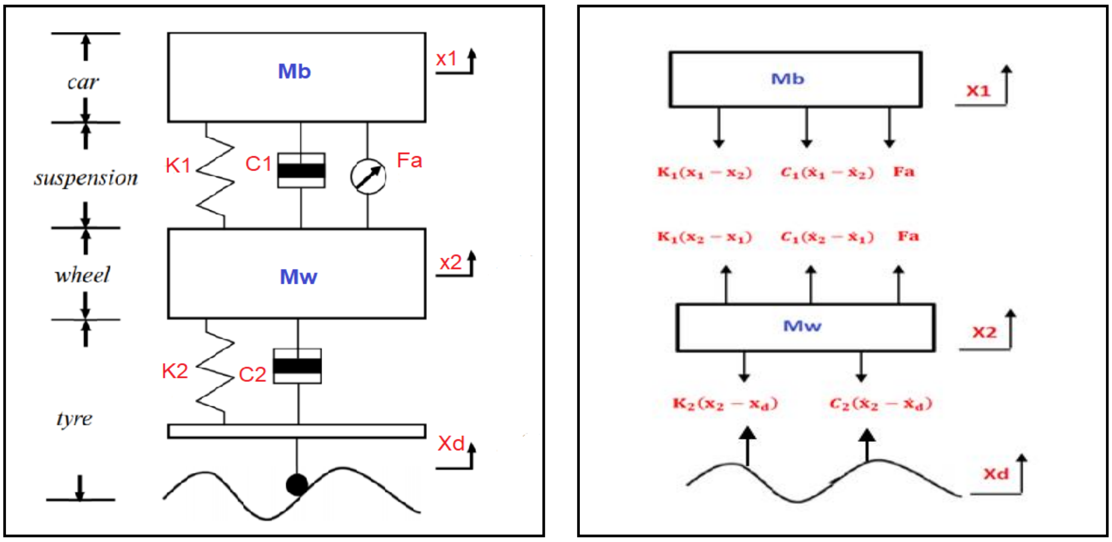


Figure 1. (a) Active suspension system model **(Han *et al.*, 2022)** (b) Free body diagram active suspension system.

For this system, the free body diagram for each mass needs to be identified to compute the Equations of Motion (EOM). The illustrations should depict the forces acting on each of the two masses in the system utilizing the notion and Newton's second law of motion., there will be two equations of motion. **Fig. 1(b)** describes the free-body diagram for M_b and the control force that the ASS's active element applies between the body and the wheel, and the damping force **(Abut and Salkim, 2023)**. The system's status variables include the displacement x_1 (m) and x_2 (m) and velocity $\dot{x}_1$(m/s) and $\dot{x}_2$(m/s) of the body and wheel masses respectively, The road's vertical displacement x_d (m) is devoted to road disturbance, **(Han et al., 2022)**. The equation of motion is associated with the body mass M_b is given by **(Kumar et al., 2022; Basargan et al., 2023; Abut and Salkim, 2023).**

$$\Sigma F = Ma \tag{1}$$

$$Spring\ force = -kx \tag{2}$$

$$Damping\ force = -C\dot{x} \tag{3}$$

$$M_b\ddot{x}_1 = -K_1(x_1 - x_2) - C_1(\dot{x}_1 - \dot{x}_2) + Fa \tag{4}$$

$$\ddot{x}_1 = \frac{1}{M_b}(K_1(x_2 - x_1) + C_1(\dot{x}_2 - \dot{x}_1) + Fa) \tag{5}$$

The equation of motion that is associated with the wheel mass M_w is given by:

$$M_w\ddot{x}_2 = K_1(x_2 - x_1) + C_1(\dot{x}_2 - \dot{x}_1) - K_2(x_2 - x_d) - C_2(\dot{x}_2 - \dot{x}_d) - Fa \tag{6}$$

$$\ddot{x}_2 = \frac{1}{M_w}(K_1(x_2 - x_1) + C_1(\dot{x}_2 - \dot{x}_1) - K_2(x_2 - x_d) - C_2(\dot{x}_2 - \dot{x}_d) - Fa) \tag{7}$$

2.1.1 System Parameters and Conditions

Table 1. Simulation parameter active suspension for a quarter vehicle **(Kumar *et al.*, 2022; Nan *et al.*, 2023)**.

Parameters	Symbol	Values	Units
Body mass	M_b	241.5	Kg
Wheel mass	M_w	41.5	Kg
Stiffness of the first spring	K_1	6000	N /m
Stiffness of the second spring	K_2	14000	N /m
The damping factor of the first damper	C_1	300	N.s /m
The damping factor of the second damper	C_2	1500	N.s /m

2.1.2 Modelling active suspension in MAT LAB Simulink

The code, as made known in **Fig. 2**, is developed in MATLAB/Simulink environment by using Eqs. (4 to 7) to establish the system's reaction **(Ghoniem et al., 2020).**

2.2. State-Space Modeling

The state-space model of the plant is often utilized by MPC controllers because it simplifies the management of MIMO systems. After all, control theorems for the state-space formulation are readily available. Four energy storage components make up a quarter vehicle model: the suspension, the sprung mass, the unsprung mass, and the springs that determine the tire's stiffness. A quarter-car active suspension's dynamics are best explained by, four state variables represented by the energy storage element **(Aktas and Esen, 2020).** Although the states that characterize the system are not unique, they can be changed into other combinations by applying the appropriate transformation. State variables are frequently selected so that they accurately represent the parameters that need to be optimized, which greatly simplifies the formulation of the optimization problem. In terms of the state-space form, a mathematical equation denoting the quarter car active suspension model in state-space representation is provided by:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{8}$$

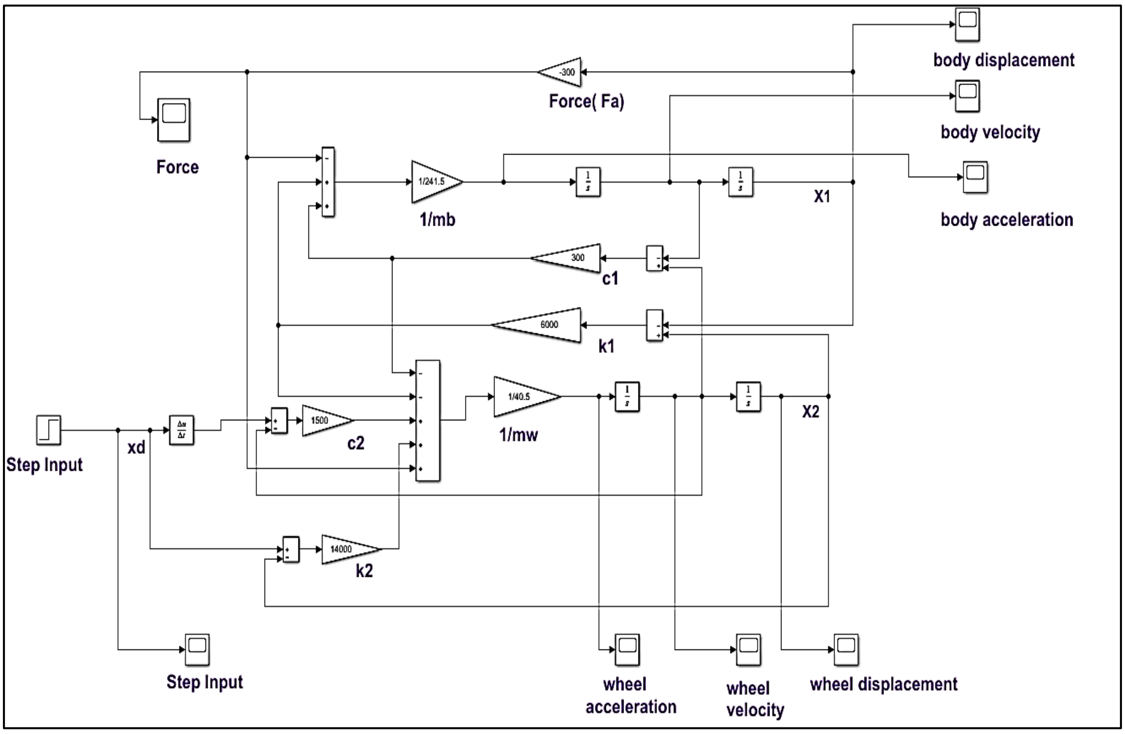


Figure 2. Simulink model for the active suspension system.

