

CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

DESIGN OF A CONTROLLER FOR ABS ANTI LOCK BREAKING SYSTEM
USING FUZZY LOGIC CONTROL

A graduate project submitted in partial fulfillment of the requirements
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in Electrical Engineering

By

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ABSTRACT

DESIGN OF A CONTROLLER FOR ABS ANTI LOCK BRAKING SYSTEM USING FUZZY LOGIC CONTROL

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Masters of Science in Electrical Engineering

Automobile vehicles of today have the need of continuously adjusting their speeds as per changing roads and traffic conditions. With the increase of speed and density of road vehicles, Anti Lock Breaking systems are being developed and implemented in these vehicles taking into account the safety performance issues. These Anti Lock Braking systems are used in modern cars to prevent the wheels from locking after brakes have been applied. The control target for the Anti Lock Braking systems is to maintain the frictional coefficients within the maximum range in corresponding operating conditions in order to obtain a maximum frictional force from the varying road surfaces and ensure the safety of the vehicle at the same time. The controller of the system in this project is developed using fuzzy logic control. The objective of the ABS controller in this project is to maintain the wheel slip ratio as close as possible to a fixed slip value of 0.2 which is ideally the desired slip value in order to reduce the stopping distance and ensure safe operation of vehicle while braking takes place. The vehicle model is also simulated using a PID controller. A comparison is made between the fuzzy controller and PID controller based on angular velocity, slip ratio and stopping time. The vehicle has been simulated under dry asphalt road condition and considering only straight line braking. It was observed that the fuzzy controller has a shorter stopping time of 0.25 seconds as compared to the PID controller and shows a better tracking capacity.

CHAPTER 1

INTRODUCTION

1.1 History of Fuzzy Logic

The origins of Fuzzy Logic can be dated back to centuries ago. Aristotle had laid the foundations of two valued logic, while Plato was one of the earliest to challenge this norm by suggesting that there was an intermediate third region between “true” and “not true” where some parts might be true and some might not. The idea thus was that for certain things there could be a degree of truth and a certain degree of false at the same time. [1]

The term Fuzzy Logic was formally introduced by Lofti A. Zadeh, who is known as the father of fuzzy logic, in 1965. He had observed that conventional two valued binary logic could not be used to manipulate data with subjective ideas such as very hot, fairly cold etc. He realized that the terms which were widely accepted as mentioned earlier differed in a way which could not be explained in a conventional way. Another clear example in this idea was that the shades of grey could not be explained using the conventional method since then it had to be either white or black. It was he who first introduced the nomenclature and fuzzy set theory with values between 0 and 1. The key idea of Fuzzy Logic comes from the multi valued logic which states that “Everything is a matter of degree” [21]. Fuzzy logic since then has been used in two different senses:

- i) “It serves as a logic based system that takes into account reasoning under uncertainty while generalizing the classical based logic which has always been two valued ” [20].

- ii) “It serves as a reference to studies and theories that have revolved around fuzzy sets having conditional boundaries” [20].

1.2 Origins of Fuzzy Logic

When we look at history, the point of view of uncertainty was not very well accepted within the scientific community. The problem in doing so was that traditionally, uncertainty always represented an undesirable state. This state had to be avoided at all costs. This thinking or approach of the scientific community was prevalent until the late nineteenth century. The issue was first tackled with the introduction of probability as a means to address uncertainty. Probability was one of the earliest concepts that dealt with the term; a certain degree of certainty. As years passed by there was a gradual trend in science to consider the influence of uncertainty on problems.

The theory of vague sets or the so called fuzzy sets of today proceed from the German philosopher and physicist Max Black who also analyzed the problem of modeling vagueness. He had proposed that traditional logic could be used by representing vagueness at an appropriate level of detail. He discussed the vagueness of terms or symbols by borderline cases. While discussing scientific measurement he pointed out that indeterminacy which is characteristic in vagueness is also present in all scientific measurements. Black had therefore put forth the idea of a consistent profile or curve to enable the analysis of the ambiguity of a word or symbol. This idea of a consistent profile or curve put forth by Black, today bear a strong resemblance to the membership functions of type-I fuzzy sets [4]. His work had greatly influenced Lofti A. Zadeh who in 1965 published the article on fuzzy sets in the journal called Information and Control.

1.3 Evolution of Anti Lock Breaking Systems

In 1929, automobile and aircraft pioneer Gabriel Voisin was the first to develop ABS systems which would be used in aircrafts. “The first system used a flywheel and a valve attached to a hydraulic line that would feed the brake cylinders. The flywheel was attached to a drum that would run at the same speed as that of the wheel. The drum and flywheel would spin at the same speed in case of normal braking conditions” [22]. However if a wheel was to slow down then the drum would follow the same and the flywheel would spin at a faster rate. As a result of this the valve would open and a small amount of brake fluid would go into a local reservoir which would in turn lower the pressure on the cylinder and release the brake. This method significantly improved the braking process since full brakes could be applied now instead of pilots looking for a skid point where they could slowly increase breaking pressure. In addition to this the problem of the tires burning out or bursting was also significantly reduced.

“Later on in 1958 the Royal Enfield super motorcycle was used to test anti lock breaks on motor cycles. The results showed that such systems could be successfully implemented on motor cycles and the problems such as skidding on wet surfaces could now be tackled in a better way” [13] .

In 1971, General motors introduced the “Trackmaster” as a rear wheel only ABS on their Cadillac model. In the same year Nissan introduced the Electro Anti Lock system on their vehicle the Nissan President which became to be Japan’s first electronic Anti Lock Breaking System. From 1988 onwards famous companies such as BMW, Harley Davidson, Suzuki etc. began to incorporate Anti Lock brakes on their range of motorcycles and vehicles.

According to the theory of Fuzzy Logic, we have a transfer function which is usually derived from a characteristic function called as the membership function. This in turn runs within the universe of discourse, U , until the closed interval of real which is $[0,1]$. This is not the case in terms of classic or crisp sets where the range of the function is reduced to a set containing of only two elements $\{0,1\}$. “Thus it could be fair to assume that the fuzzy set theory is in a way a generalization of the classical set theory” [1].

From the information gathered so far we can estimate that fuzzy systems are useful in two general contexts:

- i) In situations involving highly complex systems whose behaviors are not very well understood.
- ii) In situations which need the most approximate and instantaneous solutions.

Thus fuzzy systems can be understood to be those systems which have an organized way of dealing with imprecise data. It is more of a human way like thinking incorporated into machines for controlling action to take place. As a result, fuzzy systems have been extensively used in applications that involve artificial intelligence. As a result of its potential in dealing with intelligent control, I have chosen to use it as a tool for the controlling action of an Anti-Lock Break system that can be used in motor vehicles. Fuzzy controllers in my opinion are the most promising candidates for the control of non linear, time varying and complicated systems. An Anti Lock Breaking system which is a non linear system may not be easily controlled by a classical control approach. An intelligent fuzzy control system is very useful for this kind of a non linear and time varying system. In this project, I have tried to achieve a real time design for an ABS controller which can be adjusted to slipping performance

for a dry asphalt road surface when braking action takes place along a straight line. The simulation results of this proposed intelligent ABS controller has shown it to be reliable and deliver a better performance when compared to a classical PID controller.

Chapter 2 in this report will cover the background on fuzzy logic and its applications in various control systems.

Chapter 3 will cover the description of the anti lock breaking system. This will include the components used in the ABS system and their respective functions. This chapter will also cover the vehicle simulink model that has been used for the system along with the description of the components that build the model.

Chapter 4 will include the description of a PID controller used for the ABS system.

Chapter 5 will include the description of the fuzzy logic based controller used in the ABS system.

Chapter 6 will cover the numerical experiment with simulations and results comparing both the control models for the ABS system.

Chapter 7 will be cover the conclusions drawn when both control models were compared and look into the future scope for improvement of ABS systems.

CHAPTER 2

BACKGROUND ON FUZZY LOGIC AND ITS APPLICATIONS IN CONTROL

2.1 Classical Sets vs Fuzzy Sets

The universe of discourse is known as the universe of all the available information on a given problem. Once this universe is defined then we are able to define certain events on this information space. Figure 2.1a shows the abstraction of a universe of discourse, say X, and a classical set A somewhere in this universe.

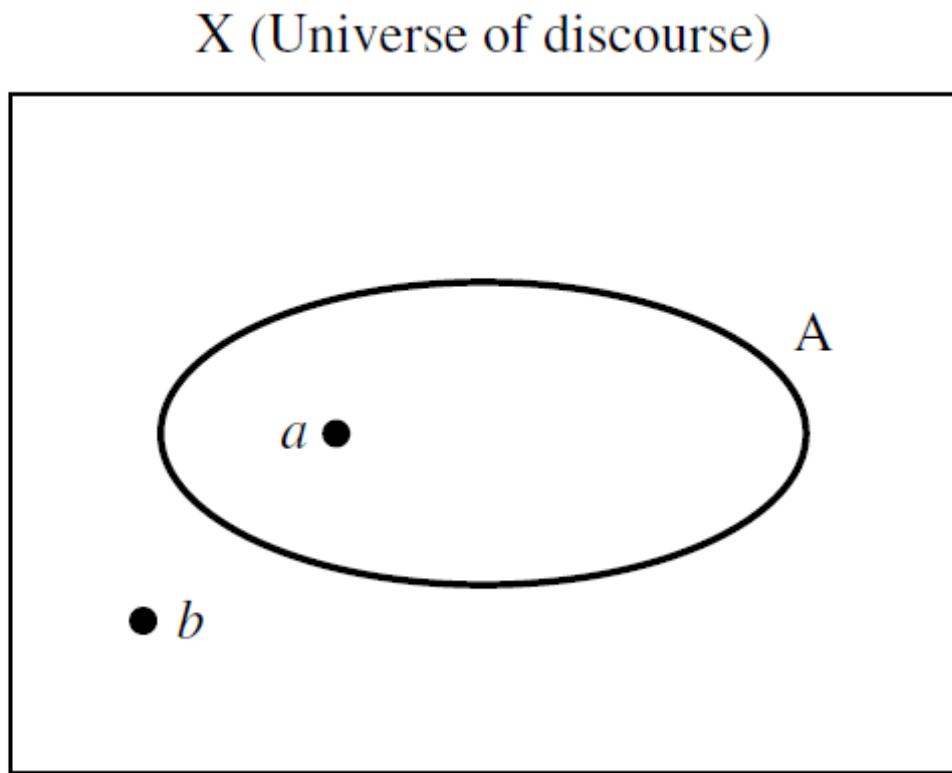


Figure 2.1a: Universe of discourse for a classical set.

A classical set is defined by a crisp boundary. In a classical set there is no uncertainty in the location of the boundaries of the set. “Classical sets define the universe of discourse as a collection of objects all having the same characteristics.

The features of the elements in X can discrete, countable integers or continuous valued quantities on a real line. In classical or crisp sets, the transition for an element in the universe between membership and non membership in a given set is abrupt and well defined. For an element in a universe that contains fuzzy sets, this transition can be gradual” [23].

Figure 2.1b shows the universe of discourse say X for a classical set $\underline{\mathbf{A}}$

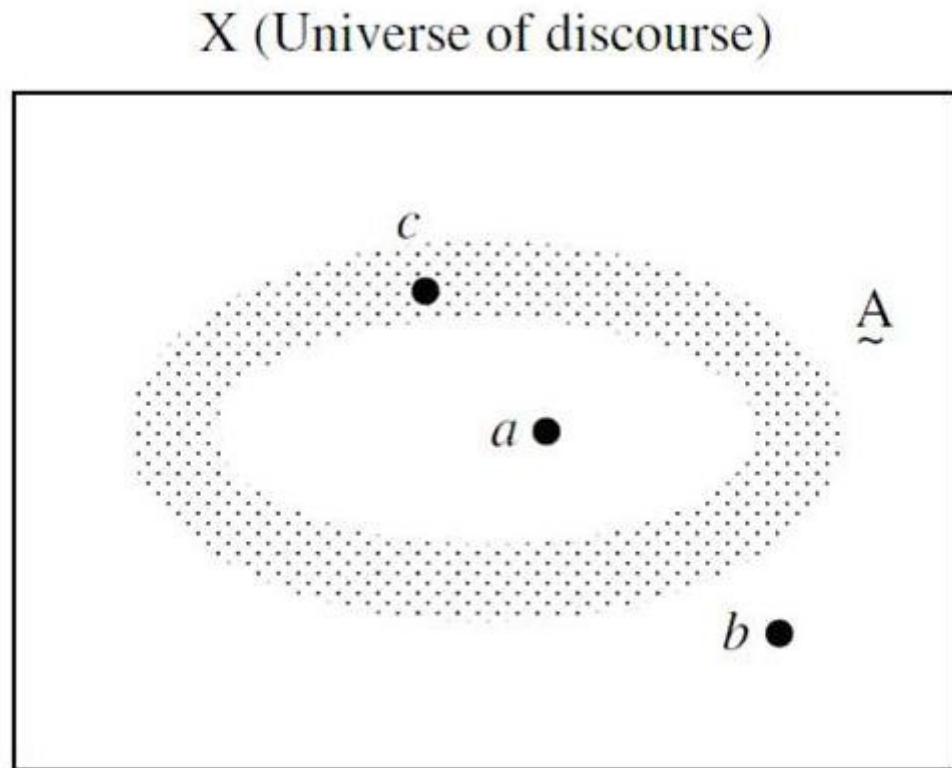


Figure 2.1b: Universe of discourse for a Fuzzy Set.

