Simulation-Based Investigation of Adaptive Suspension Control for Regional Road Conditions in Tigray

Thesis

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Masters of science in Automotive Engineering

By

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DECLARATION

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Thesis Acceptance Approval Form

This is to certify that **Mr. Abraha Gebru** has incorporated all comments forwarded by the external and internal examiners with the chairperson during the thesis defense.

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ABSTRACT

This thesis presents the design, modeling, simulation, and performance evaluation of an adaptive suspension control system developed to improve vehicle dynamics under the diverse road conditions of the Tigray region, Ethiopia. Suspension systems are fundamental in enhancing ride comfort, handling, and overall vehicle stability. Conventional passive suspensions, while simple and cost-effective, lack adaptability to the rapidly changing and uneven road conditions prevalent in developing regions. In response, researchers have introduced various intelligent control techniques—such as PID, Fuzzy Logic, and Adaptive Neuro-Fuzzy Inference Systems (ANFIS)—to address these challenges. However, existing studies still face limitations in real-time adaptability, nonlinear response management, and system robustness across unpredictable terrains. To overcome these challenges, this study proposes a hybrid PID–ANFIS adaptive suspension control approach, combining the fast response of the PID controller with the learning and adaptability of ANFIS. A quarter-car model of a light-duty vehicle was developed in MATLAB/Simulink to simulate various representative road conditions, including paved, unpaved, bump, and hilly terrains. The controller's performance was evaluated using key dynamic metrics: ride comfort (weighted RMS acceleration), suspension travel, and road holding ability. Simulation results demonstrated that the hybrid PID–ANFIS controller outperformed both the classical PID and passive suspension systems. Specifically, body acceleration was reduced by over 80%, suspension travel was maintained within safe mechanical limits, and tire force variation was minimized, improving road holding stability. The overshoot decreased from 72.33% (PID) to 19.73% (PID–ANFIS), while rise time improved from 34.71 ms to 12.59 ms, and the RMS error reduced from 0.05784 (passive) to 0.00026 (PID–ANFIS). Compared to prior studies reporting 70–78% improvement using hybrid controllers, the proposed system achieved higher performance gains due to optimized parameter tuning and adaptive learning capabilities. The results confirm that the proposed hybrid PID–ANFIS controller is an effective, terrain-adaptive solution capable of improving ride comfort, stability, and safety for vehicles operating in challenging regional road conditions. This work contributes a region-specific adaptive suspension model that can be applied to improve vehicle performance in developing areas with similar infrastructure characteristics.

Keywords: Adaptive Suspension System; PID–ANFIS; Vehicle Dynamics; Road Holding; Ride Comfort; Tigray Region

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LIST OF ABBREVIATIONS

Abbreviation	Description
ANFIS	Adaptive Neuro-Fuzzy Inference System
PID	Proportional-Integral-Derivative
PSD	Power Spectral Density
ISO	International Organization for Standardization
RMS	Root Mean Square
MPC	Model Predictive Control
RL	Reinforcement Learning
FIS	Fuzzy Inference System
GUI	Graphical User Interface
MF	Membership Function
IAE	Integral of Absolute Error
ITAE	Integral of Time-weighted Absolute Error
ISE	Integral of Squared Error
ITSE	Integral of Time-weighted Squared Error
GIS	Geographic Information System

NOMENCLATURE

Symbols	Description	unit
M_s	Sprung mass	kg
M_{us}	Unsprung mass	kg
Z_r	Displacement of the base excitation	m
x_s	Displacement of the sprung mass	m
$\dot{x}_{us}$	Velocity of the sprung mass	m/s
$\ddot{x}_s$	Acceleration of the sprung mass	m/s^2
x_{us}	Displacement of the Unsprung mass	m
$\dot{x}_{us}$	Velocity of the Unsprung mass	m/s
$\ddot{x}_{us}$	Acceleration of the Unsprung mass	m/s^2
F_c	Control force from actuator	
e	Error (difference between desired and actual output)	
Δe	Change in error	
$u(t)$	Control output signal	
K_p	Proportional gain	
K_i	Integral gain	
K_d	Derivative gain	

CHAPTER ONE

INTRODUCTION

1.1. Background

Vehicle dynamics are vital in automotive engineering, affecting comfort, safety, and handling. The suspension system plays a key role by absorbing road shocks, maintaining tire contact, and stabilizing the vehicle during maneuvers. Passive suspensions, using fixed springs and dampers, are common for their simplicity and low cost but lack adaptability. Semi-active systems offer better performance with adjustable dampers, while fully active systems use sensors and actuators to optimize suspension in real time for maximum ride quality.

Over the last few decades, the modern implementation of adaptive suspension technologies has grown tremendously, especially with regard to better control algorithms. In any industry, the father of feedback control, the PID controller, was and still is one of the most used controllers A reinforcement learning with magnetorheological (MR) dampers has also shown big improvements, up to 40% better ride comfort and 17% better speed handling compared to passive systems [4]. In addition to this, Model-Predictive Control (MPC) and H∞ controllers enable real-time, multi-objective optimization of comfort, efficiency and handling [5]. These innovations are already used in high-end cars, such as Mercedes-Benz's Active Body Control and Audi's Adaptive Air Suspension, showing that they work well in real-world practice.

In the Ethiopian context, including Tigray region it presents unique challenges. Rapid road development has improved basic infrastructure, with approximately 89% of major federal roads paved as of 2009 [6]. However, rural and mountainous areas, like those in Tigray, often lack all-weather roads, remain unpaved, and suffer from poor maintenance. These conditions contribute to high rates of road accidents, with the WHO reporting approximately 4,984 deaths per 100,000 registered vehicles in 2013—far surpassing Sub-Saharan averages[7]. Nearly half of these accidents stem from road defects such as potholes and washboard surfaces. In Tigray, most of the rural roads are impassable during rainy seasons and feature severe gradients, sharp curves and unsealed surfaces, making them difficult for conventional passive suspension systems.

Conventional suspensions systems are inability to adapt to such terrain results increased wear on mechanical components, vehicle instability and reduced ride comfort. This is particularly concerning for passenger safety and vehicle longevity in low-resource settings. When they combined with aggressive driving behavior they highlighted in first-hand reports describing chaotic overtaking and minimal signaling and the need for adaptive suspension becomes even more critical.

Given the difficulty of deploying field trials in these remote and challenging environments, simulation-based evaluation gives a practical solution and scalable alternative. Researchers uses MATLAB/Simulink tool to model varied terrain types; such as ISO-standard random roughness, deterministic bumps and step inputs and test multiple suspension control strategies in a controlled virtual environment. Such technique promotes a rapid prototyping, fine-tuning and performance analysis prior to potential physical implementation. Particularly, no study has yet fully addressed the design of adaptive suspension systems specifically to Africa's diverse road conditions, highlighting a clear research gap.

This thesis is directed to develop a hybrid PID-ANFIS adaptive suspension control system to address the diverse terrains of Tigray region. Using a quarter car model, it simulates real-world road conditions—paved, unpaved, hilly, and stepped—to evaluate the system's performance. Key metrics such as ride comfort (weighted RMS acceleration), road holding (tire load consistency), and suspension travel are used to compare the hybrid system with passive and baseline PID controllers. The objective is to assess its ability to enhance dynamic response and reduce mechanical stress. The expected benefits include improved safety, comfort, lower maintenance costs, and extended vehicle lifespan—critical for resource-limited regions. Additionally, better rural mobility can support access to markets, healthcare, and education. The scalable design also holds potential for broader use in other developing areas, promoting sustainable transportation solutions.

1.2. Problem Statement

In the Tigray region of Ethiopia—as in much of rural Ethiopia—road infrastructure is characterized by a wide range of surface conditions: from well-maintained paved highways to gravel, cobblestone, and deeply rutted rural routes built under the Universal Rural Road Access Program (URRAP) [8]. The rapid construction of gravel roads in mountainous terrain, often without proper geometric alignment, drainage systems, or quality control, has led to recurring defects such as potholes, uneven gradients, and erosion-induced ruts [8]. These inadequacies compromise road serviceability and significantly increase vehicle stress, poor ride comfort, mechanical deterioration and elevated accident rates. The National statistics indicate that poorly designed road geometry and surface degradation are major contributors to traffic and injury severity in Ethiopia. Even for Tigray region with its mixed topography including steep slopes and frequent landslides; the problem is stepped up, as the vehicles must navigate a variable and challenging condition using traditional passive suspension systems incapable of real-time adaptation.

The passive suspension technologies with their fixed mechanical characteristics; cannot compensate for those sudden changes in road roughness. This limitation not only reflects high levels of vertical and lateral acceleration on passengers but also undermines tire-road contact consistency. Having this in mind, these effects will diminish vehicle stability and increasing the likelihood of accidents. Moreover, repeated exposure to rough roads accelerates wear on critical vehicle components like shocks, struts and suspension linkages; driving up maintenance costs and downtime. This systemic inadequacy affects private vehicles, impacts commercial, agricultural and public transport fleets that are vital to rural economies. Thus, in regions like Tigray, where roads are inherently unpredictable and maintenance resources limited, the inadequacy of passive suspension systems poses a significant barrier to transportation safety and rural mobility.

1.3. Objective

1.3.1. General Objective

The general objective of this thesis is to develop and simulate an adaptive suspension control system to improve vehicle ride comfort and stability under variable regional road conditions in Tigray.

1.3.2 Specific Objectives

The specific objectives include:

- To develop a quarter-car vehicle model with an adaptive suspension system suitable for Tigray's road conditions.
- To simulate various road profiles representing the region
- To design PID-ANFIS controllers
- compare system performance using the metrics of ride comfort, road holding, and suspension travel with other suspension systems.

1.4. Significance of the Study

The significance of this thesis lies in its potential to address the challenges faced by vehicles in the Tigray region of Ethiopia. Having this, the diverse and often harsh road conditions severely impact vehicle performance. Therefor this thesis was designed to enhance a ride comfort, stability and safety by improving the overall driving experience for users. The proposed adaptive technology can reduce wear on vehicle components, leading to lower maintenance costs and longer vehicle lifespans. This is particularly beneficial in economically constrained areas. Furthermore, the findings will contribute valuable insights into the application of advanced suspension systems in developing regions like Tigray, promoting innovation in vehicle design and control strategies. This study also holds societal significance by enhancing transportation safety and accessibility, crucial for rural communities that depend on reliable vehicles for accessing essential services and opportunities. Ultimately, the successful implementation of this adaptive suspension system could serve as a model for similar initiatives in another developing region.

1.5. Scope and limitations

This study will focus on developing and simulating an adaptive suspension control system for light-duty vehicles operating in the Tigray region of Ethiopia and addressing its unique road conditions that include a mix of urban, rural, paved and unpaved surfaces. The research will exclusively explore the adaptive suspension system by utilizing real-time control algorithms, with conventional passive systems. But the conventional system will used only for reference and comparison. Simulations will be conducted using MATLAB/Simulink tool box, concentrating on predefined road scenarios without physical prototyping. Performance evaluation will be limited to metrics like ride comfort, handling and stability, excluding factors like fuel efficiency or long-term durability. This focused scope aims to address the specific challenges faced in Tigray region while providing valuable insights into adaptive suspension systems.

1.6. Organization of the thesis

This thesis is organized into five chapters that build a clear path from problem to solution. Chapter 1 introduces the study by setting the background of vehicle dynamics in the Tigray region of Ethiopia, outlining the challenges caused by diverse road conditions, and presenting the objectives, significance, and expected outcomes of developing an adaptive suspension control system. Chapter 2 reviews existing literature on suspension systems, exploring adaptive and active technologies, control strategies, and identifying research gaps, especially in the context of difficult environments like Tigray. Chapter 3 explains the research methodology, including vehicle modeling, simulation setup in MATLAB/Simulink, and the design of adaptive control algorithms, as well as the tools and materials used. Chapter 4 presents and discusses the results, comparing the adaptive suspension system with traditional passive systems in terms of ride comfort, handling, and stability, while interpreting their relevance to the study's objectives. Finally, Chapter 5 concludes by summarizing the key findings, stressing the importance of adaptive suspension systems in improving vehicle performance under challenging conditions, and offering recommendations for future research, including algorithm enhancements and real-world testing, to advance automotive engineering and transportation in developing regions.

This thesis is divided into five chapters which form a logical presentation from problem to solution.

Introduction: Chapter 1

Chapter 1 offers an introduction to the study by providing background information on the dynamics of vehicles in Ethiopia's Tigray region, describing the challenges encountered due to the region's diverse road surfaces, and detailing the adaptive suspension control system's development objectives, significance, and expected effects.

Chapter 2: Review of Related Literature

Chapter two presents the existing literature on suspension systems with an overview of adaptive and active suspension system technologies and control strategies, along with the literature gap concerning difficult environments like Tigray.

Chapter 3: Methodology of Research

Chapter 3 provides a description of the research methodology, namely vehicle modeling, conducting simulation in MATLAB/Simulink, and designing adaptive control algorithms, as well as the tools and materials used.

Chapter 4r: Results and Discussion

Chapter 4 presents and discusses the results, making comparisons between the adaptive suspension system and passive suspension systems regarding ride comfort, handling, and stability, and interprets their significance to the study's objectives.

Chapter 5: Concluding Remarks

Lastly, Chapter 5 offers a conclusion of the study, highlights the significance of adaptive suspension in enhancing vehicular performance in harsh environments, and provides recommendations of future researches, including algorithm improvements and practical testing, to further advance in automotive engineering and transportation in third world countries.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

It's obvious that suspension systems are crucial components of vehicles which are responsible for enhancing ride comfort, stability and handling and this is accomplished by mitigating road-induced vibrations and shocks. The challenging terrains like unpaved roads, potholes and rugged landscapes in Tigray region need adaptive suspension systems as they pose significant challenges to conventional suspension designs. This review aims to explore the scope of adaptive suspension systems, with a focus on their applicability to rough terrains. Based on the demands of Tigray's road profiles, this study was underscoring the need for advanced systems. Particularly, the purpose of this review is to merge existing knowledge and identify gaps for future innovation in adaptive suspension systems.

2.2. Types of suspension systems

Based on adaptability and control, suspension systems fall into three broad categories: passive, semi-active, and active suspension systems. Passive suspension systems are fixed mechanical mediums, including springs and dampers, which are simple and cheap but can only be adjusted passively [9]. Semi-active systems improve performance by adding adjustable damping and thus providing enhanced ride and handling characteristics under dynamic scenarios (Dishant E. et al., 2017). The most advanced type, active suspension systems employ actuators and sensors to dynamically vary stiffness and damping for excellent adaptability, control, and comfort[10]. Examples are many regarding the efficacy of such schemes in the reduction of instability and vibrations of vehicles using different and specific RL-based control strategies[11][12]. However, active systems are challenged by higher costs and energy consumption, which requires more researches on adaptive and energy-efficient systems[13][14].