Where $X \in \mathbb{R}^{n+1}$, $Y \in \mathbb{R}^{p+1}$, $u \in \mathbb{R}^{m+1}$ are the state, output, and input vectors, respectively. The input vector represented by the equation is the result of the state variable of the system measured, which indicates that y = x.

$$u=\begin{bmatrix} \dot{x}_d \\ Fa \end{bmatrix} \tag{9}$$

Where Fa represents the actuator's force. The tire's vertical velocity is denoted by $\dot{x}_d$. The ASS's input matrix (B), output matrix (C), feed-through matrix (D), and system matrix (A) are explained by Eq. (10).

$$A=\begin{bmatrix} 0 & 1 & 0 & -1 \\ \frac{-k_1}{M_b} & \frac{-C_1}{M_b} & 0 & \frac{C_1}{M_b} \\ 0 & 0 & 0 & 1 \\ \frac{k_1}{M_w} & \frac{C_1}{M_w} & \frac{-(K2)}{M_w} & \frac{-(C_1+C2)}{M_w} \end{bmatrix}, B=\begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{M_b} \\ -1 & 0 \\ \frac{C_2}{M_w} & \frac{-1}{M_w} \end{bmatrix}, C=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, D=\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{10}$$

The C and D matrix varies according to the set of outputs that are used for control.

3. METHODOLOGY

3.1 Linear Quadratic Regulator

For linear systems, LQR is a powerful method for designing optimal state-feedback controllers. It is a common choice in control engineering as it balances the reduction of control effort with achieving a desired system response. The controller can maintain the intended system response more effectively, even in the presence of external disturbances, by considering disturbances **(Nguyen and Nguyen, 2023)**. LQR design inherently possesses a certain level of resilience to unexpected disruptions. The goal of LQR, an optimal control approach, is to maintain zero states in the system. The cost function penalizes a state for any deviation from zero references determined by the square of two state norms. An LQR control scheme minimizes the cost function:

$$J = \int_0^\infty (x^T\, Qx + \; u^T\, Ru)\, dx \tag{11}$$

Each state's relative importance is determined by the weighting matrix Q. The Q matrix is chosen while taking the scaling factor into account. For two additional reasons, the control inputs were punished. Initially, it makes sense to penalize the control input because there are always restrictions on it, so it cannot have an arbitrarily high value. The matrix dampened the magnitude of the increased cost of the R. Secondly, the hessian has to be positive and definite to guarantee the existence of the optimization solution. According to this, positive definiteness is required for the weighting matrix R. T punished every control input. The behavior or overall performance of the controlled system is measured by the cost function J. The LQR control problem has a solution as shown in Eq. (11). U is the control input, x is the state of the system, and k is a feedback gain or controller gain as demonstrated by Eq. (12).

$$u = -k\, x \tag{12}$$

The differential Riccati equation for a finite-time LQR control problem results in a time-varying feedback control law as the solution. As the problem extends to an infinite amount of time, the feedback law approaches a time-invariant value. As determined by (11) and derived from the algebraic Riccati equation (13), the LQR feedback gain is given by (14) and the feedback control law for the infinite-time LQR problem.

$$A^T\, P + P\, A - P\, B\, R^{-1} B^T\, P + Q = 0 \tag{13}$$

$$K = \; R^{-1} B^T\, P \tag{14}$$

3.2 Model Predictive Control

MPC is a class of sophisticated control techniques that specifically utilize a model to predict the system's future behavior. The computational load of addressing the optimization issue in one sampling instant led to the first limitation of MPC use to sluggish processes in industries such as petrochemicals, paper, pulp, etc. MPC is being used in processes with rapid dynamics in light of the availability of quick optimization methods, high-speed computers, and memory. MPC, in contrast to classical controllers such as PID, is capable of handling MIMO systems and methodically managing input and output limitations **(Li et al., 2024).** The capacity of MPC to optimize the current timeslot while considering future timeslots is its main advantage. To do this, optimize a finite temporal horizon using only the current timeslot, and then optimize again and again **(Montanez et al., 2015)**. The system's current state is measured or approximated and utilized as the starting point for future predictions;

this action indirectly introduces the feedback mechanism. MPC anticipates your car's behavior shortly by utilizing a model of its dynamics, which encompasses acceleration, braking, and turning. Next, it computes a series of control actions across a finite time horizon (such as the next few seconds of driving) that will reduce a cost function to get you as close to your target speed as possible while considering your car's limitations, such as its engine power and stopping distance. Using the vehicle model, the MPC system forecasts the vehicle's behavior over a specified time frame considering different control actions. Anticipated disruptions to the roads are also taken into account. This may involve using meteorological data (such as slick or rainy roads) or historical observations of that specific stretch of road (like uneven pavement). MPC considers constraints such as engine limits, braking distances, anticipated road disruptions, and other factors to establish the sequence of control actions, such as acceleration adjustments, that minimize the cost function. This function involves deviating from the intended speed. MPC can maintain stability and the correct trajectory by anticipating road disruptions and adjusting acceleration or steering in advance. To enhance driving safety, efficiency, and enjoyment, MPC offers a powerful method for guiding cars by considering future circumstances and disruptions **(Schwenzer et al., 2021)**. The linear MPC problem's generic mathematical formulation is provided by:

$$J = \sum_{k=0}^{N_P} f\,(x_k, \Delta u_k) \tag{15}$$

$$x_k = 0 = x(t)(estimat\ value)$$

$$x\,(k+1) = Ax\,(k) + Bu\,(k)$$

$y\,(k) \in Y$ (limitation of outputs)
$\Delta u\,(k) \in \Delta\mathbb{U}$ (limitations on the input rate of the control)
u (k) $\in \mathbb{U}$ (limitation of outputs)
To estimate the system outputs for Np sampling instant in the future also referred to as the prediction horizon, MPC employs the plant model to compute the input for the immediate and the number of sampling instants in future NC. A control horizon (NC) is the period the control input is computed **(Das and Kumar, 2019)**. The horizon is constant at every instant of the prediction and control horizons. MPC gives the sense that the time horizon for prediction and control is getting closer. The strategy of receding horizon is shown in **Fig. 3.**

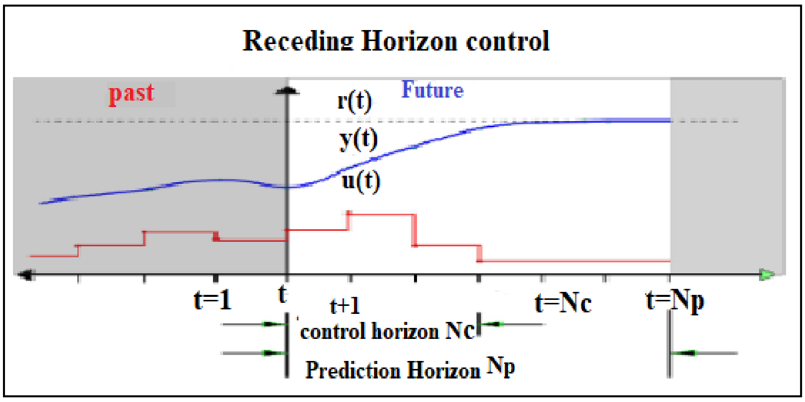


Figure 3. The receding horizon approach **(Das and Kumar, 2019).**

The calculation of optimal input ensures that future output evolution satisfies performance criteria and stays within limitations. Only the first component of the sequence is applied to the plant, discarding the remaining components, even though the optimum control computed the sequence for the complete control horizon at each instant. Fresh initial states and the cycle at the next sampling instant are utilized to address the optimization problem. Here, the MPC method is set up to compute the control signal increment, ensuring offset-free tracking output and simplifying the imposition of rate-of-control requirements. First, the increment of the control signal is used to indicate the control input and prior input. The state-space model is recast to incorporate an embedded integrator for the new plant model to accept the increase in control signal as input **(Chen et al., 2024)**. Here is the updated plant model Eq. (14). The fundamental component of MPC is its ability to predict behavior. The controller predicts the vehicle's response to impending road imperfections detected by in-vehicle sensors (e.g., accelerometers) using a mathematical model of the suspension system that was previously discussed. To reduce road disturbances, the MPC controller can adjust the suspension force before the vehicle reaches road imperfections by predicting them in advance. The system can improve passenger comfort by diminishing the amount of vibrations that are conveyed to the chassis. By preventing suspension compression and rebound caused by bumps and dips, you can enhance vehicle stability and handling **(Rodriguez-Guevara et al., 2021).**

4. RESULTS AND DISCUSSIONS

This part of the paper uses the ¼ car model in MATLAB/Simulink to simulate the vehicle's ASS. **Fig. 2** expressions the code for a ¼ car model. We present various scenarios along with the outcomes for each scenario.