A fuzzy set is prescribed by vague or ambiguous properties. It is clear from figure 2.1b as to how a fuzzy boundary would look like. Thus we can see that a fuzzy set is a set containing elements that have varying degrees of memberships in the set. This is a contrasting idea when compared with classical sets because members of a classical set would not be members unless their membership was full or complete in

that set, meaning that their membership is assigned a value 1. Elements in a fuzzy set, because their membership need not be complete, can also be members of other fuzzy sets on the same universe. [4]

2.2 Membership Functions in Fuzzy Sets

Fuzzification is the process of converting crisp values into grades of memberships in fuzzy sets. A membership function of a fuzzy set by definition is the generalization of the indicator function in classical sets. Membership functions were first introduced by Zadeh in his paper on fuzzy sets in 1965. “Every element in the universe of discourse is a member of the fuzzy set to some grade. This can and also includes zero” [20]. “A fuzzy set has membership grades assigned to its elements such as more negative, negative, positive, more positive etc. There is no sharp boundary which connects the grades; rather there is a grey area or common area between them. Thus it can be understood that the transition from one membership grade to another is more of a gradual transition. Another term that is used while defining a set of elements is called as the support of the fuzzy set. This support contains all the set of elements that have a non zero membership. The function that associates a number to each element x of the universe is called the membership function $\mu(x)$ ” [19]. Some of the commonly used shapes of membership functions are shown in figure 2.2.

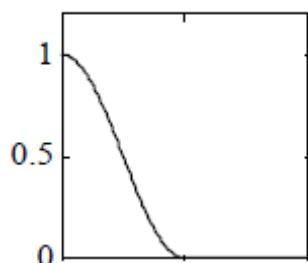


Figure 2.2a : The s-membership function

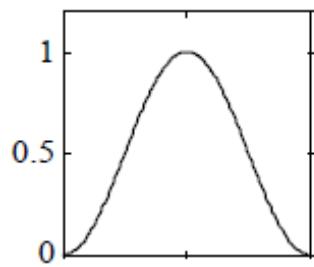


Figure 2.2b: The π - membership function.

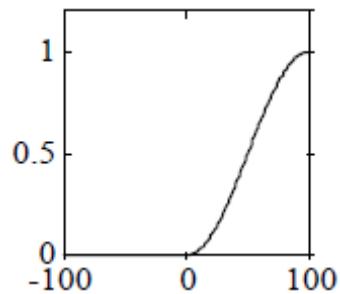


Figure 2.2c: The Z-membership function.

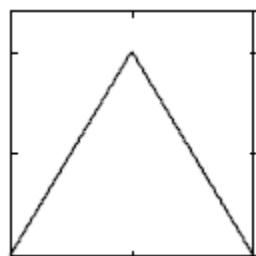


Figure 2.2d: The triangular membership function.

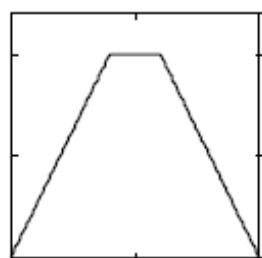


Figure 2.2e: The trapezoidal membership function.

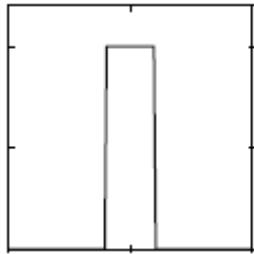


Figure 2.2f: The rectangular membership function.

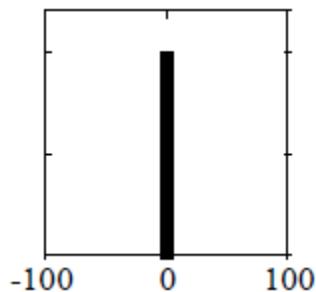


Figure 2.2g: The singleton membership function.

It should also be noted that while considering membership functions a certain degree of overlap is desirable. If the overlap is not present then there could be a possibility that the controller may run into poorly defined states. In a situation like this the controller does not return a well defined output value. [4]

2.3 Fuzzy Rules

The fuzzy rules form the basis while designing a control system using the fuzzy logic method. It is an intelligent way of describing how the inputs would interact with each other to give the required output in its gradual form. The fuzzy “if-then” rule is used in most of the applications that incorporate the fuzzy approach while designing a system. It is a generalization of logic inference called modus ponens. It is a rule that helps us reach a conclusion using a panel of experts.

Fuzzy rules have mainly two components:

i) **If –part:** It is also known as the antecedent or premise. An example would be that If the speed is high, then apply a little break. Another example is that If the income is low, then the tax deduction is low.

“Antecedent may combine multiple conditions using And, Or and Not” [4].

An example of this would be; If the speed is high And traffic is high

Another example would be; If the income is high And number of depending people are low.

ii) **Then-part:** It is also known as the consequent or conclusion. It is the part of the rule that decides the action to be taken when the particular condition is satisfied. An example would be; If the income is high, then the tax deducted is high. “The consequent can be present in three forms namely Crisp consequent, fuzzy consequent and functional consequent” [4].

2.3.1 Fuzzy Rule based Inference Mechanism

The fuzzy rule based inference mechanism consists of three parts namely fuzzy matching, fuzzy inference and fuzzy combination.

i) Fuzzy Matching

The fuzzy matching is a process which calculates the degree upto which the input data can match the condition of the fuzzy rules. In the case where there are multiple conditions and the antecedent includes conditions connected by AND, then conjunction is used to combine the matching degree of each condition.

ii) Fuzzy Inference

When fuzzy matching has been done, then fuzzy inference is used for each rule to produce a conclusion based on their matching degree. There are two methods

to produce such conclusions namely the clipping method and the scaling method. The clipping method cuts off the top portion of the membership function whose value is higher than the matching degree. The scaling method scales down the membership function in proportion to the matching degree.

iii) Fuzzy Combination

The fuzzy combination combines the conclusion drawn by all the fuzzy rules. This combination is done by superimposing all fuzzy inferred conclusions about a variable. There may or may not be overlapping. In case of crisp outputs the overlapping would be of a discrete form. For more general or complex cases conclusion through superimposition is based on fuzzy disjunction operators such as max. or min.

2.4 Defuzzification

“Defuzzification is the process of producing a quantifiable result or a crisp value in fuzzy logic for given fuzzy sets and membership functions associated with them” [10]. The resulting fuzzy set, in sense an output, is converted into a number that can be sent to the process as a control signal. “It is a crisp value that is sent as a control signal” [4]. There are several defuzzification methods which are explained below.

2.4.1 Center of Gravity (COG)

“The crisp absolute value, u , in this case is the abscissa under the centre of gravity of the fuzzy set” [19].

$$u = \left[\sum i \mu(x_i) \cdot x_i \right] / \left[\sum i \mu(x_i) \right] \quad (1)$$

“Here x_i is the running point in the discrete universe and $\mu(x_i)$ is its membership value in the membership function. The expression can be interpreted as the weighted

average of the elements in the support set. In the continuous case the summations are replaced by integrals” [19]. This method of determining the crisp value is called as the centre of gravity method and is the most widely used method of defuzzification.

2.4.2 Center of Gravity of Singletons (COGS)

If the membership functions of the conclusions are singletons then the output value is given by:

$$u = \sum_i \mu(s_i) \cdot s_i / \sum_i \mu(s_i) \quad (2)$$

Where “ s_i is the position of the singleton i in the universe and $\mu(s_i)$ is equal to the firing strength α_i of rule i . This method had a relatively good computational complexity and u is differentiable with respect to the singletons s_i which is useful in neuro fuzzy systems” [19].

2.4.3 Bisector of Area (BOA)

“This method picks the abscissa or the x co-ordinate of the vertical line that divides the area under the curve into two equal halves” [19]. In the continuous case the equation for output u is given by:

$$u = \{ x \mid \int_{x_{\min}}^x \mu(x).dx = \int_{x_{\min}}^{x_{\max}} \mu(x).dx \} \quad (3)$$

“Where x is the running point in the universe, $\mu(x)$ is its membership, Min is the leftmost value in the universe and Max is the rightmost value. The computational complexity in this method is relatively higher than other methods. The nature of results obtained using this process could be vague.” [19]. This nature of the defuzzification method can be highlighted by taking an example in case of two singletons. “If a fuzzy set consists of two singletons then any point between the two

could divide the area into two halves. Thus in this case we can conclude that in discrete cases the Bisector of Area is not defined” [19].

2.4.4 Mean of Maximum (MOM)

“The mean of maximum is an approach where a point is chosen that has the highest probability or in fuzzy logic terms that which has maximal membership. Although it could quite be possible that more of such points may exist and thus a mean is to be calculated in such cases. This method disregards the shape of the fuzzy set but the computational complexity is relatively good here” [19] .

2.4.5 Leftmost Maximum (LM) and Rightmost Minimum (RM)

This method is used when either decision needs to be taken like left or right. If we take an example of a robot, the robot for instance would either have to go right or left to avoid the obstacle in front of it. A decision in between these would not be favorable. The defuzzifier in this case must choose either left or right but not something in between. This method of defuzzification is indifferent to the fuzzy set. The computational complexity in this case is relatively small. For the purpose of illustration of a crisp output signal that is sent by the process of defuzzification is shown in figure 2.4.5a. Figure 2.4.5a shows a one input, one output rule base with non singleton output sets. This is used mostly in case of the Center of Gravity method.

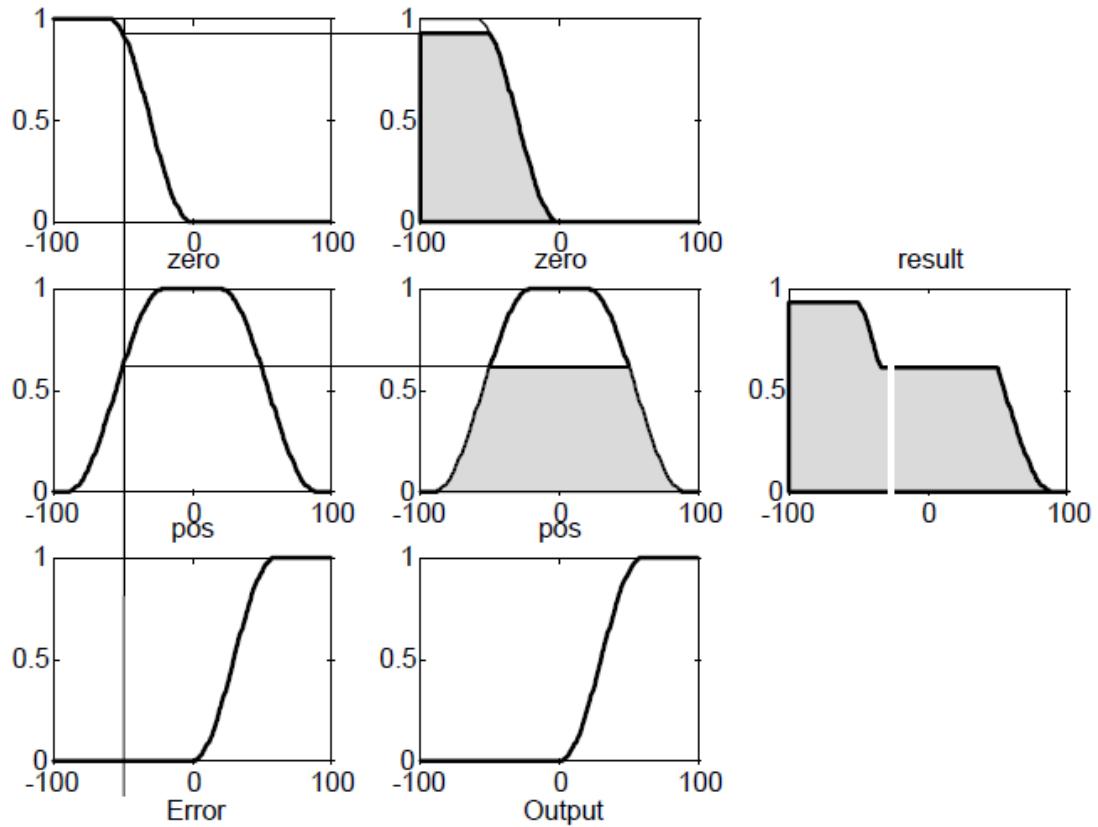


Figure 2.4.5a One input, one output rule base with non singleton output sets.