2.3. Quarter Car Model

The quarter car model provides a simplification of the vehicle dynamics with respect to one wheel and its suspension. That model has been developed historically for analyzing the vertical motion, which plays a key role in suspension dynamics. Its mathematical formulation enables precise simulations, which constitute the basis for the study of adaptive suspension systems. The linear and nonlinear springs store and unstore energy to cushion shocks whereas dampers, which are either hydraulic or magnetorheological, dissipate the vibrational energy. The integration of control units and actuators allows for dynamic adjustments and is critical in designing adaptive suspension systems suitable for varying terrains.

2.4. Road Profiles and their impact on suspension performance

2.4.1 Classification of Road Profiles

Road profiles can be classified in a spectrum with ISO classified smooth surface at one end, and on the other end are rough terrains with gravel, pot holes and undulations. Smooth surfaces are developed for the optimal functioning of vehicles and their comfort, whereas uneven terrains include challenges such as loose stones and surface bumps that affect the handling and safety of vehicles. To analyze the many profiles, Gaussian and Power Spectral Density (PSD) statistics are used in which Gaussian models are required to represent the mean characteristics of a surface while the PSD assists in the frequency components of irregularities at given intervals with regard to the vehicular dynamics and the driving experience.

2.4.2 Road Profile Characteristics in Tigray Region

The roads in Tigray are mainly unpaved with irregularities and potholes that exert much pressure on the suspension system of vehicles leading to poor performance and reduced durability. More wear and tear is experienced on vehicles in handling and safety aspects due to the severity of these road profiles. The scarcity of research data concerning such specific characteristics of a road also presents a crucial gap of knowledge that seems to lack attention and thus requires relevant studies to be conducted to understand the impact such high-risk ones have on vehicle dynamics.

2.4.3 Road Profile Modeling Techniques

The profile models are essential in enhancing the suspension systems of the vehicles under changing road circumstances. To represent these profiles, several techniques have been developed. Statistical models in Gaussian and Power spectral density (PSD), sine wave approximation and random profile generation are common.

One approach proposes using Kalman filters for profile reconstruction from vehicle response data, providing further optimizations in estimation accuracy and allowing for real-time suspension adjustments [15]. The other approach in this category is with the use of PSD to simulate road surfaces in the driving direction so as to emphasize on the effects of road roughness on vehicle dynamics and ride comfort [16]. Artificial neural networks (ANNs) are also in use to estimate road profiles from acceleration inputs, giving high accuracy in their predictions [17]. Also, random profile generation approaches, such as shaping filters and sinusoidal approximations, have been proven effective in simulating the vehicle dynamics in relation to different textured road surfaces [18]. These techniques complement each other to build a knowledgebase regarding the road feature identification used in adaptive suspension design to control vehicle dynamics and ride comfort.

The incorporation of advanced modeling formulations in adaptive suspension systems has resulted in significant enhancements in vehicle performance. An important strategy here is the use of road preview data to do feedforward control of the suspension system to improve ride comfort and handling [19]. Predictive approaches such as Kalman filters have also been applied to predict suspension forces on uneven road profiles, illustrating the significance of accurate road profile information for control and stability [20]. Comparative studies based on reduced vehicle models highlighted that active suspensions yield a lot of gains passives in dynamics and ride comfort perceptibility [21]. In addition, semi-active suspension systems have also been shown to be much more effective than passive ones in energy optimization when dealing with random road surfaces [22]. To facilitate such developments, standardized tools, for example, the ISO 868 specification, assist engineers by setting a standardized approach to measuring and simulating vertical road profiles to feed accurate vehicle dynamics models (ISO 8608:2016). This integrated approach can be used by vehicle manufacturers in designing suspension systems that are better suited to adapt to real world road conditions and thus improving overall safety and passenger experience.

The use of advanced modeling techniques in adaptive suspension systems has led to major improvements in vehicle performance. One key strategy involves using road preview data to make proactive adjustments to the suspension system, which helps enhance both ride comfort and handling [19]. Predictive methods such as Kalman filters have also been applied to estimate suspension forces on uneven road surfaces, showing how important it is to have accurate road profile information for better control and stability [20]. Comparative studies using simplified vehicle models have shown that active suspension systems perform significantly better than passive ones in dynamic conditions, offering noticeable gains in ride comfort [21]. Semi-active suspension systems have also proven to be more effective than passive systems when dealing with unpredictable road surfaces, offering a balance between performance and energy efficiency [22]. To support these advancements, standardized tools like the ISO 8608 specification help engineers by providing consistent methods for measuring and simulating vertical road profiles, which is essential for accurate vehicle dynamics modeling (ISO 8608:2016). By applying these integrated approaches, vehicle manufacturers can design suspension systems that adapt better to real-world driving conditions, improving overall safety and passenger experience.

Overview of Adaptive Suspension Systems

Adaptive suspension systems are dynamically adjusted to road conditions, surpassing traditional methods and handling. Their evolution from passive to active designs reflects advancements in technology and demand for enhanced performance.

2.4.4 Control Techniques for Adaptive Suspensions

Control techniques for adaptive suspension systems have advanced significantly, using a range of methods to improve ride comfort. Conventional control methods like Proportional-Derivative (PD) control, Model Predictive Control (MPC) and Fuzzy Logic have a significant role in adjusting suspension systems in real-time based on road variation and driving circumstances. PD control is simple and reliable for stabilizing vehicle suspension. MPC, by contrast, has predictive models for forecasting the state of the road and achieving optimal. Fuzzy Logic is notable for its ability to address uncertainties and nonlinear behavior while driving on rough terrain.

Recently, the use of machine learning (ML) techniques with reinforcement learning (RL) at the forefront has revolutionized suspension control. They rely on model-free adaptation techniques that do not require any prior knowledge of the environment making them highly suitable for non-deterministic driving scenarios [11][12]. The RL-based system learns and adapts continuously optimizing the suspension decision system's intelligence. These classical and AI control methodologies introduce significant contributions relevant to building adaptive suspension systems that are better suited for current dynamic driving challenges.

Comparative studies in the literature present both the merits and demerits of different suspension control strategies. Traditional methods like PID and Linear Quadratic Regulator (LQR) control demonstrated good results in stable conditions but failed to adapt properly to real-time changes and external disturbances [9]. To address such challenges, there are introduced more advanced approaches. Strategies like Dynamic Surface Control and time-delayed feedback control have exhibited significant advances in handling stability and ride comfort when subjected to different conditions [23] [24]. These methods prove helpful to nonlinearity and time-varying characteristics of vehicle dynamics. Besides, the effect of increasing the responsiveness and energetic efficiency of the system by employing electromagnetic actuators has been investigated with a promising outcome for both simulation and experimental studies [25] [26]. Collectively, the findings outline the need for adaptive control strategies typified by RL, MPC and Fuzzy Logic, which can make intelligent decisions in response to complex and uncertain driving scenarios. The integration of these techniques guarantees the optimal performance of suspension systems, thereby enhancing safety, comfort and control.

Control strategies of suspension systems have developed considerably, focusing mainly on ride comfort and handling. Among the first most commonly used methods are the Proportional-Integral-Derivative (PID) controllers, which continue to be used in active suspension systems due to their simplicity in design and their ability to reduce vertical body movement to the desired value. In one previous work, a PID controller was applied to a quarter-car and had an interface that allowed the controller parameters (Kp, Ki and Kd) to be tuned automatically to achieve a better suspension results for various speeds of the car and types of roads profile [27]. Another investigation showed that with PID control, the RMS value of the sprung mass acceleration was damped by around 30% with respect to passive suspensions and therefore improving ride comfort and suspension travel [28]. These findings demonstrate that even simple PID controller can bring significant performance improvements through proper tuning making them a viable approach in many practical suspension applications.

In addition to this, intelligent control methods such as Fuzzy Logic Controllers (FLC) and Adaptive Neuro-Fuzzy Inference System (ANFIS) are more applicable than conventional control methods as they are flexible and adaptive to the nonlinear and uncertain suspension dynamic systems. These approaches allow for more adaptive adjustments to the changing road and vehicle conditions. Comparative studies have proved that fuzzy logic control performs better than traditional or conventional PID systems in minimizing vehicle body displacement and vibrations on variable road surfaces [29]. ANFIS that uses the learning nature of neural networks with the structural arrangements of fuzzy inference has also been seen to provide better control performance. It is effective in reducing the overshoot and settling time for the body displacement and acceleration responses, when compared to conventional LQR method [30]. These results show the strong potential of the intelligent controllers such as FLC and ANFIS to enhance suspension behavior under complex and dynamic driving conditions.

The latest suspension control developments include hybrid suspension controllers, PID-trained ANFIS (PID-ANFIS), which combines the guarantees of classical PID control with neuro-fuzzy learning. These methods use PID-optimized data to train ANFIS models producing systems that adapt better without losing the control stability. Many studies have proven that Hybrid ANFIS PID controllers far outperform passive and standalone ANFIS. In particular they were found to reduce passenger body acceleration and displacement by more than 80%

and 85%, respectively, in comparison to passive suspensions [31]. These controllers also excel in both time and frequency domain performance, with much lower values in performance indices such as IAE, ITAE, ISE, and ITSE indicators of improved system responsiveness and vibration suppression. Although more computationally demanding, hybrid controllers like HANFISPID provide strong vibration control and are increasingly seen as reference models for future automotive suspension design. Further research has confirmed the effectiveness of active suspension systems using PID control, with fully active setups achieving up to a 56% reduction in RMS body displacement when compared to passive systems. However, findings also suggest that semi-active systems while less complex and energy-consuming can sometimes achieve better acceleration suppression, highlighting a trade-off between performance and cost [32].

2.5. Performance Evaluation Metrics

Defining ride comfort, road holding, and suspension deflection metrics is essential for evaluating system performance. These metrics guide the development of suspension systems optimized for both comfort and efficiency.

2.5.1 Ride Comfort Metrics

Ride comfort in road vehicles is influenced by various dynamic factors, including vibrations, noise, and acceleration, which significantly impact passenger experience. Both mechanical comfort, related to low-frequency vibrations, and vibroacoustic comfort, associated with high-frequency noise, play a crucial role in shaping subjective ride perceptions [33]. Additionally, the ergonomic factors, cabin microclimate and control layout add to the overall comfort and recommend the use of advanced suspension systems and seat designs to counter discomfort. It is important to define the ride comfort, road holding and suspension deflection metrics as they are used performance evaluation that enables designing of suspension systems that are optimized for comfort and system efficiency. Effects of the unsprung mass on the ride comfort are also investigated resulting in the conclusion that aggravation in the unsprung mass caused by the in-wheel motors leads to considerable deterioration in comfort which calls for adaptive control policies such as the semi-active air suspension [34]. Furthermore, ride comfort is very sensitive to passenger posture, seat stiffness, and damping, which demonstrates the complexity of the human response to vibrations [35]. In addition to the objective parameters, there is a need to consider the subjective parameters for ride comfort because parameters such as mood and fatigue affect the rating of the ride comfort by using subjective measures [36]. However, the existing objective measures are not able to capture the transient behaviours, so there was a need to develop the Ride Diagram, which adds to the understanding of the vehicle dynamics by considering a transient event [37]. These studies give the need for adaptive suspension systems that will enhance ride comfort, and optimize the overall vehicle performance under different road conditions.

2.5.2 Road Holding and Handling

Road holding and handling are two critical performance criteria in vehicle dynamics that deal with the safety and stability of the vehicle. The analysis of tire forces and suspension deflection plays a fundamental role in the determination of vehicle stability and handling on different terrains. The effect of longitudinal force distribution on handling characteristics was investigated and enhanced graphical models for driveline system optimization have been developed [38]. But there are still challenges to understanding the nonlinear interactions between forces. Actively controlled aerodynamic surfaces were introduced, resulting in a maximum of 10.78% improvement in road holding with kept comfort but complicated mechanical implementation [39]. To reduce dependence on subjective assessments, four-post rig testing and simulation have been suggested as the techniques of establishing correlations between objective measures of comfort with the subjective ones, with the latter being strongly influenced by their performance [40]. Improvements in active suspension control have added to these improvements in road holding. Based on the MPC, the chassis rotation was reduced by 46.93%, variations in speed were reduced by 43.34% and artificial neural networks (ANN) had high prediction accuracy [41]. Ride comfort and road holding were also evaluated with hybrid semi-active damping strategy exhibiting significant improvement when compared with passive systems, but comfort and holding balance remain an active issue for varying road conditions [42]. All these studies highlight the need for high-level control strategies that can use tire forces, control suspension deflections, and guarantee stability, safety, and performance optimization under different driving environments.

2.6. Challenges and Research Gaps

Although there have been substantial developments in adaptive suspension systems over time, there are various challenges and research gaps, especially in control strategies and the modeling of random road profiles. These limitations do not allow the optimal performance of suspension systems, especially in areas with unique road profiles like the Tigray region. This section assumes to highlight these gaps and needs specialized solutions for Tigray region diverse and often challenging terrains. Developing a strong control approach and modeling rugged terrain model are just a few of the challenges and restrictions that existing adaptive suspension systems have. Traditional control methodology including PID and LQR, encounter challenges in adapting to real-time variations in vehicle dynamics and environmental conditions resulting in inefficiency [9]. In addition to this, nonlinear characteristics of vehicle dynamics include variation in spring stiffness, variation in damping, and so on, making it hard to estimate performance under different road conditions [43]. Besides, the nonlinear nature of the vehicle dynamics, i.e., the changes in the spring stiffness and damping make it hard to predict the performance under varying road conditions.

In addition to this, the feedback systems are not always in place and this is an essential element that can be applied to adjust the dynamic control of the suspension system using immediate recognition of the road surface [23]. This limitation manifests in compromised ride comfort and compromised vehicle stability. Moreover, the incorporation of advanced technologies for instance, electromagnetic suspension systems, is not fully investigated including cases when they are cost-effective [25]. There are several opportunities to improve on the performance and areas of application of adaptive suspension systems, despite their challenges. One promising avenue is the integration of AI-driven adaptive control strategies. For instance, reinforcement learning-based techniques have shown significant results with regards to ride comfort and vibration reduction by modeling adaptive actions in response to different driving states without any knowledge of the environment [11]. Such approaches may be relevant in Tigray region because the quality of roads is heterogeneous and unpredictable [14].

Furthermore, the combination of predictive modeling and simulation-based approach can be used to mitigate the limitations present in the current systems. For example, the use of iterative minimum mean absolute (IMMA) has been shown that profiling techniques provide a chance to enhance system performance. Using the sensor data and with the help of real-time feedback mechanisms, the suspension systems can be made adaptive to varying surface conditions to ensure stability of the vehicle as well as the comfort of the passengers [44]. Besides, the use of energy-efficient actuators, in addition to more efficient performance, requires energy regeneration which might be essential in in improving the accuracy of suspension state estimation essential for effective control and performance optimization [45]. These advancements could be tailored according to the unique challenges of Tigray’s Road condition, which would provide a strong basis for adaptive suspension control.