4.1 Road Disturbance (Profiles)

Road disturbances are the main source of vibrations that hit drivers of automobiles; these vibrations travel through the vehicle's body and then to the driver and passengers. To inspect the suspension system and reduce vibrations, it is necessary to replicate road disturbances **(Yu et al., 2023).** After reviewing the several kinds of traffic disruptions, tests were conducted on one of the types. The identical approach can be used to repeat this for all types.

1. The step input road profile1 can be obtained through MATLAB/Simulink's step tool. **Fig.4**. Initial value = 0 m, final value = 0.1 m, step time = 1 t.

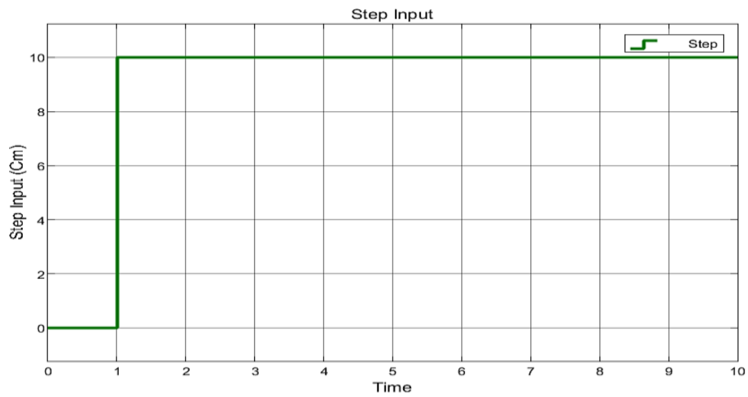


Figure 4. Simulink of step input road profile1.

2. The bump road profile1 in **Fig. 5** represents the second type, which was created using Simulink tools. Each sine wave had an amplitude of 0.1 m and a frequency of (2 * pi), and we used transport delay1 with a value of 0.5 t (the time it takes to complete half a sine wave) to produce two opposite sine waves. As illustrated in **Fig. 6.**

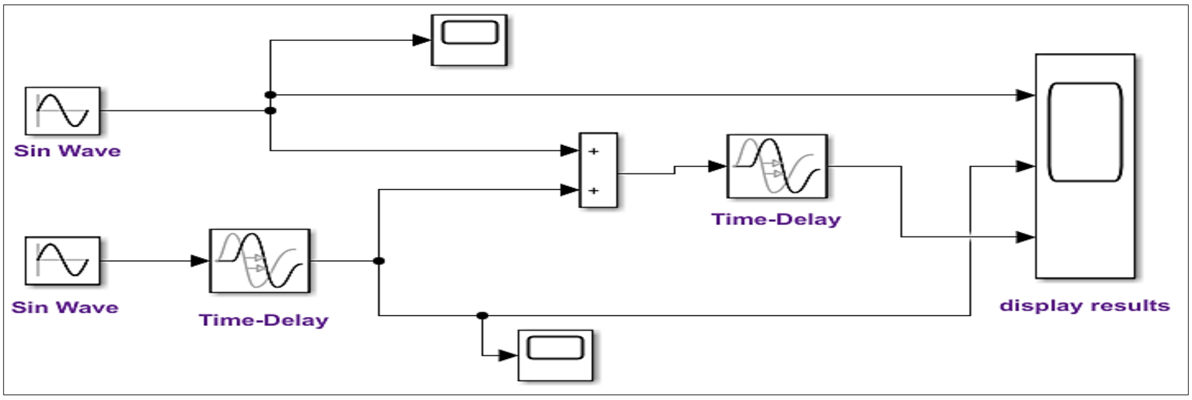


Figure 5. Simulink of bump road profile2.

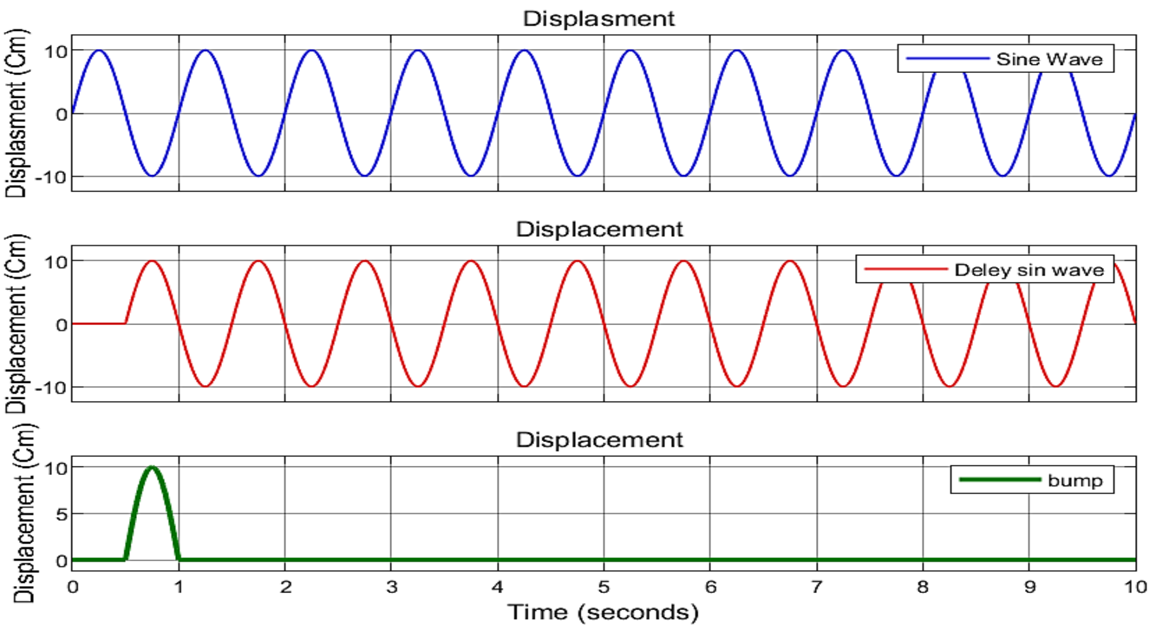


Figure 6. Road Disturbance-bump road profile2.

3. The random road profile3 in **Fig.7** represents the third type, which was created using Simulink tools. As illustrated in **Fig. 8.**

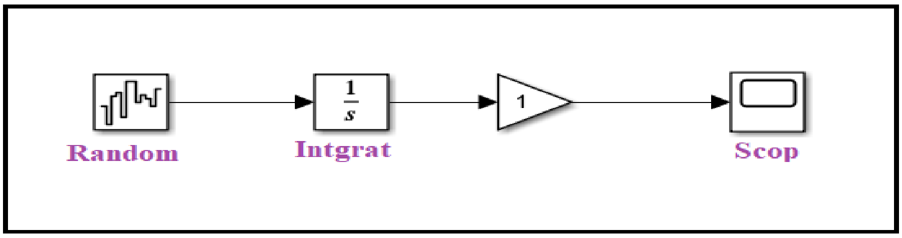


Figure 7. Simulink of Random road profile3.