The x co-ordinate marked by the white vertical dividing line becomes the control signal that is sent after the process of defuzzification.

2.4.6 Fuzzy Rule Base System

The figure 2.4.6a gives us the architecture of a fuzzy rule based system. It shows the system from input to output stage and what processes take place within the system.

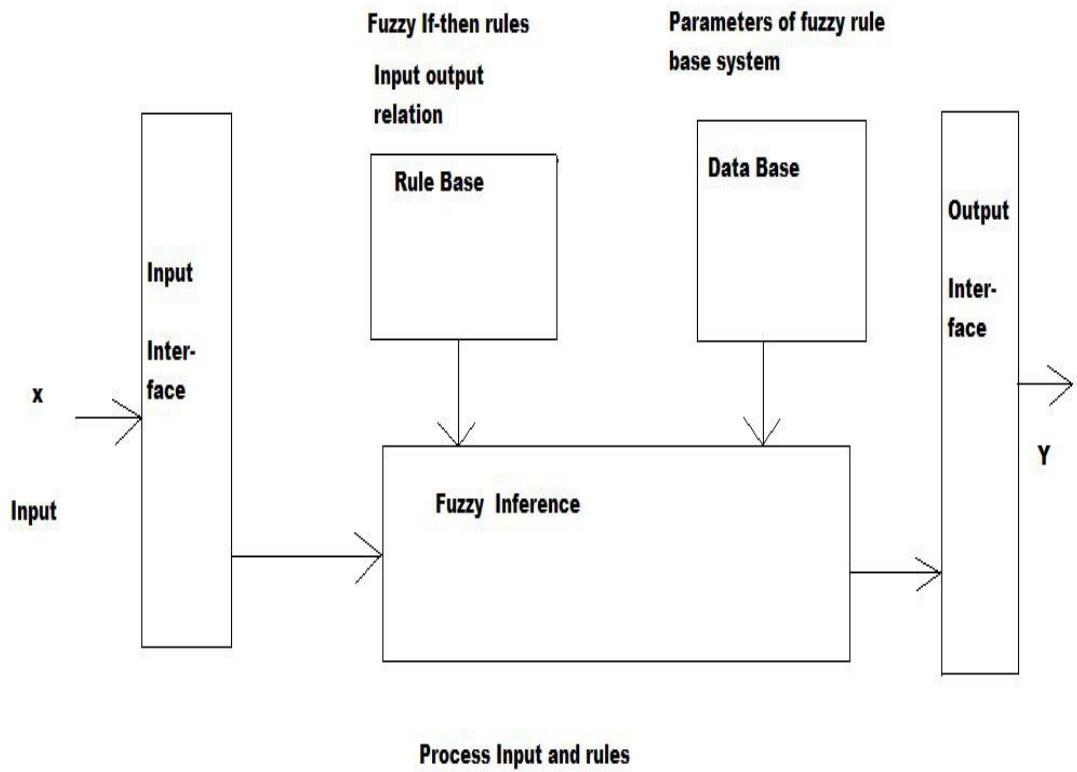


Figure 2.4.6a Architecture of fuzzy rule base system

2.5 Fuzzy Logic Toolbox in Matlab

The fuzzy logic toolbox is very user friendly software that allows us to do various things. The most important aspect of this toolbox is that it allows us to create and edit fuzzy inference systems. These systems can be created using command line functions or graphical tools. We can also generate them automatically using clustering or adaptive neuro fuzzy techniques. Figure 2.5a shows us how the toolbox is integrated in Matlab. [5]

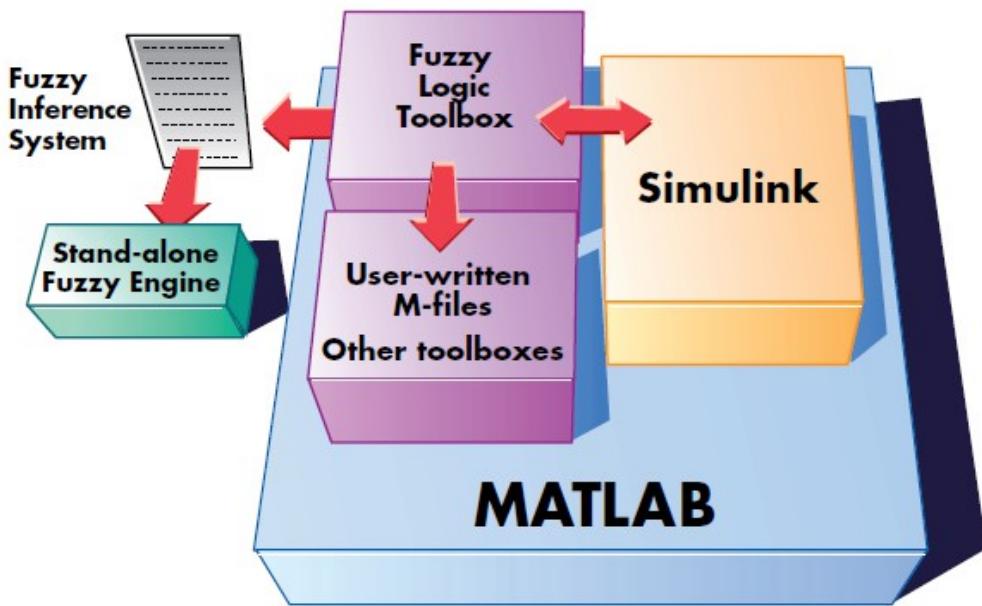


Figure 2.5a Integration of fuzzy logic toolbox in Matlab.

2.5.1 Fuzzy Inference System

“Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic” [20]. Using this mapping, decisions can be made and patterns can be discerned. As described earlier, membership functions, fuzzy logic operators and if-then rules are used to build the fuzzy inference system. There are two types of systems that can be built in the toolbox, namely the Mamdani type and Sugeno type. These two inference systems differ in the way the outputs are determined. The Mamdani Fuzzy inference model is the more commonly used model among the two. Figure 2.5.1a shows the fuzzy inference system.

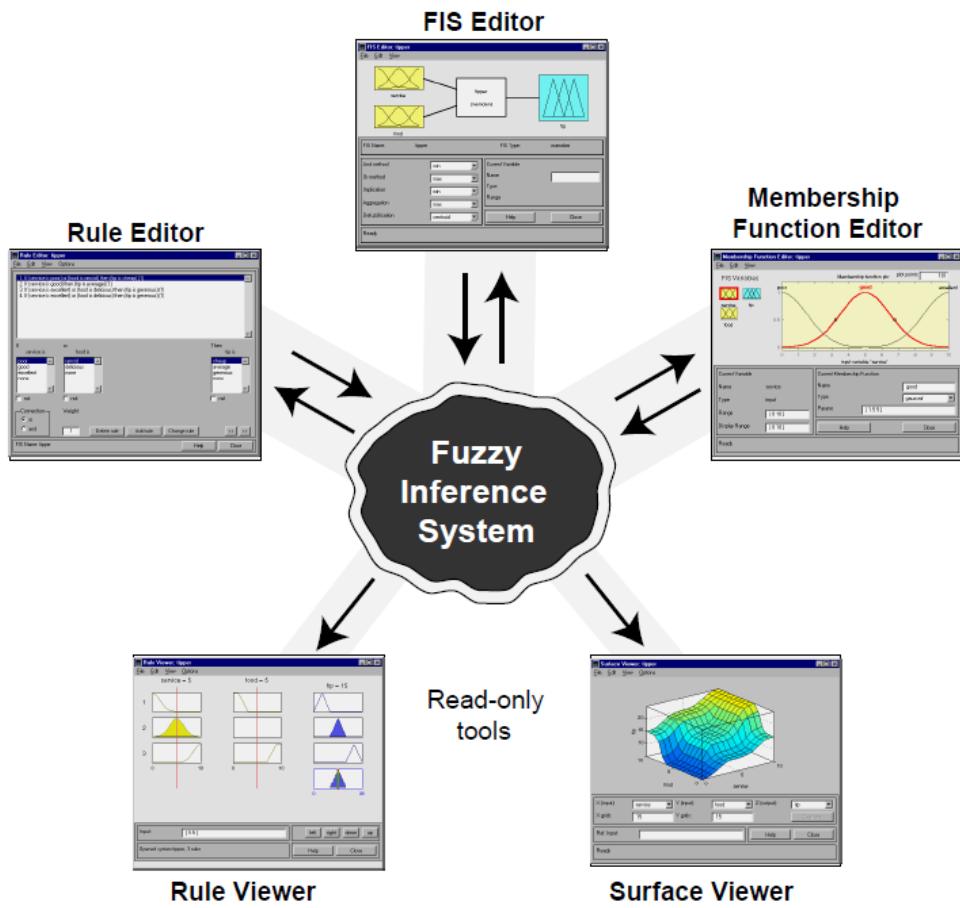


Figure 2.5.1a The Fuzzy Inference System

The FIS editor handles the various issues for the system. It defines the number of input and output variables.

The membership function editor is used to define the shapes of all the membership functions associated with each variable.

The rule editor is used for editing the list of rules that defines the behavior of the system.

The Surface viewer is a diagnostic tool which shows which rules are active and how the membership function shapes influence the results.

2.6 Applications of Fuzzy Logic in Modern Control Systems

The idea that uncertainties in a system could be modeled by the use of fuzzy sets and fuzzy rules was what gave rise to the use of fuzzy logic in control systems. Fuzzy logic showed the way for implementing control laws on the basis of linguistic description. Fuzzy logic provided that breakthrough where non linear controllers had to be used.

In a vast majority of systems that require controlling action, the behavior of that system could be defined by a set of rules that depend on linguistic terms with a small percentage of uncertainty. An example of this type is “If the volume is small then pressure is large.” When a system is to be modeled we can use the behavior pattern of the system as a tool while using the control logic. Thus a set of rules could be defined to carry out actions on the system and make the system behave in a certain way in certain conditions. Through the use of the Mamdami fuzzy inference, fuzzy logic could be used to real time systems. Figure 2.6a shows the block diagram of a fuzzy control system.

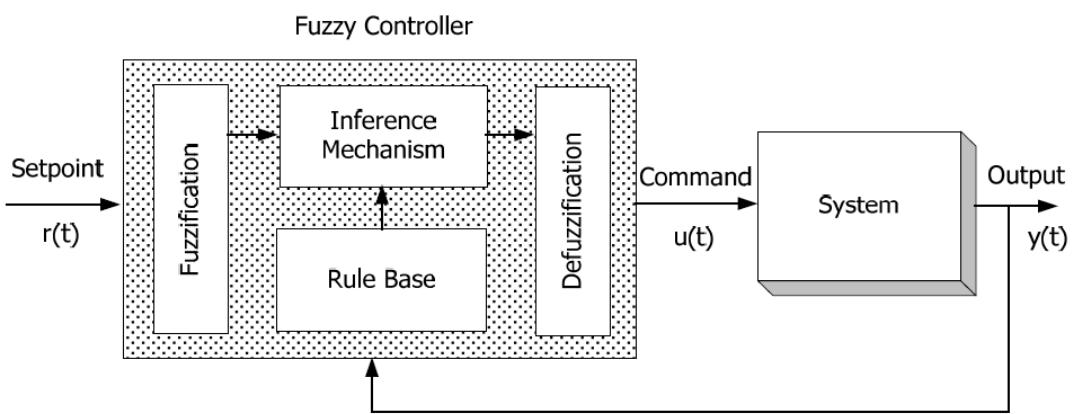


Figure 2.6a Block diagram of fuzzy control system

A fuzzy control system can be implemented in real time systems with the use of a sensor and actuator technology. The actual values calculated by the sensor must be converted into fuzzy values that comprise of the variables of the antecedent in the rule base. In a similar way, the fuzzy values that are calculated using these rules need to be transformed into exact values for the use in actuators. Thus, with the help of a rule base the logic can be developed on how the plant can be controlled. The inference mechanism will make the decision as to what kind of controlling action should take place. The fuzzification will convert the inputs into fuzzy information and inference mechanism will generate the corresponding rule or controlling action. Defuzzification will convert the action into a real value or exact crisp value as an input to the system to be controlled. This was how fuzzy logic could be applied in the design of modern control systems.