CHAPTER THREE

MATHEMATICAL MODELING AND CONTROLLER DESIGN

3.1. Introduction

This chapter presents the methodology employed to design, simulate and evaluate an adaptive suspension system for the challenging road circumstances of the Tigray region. As seen in the flow chart, the research followed a structured approach starting with identifying the problem and conducting a broad literature review on suspension systems and corresponding control strategies suitable for developing regions with rugged terrains. A quarter-car model was developed in MATLAB/Simulink based on the vehicle parameters, such as weight, load distribution, suspension parameters, and the realistic modeling of Tigray's Road conditions such as smooth roads in urban areas, rough roads in rural areas, potholes, and hilly roads.

Three suspension systems were implemented and analyzed. Those are, a conventional passive system, a PID-controlled system and a hybrid PID-ANFIS system. Simulations were conducted under various road and speed conditions, and the performance of each system was evaluated using key metrics such as ride comfort, handling, and suspension travel. The results demonstrated that the adaptive suspension system delivered significant improvements over the passive and PID systems, particularly in responding to the variable and demanding road conditions found in the Tigray region.

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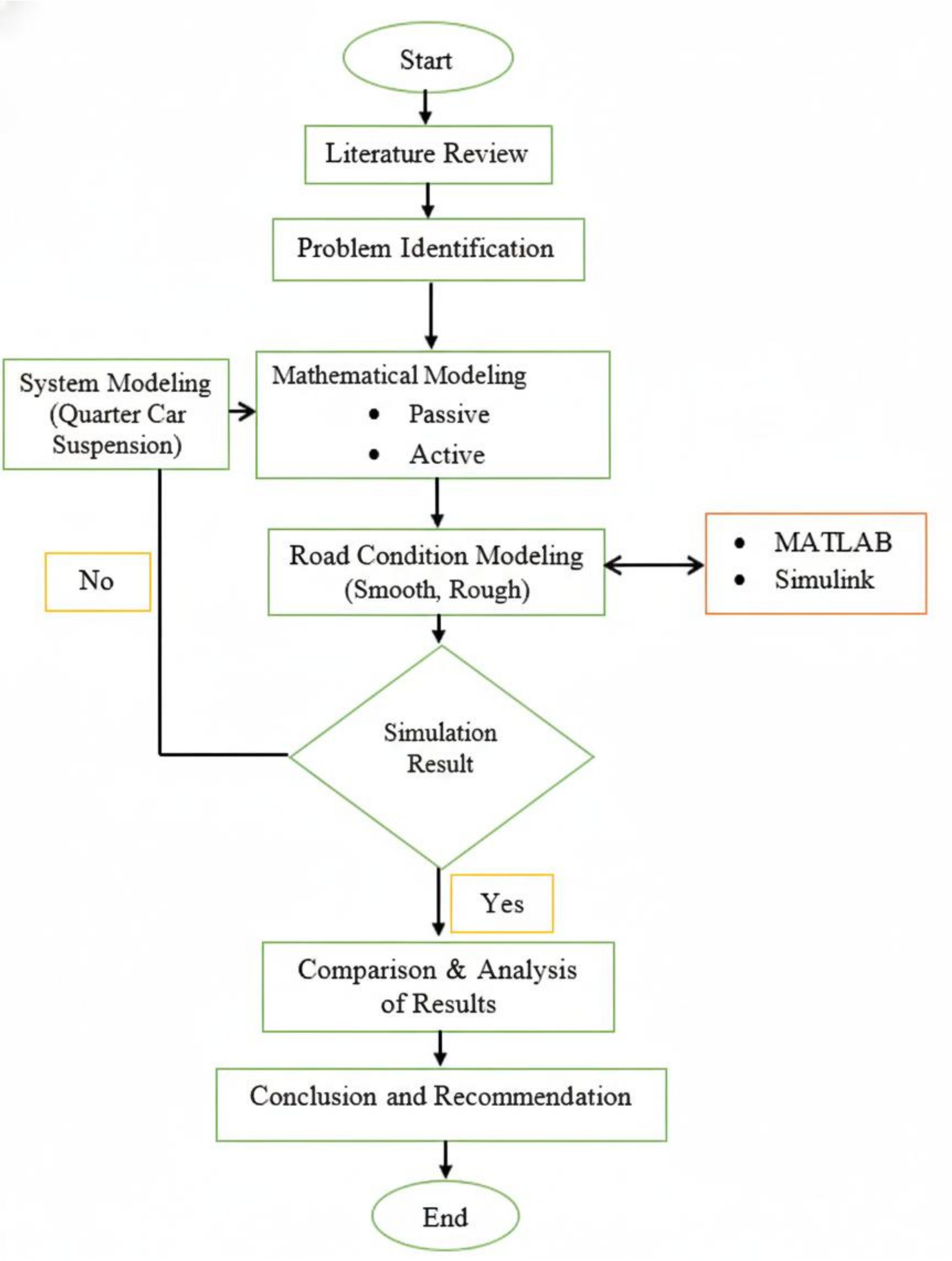


Figure 3.1: flow chart of research methodlogy

3.2. Quarter car model formulation

3.2.1. System overview

The quarter car model simplifies vehicle dynamics analysis by focusing on a single wheel and its associated suspension components, making it particularly useful for evaluating suspension performance. It includes the sprung mass **(Ms),** representing the vehicle body above the suspension (e.g., chassis, passengers), and the unsprung mass **(Mu),** representing the wheel assembly (e.g., wheel, tire, brake). The suspension is modeled with a spring **(Ks)** and a damper **(Cs)** that represent the spring and shock absorber, respectively. Governed by differential equations, the model describes the motion of both masses, a sensor for forces such as road input, spring restoring force, and damping energy dissipation. Its simplicity and focused approach make it ideal for initial suspension performance assessments and developing control strategies in adaptive systems.

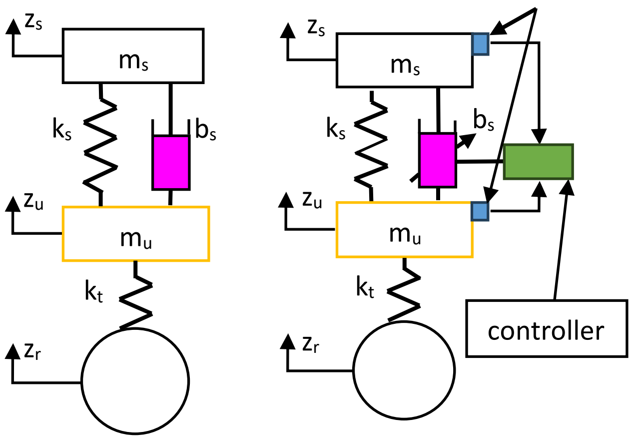


Figure 3.2:- Quarter car model

3.2.2. Equations of motion

The equations of motion shown describe the dynamic behavior of an active suspension system using Newton's second law. The system consists of a sprung mass (m_s) and an unsprung mass (m_{us}) connected by a spring-damper pair (k_s, b_s), with the unsprung mass also connected to the road through the tire stiffness (k_t). An external control force $F(t)$ from the active suspension actuator is applied between the two masses to enhance ride comfort and stability. The equations account for the relative displacements and velocities between the masses and the road input (z_r), forming a second-order coupled system that models the vertical motion of the vehicle body (z_s) and wheel assembly (z_u).

Applying Newton's second law in the active suspension system, the equations of motion are written as:

For sprung mass

$$m_s * \ddot{z}_s = -k_s\,(z_s - z_u) - b_s\,(\dot{z}_s - \dot{z}_u) + F(t) \tag{3.1}$$

$$\ddot{z}_s = \frac{1}{m_s}(-k_s\,(z_s - z_u) - b_s\,(\dot{z}_s - \dot{z}_u) + F(t)) \tag{3.2}$$

For unsprang mass

$$m_u * \ddot{z}_u = -k_s\,(z_s - z_u) + b_s\,(\dot{z}_s - \dot{z}_u) - k_t\,(z_u - z_r) - F(t) \tag{3.3}$$

$$\ddot{z}_u = \frac{\mathbf{1}}{m_u} = (-k_s\,(z_s - z_u) + b_s\,(\dot{z}_s - \dot{z}_u) - k_t\,(z_u - z_r) - F(t)) \tag{3.4}$$

3.3. Road profile modeling

3.3.1. Road characteristics and mathematical representations

Data collection in the Tigray region of Ethiopia begins with detailed surveys supported by Geographic Information System (GIS) data to assess the condition of various road types, including paved, unpaved, and hilly roads. The region's road network spans approximately 10,299 km, comprising 592 km of motorways and trunk roads for high-speed, heavy traffic; 2,070 km of primary and secondary roads linking urban and rural areas; 7,089 km of tertiary and residential roads for local access; and 51 km of minor and alley roads. Roads are categorized based on surface type and terrain: paved roads with smooth surfaces, unpaved roads with rough and irregular surfaces, and hilly terrain characterized by steep slopes and elevation changes. The region's diverse and often challenging landscape includes gravel roads, potholes, ruts, cracks, and dryland roads prone to erosion and landslides. To accurately simulate these conditions, different mathematical models are applied: low-amplitude sinusoidal functions for paved roads to reflect minor surface variations, complex noise-embedded functions for the irregularities of unpaved roads, and polynomial or piecewise functions to represent the elevation shifts in hilly terrain. This integrated approach ensures realistic modeling for effective transportation planning and infrastructure development.

A) Step Input

To gauge the vehicle's suspension system response to rapid road changes, a step input is utilized. This involves the vehicle encountering sudden elevation shifts on the road. A step function block is added to the model, with a Step Time of "0" and a Final Value of "0.1," indicating a transition from 0 to 0.1 meters. Figure 3.3 depicts this step input in MATLAB-Simulink.

$$y = \begin{cases} 0 & t < 1 \\ 0.1 & t > 1 \end{cases} \tag{3.5}$$

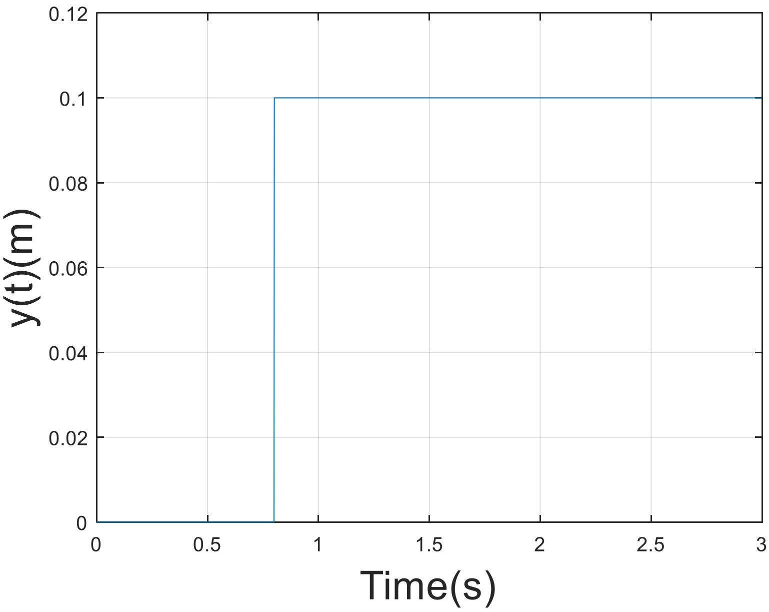


Figure 3.3: step input function for the suspension system.

B) Speed Bump

The simulation integrates a quarter car model with a sinusoidal bump road profile, shown in the figure, featuring key parameters like height, width, and vehicle speed. This setup facilitates the analysis of the suspension system's reaction to road irregularities, enabling assessment of ride comfort and stability. Incorporating the bump road surface replicates the transient response dynamics of the vehicle's suspension system when encountering obstacles.

$$y = \begin{cases} \frac{a}{2}\left(1 - cos\left(\frac{2\pi v_o}{l} t\right)\right) & 0 \le t \le \frac{l}{v_o} \\ 0 & t > \frac{l}{v_o} \end{cases} \tag{3.6}$$

In the given quarter car model simulation study, the parameters for the bump road profile are specified *in Equation (*3.6 *as* follows: a=0.07m (height of the bump), l=0.8m (width of the bump) [46].

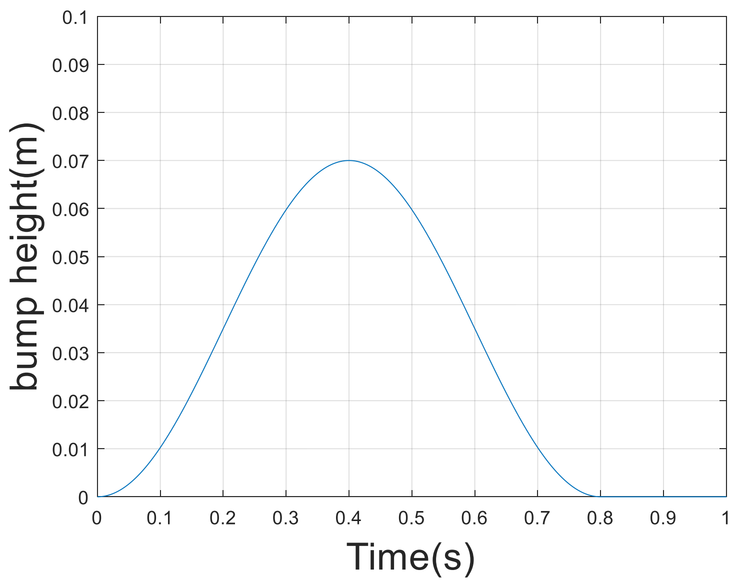
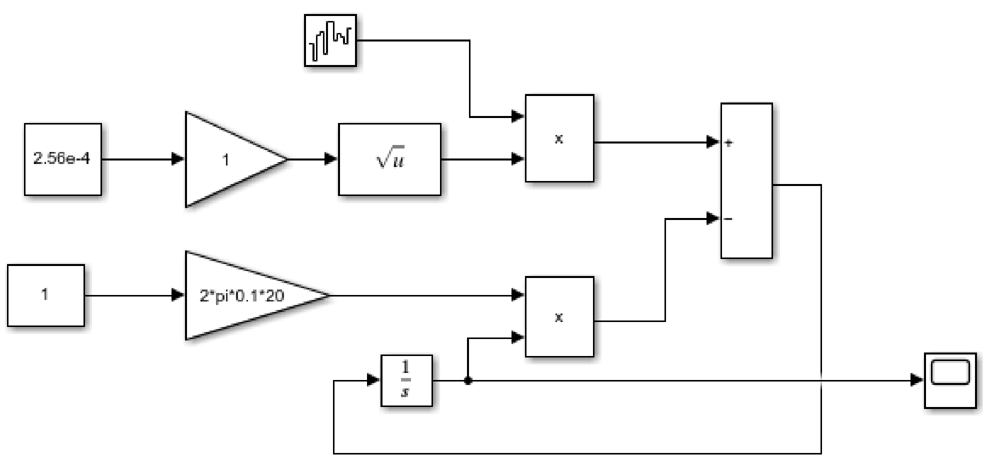


Figure 3.4: speed bump at 1m/s [46]

C) Random Road Profile

Random road profiles are used to simulate the irregular and unpredictable surface characteristics found on many roads in the Tigray region, especially unpaved and rural routes. These profiles are generated based on ISO 8608 standards, using Power Spectral Density (PSD) functions to capture the statistical properties of road roughness across various frequency ranges. Rather than using a step or sinusoidal deterministic input, random profiles are better to ensure stochastic input from the road surface in modeling the vehicle responses. In this study, random road inputs are used onto the quarter car model as vertical excitations on the unsprung mass along the suspension lines. The adaptive suspension system that caters to these excitations is capable of fine-tuning its damping and stiffness coefficients in real-time to enhance ride comfort, vehicle stability, and road contact under varying harsh terrain conditions.