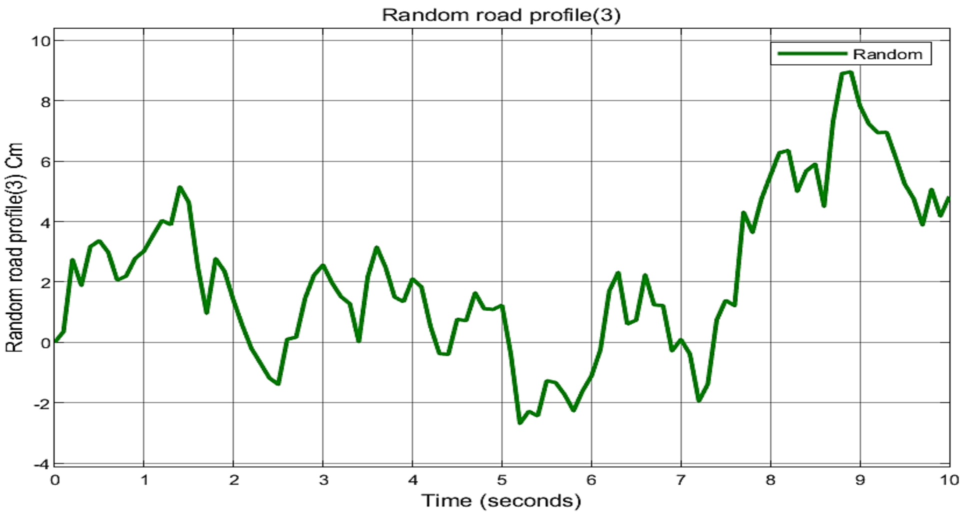
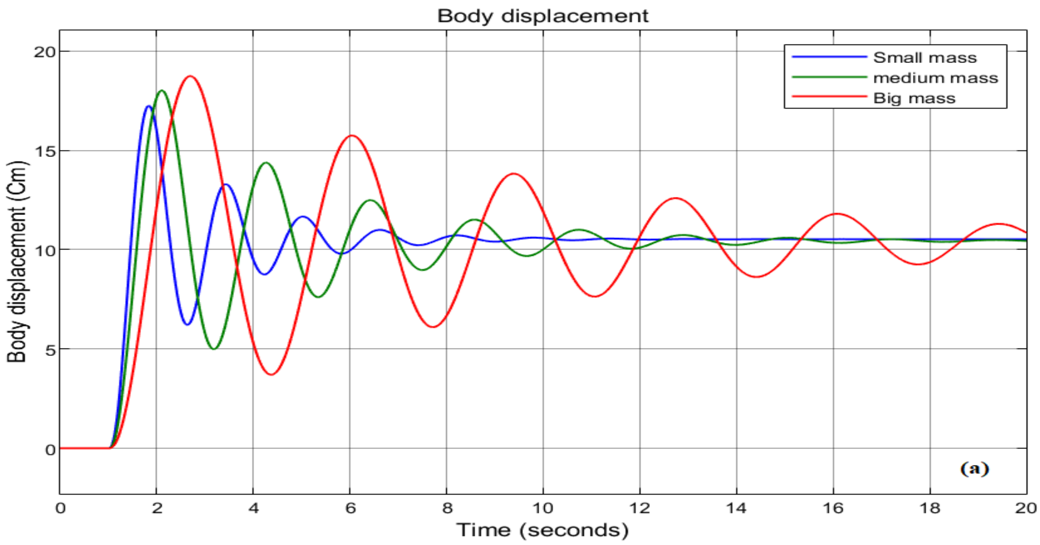


Figure 8. Road Disturbance-Random Road profile3.

4.2 Uncertainty in the Model (variable masses)

The uncertainty in the model is another matter that needs to be by taking into account all relevant factors, we can make informed decisions that lead to better outcomes. In the model system implement ASS in the real world. ASS's sprung and unsprung masses have different weights depending on the load and passenger count. If these variations are not considered throughout the controller design phase, the suspension's performance will suffer **(Alshamma and Zainalaabdeen, 2017; Nguyen, 2021)**. Owing to the significance of uncertainty in the suspension's performance **(Gu et al., 2022)**. The accuracy of the proposed design was confirmed by the simulation results from the control of quarter car suspension, with three changing body masses and fixed all other parameters, which was also carried out. The temporal response is given by **Figs. 9 to 11** for different Mb values (250 kg, 500 kg, and 750 kg) when step input is used as a road disturbance.



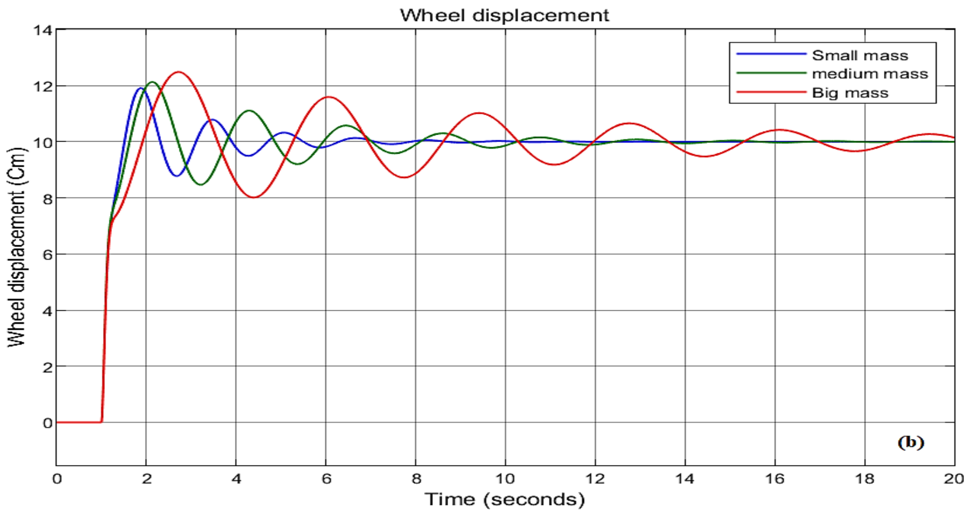


Figure 9. (a) Simulink of Body Displacement. (b) Simulink of Wheel Displacement.