A few examples of where fuzzy logic controllers have been applied in real time applications are automatic control of dam gates for hydroelectric power plants which are currently functional at the Tokyo Electric Power plant, simplified control of robots, automatic assessment of stock exchange activities, camera aiming for the telecast of sports events which is currently developed by Omron, efficient and stable control of car engines implemented by Nissan, cruise control for automobiles implemented by Nissan and Subaru, positioning of wafer steppers in the production of semiconductors implemented by Canon, prediction system for early recognition of earthquakes implemented by Seismology Bureau of Meteorology in Japan, archiving system for documents implemented by Mitsubishi Electronics, recognition of handwritten symbols with pocket computers developed by Sony, back light control for camcorders implemented by Sanyo, controlling of machinery speed and temperature

for steel works implemented by Kawasaki steel and NKK, flight aid for helicopters by Sugeno are just a few to mention amongst the thousands of applications. [3]

CHAPTER 3

THE ANTI LOCK BEAKING SYSTEM

An anti lock breaking system is a system used for the safety of motor vehicles. “This system allows the wheels of a motor vehicle to maintain frictional contact with the road surface according to the inputs by the driver, while the breaking prevents the wheels from locking up.”[13] This locking up of wheels occurs when the rotation of the wheels comes to a halt. The system is designed in a way that it prevents the wheels to stop rotating instantly which could cause the vehicle to skid and the driver could loose control of the vehicle. The system of the ABS is designed in a way that it helps to increase the breaking distance when the road surface is loose like in case of a snow clad surface or if the road has gravel on it. On the other hand the system reduces the breaking distance when the surface is dry or slippery like in case of a wet surface. The idea of a decreased stopping distance on wet and dry surfaces has shown to improve the control over the vehicle by the driver.

3.1 Objectives of Anti Lock Breaking Systems

3.1.1 Reduction in Stopping Distance

The primary objective of breaking while a vehicle is in motion is to bring the vehicle to a halt or to reduce the speed of the vehicle. The distance that the vehicle will cover before coming to a halt is a function of the mass of the vehicle, the initial velocity and the force of breaking. If all factors remain constant then a maximum breaking force will end result into a minimum of stopping distance. However, the peak of frictional coefficient between the wheels of the vehicle and road surface will vary depending upon the road conditions or surfaces. It is understood that by keeping all the wheels of a vehicle near the peak, an antilock system can achieve maximum

frictional force and thus keep the stopping distance to a minimum. Although this is the primary objective of the breaking system, the system also needs to take into account the safety of the vehicle. The safety of the vehicle is accounted by two factors namely the vehicle stability and the vehicle steerability

3.1.2 Vehicle Stability

As it is mentioned before, although reducing the stopping distance in the action of breaking is the primary objective of antilock systems they also need to account for the stability of the vehicle. A maximum frictional force may not be desirable in all cases. In cases where the road surface is snowy or has gravel on it, the antilock system will tend to increase the stopping distance. If maximum breaking force is applied on both sides of the vehicle on such a surface, it will result into a yaw movement that will tend to pull the vehicle into the higher frictional side and significantly increase the vehicle instability. This will cause the driver to counteract this force by making excessive steering on other side resulting in instability of the vehicle. Thus the antilock breaking system maintains the slip of both rear wheels at the lower frictional peaks between the two. In doing so the lateral force is reasonably increased and thus better vehicle stability can be achieved.

3.1.3 Steerability

This is one of the most important factors while considering design of antilock breaking systems. A good peak frictional force control is extremely important to achieve satisfactory steerability as it contributes to balance of lateral forces acting on the vehicle. Achieving good steerability is extremely critical since it can help to avoid unwanted obstacles in the way. For vehicles that come with antilock breaking systems

the tire characteristics play an important role. Slip ratio is one of the important factors that contribute to system stability and steerability. Slip ratio is defined as vehicle speed – wheel speed whole divided by vehicle speed. It can be expressed as a percentage.

$$\text{Slip Ratio \%} = [(\text{vehicle speed} - \text{wheel speed}) / (\text{vehicle speed})] \times 100 \quad (4)$$

3.2 Theory of Operation of ABS

The components that make up a typical Anti Lock Braking system are Speed sensors, valves, a pump and a controller. The controller for the ABS is known as the ECU or the electronic control unit. A minimum of two hydraulic valves are located within the brake hydraulics. The function of the Electronic Control Unit is to monitor the rotational speed of each wheel. If the ECU detects that a particular wheel is moving significantly slower than the others then corrective action needs to be taken in this case. The main reason for this is that if a wheel is moving slower than the other wheels then that is an early indication that there could be a case of wheel lock up. As discussed earlier, a case of a wheel lock up could be harmful since it would compromise the safety of the vehicle and the driver. It could lead the vehicle to skid or cause unwanted yaw movement. In case where such a slower moving wheel is detected, the ECU actuates the valves to reduce the hydraulic pressure to the brake at the affected wheel. By reducing the braking pressure on that wheel, it in turn now begins to rotate faster and match the speed of the other wheels correspondingly. The valves within the braking system have some typical functions. The valves primarily open up and allow the hydraulic fluid from the pump to reach the braking system. Another important function of the valves is to see the pressure provided to the braking pressure is maintained. This is done by closing the valves to resist any further pressure

provided to the braking system. Thirdly the reduction in the braking pressure is also attributed to the valves as they open to allow the hydraulic fluid to be released from the system. Valves may face problems of clogging over time and may cause the braking systems to fail thus they need to be checked in regular intervals. Figure 3.2.1a shows the pump and valve assembly.

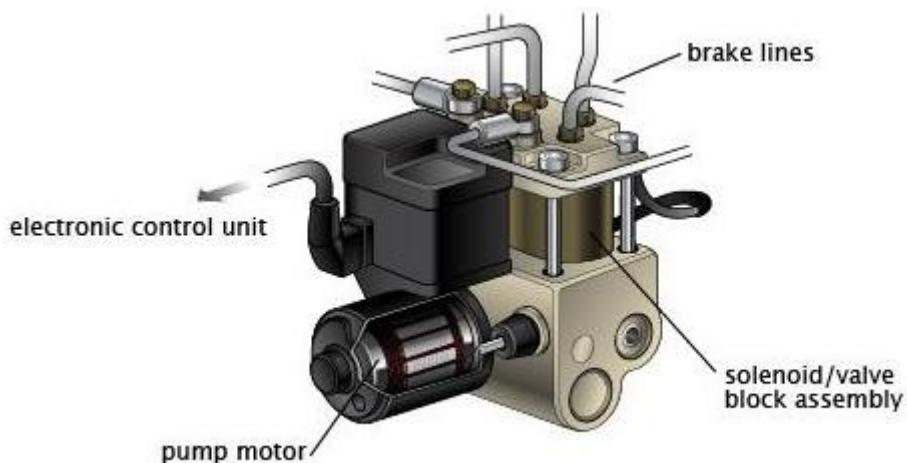


Figure 3.2.1a Pump motor and valve assembly.

The ECU, as discussed above also monitors if a particular wheel is rotating significantly faster than the other wheels. There is a strong possibility that the converse of the above situation could also occur. If such a situation is detected then the brake hydraulic pressure to that particular wheel is increased which in turn slows down the speed of the wheel. Again this is done until it matches the speed of rotation of the other wheels. This process is repeated continuously so as to maintain a constant wheel speed for all wheels. The ECU is also intelligently programmed to disregard differences in the wheel rotation speeds below a critical threshold. The reason for doing so is that when a car is making a turn, the two wheels towards the centre of the

curve turn slower than the other two. If a fault is developed in any part of the ABS then a warning light is illuminated, which is usually located near the speedometer of the vehicle. In such cases the ABS could be disabled until the fault is corrected.

An ABS equipment may also be used to implement a TCS or a Traction Control System on acceleration of the vehicle. If while accelerating, the tire loses traction, the ABS controller can detect the situation and can take suitable corrective action so that the traction is regained.

Figure 3.2.1b shows the typical components for an ABS system

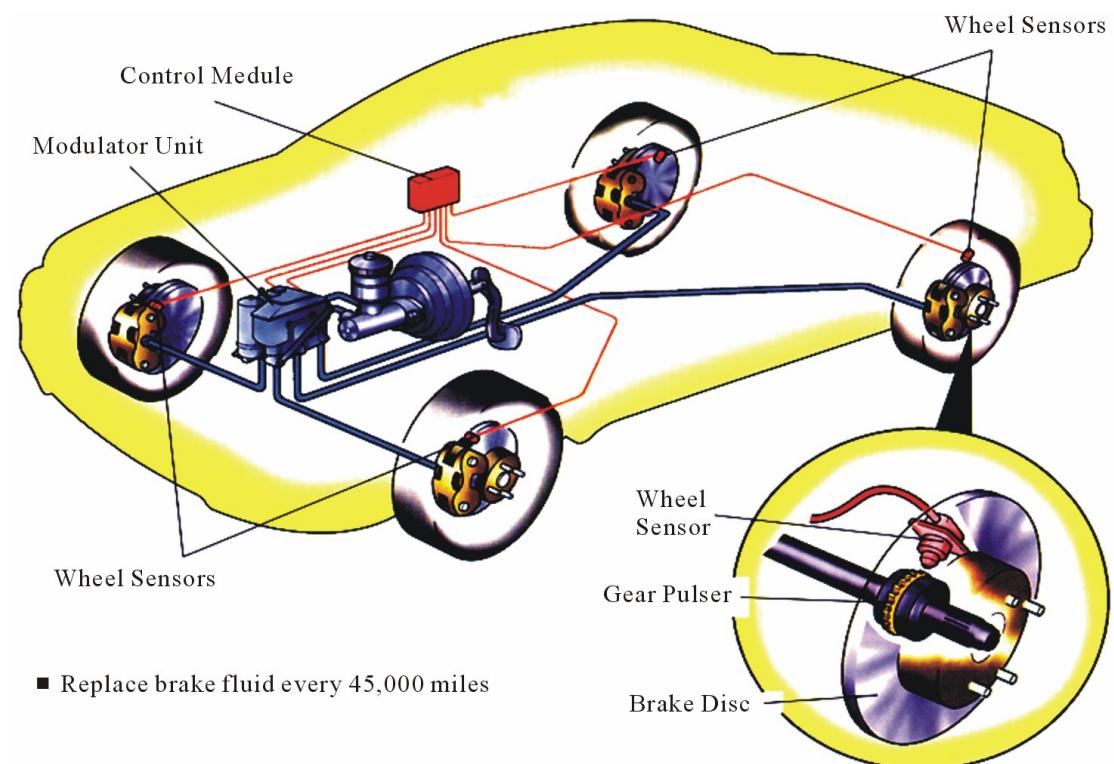


Figure 3.2.1b Typical Components for an ABS system

Figure 3.2.1c describes the closed loop which incorporates all the main parts in the ABS system and gives an overview of the working that was described above.

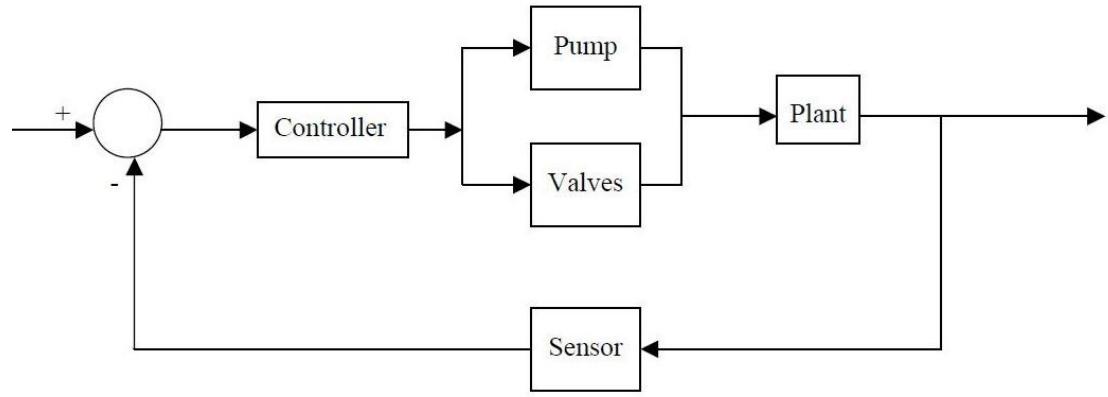


Figure 3.2.1c Closed loop system with main ABS components.

3.3 Modeling of the Vehicle System

A vehicle system in whole consists of many parts and parameters. To build a complete model for a vehicle system with all these parts and characteristics would be extremely complicated and there could be several design issues with the same. In this case a simplified quarter car vehicle model has been used for illustration. In doing so, all essentials features of the vehicle which can affect the performance of the vehicle have been retained. This quarter vehicle model has been used previously for designing ABS systems. Figure 3.3.1a shows the quarter vehicle model.