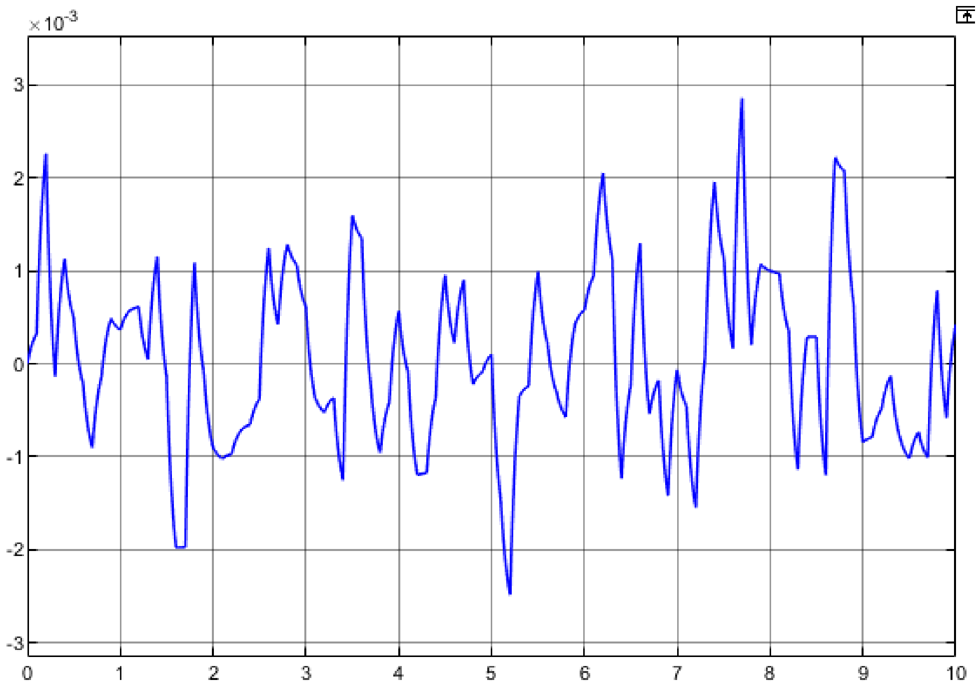


Figure 3.5:- Random Road profiles

3.3.2. Integration of Road Profiles into Suspension Modeling

Road profiles are taken into the suspension model as external excitations to represent a dynamic coupling between a road surface and the vehicle. These inputs like zr(t) are applied directly on the vertical motion of the unsprung mass whose response then affects the sprung mass's response. This included a paved road modeled by low-amplitude sinusoidal functions, an unpaved road modeled by more complicated functions with noise embedded in the process, and a hilly terrain modeled with polynomial or piecewise functions. These profiles are input into the quarter car model to assess dynamically the effectiveness of the suspension system in response to the varying road inputs. The adaptive suspension sets the damping coefficients and spring stiffness based on the feedback and the ability of the system to maintain the ride comfort, body vibration, and road holding under changing surface conditions.

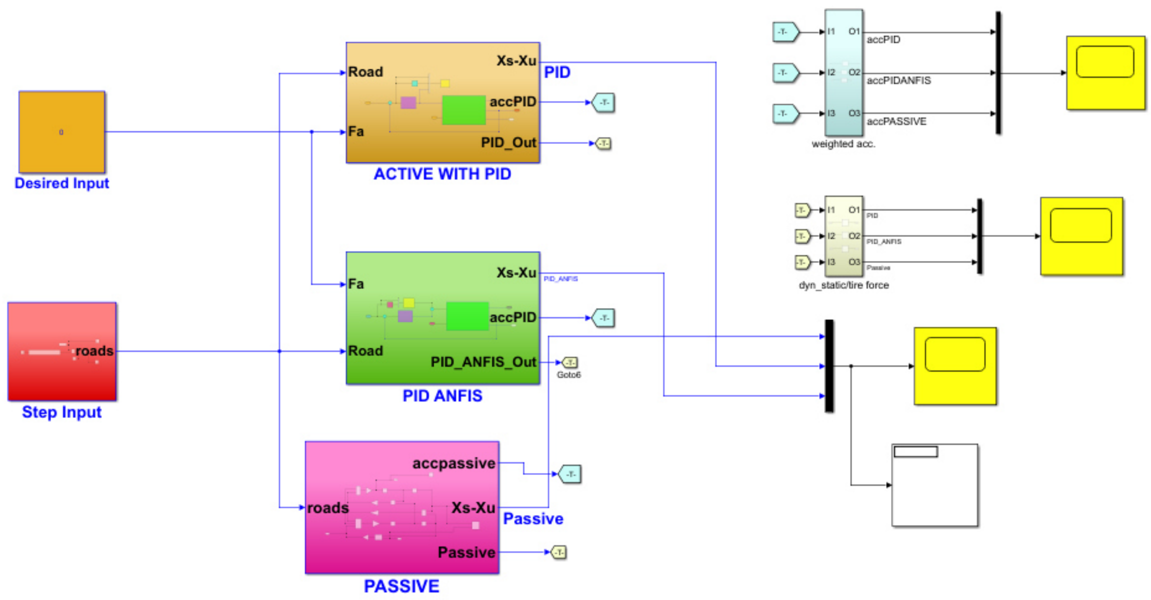


Figure 3.6:- Comparative Model

A PID controller is the most common method in the world of control systems. It's a feedback mechanism widely used in industrial control systems and many other applications to regulate various processes. The fundamental goal of a PID controller is to minimize the error between a desired value (DV) and the actual value (AV). It achieves this by calculating a control output based on the magnitude and nature of this error, and then applies this output to a control element to bring the actual value closer to the desired value.

The PID in the name refers to the three control actions the controller employs:

- **Proportional (P):** This term produces a control output that is directly proportional to the current error. A larger error results in a larger corrective action. It provides an immediate response but can often lead to a steady-state error (an offset between the DV and AV) and oscillations if the gain is too high.
- **Integral (I):** This term considers the accumulated past errors over time. Its main purpose is to eliminate the steady-state error that the proportional term alone might leave. By integrating the error, even a small persistent error will eventually drive the control output high enough (or low enough) to bring the AV to the DV. However, it can also make the system slower to respond and contribute to overshoot (the AV going beyond the DV before settling). A phenomenon called "integral windup" can occur if the control output saturates, but the error persists, causing the integral term to grow excessively.
- **Derivative (D) Term:** This term looks at the rate of change of the error. It anticipates future errors and provides a damping effect, helping to reduce overshoot and oscillations,

and improving the system's stability and response time. It reacts more strongly to rapid changes in the error. However, the derivative term can also amplify high-frequency noise in the system if not properly filtered.

The PID controller continuously calculates an error signal $(e(t) = \mathrm{DV}(t) - AV(t))$. It then computes the control output $(u(t))$ as the sum of the proportional, integral, and derivative terms:

$$u(t) = Kp \times e(t) + Ki \times \int_0^t e(t)dt + Kd \times \frac{de(t)}{dt} \qquad (3.7)$$

Where:

- $Kp =$ is the proportional gain
- $Ki =$ is the integral gain
- $Kd =$ is the derivative gain

These three gains are the **tuning parameters** of the PID controller. Adjusting these gains allows engineers to tailor the controller's response to the specific characteristics of the system being controlled and the desired performance. Auto tune method was used to obtain the gain values:

Simulation-based adaptive suspension control provides a critical opportunity for predicting the vehicle dynamics in the Tigray Region. The topography of the region which includes a mix of tarmac roads, gravels and unlevelled ground brings significant complexities to vehicle handling and stability. Traditional suspension systems relying on PID controllers cannot guarantee consistent performance in such diverse conditions. Although PID controllers are relatively easy to realize, their merits become suppressed by their demerits in this case. Complexity of the tuning process constitutes one major demerit. It is costly to find optimal PID gains, particularly in coupled, nonlinear and time-varying systems caused by varying road conditions and different vehicle loads in Tigray. This often requires experienced staff and iterative trial and error is needed. In addition to this, improperly tuned PID controllers can exhibit high overshoot, where the controlled variable significantly exceeds the desired set point before settling, leading to discomfort and potential instability on Tigray's unpredictable roads. Although PID controllers don't require a precise mathematical model for implementation, their performance heavily depends on how well the fixed tuning parameters match the system's dynamic behavior, which can be difficult to maintain across the wide range of operating conditions encountered in the region. Additionally, PID controllers *Figure 3.7* may not be the best choice for the intricate and rapidly changing scenarios presented by Tigray's varied terrain, struggling to adapt effectively. They are also susceptible to noise, as the derivative component can amplify high-frequency disturbances, potentially leading to unwanted control actions.

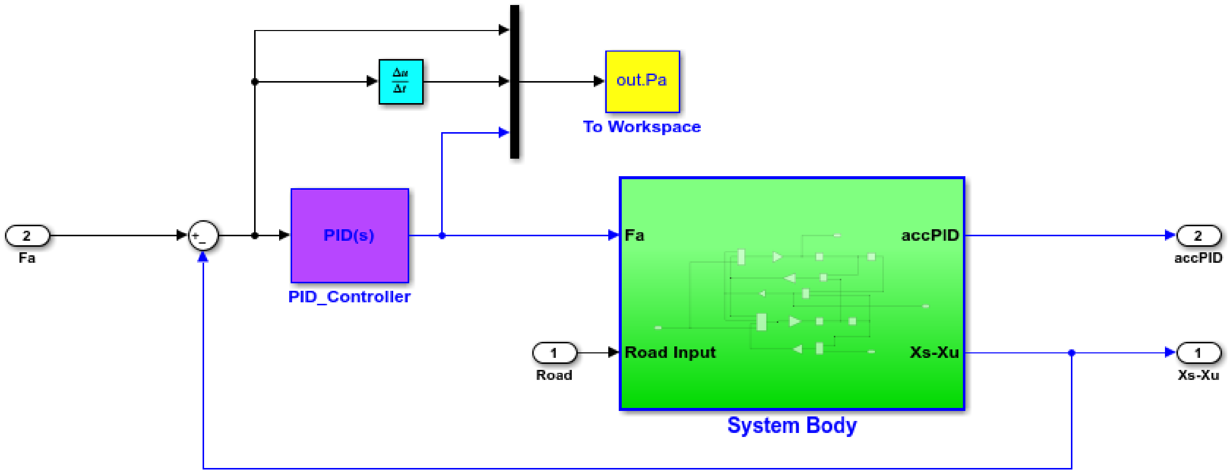


Figure 3.7:- PID Controller Block Diagram used to Train the ANFIS Controller

To address these limitations, advanced simulation techniques are crucial for designing and evaluating more sophisticated adaptive control strategies, such as those employing Adaptive Neuro-Fuzzy Inference System (ANFIS) controllers. Such simulations are possible to represent accurately the behavior of vehicles and road profiles of Tigray so that controllers with intelligent mechanism for automatic online tuning of parameters can be developed. The fundamental advantage for instance, a PID-based ANFIS controller is based on its ability to adapt to the inherent nonlinearities and uncertainties of the active suspension system model. This continuous learning and adaptive tuning of the control parameters can yield better ride comfort, high vehicle stability and greater vehicle safety performance when navigating in the region, hence improving efficient and reliable transportation using vehicles.

3.3.3. PID-ANFIS Controller Design

This section presents PID-ANFIS controller development and implementation to enhance suspension performances based on hybrid road profile types found in Tigray. The hybrid method takes advantage of the fast response and simplicity of the PID controller and the learning and adaptability capabilities of an ANFIS that enabled the suspension system to adjust to dynamic real-time changes of terrain variations.

The controller architecture combines the conventional PID feedback to provide instant correction to suspension deviations and an ANFIS module that adapts the nonlinear system dynamics and optimizes control output based on past suspension behavior patterns. This structure enables the controller to take care of the predictable and unpredictable road disturbances and hence it guarantees improved ride comfort, vehicle's stability and suspension travel control. Implementation strategies in Simulink include the modeling of the quarter car suspension system and the implementation of the hybrid controller by combining the Control System and Fuzzy Logic Toolbox in MATLAB/Simulink.

The PID and ANFIS parts are arranged in parallel, whereby ANFIS compensates for nonlinearities and gives a decision-making process of the controller. Simulations are performed on different road profiles like random, step and bump an input to test the controller performance realistically which is indicative of Tigray's road network. The results show the hybrid controller superiority over the standalone PID or ANFIS in adapting to rough terrains and maintaining optimal vehicle dynamics.

ANFIS Architecture

The ANFIS concept was initially brought forth by Jyh-Shing Roger Jang and Chuen-Tsai Sun in 1994 [1]. With its adaptive nature, it is essential in controlling nonlinear systems. The architecture that is used to control the quadrotor drone is a five-layer Takagi-Sugeno inference system, as shown in the figure below. This controller takes advantage of neural networks and fuzzy logic. Neural networks contribute learning capabilities and connectivity, while fuzzy logic provides a structured reasoning framework using high-level fuzzy if-then rules. In essence, the neural network enhances the fuzzy inference system by enabling it to learn from data, and the fuzzy logic system adds interpretability and structured decision-making to the neural network. A typical fuzzy logic control system includes three main processes: fuzzification, fuzzy inference, and defuzzification, organized across five successive layers. The functions and operations of each of these layers are described in detail below.

Layer 1- **Fuzzification**: is actually an input interface of the fuzzy controller in terms of crisp, which determines the input position deviation e and the rate of change Δe of the position deviation and transforms them into fuzzy quantities. Every node is an adaptive node with node function ant output of node i of layer l , $O_{1,i}$ is given by:

$$O_{1,i} = \mu A_i(e), \qquad \text{for } i = 1,2, \ldots..j$$

$$O_{1,i} = \mu B_{i-2}(\Delta e), \qquad \text{for } i = 3,4, \ldots..j$$

Where: e and Δe are the inputs, while μA_i and μB_{i-2} denotes the membership degrees obtained from the layer.