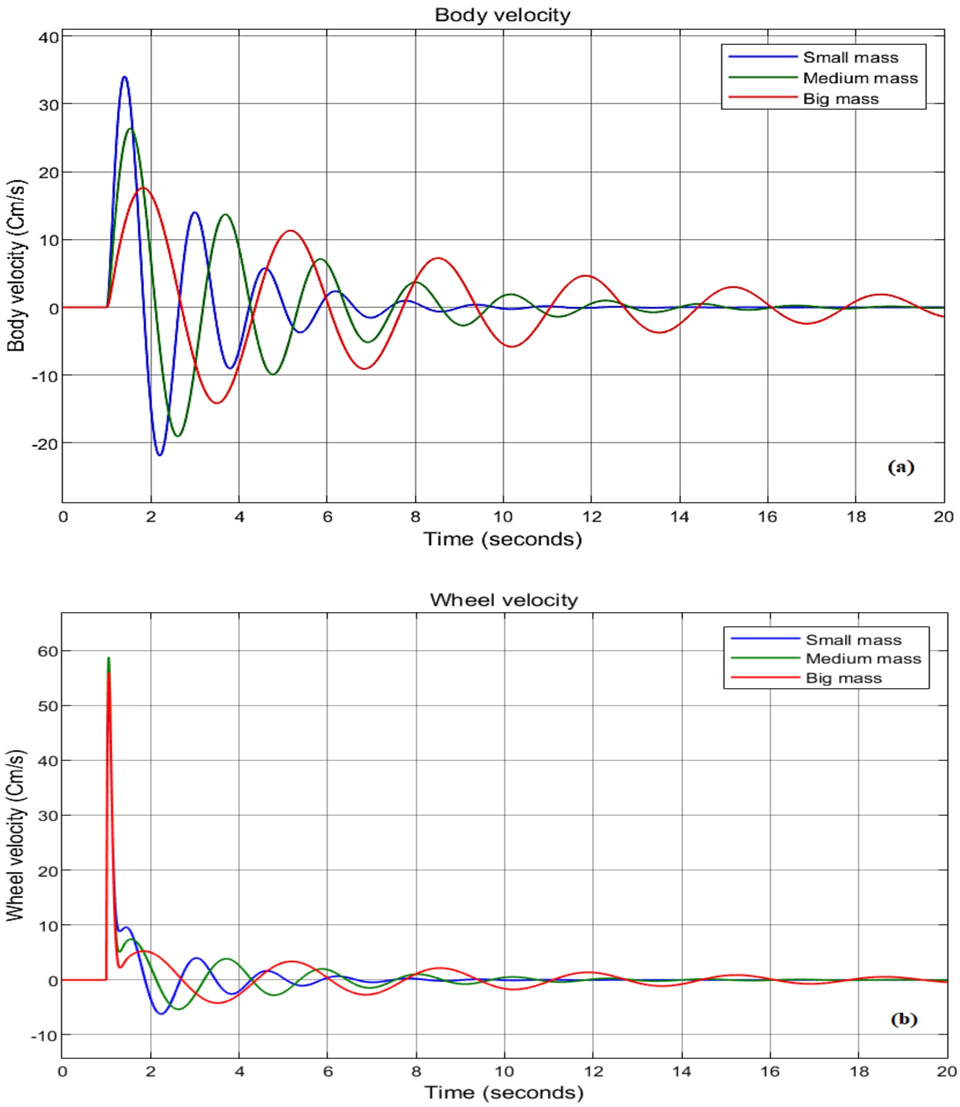
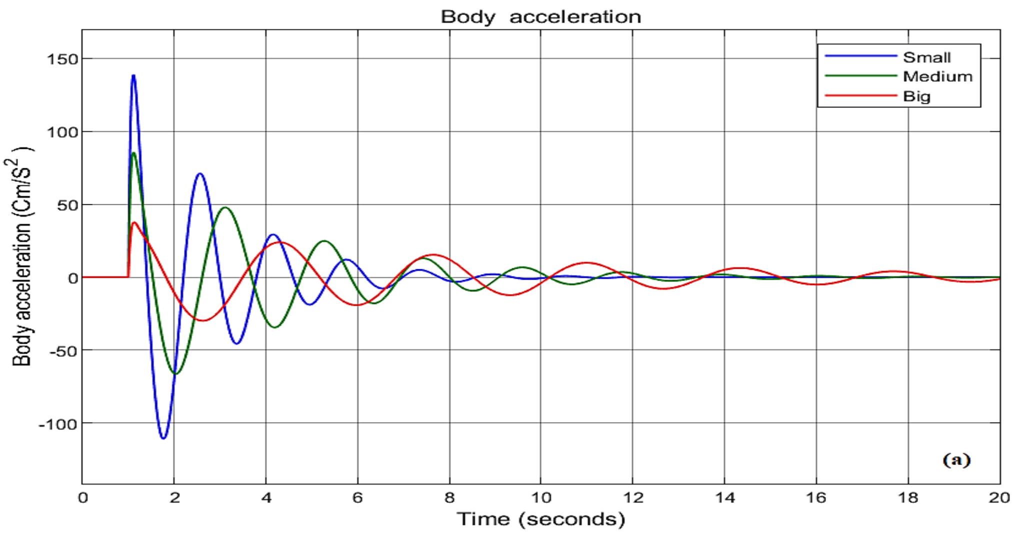


Figure 10. (a) Simulink of Body Velocity. (b) Simulink of Wheel Velocity.



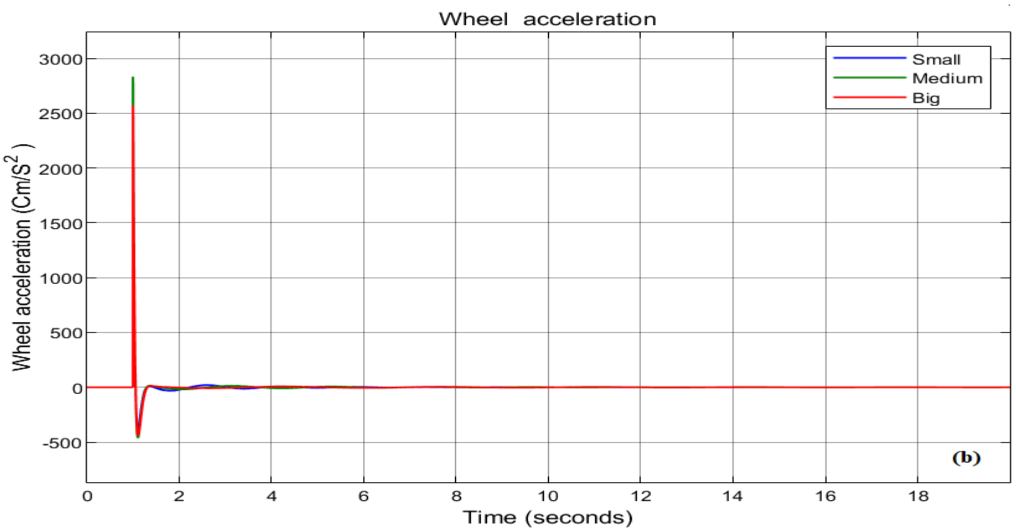


Figure 11. (a) Simulink of Body Acceleration. (b) Simulink of Wheel Acceleration.

Results are shown in **Figs. 9 to 11** after varying the Mb (body mass) and fixing all parameters.

1. In the three examination scenarios with varying mass values, its highest value in the first example (Big mass) is 18.3 (Cm), (Medium mass) 17.38 (Cm), and (small mass)16.73 (Cm). While The springs' potential travel range will be reduced by increased load compression. This may limit the system's greatest acceleration and desired velocity, mostly under heavy loads.
2. The increased body load can reduce the effectiveness of the ASS because it will require more effort on the part of the ASS to counteract the increased body load. This can reduce the system's ability to isolate the vehicle from road disturbances and control roll and pitch because the increased body load may overload the suspension system's springs and dampers. And reduce tire grip. Additionally, when tires are overloaded, their capacity to keep traction on the road is also diminished **(Nguyen and Nguyen, 2022)**.
3. The decreased body load can help the ASS work more effectively by reducing the amount of work it must do to counteract road disturbances. However, it also causes the vehicle's roll and pitch to cause the suspension system's springs and dampers to become less

overloaded. Boost tire grip because the tires' capacity to stay traction on the road may be higher by the reduced body weight making them less overloaded **(Huang et al., 2022).**

4. There is a trade-off between enhancing high-frequency vibration attenuation and potentially compromising low-frequency ride comfort and responsiveness when increasing the damping effect in an ASS for a quarter car. A compromise between comfort and performance can be achieved by adjusting the ideal damping level, which depends on several variables such as road conditions, vehicle type, purpose, and passenger preferences **(Nguyen and Nguyen, 2023)**.

4.3 Effect of Time Delay on the Operation of an Active Suspension System

In the experimental ASS, measuring suspension data including wheel velocity, suspension displacement, and body velocity is a sensor's main responsibility. By monitoring the actuator's pressure and flow rate through wheel or body acceleration when the proper controller is connected, performance can be enhanced **(Nan et al., 2023)**. ASSs are susceptible to time delays, which could negatively impact their effectiveness. To determine the probable causes of temporal delays

1. Sensor Dynamics: The internal dynamics of sensors, such as accelerometers, introduce a slight delay in their responsiveness to road disturbances.
2. Delays in Signal Processing: Analog-to-Digital Conversion (ADC): A slight time delay occurs during the conversion of analog sensor signals to digital format.
3. Filtering: Depending on their sophistication, filters used to remove noise from sensor data may introduce additional delays **(Kim et al., 2023).**

Ignoring time delays can lead to a decline in control efficiency or perhaps create instability within the dynamic system. Increased body accelerations and less comfortable riding may arise from the ASS's reaction to road disturbances being delayed. Instability may result from it as well as increased control difficulties for the system **(Mahmoud and Kadhim, 2023) (Wu and Ren, 2020).** MPC controllers and ASSs can minimize time delays, but they cannot eliminate them. It can predict delays and compensate for them. This greatly diminishes its influence. The controller anticipates future imperfections in the road and can begin adjusting the suspension before the automobile encounters them. By being proactive, you can reduce the amount of time the car spends reacting to bumps, which will make the ride smoother**(Kim et al., 2023).**

4.4 Comparative Results of Using MPC and LQR on the Operation of an Active Suspension System

In this simulation, we take into consideration the ASS discrete-time model with LQR and MPC control methods, these are the settings chosen for the MPC. The control horizon is Hu=1, the prediction horizon is constrained to Hp=12, and the weighting matrices are Q = I, R = 0.4 I, and S = 0.15 I. The hard limitation on the ASS is $|u(k)| \leq umax$; umax=1500 to limit the power of the hydraulic actuator. A steady-state error, maximum overshoot, delay time, rising time, and settling time are some of the characteristics of each controller that we take into account while assessing their performance **(Bououden et al., 2016)**.