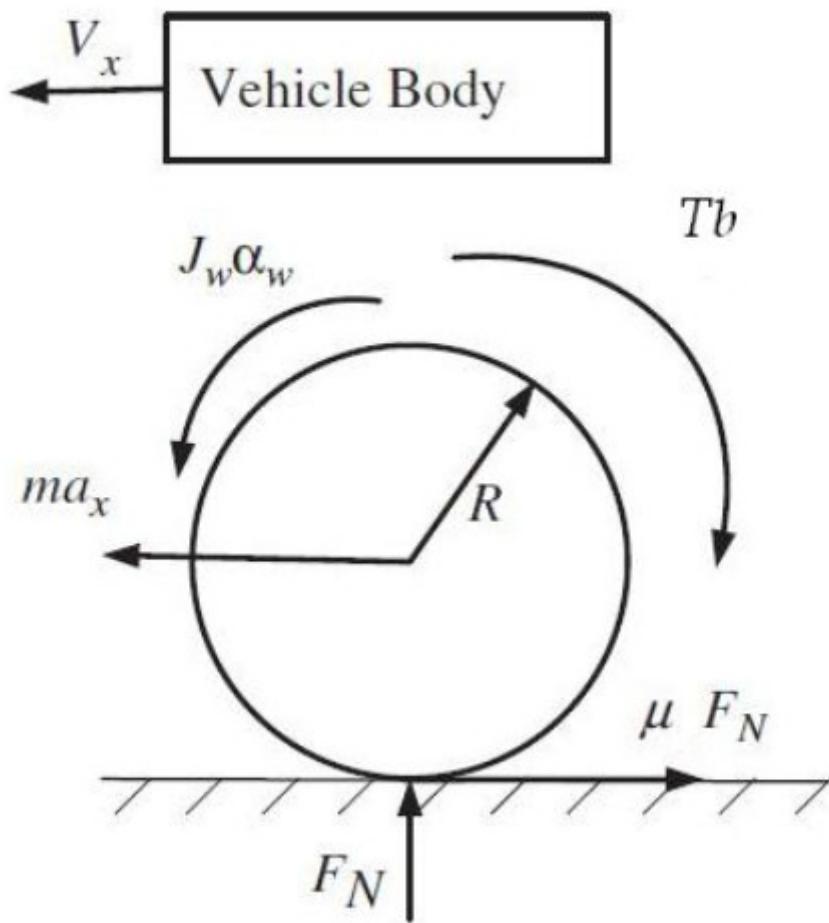


Figure 3.3.1a Quarter Vehicle Model

The rotational speed of the wheel and the longitudinal velocity of the vehicle constitute the degrees of freedom for this particular model.

The torque at the wheel centre is given by:

$$J_\omega \alpha_\omega = \mu \times R \times F_n - T_b \quad (5)$$

The braking force balance in longitudinal direction for the vehicle is given by :

$$m \times a_x = -\mu \times F_n = m \times (dV_x/dt) \quad (6)$$

The wheel slip is given by:

$$\lambda = (V_x - \omega R) / V_x \quad (7)$$

Where

α_ω = angular acceleration

a_x = linear acceleration

J = Inertia

ω = rotational speed of wheel

R = radius of tire

Vx = Linear velocity of vehicle

F_n = Vertical force from tire to road

T_b = braking torque

μ = frictional coefficient

λ = wheel slip

m = mass of the model

where $\alpha_\omega > 0$, $Vx > 0$, thus $-1 < \lambda < 1$

Figure 3.3.1b shows the simulink model for the quarter car simulation.

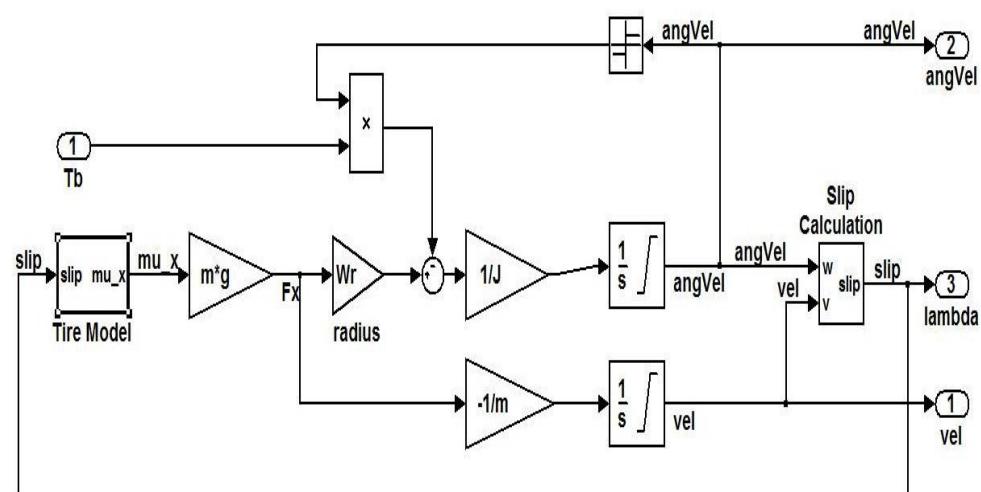


Figure 3.3.1b Simulink model for quarter car

3.4 Actuator Model

Particular time delays and the dynamics of an actuator are important factors while designing the vehicle model. These are critical for the design of control algorithms. In this model a simple first order lag in series with a time delay is used to model the actuator.

$$T_d = e^{-\tau_s} a/(s+a) \times T_{ref} \quad (8)$$

Where T_d is the time delay and assumed that it is less than the saturation value $T_{d_{sat}}$
 a is the file pole location whose value is assumed to be 70.

It should be noted that in most cases a second order model is used and here we have used the first order model for simplifying the design constraints. Most actuators have different responses when they are opening and closing.

Figure 3.4.1a shows the model of the actuator subsystem.

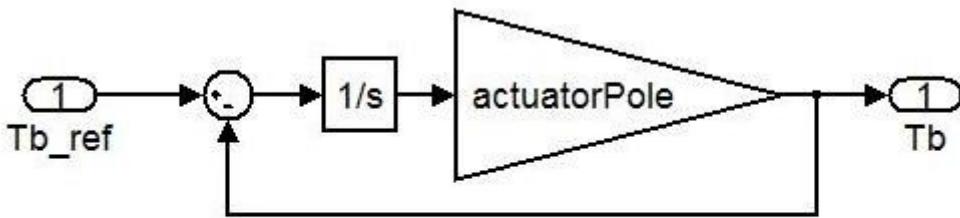


Figure 3.4.1a Actuator Model Subsystem

The first order lag has been implemented using an integrator, gain and summation block, rather than using a transfer function block from the continuous library. The transfer function block does not allow the vector signals as inputs thus we have implemented it the other way. In doing so the model can be expanded to allow for 4 channels, one for each wheel.

3.5 The Tire Model

The Pacejka's non linear tire model is used in this study. Pacejka curves are an integral part of tire models today and tire modeling is about close to 50% of a car simulator. Pacejka curves basically represent forces that are generated by the tire. These forces are generated by the tire as a result of the tire not following the road precisely. Figure 3.5.1a shows how the typical Pacejka curves looks like. The curves are generated on a few inputs such as slip angle, slip ratio, angle of tire with respect to surface and the load (amount of force pressing down on the tire). In figure 3.5.1a the black line indicates the longitudinal force which is a result of the slip ratio, the red line indicates lateral force and the green line indicates the aligning moment or what is more often expressed as a force feedback. This figure is used just to give an insight on how these curves look like and values used to demonstrate the curves are just for reference and serve as examples only.

In the tire model implemented in this design, the Pacejka's magic formula has been used. The equation of the longitudinal friction coefficient is given by:

$$\mu_x = a(1 - e^{-b\lambda} - c\lambda) \quad (9)$$

Where

λ = wheel slip and coefficients a,b,c vary depending on the current road condition/surface.

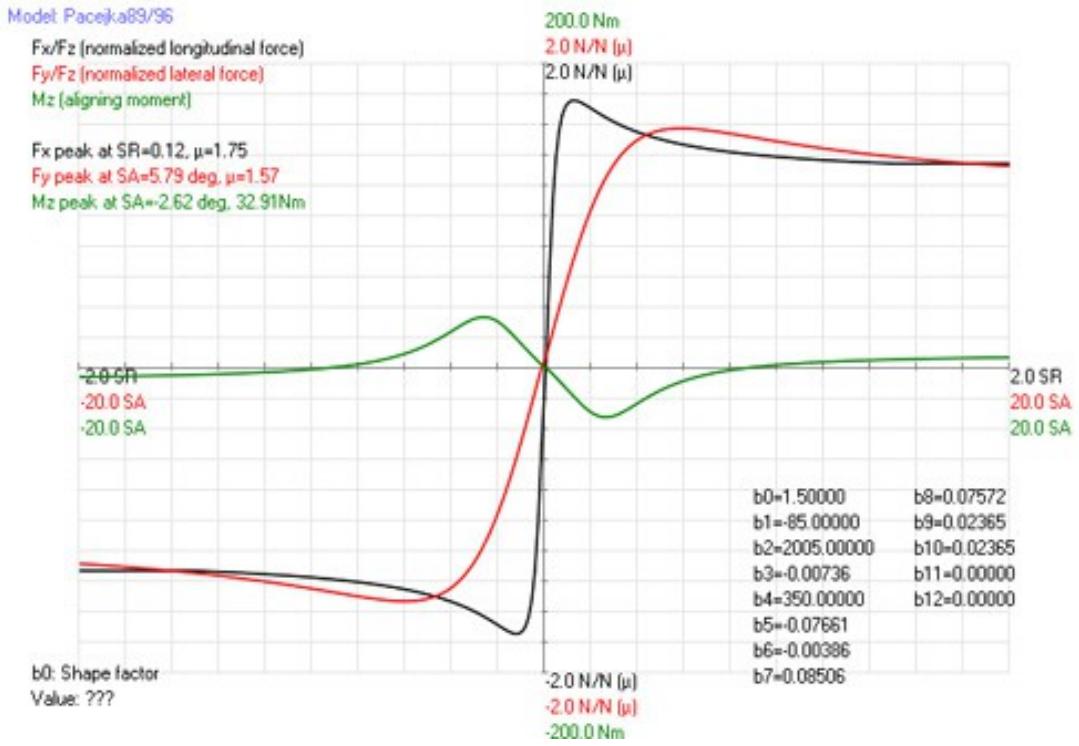


Figure 3.5.1a Typical Pacejka curves representing forces generated by tires.

Figure 3.5.1b shows the tire simulink model used in the vehicle model.

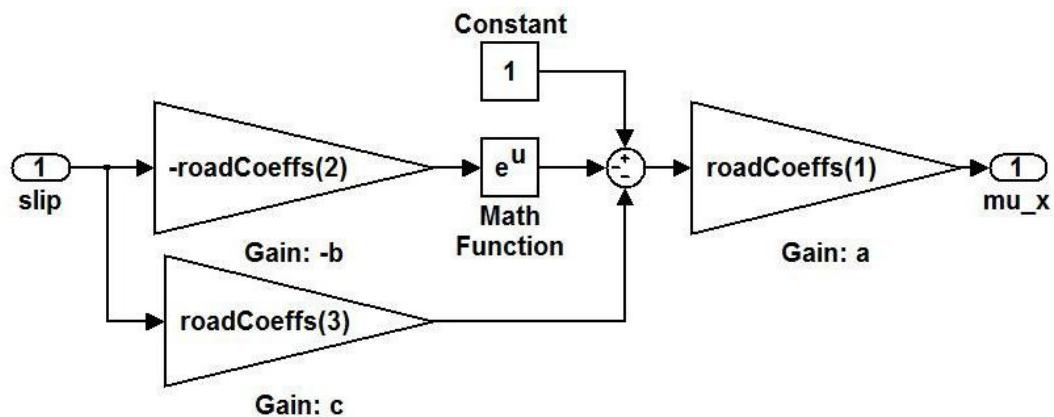


Figure 3.5.1b Tire model used in the vehicle simulation.

Figure 3.5.1c is a graph of frictional coefficient of road surfaces vs the wheel slip ratio. To obtain a fixed value of optimum slip we have to see the best compromise between the frictional coefficient between tire and road. From figure 3.5.1c we can clearly see that for almost all road surfaces, the optimum value of slip is close to 0.2. Thus our aim is to make the ABS controller wheel slip as close as possible to this target value to maximize the frictional coefficient.