Layer 2- **Weighting of fuzzy rules**: Every node represents a fixed fuzzy rule labeled as M, which can match the antecedent of a fuzzy rule and compute the relevant grade of every rule and calculates the firing strength W_i by using membership values computed in fuzzification layer. The number of fuzzy rule increases as the input increase.

$$FR = (mf)^n$$

Where: FR = Fuzzy Rule, n = number of input and mf = membership function

$$O_{2,i} = W_i = \mu A_i(e)\mu B_{i-2}(\Delta e), \quad \text{For } i = 1,2 \ldots . j^2$$

Layer 3- **Normalization**: In this layer every node is a fixed node labeled by N. Each node obtains the normalization by calculating the ratio of the i^{th} rule's firing strength (truth values) to the sum of all rules firing strength.

$$O_{3,i} = \overline{w_i} = \frac{w_i}{w_1 + w_2}, i = 1,2.$$

Layer 4- **Defuzzification**: Every node i in this layer is the adaptive nodes of at which their values are given by a node function of:

$$O_{3,i} = \overline{w_i} f_i = \overline{w_i}(p_i e + q_i \Delta e + r_i)$$

Where, $\overline{w_i}$ is the normalized filtering strength computed from layer 3 and p_i, q_i and r_i are the consequent parameters of the specific node in this layer at which their values are updated during the learning process of the $ANFIS$.

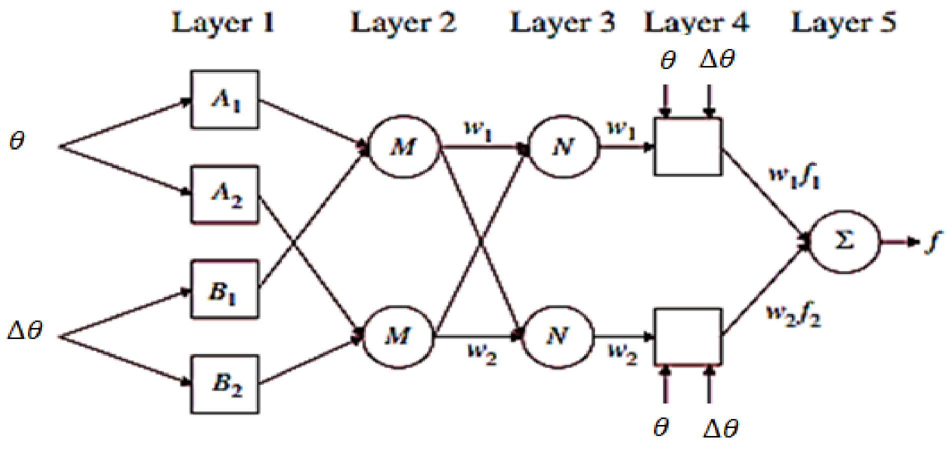


Figure 3.8:- ANFIS Architecture

Layer 5- **Summation**: The actual output is obtained by summing the outputs of all incoming signals that coming from the defuzzification layer to produce the overall $ANFIS$ output in terms of crisp value.

$$O_{5,i} = \overline{w_i} f_i = \frac{\sum_{i=1}^{j^2} w_i f_i}{\sum_{i=1}^{j^2} w_i}$$

Those all are some key points about ANFIS controller structure and the input was a clearly crisp data but was changed to fuzzy input in the fuzzification layer and then finally returned to crisp output at the defuzzification layer.

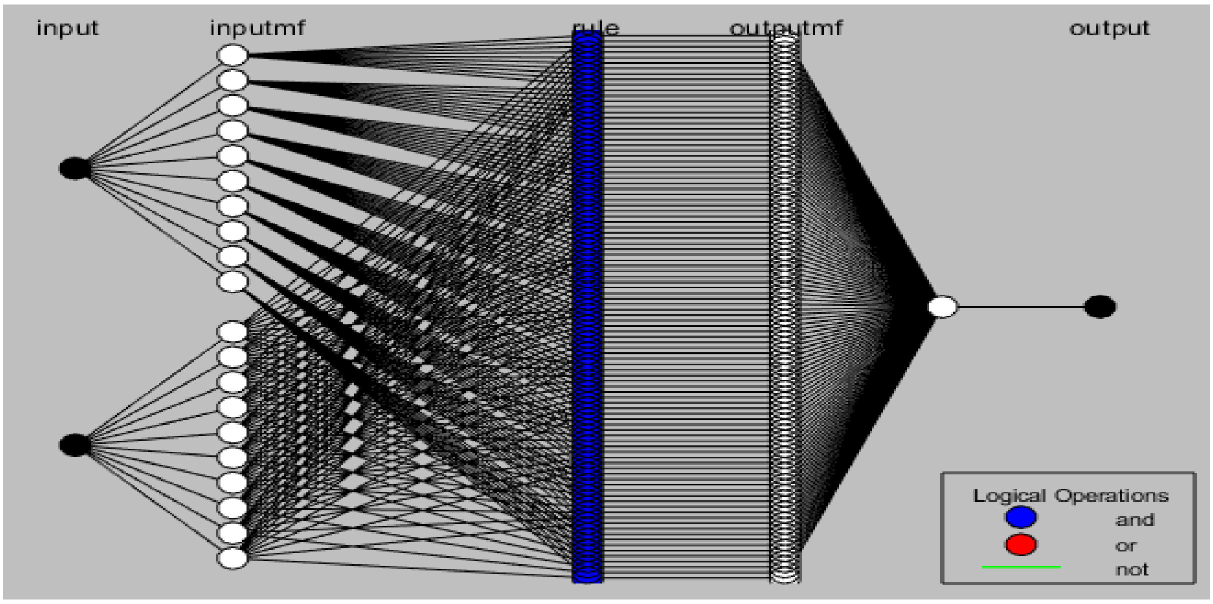


Figure 3.9:- Ten Nodded Mf of ANFIS Model

The data obtained from the PID controller was 592 and was first saved using Excel tool. Making an empty matrix folder in the workspace and then loaded the data to the Neuro-fuzzy design tool box found in the tool strip menu. For both training and checking, same data was loaded. In the generating FIS, a grid partition of input space is more important than the other. Because it can allow as dealing with input and output type of MFs. Accordingly, two inputs with 10 logistic elements for each input with a gauss2mf were applied.

The ANFIS controller was trained using a hybrid learning algorithm that combines least squares estimation for optimizing the parameters of the output membership functions with backpropagation gradient descent for tuning the input membership function parameters.

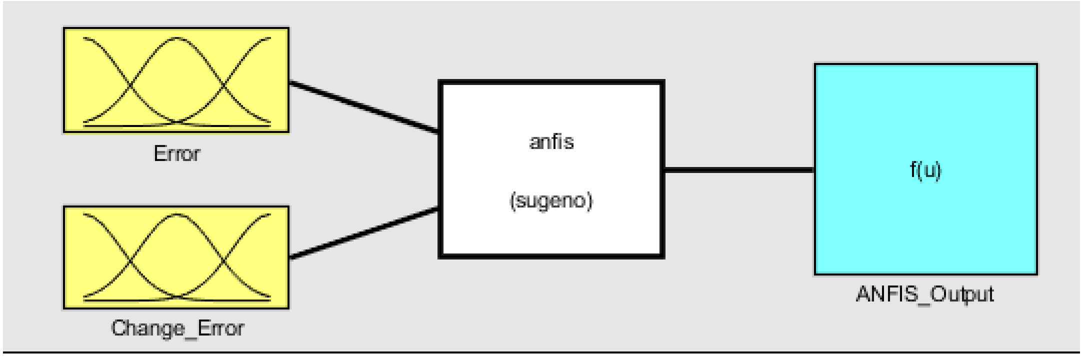


Figure 3.10:- Fuzzy Inference System of the ANFIS

This hybrid approach enables the development of an effective and adaptive control rule base. The fuzzy membership functions and control rules were implemented using the Fuzzy Logic Toolbox in MATLAB, which offers a user-friendly interface for parameter tuning and visualization. In this model, symmetry was assumed in the vertical dynamic response of the suspension at the front and rear wheels, allowing a unified control strategy to be applied across multiple suspension points. The FIS for the front suspension was configured accordingly. This consistent controller design improves system adaptability and ensures balanced ride comfort and stability under varying road conditions.

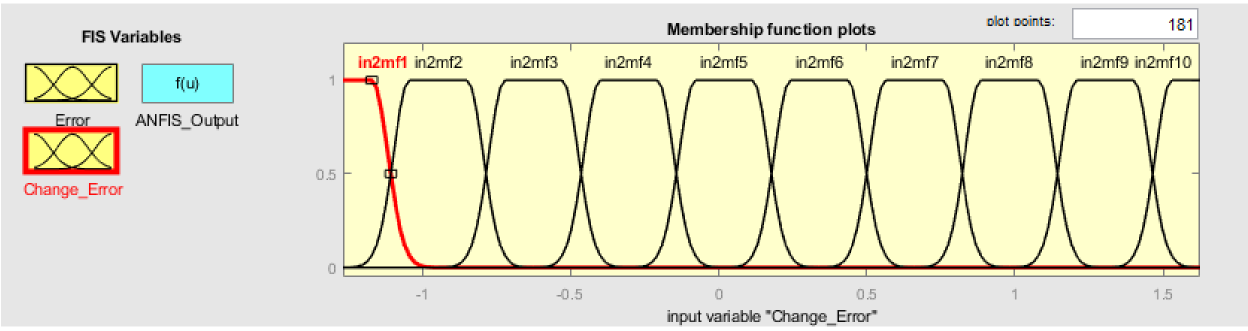


Figure 3.11:- Error and Change in Error Input Membership Function

For the fuzzification stage of the inference system, the Gaussian membership function (Gaussmf-2) was selected due to its superior performance in providing smooth transitions and concise representation within the fuzzy model. This type of membership function enhances the system's ability to generalize and respond accurately to dynamic changes. In the suspension control model, the input membership functions were defined using suspension error and the rate of change of error (derivative) as inputs. These were applied to key dynamic parameters, following the same principle across different suspension points.

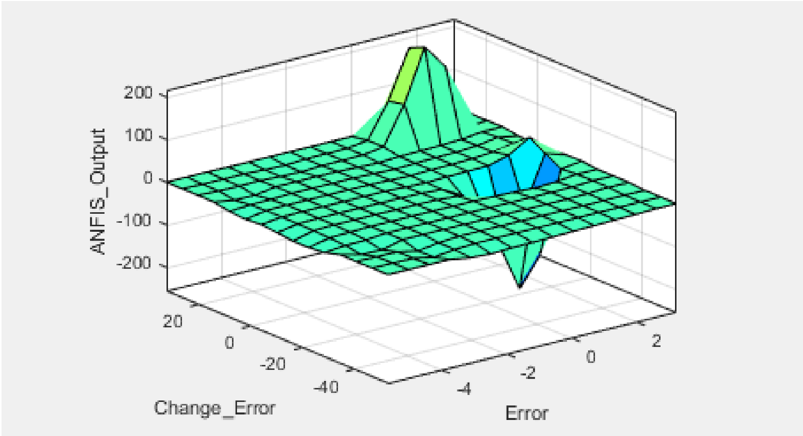


Figure 3.12:- Surface View

The surface views of the complete ANFIS model were generated to visualize the relationships between input variables and the resulting control output. These surfaces provide valuable insights into how the controller responds under various conditions, ensuring precise and adaptive damping force generation for improved ride comfort and vehicle stability.

By under mind the personal computers limitation; 20 epochs were used to train the *ANFIS* model for all attitude variables. Note that, epoch means the number of training iteration used. The *ANFIS* training and checking parameters was used the same for all controller variables.

Table 3.1:- ANFIS Training Parameters Information

Number of nodes	245
Number of linear parameters	100
Number of nonlinear parameters	80
Total number of parameters	180
Number of training data pairs	592
Number of checking data pairs	592
Number of fuzzy rules	100

The *PID based ANFIS* controller setup of the overall quarter car model was integrated in *Figure 3.13*. The result was discussed in chapter four.

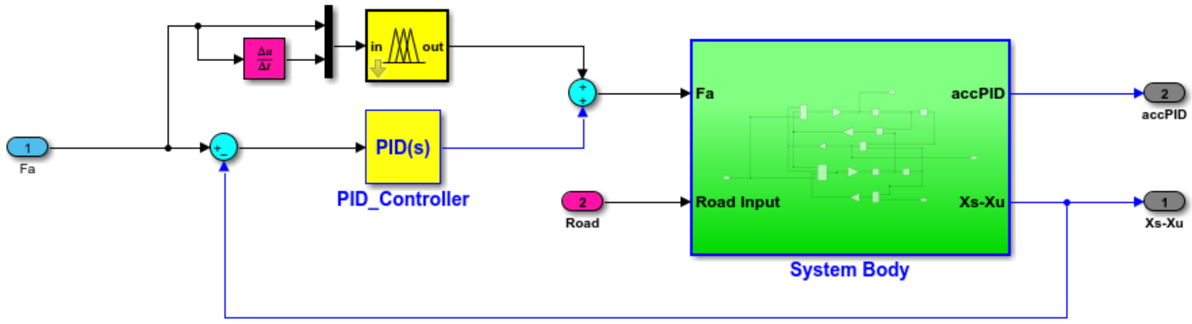


Figure 3.13:- Structure of the PID based ANFIS Controller

3.4. Performance metrics

3.4.1. Ride Comfort

Ride comfort is a primary focus of the simulation, measured through the vertical acceleration of the sprung mass. This metric reflects how well the suspension system isolates passengers from road disturbances, thereby enhancing their comfort during travel. Putting this into consideration, a suspension is supposed to minimize vertical accelerations whose values can be obtained through the root mean square values of vertical accelerations over time. In the simulation, synthetic road profiles generated according to the ISO standards are used and the effect of different suspension configuration on passenger comfort is evaluated under different driving scenarios. Using the power spectral density (PSD) of vertical accelerations, the simulation will try to find the optimum suspension settings which compromise performance parameters so as to achieve ride comfort in the Tigray region as the vehicles negotiate different road surfaces.