Fig. 12 illustrates the step response of the suspension deflection. We observe that the conditions for overshoot percentage and settling time are met. The output has an overshoot of less than 5% and a settling time of less than 1.2 seconds. Furthermore, the steady-state error also approaches zero. We conclude that the reaction is satisfactory. The MPC control is 87% faster at eliminating oscillations compared to LQR which is 30%, as shown in **Table 2.**

Table 2. Percentage of improvement in the performance of the active suspension system.

Active suspension system	LQR	MPC	Improvement (%)	
			LQR	MPC
Stabilizing time	6.3 s	1.17 s	30 %	87 %

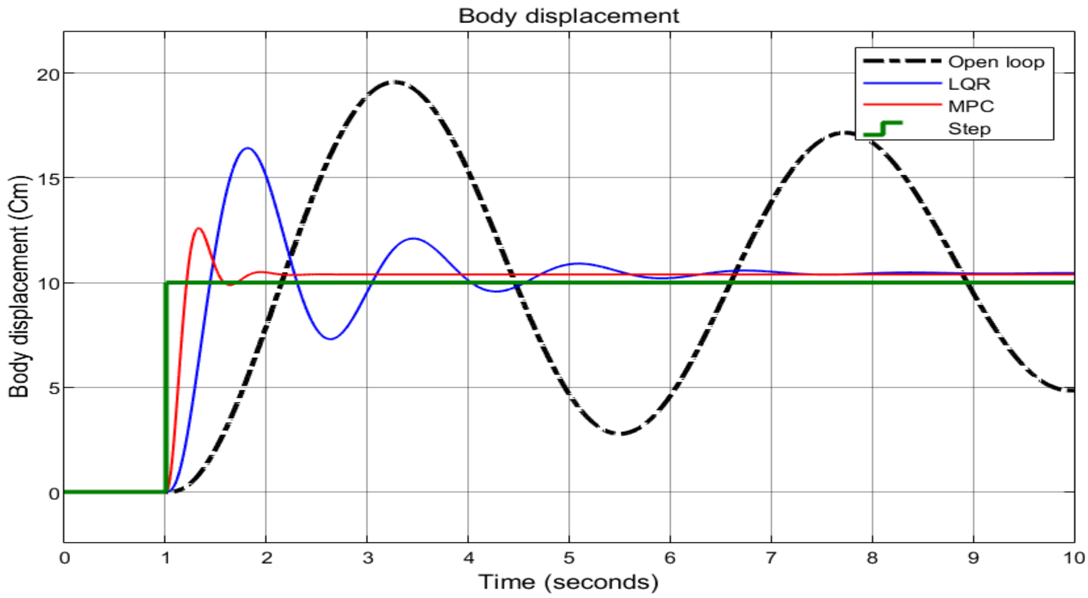


Figure 12. Simulink Step reaction of deflection in suspension.

Fig. 13 shows that when comparing the MPC controller to the LQR controller, the MPC controller's sprung mass acceleration produces the lowest value of the maximum sprung mass acceleration.

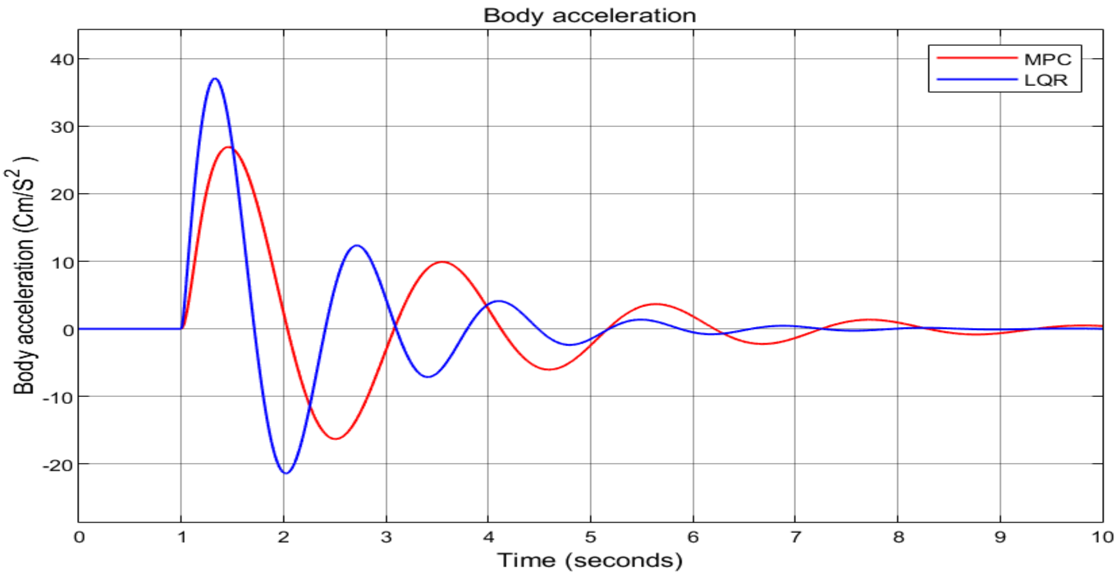


Figure 13. Step response of acceleration of the sprung mass.

Fig. 14 illustrates how the MPC control respects the active control force restriction, while the LQR controller does not since it was not made aware of the hard limits throughout the controller design process. This significantly improves the ride quality of the vehicle suspension system as compared to the standard LQR controller.

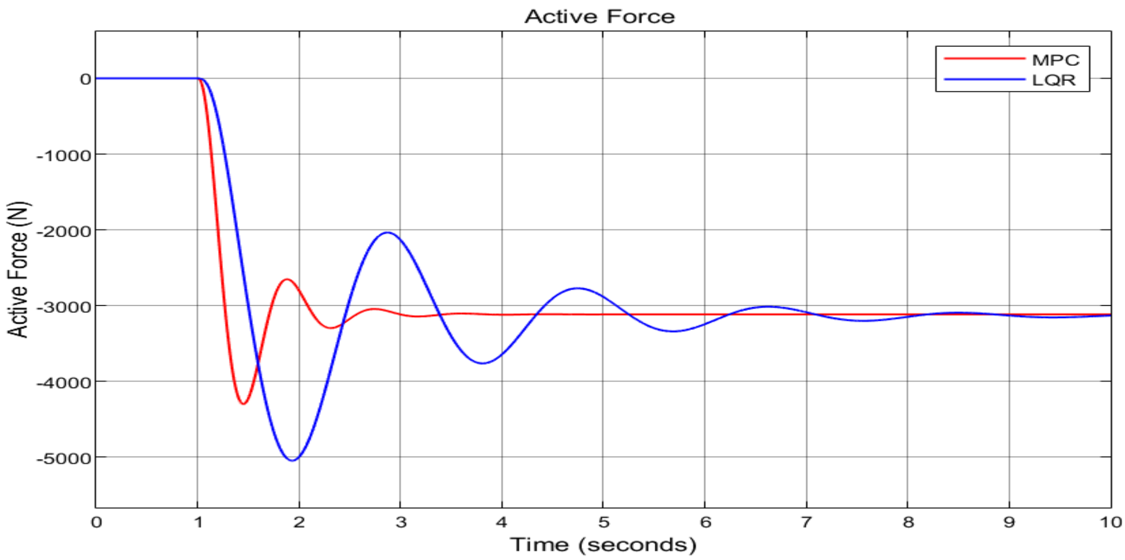


Figure 14. An active force step reaction.

Fig. 15 shows that the MPC's tire deflection is less than the LQR controller's. This implies that MPC can generate superior road holding, and it is evident that the LQR significantly enhances handling and ride quality.