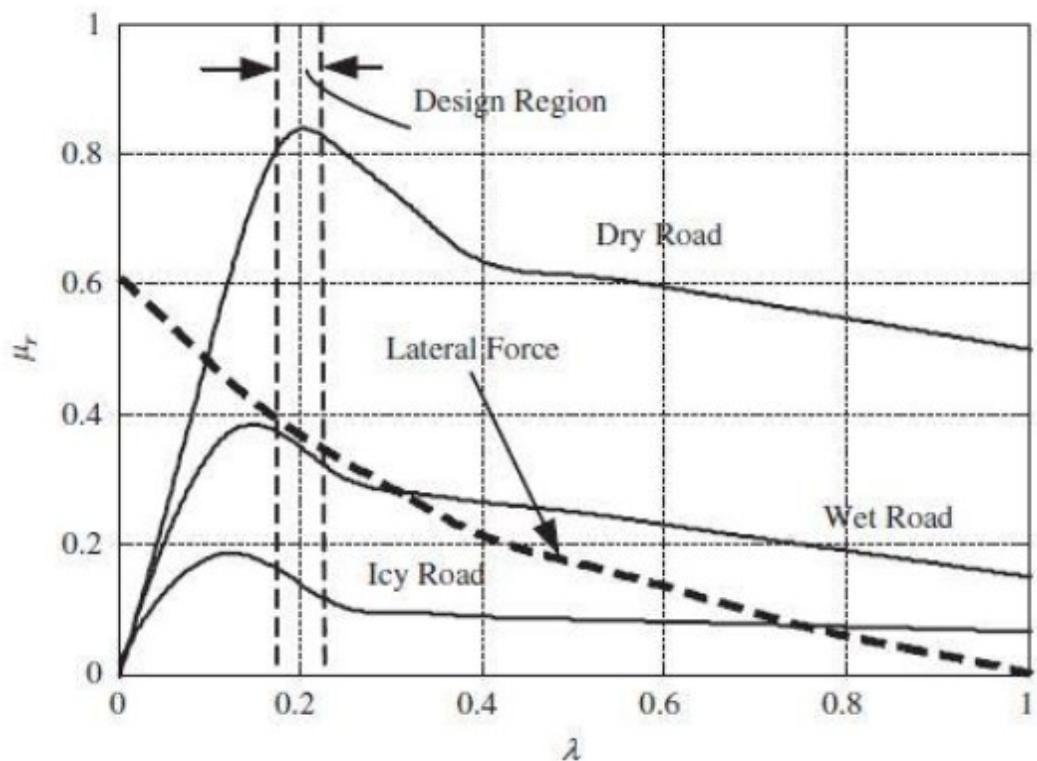


Figure 3.5.1c Frictional coefficient of road surfaces vs slip ratio

3.6 Closed Loop Feedback Control System

A closed loop feedback control system needs to be implemented to study the controlling action on the vehicle model. Figure 3.6.1a shows the block diagram of such a system

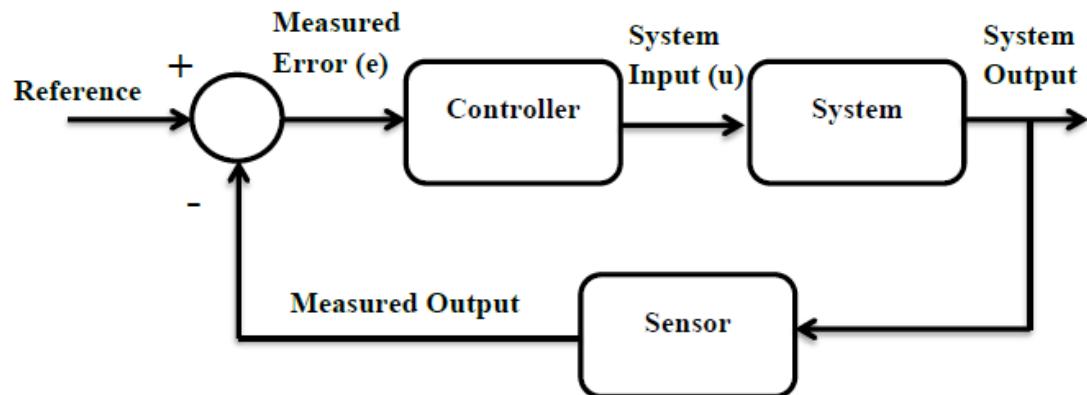


Figure 3.6.1a Closed loop feedback control system.

In our case, the output slip ratio is fed back into the controller where it compared with the fixed 0.2 value slip. This measured error is then fed as input to the controller.

The controller will then adjust the output accordingly to varying value of the measured error in slips. This output is the relative change in braking pressure.

Two controller models have been built and studied namely a PID controller and a fuzzy logic controller. The vehicle model along with these controllers is then individually simulated to see how the model behaves under a dry asphalt road condition when straight line braking is considered.

CHAPTER 4

PID CONTROLLER FOR THE SYSTEM

4.1 The PID Controller

The proportional-integral-derivative controller, commonly known as the PID controller is one of the most widely used controller schemes in the control system industry. Figure 4.1a shows the block diagram of a typical PID controller.

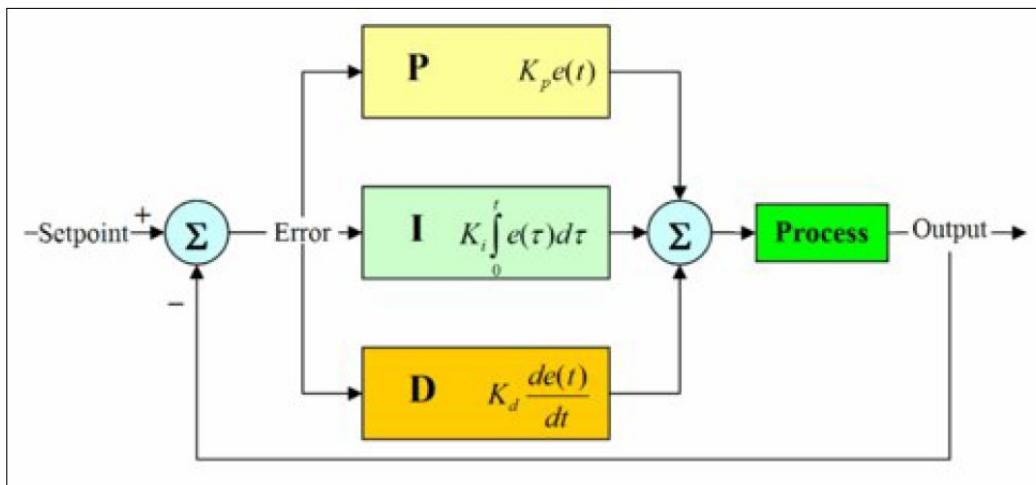


Figure 4.1a Block Diagram of PID Controller

“PID controllers are today found in almost all applications of process control and are an important aspect in the field of distributed control systems. They are widely used in automations systems, manufacturing, transportation, energy production etc” [24].

The control action in this type of controller is achieved by tuning the 3 constants in the algorithm. The values of these constants can be interpreted in terms of time where P would depend on the present error, I would depend on the accumulated past errors and D would be accounted on the basis of future errors. The prediction of these future errors is based on the present rate of change of error.

In our PID controller, the system input is the addition of error with constant gain K_p, integral of error with constant gain K_i and differential of error with constant gain K_d.

The system input u is given by :

$$u = K_p e + K_i \int e dt + K_d de/dt \quad (10)$$

“A proportional controller (K_p) has the effect of reducing the rise times. However, the proportional controller does not eliminate the steady state error. An integral controller (K_i) has the effect of eliminating the steady state error. However the use of the integral controller, on most occasions would cause the transient response to deteriorate. A derivative control (K_d) has the effect of increasing the stability of the system, reducing the overshoot and in turn improves the transient response as well” [24].

Figure 4.1b shows the effect of each controller on a closed loop system.

CL RESPONSE	RISE TIME	OVERSHOOT	SETTLING TIME	S-S ERROR
K _p	Decrease	Increase	Small Change	Decrease
K _i	Decrease	Increase	Increase	Eliminate
K _d	Small Change	Decrease	Decrease	Small Change

Figure 4.1b Effect of each controller on closed loop system.

Where

K_p = Proportional controller

K_i = Integral controller

K_d = Derivative controller

CL response = Closed loop response

S-S error = Steady state error.

In the PID controller used in this model the proportional gain $K_p = 1200$, integral gain $K_i = 10000$ and derivative gain $K_d = 3$. These values have been determined by manual tuning and using trial and error for different values.

Figure 4.1.c shows the block diagram of the PID type feedback control system.

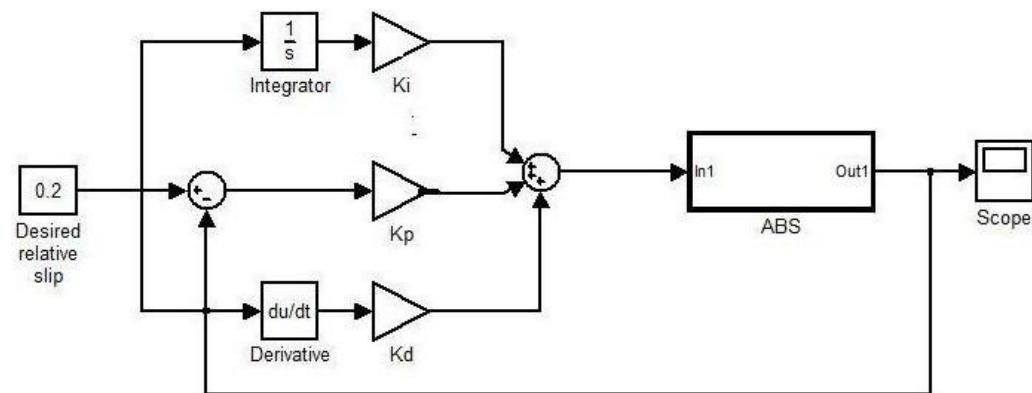


Figure 4.1c PID type feedback control system.

CHAPTER 5

FUZZY CONTROLLER FOR THE SYSTEM

5.1 The Fuzzy Controller

The control objective of the ABS controller is to maintain the wheel slip as close as possible to the fixed value. The fixed value of the slip has proven to provide optimal friction between tire and road surface under varying road conditions. The closer the slip is to the fixed value the better the control. Not only does it ensure a safe mode of operation, it also emphasizes on reduced stopping time and distance. Moreover a fuzzy controller can easily adapt to changing road conditions, traffic conditions, non linearity's in the vehicle system etc. Fuzzy controllers are based on rule bases and membership functions for their design aspect. They are effective because they consider grey areas of design aspects. Fuzzy controllers are more robust and easier to implement as compared to classical control schemes. This is the main reason why fuzzy controller schemes are implemented in artificial intelligence projects because they cover the grey area aspects of design.

5.2 The Fuzzy Inference System Design of the Controller

For the current project the fuzzy controller has two inputs, namely the error in slip, which is the actual slip minus the fixed slip ratio of 0.2, and the rate of change of this slip which is the deceleration of the vehicle. This deceleration of the vehicle changes with respect to time and is in sense real time simulated. The purpose of the controller is to maintain the vehicle slip as close as possible to the value of 0.2. From Chapter 3 we could see that the vehicle stability is maintained best when the actual calculated slip is maintained as close as possible to this desired value of 0.2. A set of

fuzzy rules were defined to get the vehicle to operate in the stable range when braking action took place. Figure 5.2a shows the fuzzy inference system for the vehicle model.

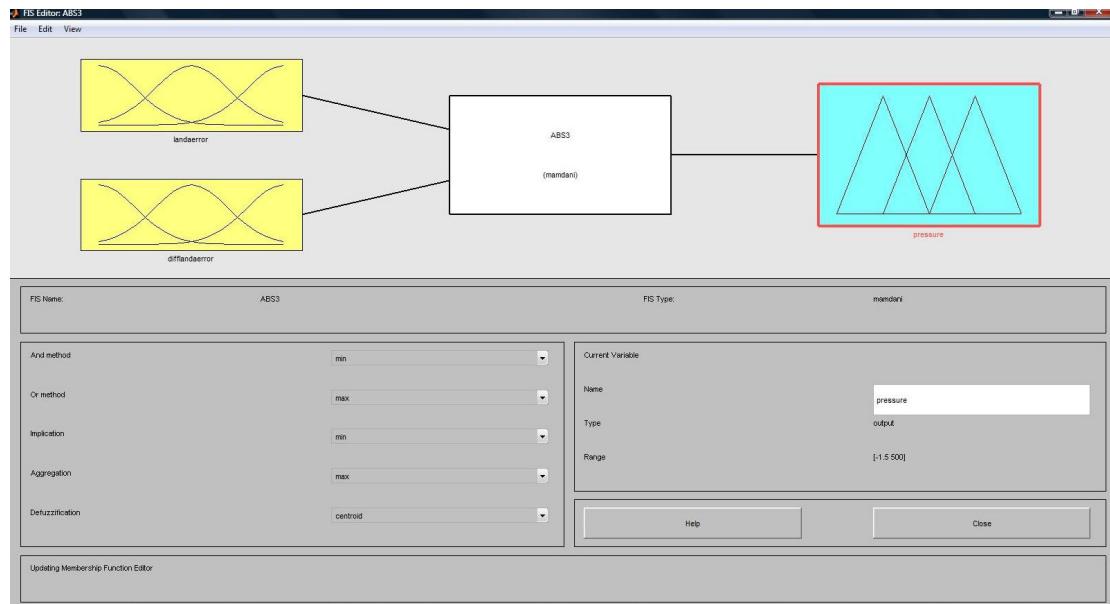


Figure 5.2a Fuzzy Inference System for vehicle model

Figure 5.2b shows the membership functions used for the input 1 which is the error in slip.