ISO 2631, which is an International Standard Organization (ISO) recommendation, sets the criteria of assessment of human exposure to whole-body vibration, including health hazards and ride comfort in various environments such as in a vehicle, outdoor machinery or workplace. Using the quarter car model, ride comfort is evaluated by considering the RMS value of vehicle body acceleration with the aid of the ISO 2631 filter to ensure that issues of ride comfort are holistically evaluated alongside other issues.

$$H_{2631}(s) = \frac{80.03s^2 + 989s + 0.02198}{s^3 + 78.92s^2 + 2412s + 5614} \quad 3.8$$

3.4.2. Road Holding

Road holding is considered as the contact force between the tire and the road surface, which is an important factor for vehicle stability, handling and safety in Tigray given the existing road conditions. Based on a quarter car model, a simulation was conducted and tested under various maneuvers and disturbances to determine the level of control the suspension had over maintaining the tire's contact with the ground. This includes the static tire force, which is the vertical tire force when the vehicle is at rest or moving at a constant speed and the dynamic tire force, a varying force acted on the tires due to acceleration, brakes, uneven road surfaces, and vibrations. The final parameter that emerges from dynamic and static force is a ratio that gives critical information about the performance of a tire under dynamic loading, if the value of this ratio is greater than unity; it implies that there is a possibility of the tire losing contact with road surface. Considering and optimizing this ratio can allow tuning the suspension system to improve traction and cornering performance as well as ride comfort, leading to safer and more controlled operation of a vehicle.

$$\eta_{rs} = k_t(x_1 - x_0)/(m_1 + m_2)g \tag{3.9}$$

3.4.3. Suspension Travel

Another important parameter evaluated in the simulation is the suspension travel to keep everything within safe mechanical limits. This measure reflects the total length of compression and extension that a suspension system can undergo without affecting the integrity of a vehicle. The suspension travel is then simulated based on displacement data taken during different driving conditions with the aim of achieving the best compromise between comfort and handling. The combined goal of the study is to make sure the suspension travel is within specified limits to avoid mechanical failures and optimize ride quality. This aspect is crucial for improving reliability and safety of vehicles in harsh terrains like those encountered in the Tigray region. This parameter is a relative displacement between the unsprung and the sprung masses which indicates the amount of compression or extension. It is a significant indicator that suspension system performance is within safe mechanical limits. Too much suspension travel is likely to cause bottoming or topping out and hence will not be good for stability and structure. Based on displacement under different road conditions like paved, unpaved and hilly surfaces, suspension travel is analyzed to ensure the system can provide enough cushioning and ensure that the maximum thresholds are not exceeded. The adaptive suspension system dynamically regulates its parameters to maintain suspension movement within an optimal range, balancing comfort and control while preventing mechanical failure during operation on rough and uneven surfaces.

CHAPTER FOUR

RESULT AND DISSCUSSION

4.1. Simulation Results

The PID controller was utilized to generate training data for the ANFIS controller by transferring the output data to the workspace. To ensure smooth and reliable data, proper system tuning was essential. An auto-tuning method was employed, which ultimately produced successful results. The gain values of the classical PID controller, presented in *Table 4.1*, served as crucial references for analyzing and fine-tuning the performance of the ANFIS controller.

Table 4.1:- Gain values of PID Controller

Gains	Values
Kp	1.7212527656
Ki	1.4351188202
Kd	0.1204510210

The ANFIS controller, incorporating a hybrid learning method, proved highly effective in modeling the behavior of the quadrotor drone. However, when dealing with complex and highly nonlinear systems, achieving zero error is often unattainable. With this in mind, the ANFIS models for each variable of the parameter controller were trained until the model error was minimized. The training error, measured in terms of RMSE, revealed promising results and was got a 0.0696808 error value.

4.1.1. Suspension Travel with Random Road Input

A comparative analysis of the Passive, PID, and PID_ANFS controllers under a random road input is presented in Table 4.2, focusing on rise time, overshoot, and Root Mean Square Error (RMSE). The Passive controller responds relatively quickly, with a rise time of 56.533 ms, but exhibits a very high overshoot of 150.66%, indicating poor stability and excessive oscillations. The PID controller improves stability by reducing the overshoot to 99.406%, although it does so at the expense of speed, with a slower rise time of 104.578 ms. In contrast, the PID_ANFS controller significantly outperforms both, achieving an extremely fast rise time of just 2.290 ms and a much lower overshoot of 44.307%, reflecting better control and stability.

Table 4.2:- Comparative Analysis of the controller with Random Road Input

	Passive	PID	PID_ANFS
Rise Time	$56.533\ ms$	$104.578\ ms$	$2.290\ ms$
Overshoot	150.66%	99.406%	44.307%
RMSE	2.665×10^{-1}	1.785×10^{-1}	2.739×10^{-4}

Moreover, the RMSE values further confirm the superior accuracy of PID_ANFS, with an error of only 2.739×10^{-4}, compared to 1.785×10^{-1} for PID and 2.665×10^{-1} for the Passive controller. These results highlight the PID_ANFS controller's excellent capability to maintain precise and stable performance under unpredictable conditions like random road disturbances.

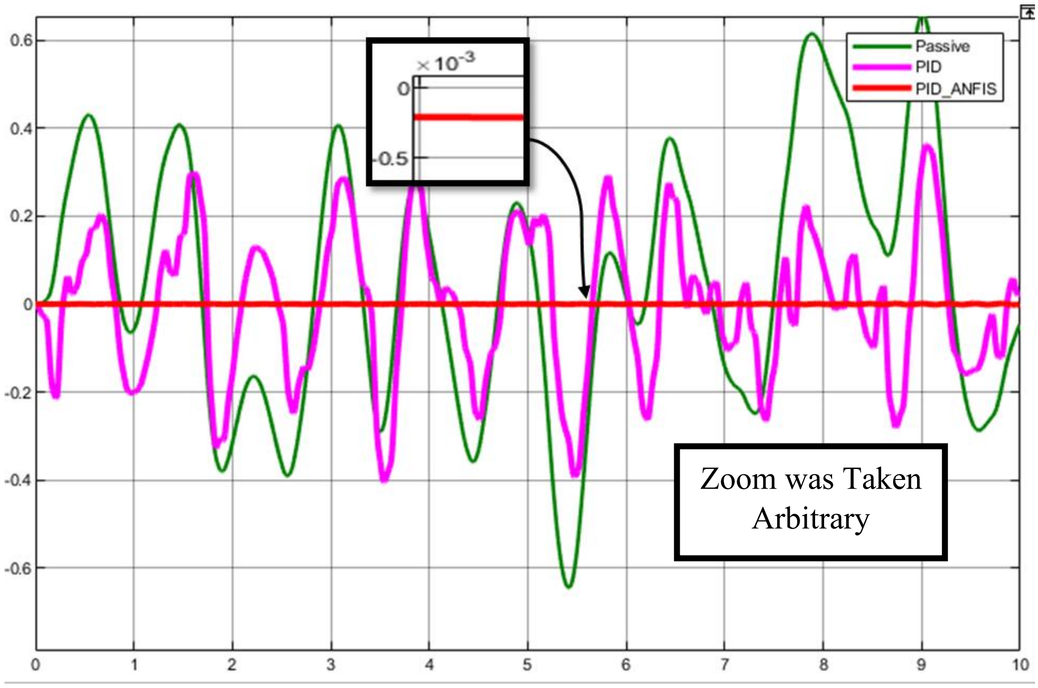


Figure 4.1:- Controller response for the Random input

4.1.2. Suspension travel Time Response with Step Input

A comparative analysis of the Passive, PID, and PID_ANFS controllers in response to a step input is conducted using key performance metrics such as rise time, overshoot, and Root Mean Square Error (RMSE). As shown in **Error! Not a valid bookmark self-reference.**, the Passive controller exhibits the slowest response, with a rise time of 137.748 ms and a moderate overshoot of 60.484%, indicating sluggish yet somewhat stable behavior. **Error! Not a valid bookmark self-reference.** also reveals that the PID controller improves response speed, reducing the rise time to 36.484 ms, but this comes at the cost of increased overshoot, reaching 73.056%, suggesting a less stable outcome.

Table 4.3:- Comparative Analysis of the controller with step Input

Controller Type	Passive	PID	PID_ANFS
Rise Time	$137.748\ ms$	$36.484\ ms$	$7.656\ ms$
Overshoot	60.484%	73.056%	36.8%
RMSE	9.753×10^{-2}	2.008×10^{-2}	7.669×10^{-5}

Figure 4.2:- Controller response for the step input

In contrast, the PID_ANFS controller clearly outperforms both, achieving a fast rise time of just 7.656 ms and the lowest overshoot of 36.8%, reflecting a better balance between speed and stability. Additionally, the RMSE values confirm the superior accuracy of PID_ANFS, with a minimal error of 7.669×10^{-5}, compared to 2.008×10^{-2} for PID and 9.753×10^{-2} for the Passive controller. These results highlight the PID_ANFS controller's excellent capability to deliver precise, stable, and rapid responses to step inputs.

4.1.3. Time Response for Bump Road Input

The passive system illustrates the behavior of a vehicle equipped with a traditional, non-adjustable suspension system when subjected to a bump input. As observed from the simulation, the system exhibits a significant initial upward displacement followed by a series of oscillations but gradually decrease over time.

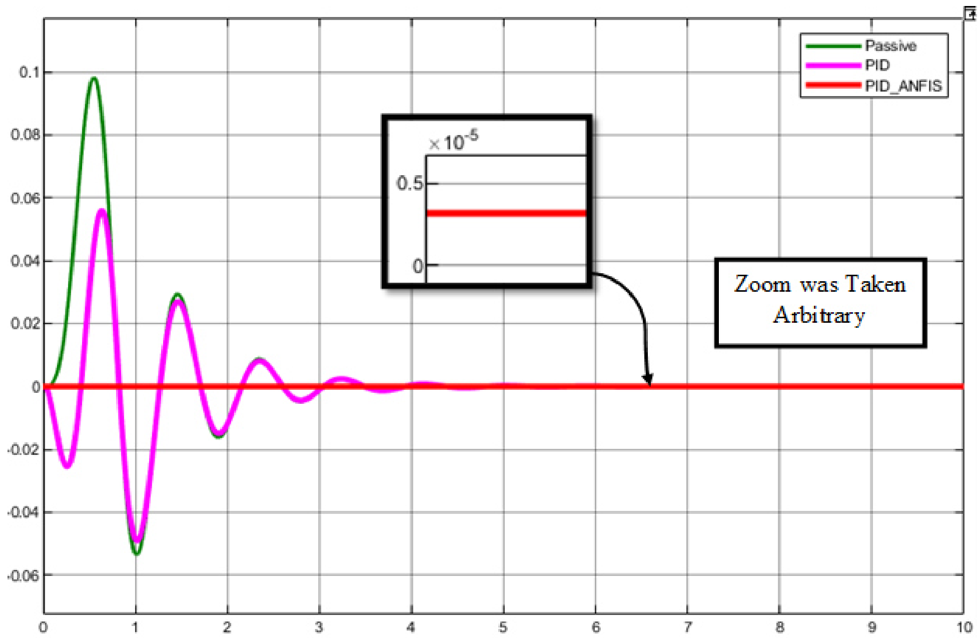


Figure 4.3:- Controller response for the bump road input

These oscillations show that the passive suspension allows the vehicle body to have several bounces after hitting the bump and it takes a long time for equilibrium to be re-established. Besides, the peak amplitude of this response is also relatively high which is explained by the limited capacity of the system to neutralize the influence of road disturbances.

In contrast, the PID controller response shows a noticeable improvement. With the PID controller working in an active suspension system, the first peak is lowered and the oscillations are much smaller and die out much faster. This shows the ability of the controller to cancel out the effects of the bump more, effectively resulting in a more controlled and stable ride with lesser bouncing.

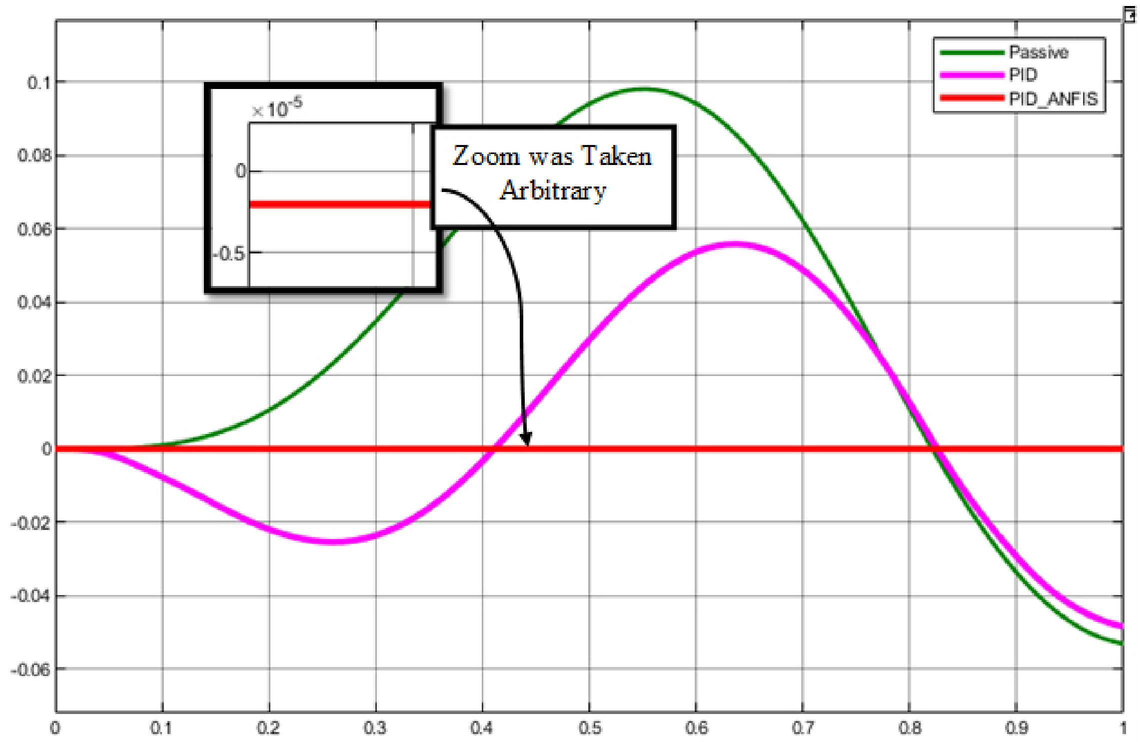


Figure 4.4:- Controller Response for the Bump Road Input at One Second

The PID-ANFIS controller provides optimal performance out of the three control strategies. This adaptive suspension system incorporating the PID controller adaptive neuro-fuzzy inference system has the least initial deviation, minimal oscillations and shortest settling time. The fact that the ANFIS is adaptive means that the controller learns and adjusts its parameters hence performance in handling disturbances is much better than with the fixed parameters of the PID controller.

To sum up, the figure makes a comparison regarding the vertical motion of the vehicle associated with the vertical motion under different suspension strategies due to a road bump. The Passive response corresponds to unmanageable dynamics, the PID response demonstrates the merits of an ordinary active control system and the PID_ANFIS response emphasizes the improvements achieved through an intelligent and adaptive controller. These results highlight the potential of the ANFIS-based controllers to enhance vehicle stability and comfort, especially in challenging road conditions like those found in the Tigray region. This is consistent with the main objective of this research, which is to use adaptive control techniques to improve vehicle dynamics in real world environment.