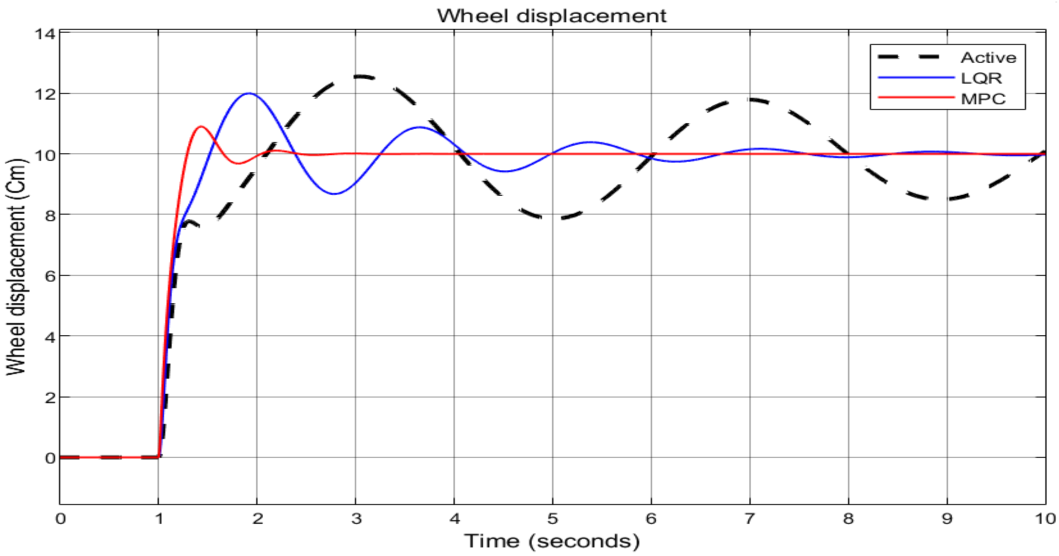


Figure 15. Step reaction of tire deflection.

5. CONCLUSIONS

The study presents modeling and control of an ASS for a quarter car with two degrees of freedom, featuring unknown masses, time delay, and various types of road disturbances, utilizing the MATLAB/Simulink environment. Creating an LQR control scheme and an MPC.

To determine the effectiveness of LQR and MPC schemes for ASSs, the movement of sprung and unsprung masses, actuator force, and vertical acceleration of the sprung mass for a specific type of road profile were examined. The following conclusions were obtained:

1. MPC offers a viable solution for the time delay issues in ASSs. The ability to predict future behavior and optimize control signals in a receding horizon manner contributes to enhanced vibration attenuation and handling performance, while also reducing the adverse effects of delays.
2. With MPC, the ASS becomes more resilient to unforeseen events on the road. Vibration-causing oscillation, overshoot of the sprung mass, and overshoot of the unsprung mass are significantly decreased. The MPC's performance improvement compared to an LQR.
3. The overload causes reduced effectiveness: Although ASS can mitigate some of the impacts of a severe overload, it might not be able to completely do so. Also, Increased Power Consumption: A larger load will require more effort from the ASS to sustain performance. This may result in increased energy usage, which could affect fuel economy.

MPC is a viable method for active suspension management beyond the 1/4 vehicle model due to its strength in handling complex systems. Despite computational obstacles, research is ongoing to find solutions. Engineers can enhance the performance of active suspension systems by incorporating MPC into more sophisticated vehicle models.

NOMENCLATURE

Symbol	Description	Symbol	Description
M_b	Mass of body (Kg)	x_2	Vertical Wheel displacement(m)
M_w	Mass of wheel (Kg)	x_d	Road profile displacement(m)
$\ddot{x}_1$	Acceleration of body mass(m/s^2)	C_1	Coefficient of suspension damping (N.s/m)
$\ddot{x}_2$	Acceleration of wheel mass(m/s^2)	C_2	Coefficient of tire damping (N.s/m)
$\dot{x}_1$	The velocity of body mass (m/s)	K_1	Coefficient of suspension spring (N/m)
$\dot{x}_2$	The velocity of wheel mass (m/s)	K_2	Coefficient of tyre spring (N/m)
x_1	Vertical Body displacement (m)		

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Credit Authorship Contribution Statement

Lamyaa Mahdi Ali: Writing – review & editing, Writing – original draft, Validation, Software, Methodology. Ali I. Al-Zughaibi: Supervising and following up the research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Ahmed, A.A., 2021. Quarter car model optimization of active suspension system using fuzzy PID and linear quadratic regulator controllers. *Global Journal of Engineering and Technology Advances*, 6(3), pp.088-097. https://doi.org/10.1016/j.vacuum.2020.109766

Abut, T., and Salkim, E., 2023. Control of Quarter-Car Active suspension system based on optimized fuzzy linear quadratic regulator control method, *Applied Sciences (Switzerland)*, 13(15). https://doi.org/10.3390/app13158802

Aktas, K.G., and Esen, I., 2020. State-Space modeling and active vibration control of smart flexible cantilever beam with the use of finite element method. *Engineering Technology and Applied Science Research*, 10(6), pp. 6549–6556. https://doi.org/10.48084/etasr.3949.

Al-Ashtar, W., 2023. Fuzzy logic control of active suspension system equipped with a hydraulic actuator. *International Journal of Applied Mechanics and Engineering,* 28(3), pp. 13–27. https://doi.org/10.59441/ijame/172895.

Aljarbouh, A., and Fayaz, M., 2020. Hybrid modeling and sliding mode control of semi-active suspension systems for both ride comfort and road-holding. *Symmetry*, 12(8). https://doi.org/10.3390/SYM12081286.

Alshamma, F. and Zainalaabdeen, S.A., 2017. The effect of cyclic bending loads on crack growth in pipes for inclined and transverse cracks with or without internal pulsing pressure. *Journal of Engineering*, 23(6), pp. 93–109. https://doi.org/10.31026/j.eng.2017.06.07.

Alzughaibi, A., Xue, Y. and Grosvenor, R., 2019. A new insight into modeling passive suspension real test rig system with consideration of nonlinear friction forces. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 233(8), pp. 2257–2266. https://doi.org/10.1177/0954407018764942.

Basargan, H., Mihaly, A. and Gaspar, 2023. Intelligent road-adaptive semi-active suspension and integrated cruise control. *Machines*, 11(2), pp. 1–18. https://doi.org/10.3390/machines11020204.

Bayar, K. and Khaneghah, F.S., 2020 Optimal sliding mode control method for active suspension control. *IFAC-PapersOnLine*, 53(2), pp. 14285–14291. https://doi.org/10.1016/j.ifacol.2020.12.1178.

Boulaaras, Z., Aouiche, A. and Chafaa, K., 2024. Optimal and robust control of active suspension system for a quarter car model. *AIJR Abstracts*, pp.39-41.

Bououden, S., Chadli, M. and Karimi, H., R., 2016. A robust predictive control design for nonlinear active suspension systems. *Asian Journal of Control*, 18(1), pp. 122–132. https://doi.org/10.1002/asjc.1180.

Chen, S., Preciado, V., Morari, M. and Matni, N., 2024. Robust model predictive control with polytopic model uncertainty through System Level Synthesis, *Automatica*, 162, pp. 1–26. https://doi.org/10.1016/j.automatica.2023.111431.

Das, R.R. and Kumar, V., 2019. Active suspension with model predictive control. Int. J. Eng. Adv. Technol., 8(6), pp.2826-2831. https://doi.org/10.35940/ijeat.F9038.088619.

Drdi, I., Hamza, A. and Ben Yahia, N., 2023. A new approach to controlling an active suspension system based on reinforcement learning. *Advances in Mechanical Engineering*, 15(6), pp. 1–21. https://doi.org/10.1177/16878132231180480.

Florea, A., Patrausanu, A., Cofaru, N. and Fiore, U., 2023. Superposition of populations in multi-objective evolutionary optimization of car suspensions. *Engineering Applications of Artificial Intelligence*, 126(PC), p. 107026. https://doi.org/10.1016/j.engappai.2023.107026.

Fu, Z.J. and Dong, X.Y., 2021. H∞ optimal control of vehicle active suspension systems in two-time scales. *Automatika,* 62(2), pp. 284–292. https://doi.org/10.1080/00051144.2021.1935610

Findeisen, R., 2006. *Nonlinear model predictive control: A sampled-data feedback perspective* (Doctoral dissertation, Stuttgart, Univ., Diss., 2004).