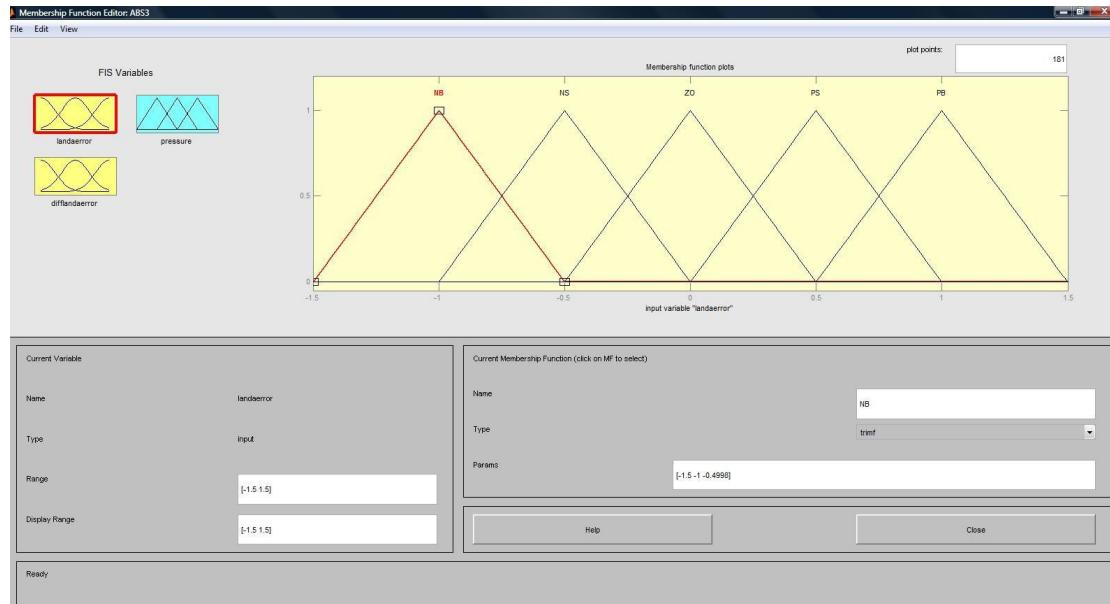


Figure 5.2b Input 1 for the fuzzy controller.

Figure 5.2c shows the Input 2 for the controller which is the rate of change of slip. It is the differential of the actual slip subtracted from the fixed slip vale of 0.2.

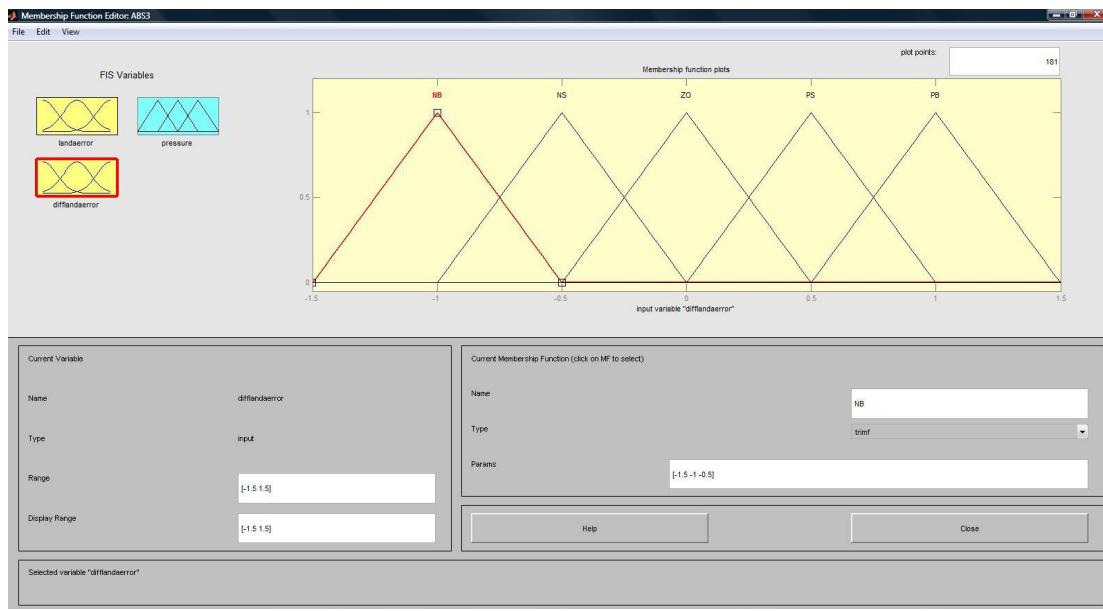


Figure 5.2c Input 2 for fuzzy controller.

Figure 5.2d is the output variable of the controller. The output in this case is the braking pressure. The braking pressure is what controls the slippage of the vehicle and ensures it for stability.

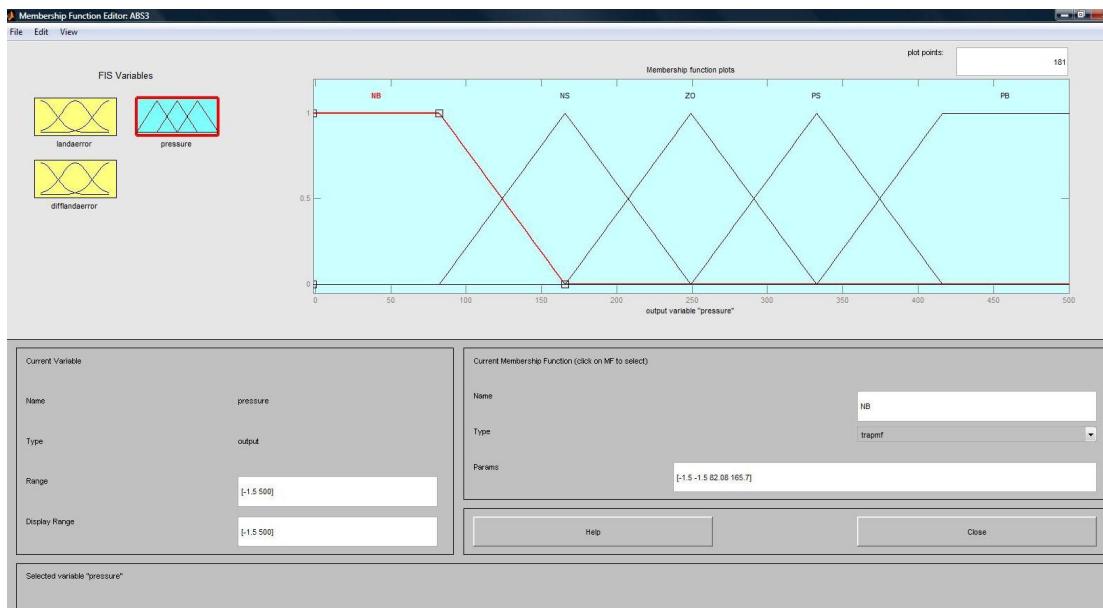


Figure 5.2d Output variable of fuzzy controller.

Note that the nomenclature used for the membership functions is as follows:

NB: Negative Big

NS: Negative Small

ZO: Zero

PB: Positive Big

PS: Positive small

The rule base:

There were two inputs used namely Slip Error and Rate of change of Error. The output of the controller is the braking pressure which varies with corresponding changes in inputs. Five states were considered while forming the rule base namely negative small (NS), negative big (NB), positive small (PS), positive big (PB) and zero(ZO). The rules for the fuzzy controller are as follows:

1. When Slip Error is PB and Rate of change of error is PB then pressure is NB.
2. When Slip Error is PB and Rate of change of error is PS then pressure is NB.
3. When Slip Error is PB and Rate of change of error is ZO then pressure is ZO.
4. When Slip Error is PB and Rate of change of error is NS then pressure is NS.
5. When Slip Error is PB and Rate of change of error is NB then pressure is NS.
6. When Slip Error is PS and Rate of change of error is PB then pressure is NB.
7. When Slip Error is PS and Rate of change of error is PS then pressure is NB.
8. When Slip Error is PS and Rate of change of error is ZO then pressure is NS.
9. When Slip Error is PS and Rate of change of error is NS then pressure is NS.
10. When Slip Error is PS and Rate of change of error is NB then pressure is NS.
11. When Slip Error is ZO and Rate of change of error is PB then pressure is NB.
12. When Slip Error is ZO and Rate of change of error is PS then pressure is NS.
13. When Slip Error is ZO and Rate of change of error is ZO then pressure is ZO.

14. When Slip Error is ZO and Rate of change of error is NS then pressure is ZO.
15. When Slip Error is ZO and Rate of change of error is NB then pressure is PS.
16. When Slip Error is NS and Rate of change of error is PB then pressure is NS.
17. When Slip Error is NS and Rate of change of error is PS then pressure is PS.
18. When Slip Error is NS and Rate of change of error is ZO then pressure is PS.
19. When Slip Error is NS and Rate of change of error is NS then pressure is PB.
20. When Slip Error is NS and Rate of change of error is NB then pressure is PB.
21. When Slip Error is NB and Rate of change of error is PB then pressure is ZO.
22. When Slip Error is NB and Rate of change of error is PS then pressure is PS.
23. When Slip Error is NB and Rate of change of error is ZO then pressure is PB.
24. When Slip Error is NB and Rate of change of error is NS then pressure is PB.
25. When Slip Error is NB and Rate of change of error is NB then pressure is PB.

Figure 5.2e represents the rule viewer with defuzzified output.

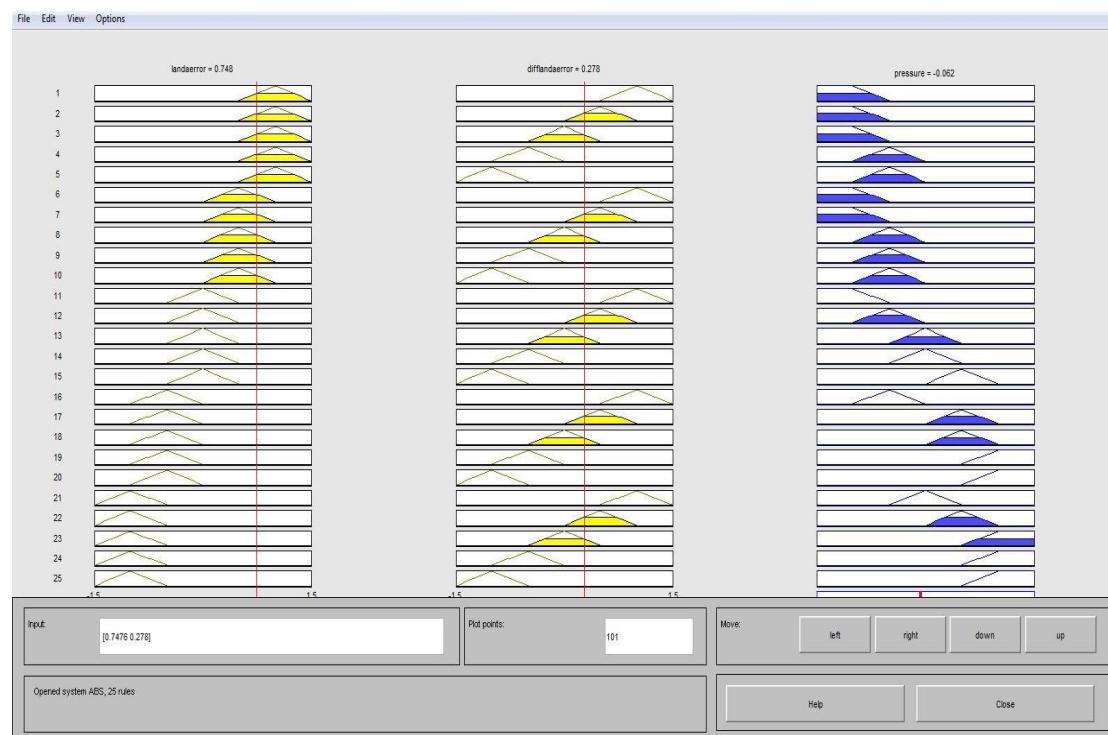


Figure 5.2e Rule viewer with crisp output

CHAPTER 6

NUMERICAL EXPERIMENT

The following parameters are used for the vehicle system

$g = 9.81$	Centre of gravity
$T_s = 0.005 \text{ s}$	Sampling rate of controller
$W_r = 0.32 \text{ m}$	Radius of Wheel
$V_0 = 40 \text{ Kmph}$	Initial velocity of vehicle
$m = 450 \text{ Kg}$	Quarter mass of vehicle

Maximum braking torque = 1200 Nm

The simulink model for the vehicle was described in detail in Chapter 3.