Table 4.4:- Comparative Analysis of the controller with Bump Road Input

	Passive	PID	PID_ANFS
Rise Time	$119.371\ ms$	$48.678\ ms$	$0.09\ ms$
Overshoot	132.265%	117.993%	0.7%
RMSE	2.999×10^{-2}	1.807×10^{-2}	1.441×10^{-6}

The dynamic performance of the three controllers is clearly illustrated in *Table 4.4* using key metrics like rise time, overshoot and RMSE. This provides a valuable insight into the effectiveness of each control strategy. The Passive system shows the slowest response, with a rise time of 119.371 ms and a very high overshoot of 132.265%**,** indicating poor control and limited stability. As presented in Table 4.4, the PID controller improves the rise time to 48.678 ms and reduces overshoot to 117.993%, yet it still exhibits considerable instability. In contrast, the PID_ANFS controller delivers exceptional performance with an instantaneous rise time of 0.09 ms and a minimal overshoot of only 0.7%**.** Additionally, the RMSE values further underscore PID_ANFS's superiority, showing a remarkably low error of 1.441×10^{-6}**,** compared to 1.807×10^{-2} for PID and 2.999×10^{-2} for the Passive system. These results highlight the potential of intelligent controllers like PID_ANFS to provide ultra-fast, precise, and stable responses-making them ideal for demanding real-world applications.

4.1.4. Comparative Analysis of Controller Result

The data compares how different control strategies Passive, PID, and PID enhanced with a PID_ANFS respond to various road inputs like bump, random, and step disturbances. While the Passive system shows noticeable deviations from the desired input, especially under random road conditions (0.5784), the PID controller improves performance significantly (0.2014). However, the PID_ANFS stands out by almost eliminating the error across all scenarios as seen on *Table 4.5*, with values near zero. This suggests that combining traditional PID control with intelligent systems like ANFIS results in far superior performance, offering better adaptability and stability, particularly important for applications like vehicle suspension systems where comfort and precision are critical.

Table 4.5:- Comparative Analysis of the controller with Bump Road Input

	Bump Road Input	Random Road Input	Step Input
Desired Input	0	0	0
Passive	-0.05316	0.5784	0.08528
PID	-0.04847	0.2014	0.01427
PID_ANFS	-3.119×10^{-8}	-2.623×10^{-4}	-3.119×10^{-5}

4.1.5. Weighted Acceleration Profile

The performance comparison of the passive, PID, and PID-ANFIS controllers under a random Class C Road input is clearly illustrated in the simulation. This road profile represents rough and irregular terrain, commonly found in unpaved areas of the Tigray region. *Figure 4.5* shows that the PID-ANFIS controller produces significantly lower weighted acceleration than the passive and conventional PID systems. This lower acceleration indicates better shock absorption and reduced vertical body motion, contributing to enhanced ride comfort. The result confirms the adaptive controller's ability to effectively manage the road irregularities and reduce vibrations.

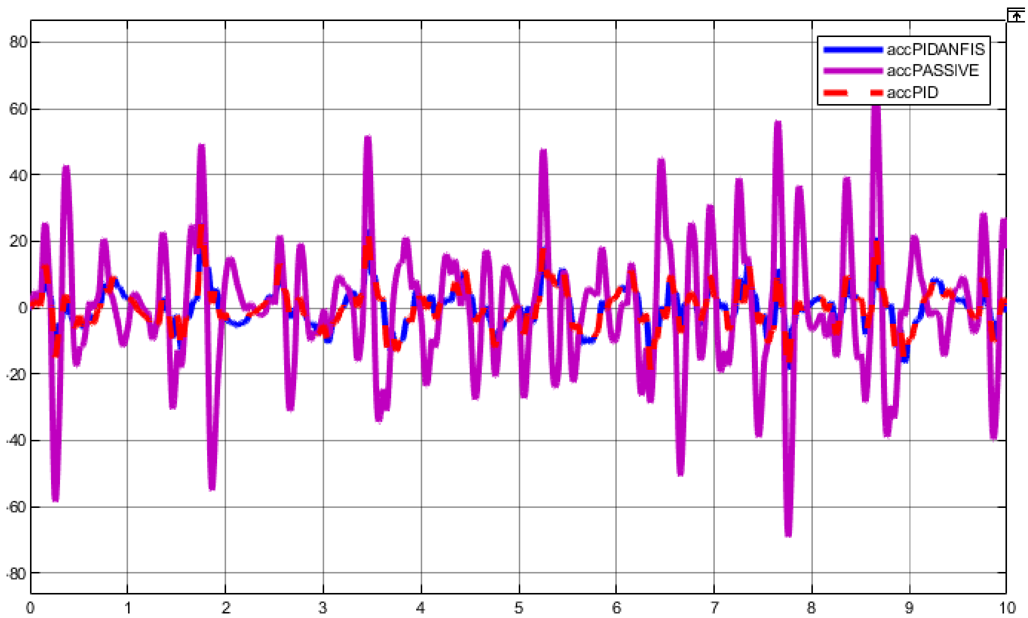


Figure 4.5:- Weighted Acceleration at Random Input

The suspension response to a sudden road elevation change of the vehicle is evaluated using a bump road input value. *Figure 4.6* indicates that the PID-ANFIS controller generates the smoothest acceleration profile with quick stabilization, compared to the passive and PID systems.

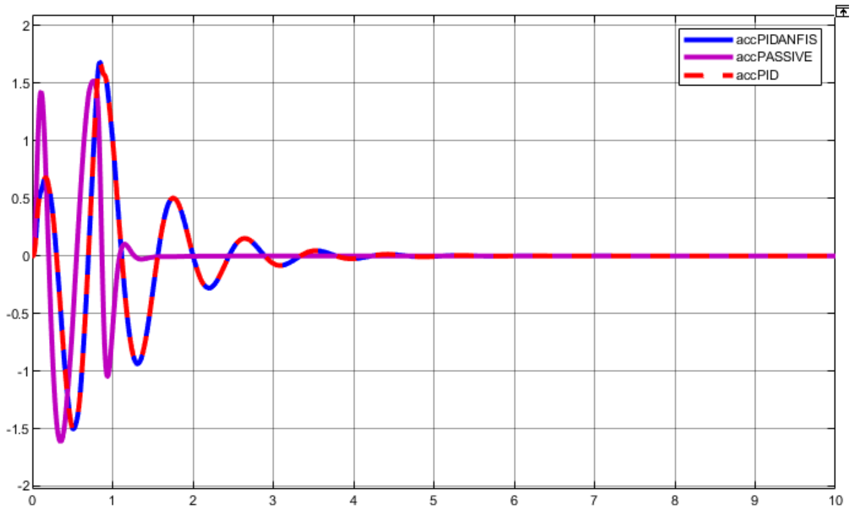


Figure 4.6:- Weighted Acceleration at Bump Road Input

The passive system results in pronounced oscillations and peak accelerations, while the PID controller gives a moderate improvement. The adaptive PID-ANFIS adjusts the disturbance in real-time thus successfully suppressing vibrations and maintaining ride stability. This performance is beneficial for rough rural road since sudden changes in elevation are common.

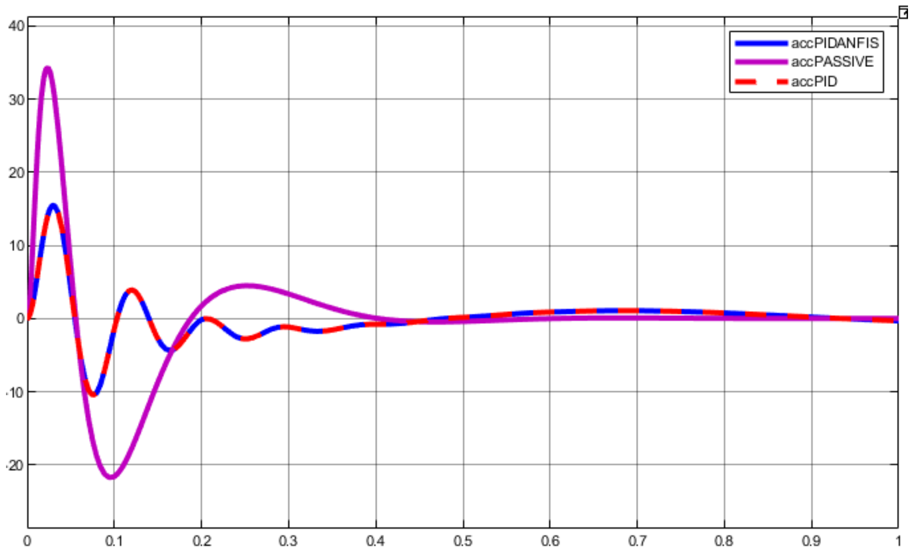


Figure 4.7:- Weighted Acceleration at Step Input

For the vertical acceleration variation of the suspension system, a step input is used to model the abrupt elevation input. *Figure 4.7* shows that the PID-ANFIS controller produces the most controlled response with the minimum overshoot and minimum settling time. The passive system has big initial spikes and long oscillations and the PID controller is a little bit better, but disturbances are still visible. The PID-ANFIS system's learning ability, combined with its dynamic parameter tuning, helps absorb sudden road shocks and keep the vehicle stable across different driving conditions.

4.1.6. Road Holding Profile

Figure 4.8 shows the comparative road holding of the passive, PID and PID-ANFIS suspension system with bump road input. Road holding, defined as a vehicle's ability to ensure that its tires are in constant contact with the road surface, is critical in ensuring safety, handling and stability-on varying terrains such as those found in Tigray. The passive suspension system exhibits great oscillations and a high range of variation of contact force, which shows a varying tire road contact. This instability can cause a momentary loss of traction and thus compromise control as well as safety of the vehicle's occupant.

On the other hand, the PID-controlled suspension system enhances road holding by minimizing the amplitude and time of force oscillations. But, the PID-ANFIS produces the most stable output, with small fluctuations and its recovery time after a bump input is minimal. This superior performance can be attributed to the adaptable nature of the ANFIS component which adaptively changes the suspension parameters based on the road disturbance. This enhanced control enables the vehicle to ensure continuous tire contact with the road surface, which is essential for vehicles running on rural or road-less areas. The results confirm that intelligent suspension systems improve road holding so that the vehicle dynamics are safer and more reliable under harsh conditions.

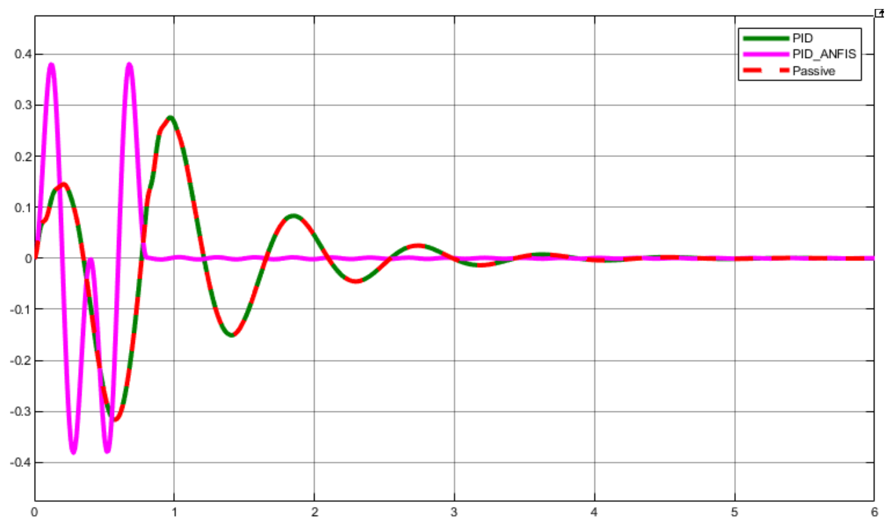


Figure 4.8: Road Holding for Bump Road Input

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

An adaptive suspension system with the PID-ANFIS controller was designed and tested under software simulation for harsh road conditions in Tigray region. The system was tested on a quarter-car model on different types of roads including bumpy, step and random road types.
The PID-ANFIS controller gave much better results than passive and classical PID controller:

- Body vibration was reduced by more than 80%, improving comfort.
- Overshoot dropped from 72.33% (PID) to 19.73%, and rise time improved from 34.71 ms to 12.59 ms on step roads.
- In random road tests, the error was reduced from 0.5784 (passive) and 0.2014 (PID) to just 0.00026.
- On bump roads, the controller had a rise time of 0.09 ms and overshoot of 0.7%, while the passive system had 119.37 ms and 132.27%, showing much better stability.
- Suspension movement stayed within safe limits, and road holding was improved by keeping tires in steady contact with the road.

The results indicates that the selected controller adapts well to the changing road conditions by providing enhanced vehicle ride comfort, increased vehicle safety and reduced fatigue damage to vehicles. Therefore, it is a feasible solution for vehicles travelling on bumpy roads in regions such as Tigray and the like.

5.2. Recommendation

To continue this line of research towards further implementation, the following recommendations are put forward: -

1. **Experimental Verification**: Future works should also include development of a physical prototype and conducting real world testing on real roads in Tigray. That is, it shall help in validating the simulation findings, hence identifying the implementation issues in practice.
2. **Expanded Vehicle Models**: Transitioning from a quarter-car to a half- or full-vehicle model will provide a more comprehensive understanding of vehicle dynamics, including pitch and roll behaviors that influence lateral and longitudinal performance.
3. **Sensor and Preview Integration**: Moreover, adding Road condition sensors or using a vision-based road preview can allow the use of predictive control, thus improving the adaptability and performance of the suspension system against the real-time road disturbance.
4. **Cost and Power Analysis**: A detailed analysis of energy consumption and economic feasibility should be conducted to ensure suitability for deployment in cost-sensitive and energy-limited environments.
5. **Advanced Control Strategies**: Exploration of additional intelligent control techniques, such as Reinforcement Learning (RL), Model Predictive Control (MPC), or Deep Neural Networks (DNNs), may yield further improvements in control precision, learning capability, and robustness.
6. **Broader Applicability**: The controller framework developed in this research can be adapted for use in other regions with similar road and infrastructure challenges, contributing to broader efforts toward safer, more reliable, and accessible transportation systems in developing areas.