Ghoniem, M., Awad, T. and Mokhiamar, O., 2020. Control of a new low-cost semi-active vehicle suspension system using artificial neural networks. *Alexandria Engineering Journal*, 59(5), pp. 4013–4025. https://doi.org/10.1016/j.aej.2020.07.007.

Gu, B., Cong, J., Zhao., Chen, H. and Golshan M., F., 2022. A novel robust finite time control approach for a nonlinear disturbed quarter-vehicle suspension system with time delay actuation. *Automatika*, 63(4), pp. 627–639. https://doi.org/10.1080/00051144.2022.2059205.

Han, S.Y., Dong, J., Zhou, J. and Chen, Y., 2022. Adaptive fuzzy PID control strategy for vehicle active suspension based on road evaluation. *Electronics (Switzerland)*, 11(6). https://doi.org/10.3390/electronics11060921.

Huang, Y., Wu, J., Na, J., Han, S. and Gao, G., 2022. Unknown system dynamics estimator for active vehicle suspension control systems with time-varying delay *IEEE Transactions on Cybernetics*, 52(8), pp. 8504–8514. https://doi.org/10.1109/TCYB.2021.3063225.

Kim, J., Lee, T., Kim, G., J. and Yi, K., 2023. Model predictive control of a semi-active suspension with a shift delay compensation using preview road information. *Control Engineering Practice*, 137(December 2022), p. 105584. https://doi.org/10.1016/j.conengprac.2023.105584.

Kumar, S., Medhavi, A., Kumar, R. and Mall, P.K., 2022. Modeling analysis and PID controller implementation on suspension system for quarter vehicle model. *Journal of Mechanical Engineering and Sciences*. S. Kumar1, pp. 8905–8916. https://doi.org/10.15282/jmes.16.2.2022.08.0704.

Li, Q., Chen, Z., Song, H. and Dong, Y., 2024. Model predictive control for speed-dependent active suspension system with road preview information. pp. 1–17. https://doi.org/10.3390/s24072255.

Mahmoud, W. A. and Kadhim, D. J., 2023. A proposal algorithm to solve delay constraint least cost optimization problem. *Journal of Engineering*, 19(1), pp. 155–160. https://doi.org/10.31026/j.eng.2013.01.09.

Matrood, M.M. and Nassar, A.A., 2021. Vibration control of quarter car model using modified PID controller. *Basrah Journal for Engineering Sciences*, *6*. https://doi.org/10.33971/bjes.21.2.1.

Montanez, G., Patino, D. and Mendez, D., 2015. Comparison of model predictive control techniques for active suspension. *International Conference on Applied Electronics*, 2015-Octob, pp. 157–160.

Nan, Y., Shao, S., Ren, G., Wu, K. and Cheng, Y., 2023. Simulation and experimental research on active suspension system with time-delay feedback control. *IEEE Access*, 11(August), pp. 88498–88510. https://doi.org/10.1109/ACCESS.2023.3305265.

Nguyen, D.N. and Nguyen, T.A., 2023. The dynamic model and control algorithm for the active suspension system. *Mathematical Problems in Engineering*. https://doi.org/10.1155/2023/2889435.

Nguyen, D.N. and Nguyen, T.A., 2022. Evaluate the stability of the vehicle when using the active suspension system with a hydraulic actuator controlled by the OSMC algorithm. *Scientific Reports*, 12(1), pp. 1–15. https://doi.org/10.1038/s41598-022-24069-w.

Nguyen, T. A., 2021. Advance the efficiency of an active suspension system by the sliding mode control algorithm with five state variables. *IEEE Access*, 9, pp. 164368–164378. https://doi.org/10.1109/ACCESS.2021.3134990.

Rodriguez-Guevara, D., Favela-Contreras, A., Beltran-Carbajal, F. and Sotelo, D., 2021. Active suspension control using an MPC-LQR-LPV controller with attraction sets and quadratic stability conditions. *Mathematics*, 9(20), pp. 1–17. https://doi.org/10.3390/math9202533.

Schwenzer, M., Ay, M., Bergs, T. and Abel, D., 2021. Review on model predictive control: an engineering perspective. *International Journal of Advanced Manufacturing Technology*, 117(5–6), pp. 1327–1349. https://doi.org/10.1007/s00170-021-07682-3.

Udwadia, F. E. and Phohomsiri, P., 2006. Active control of structures using time-delayed positive Feedback proportional control designs. *Structural Control and Health Monitoring*, 13(1), pp. 536–552. https://doi.org/10.1002/stc.128.

Wang, D., 2022. Adaptive control for the nonlinear suspension systems with stochastic disturbances and unknown time delay *Systems Science and Control Engineering*, 10(1), pp. 208–217. https://doi.org/10.1080/21642583.2021.1949403.

Wu, K. and Ren, C., 2020. Control and stability analysis of double time-delay active suspension based on particle swarm optimization. *Shock and vibration*, 2020. https://doi.org/10.1155/2020/8873701.

Xue, W., Li, K., Chen, Q. and Liu, G., 2019. Mixed FTS/H ∞ control of vehicle active suspensions with shock road disturbance. *Vehicle System Dynamics*, 57(6), pp. 841–854. https://doi.org/10.1080/00423114.2018.1490023.

Yan, G., Fang, M. and Xu, J., 2019. Analysis and experiment of time-delayed optimal control for vehicle suspension system. *Journal of Sound and Vibration*, 446(1239), pp. 144–158. https://doi.org/10.1016/j.jsv.2019.01.015.

Yang, H., Qin, Y., Xiang, C., Bai, W. and Xu., B., 2023. Active suspension robust preview control by considering actuator delay. *IEEE Transactions on Intelligent Vehicles*, 8(9), pp. 4263–4274. https://doi.org/10.1109/TIV.2023.3280599.

Yu, M., Evangelou, S. and Dini, D., 2023. Advances in active suspension systems for road vehicles. *Engineering*. 33, pp. 160-177. https://doi.org/10.1016/j.eng.2023.06.014.

Zhang, Y. and Chen, C., 2024. Robust predictive compensation control for lateral magnetorheological semi-active suspension of high-speed trains with time delay *Automatika*, 65(1), pp. 14–33. https://doi.org/10.1080/00051144.2023.2277492

دراسة سلوك التحكم من خلال نظام التعليق النشط مع الأخذ في الاعتبار الكتل المتغيرة والتأخير الزمني

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الخلاصة

تعتمد راحة وسلامة السائقين بشكل كبير على تصميم نظام التعليق في سيارات الطرق. تقدم الدراسة النمذجة والتحكم في نظام التعليق النشط (ASS) لسيارة ¼ بدرجتين من الحرية، مع الأخذ بعين الاعتبار الكتل غير المعروفة، والتأخير الزمني، وأنواع مختلفة من اضطرابات الطريق باستخدام بيئة MATLAB/Simulink حيث تناولت الدراسة أداء نظام التحكم التنبؤي النموذجي (MPC) من خلال استخدام العديد من وحدات التحكم في الأدب، بما في ذلك الشبكات العصبية الاصطناعية (ANN)، ووحدات التحكم المنطقية الضبابية، منظمات الخطية التربيعية (LQR)، وأجهزة التحكم المشتقة التكاملية التناسبية (PID). تم تقديم إعداد MPC لنموذج ASS في هذه الورقة. MPC هي استراتيجية تحكم مثالية تتنبأ بالإنتاج المستقبلي باستخدام نموذج المصنع. تمت مقارنة أداء MPC بأداء طريقة التحكم LQR. تشير النتائج إلى أن MPC يمكن أن يحقق ثباتًا أفضل على الطريق، أن جودة التحكم والركوب قد تحسنت بشكل كبير بواسطة LQR. إن التحكم في MPC أسرع بنسبة 87% في القضاء على التذبذبات مقارنة بـ LQR الذي يبلغ 30%، الاستنتاج اثبت أن فعالية نظام MPC تتفوق بكثير على LQR في جميع الجوانب. على الرغم من بعض التحديات، مثل انخفاض الفعالية في ظل التحميل الزائد الشديد وزيادة استهلاك الطاقة مع الأحمال الكبيرة.

الكلمات المفتاحية: نظام التعليق النشط، المنظم التربيعي الخطي، نموذج التحكم التنبؤي، الكتل المتغيرة، اضطراب الطريق.