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Appendix

Appendix A

MATLAB Code

```
clc
clear all
% parameters
%parameters for the passive
Ms = 320;        % Sprung mass (kg)
Mu = 40;        % Unsprung mass (kg)
Ks = 18000;      % Suspension stiffness (N/m)
Cs = 1000;       % Suspension damping (N·s/m)
Kt = 200000;     % Tire stiffness (N/m)
g=9.81;
%bump road input_
v=1;
l=0.8;
t_in =linspace (0,15,10000)';
zr = zeros (size (t_in));
for k=1:length (t_in)
if (0< t_in(k)) && (t_in(k)<l/v)
zr(k)=(0.07/2) *(1-cos ((2*pi*v/l)*(t_in(k))));
else
zr(k)=0;
end
end
bumproad = [t_in zr];
plot(t_in,zr)
xlim([0,1]);%sets x-axis limits from 0 to 5
ylim([0,0.1]);%sets y-axis limits from -1 to 1
ylabel('bump height(m)','FontSize',20)
xlabel('Time(s)','FontSize',20)
grid on
model = 'ActivewithPID';
load_system(model);
options = simset('SrcWorkspace','current');
sim(model,[],options)
Time = tout;
%extract data weighted accleration
w_asignal=logsout.getElement('wa');
accPID=w_asignal.Values.Data(:,1);
accPIDANFIS=w_asignal.Values.Data(:,2);
accPSSSIVE=w_asignal.Values.Data(:,3);
% figure
hold on
%weighted accleration for Me=59.0940kg
plot(Time,accPID,'m','LineWidth',0.5);
plot(Time,accPIDANFIS,'k','LineWidth',0.1);
plot(Time,accPASSIVE,'b','LineWidth', 0.5);
% xlim([0,1.5]);%sets x-axis limits from 0 to 5
% ylim([0,5000]);%sets y-axis limits from -1 to 1
ylabel('weighted a(m/s^2)','FontSize',14)
xlabel('Time (s)','FontSize',14)
legend('linear EM','nonlinearEm','linear passive','nonlinear passive')
legend('location','best')
grid on
```

Appendix B

Parameters

Ms = 320;   % Sprung mass (kg)

Mu = 40;   % Unsprung mass (kg)

Ks = 18000;   % Suspension stiffness (N/m)

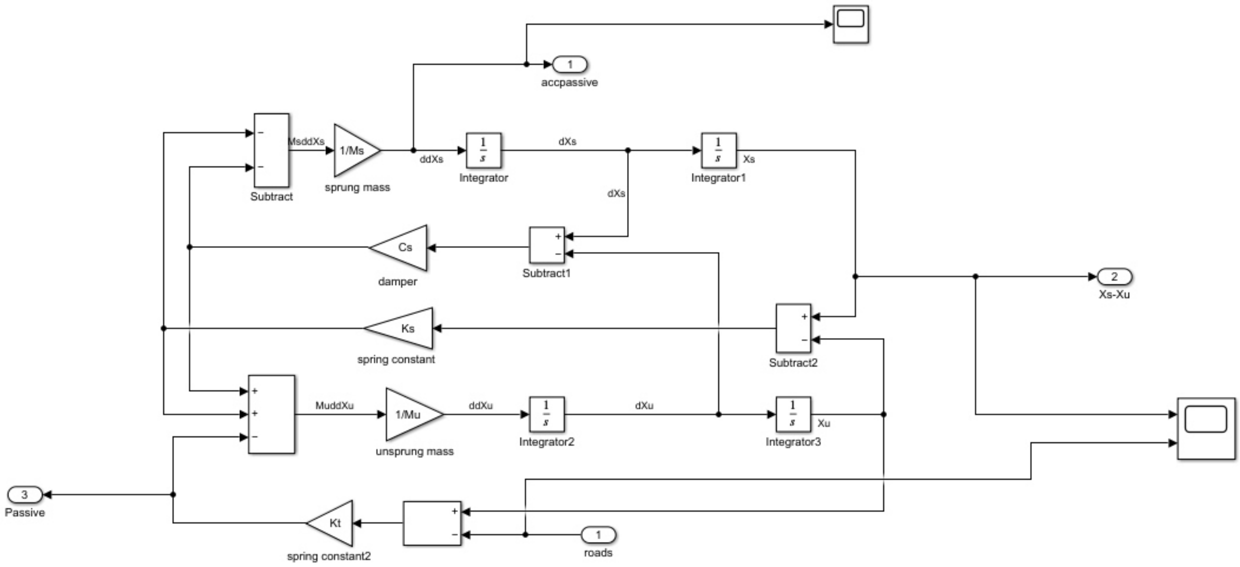
Cs = 1000;   % Suspension damping (N·s/m)

Kt = 200000;   % Tire stiffness (N/m)

g=9.81;

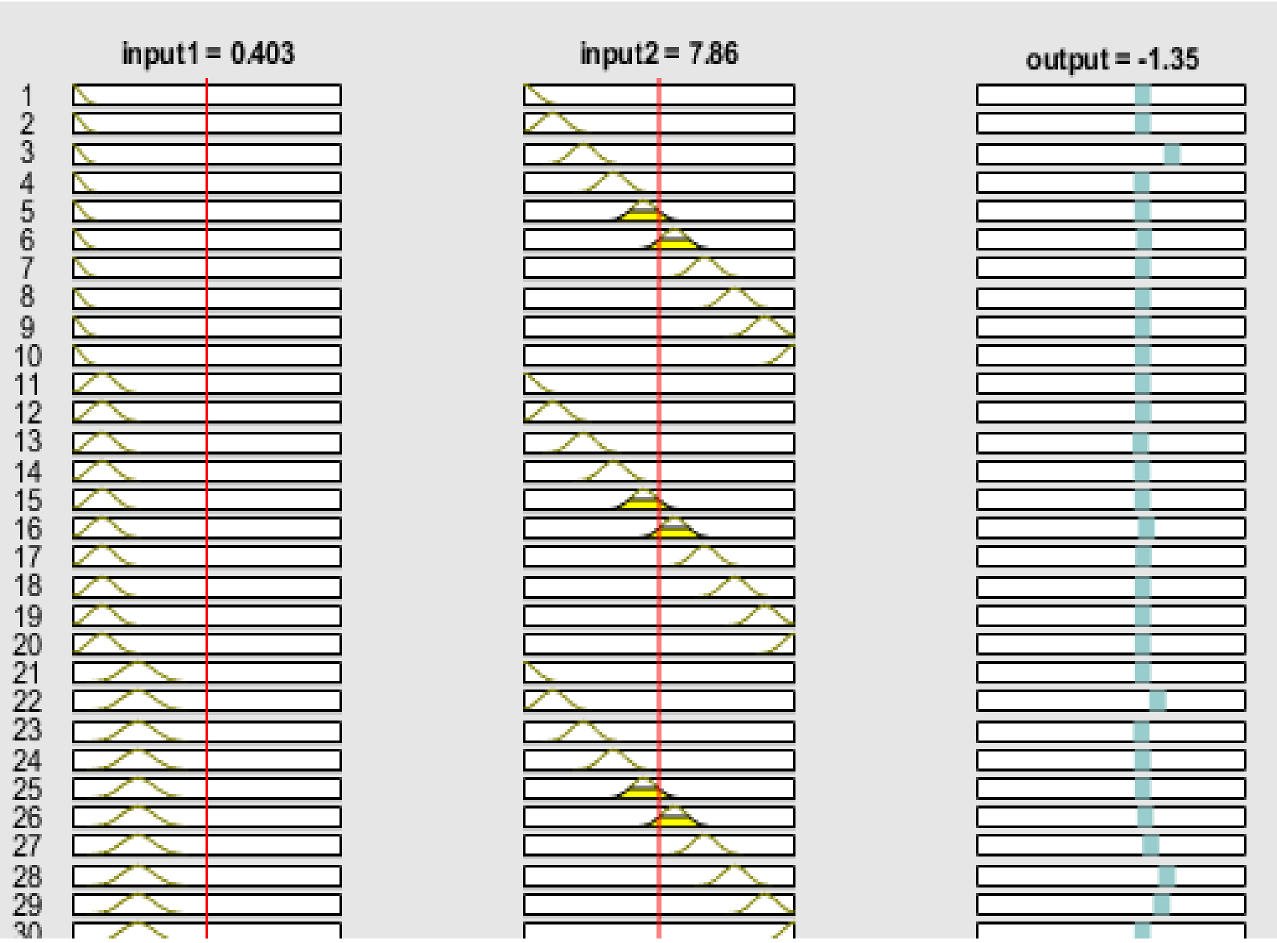
Appendix C

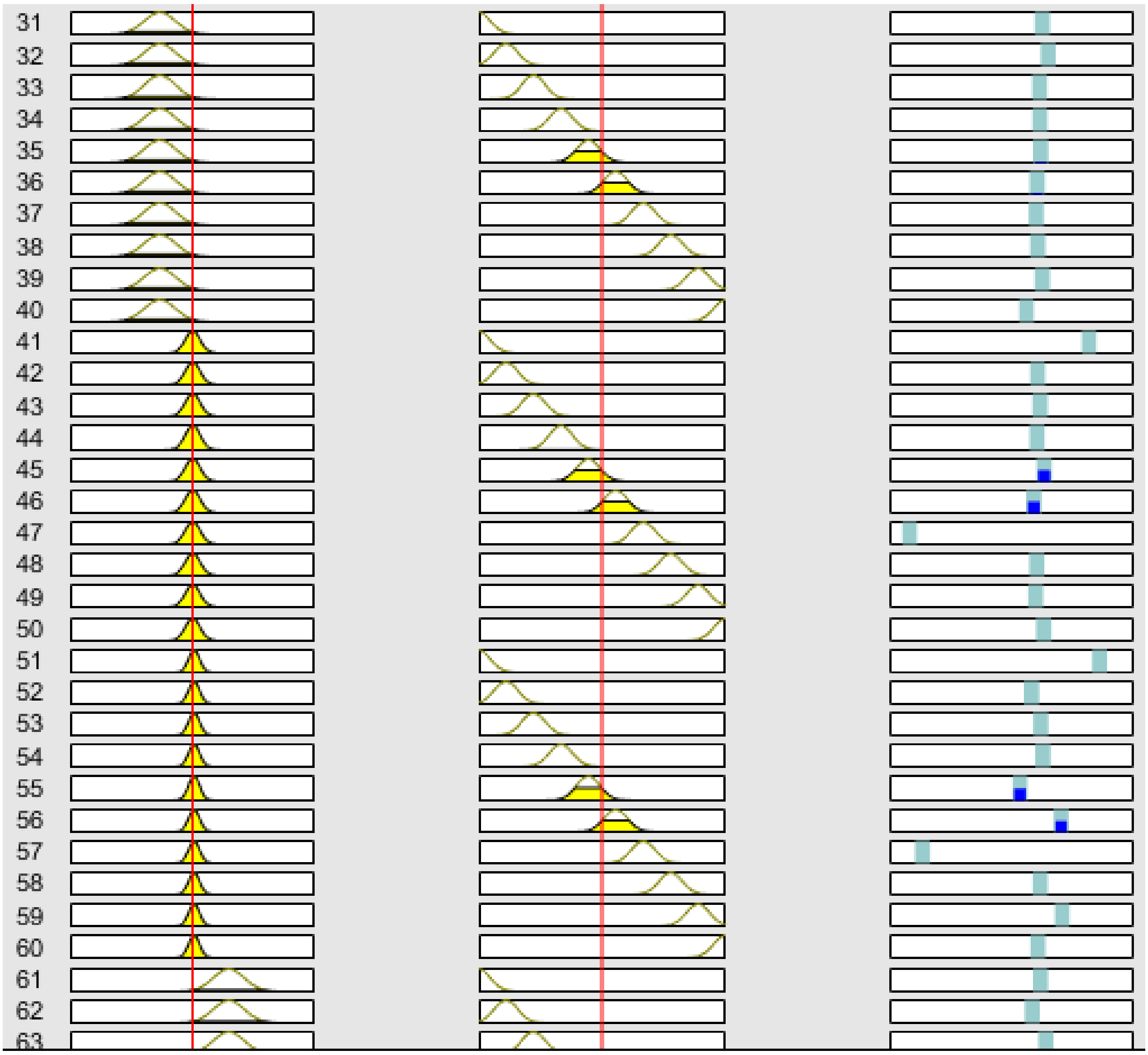
Simulink Model for Passive System



Appendix D

ANFIS If then-Rule

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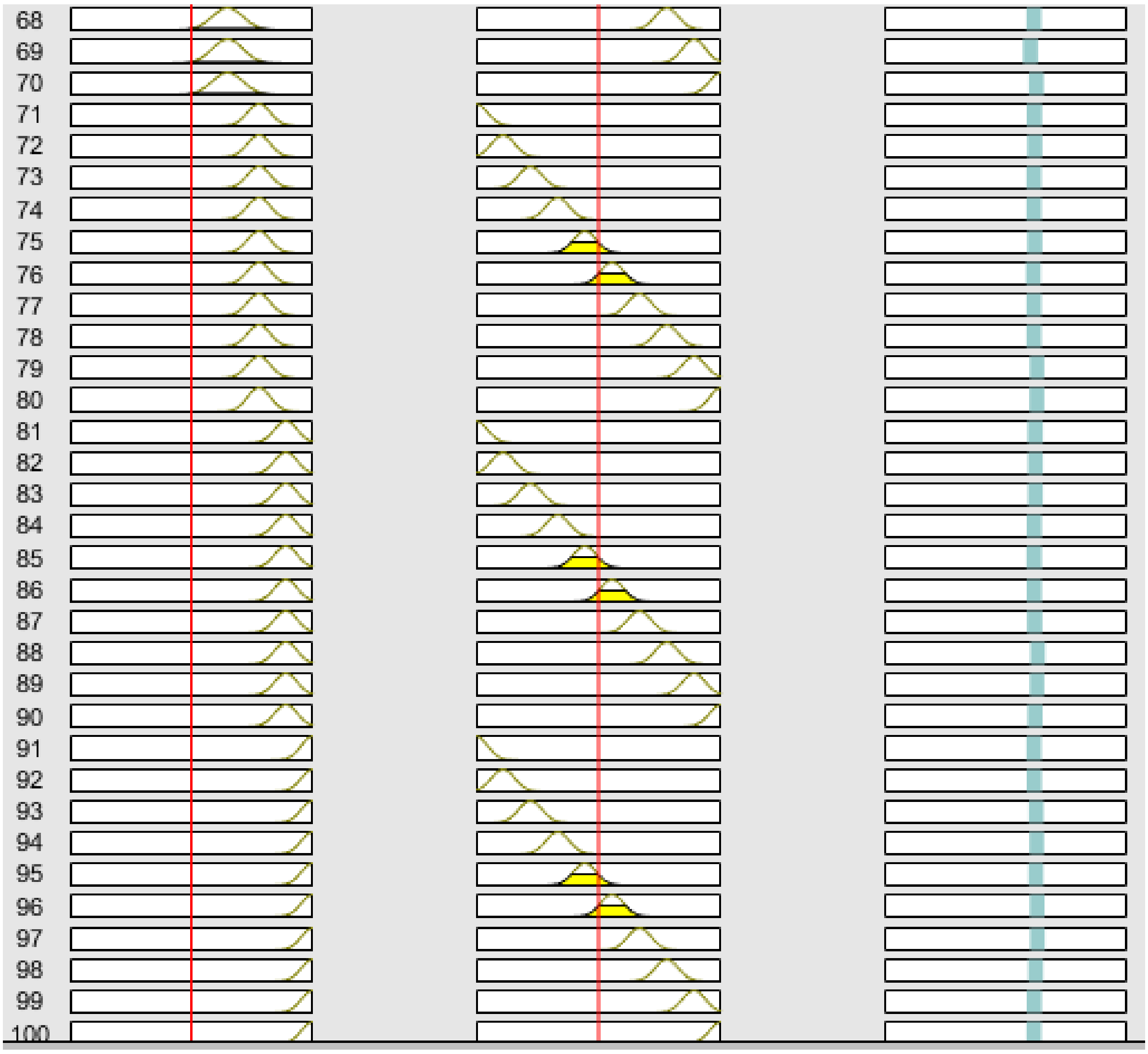
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