6.1 Vehicle model with PID Controller

Figure 6.1a shows the full vehicle simulink model with the PID controller

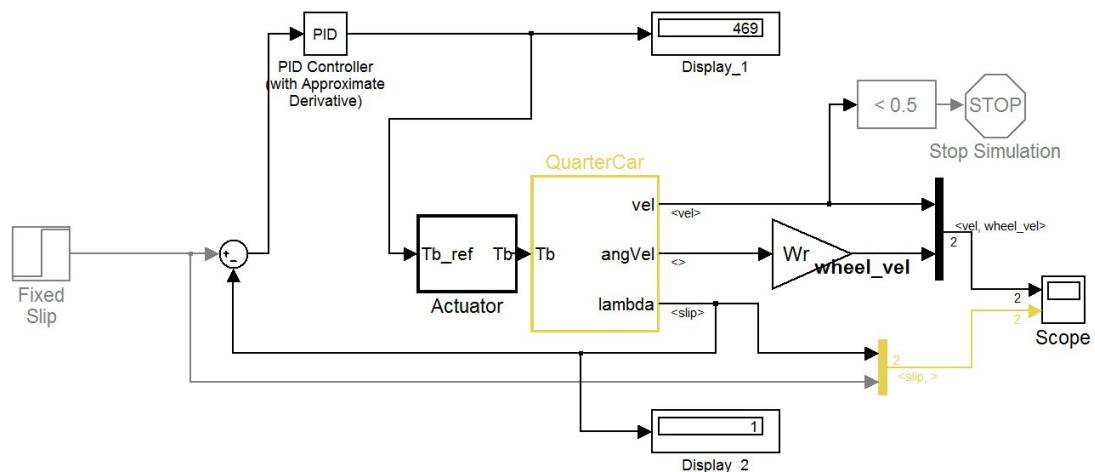


Figure 6.1a Vehicle simulink model with PID controller

Figure 6.1b shows the graph of the output for the vehicle when PID controller is used.

The graph is a measure of the deceleration of the vehicle after brakes have been applied. The yellow line marks the linear velocity of the vehicle while the pink line shows a measure of the wheel velocity of the vehicle.

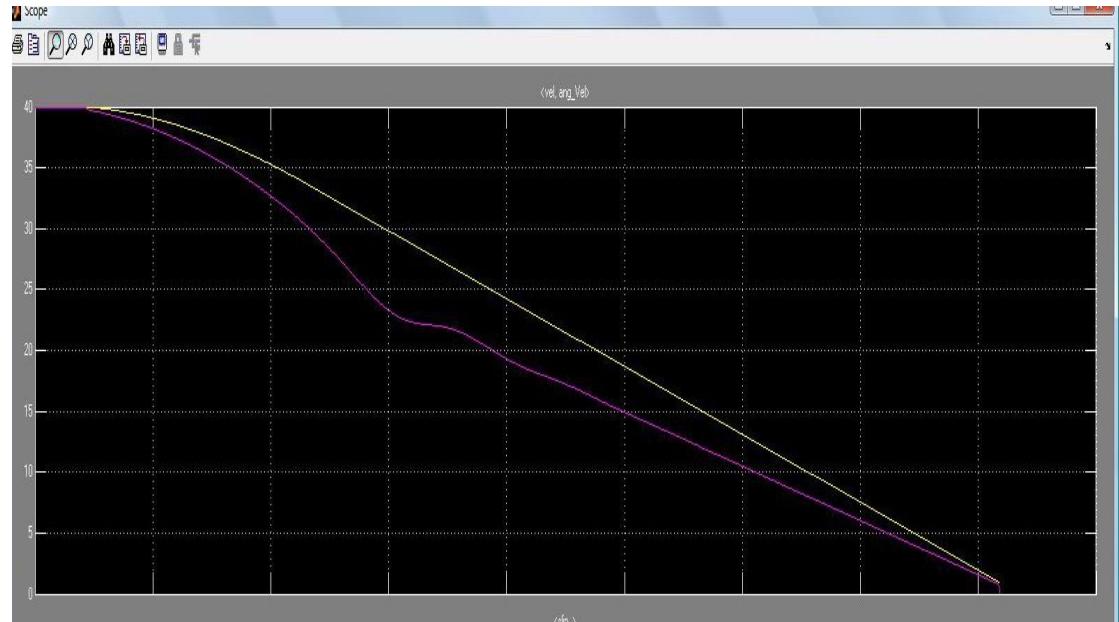


Figure 6.1b Vehicle deceleration for PID controller

From the above graph we can clearly observe that the vehicle comes to a halt after 4.1 seconds after brakes have been applied. When both the lines are the same there is no wheel slip. After $t = 0.2$ seconds a slip of 0.1 is demanded which is achieved by applying the brakes. The controller has the desired effect of tracking the desired slip at the required value of 0.1. However this is achieved after 0.2 seconds which is relatively a slow reaction considering the urgency and safety issues of the vehicle. Ideally there has to be a faster tracking.

Figure 6.1c gives the graph of the slip ratio of the vehicle in case of PID controller. In the figure the magenta line indicates the fixed or desired slip and the yellow line indicates the actual slip generated.

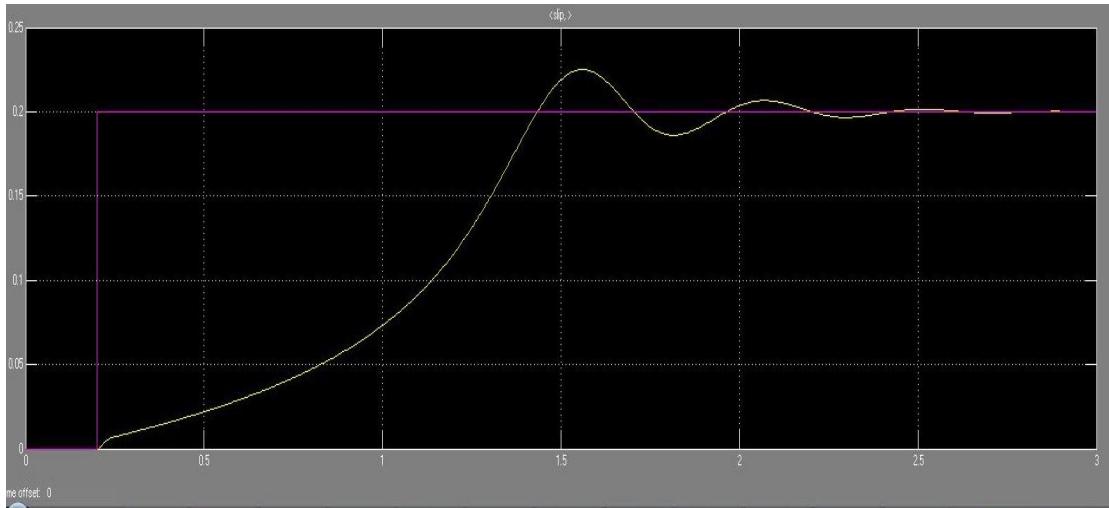


Figure 6.1c Slip ratio vs time for PID controller

From the figure 6.1c we can see the graph of the slip ratio vs time for the vehicle in case of PID controller. We can clearly see that the actual slip takes about 1.8 to 1.9 seconds before settling with the required fixed slip of the vehicle. Thus the settling time for wheel slip in case of PID controller is close to approximately 1.85 seconds.

6.2 Vehicle model with Fuzzy Controller

Figure 6.2a shows the vehicle simulink model with the fuzzy controller.

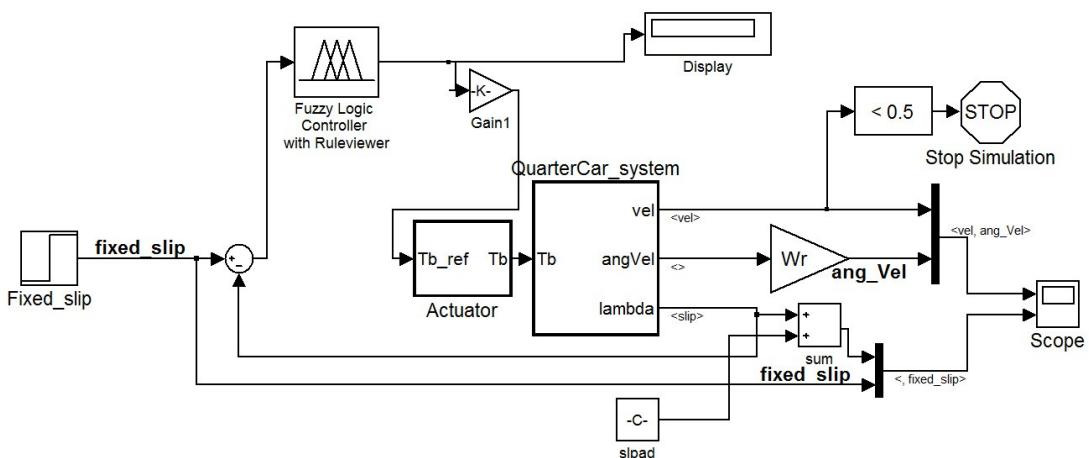


Figure 6.2a Vehicle simulink model with fuzzy controller

The fuzzy inference system used for the controller along with membership functions and rules used has been shown in the previous chapter.

Figure 6.2b shows the graph of the deceleration of the vehicle when Fuzzy Controller is used.

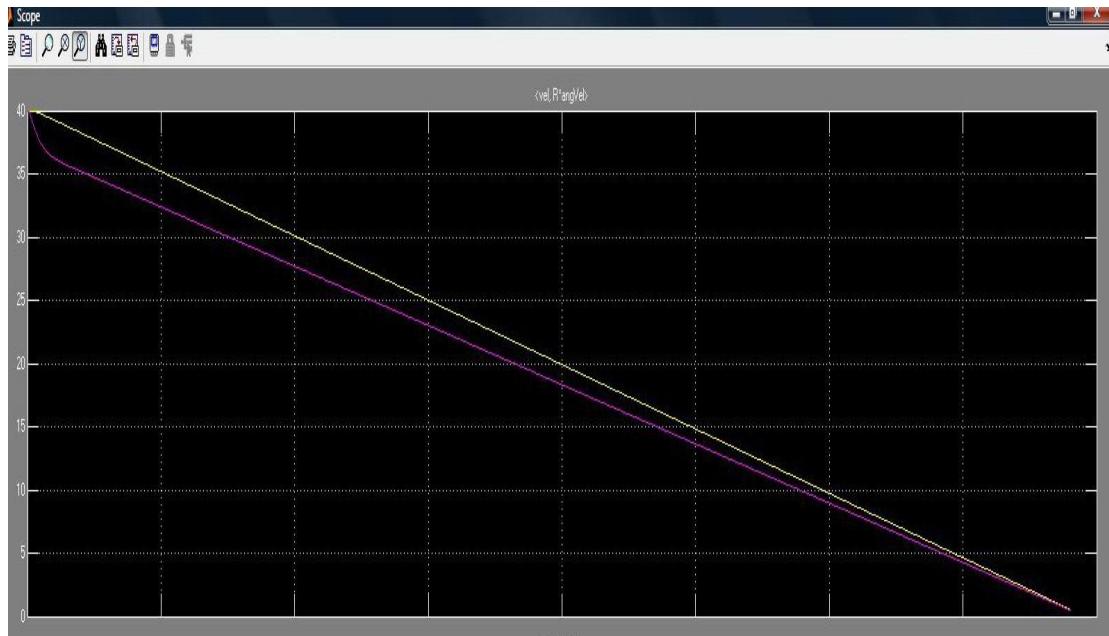


Figure 6.2b Vehicle deceleration for Fuzzy Controller

From the figure 6.2b we can clearly see that the vehicle comes to a halt after 3.85 seconds. The initial speed in both cases was considered to be 40 Km/hr or 11.1 m/s. By comparing figures 6.1b and 6.2b we observe that the fuzzy controller has better tracking as compared to the PID controller. The stopping time is also reduced by 0.25 seconds. More strikingly the tracking in case of the fuzzy controller is immediately provided at the instance of braking. When compared with that of the PID controller which takes 0.2 seconds for the same, the fuzzy controller reacts much faster to the

application of braking which clearly suggests it is a more stable approach with superior tracking capability.

Figure 6.2c shows the graph of the slip ratio vs time for the vehicle in case of fuzzy controller.

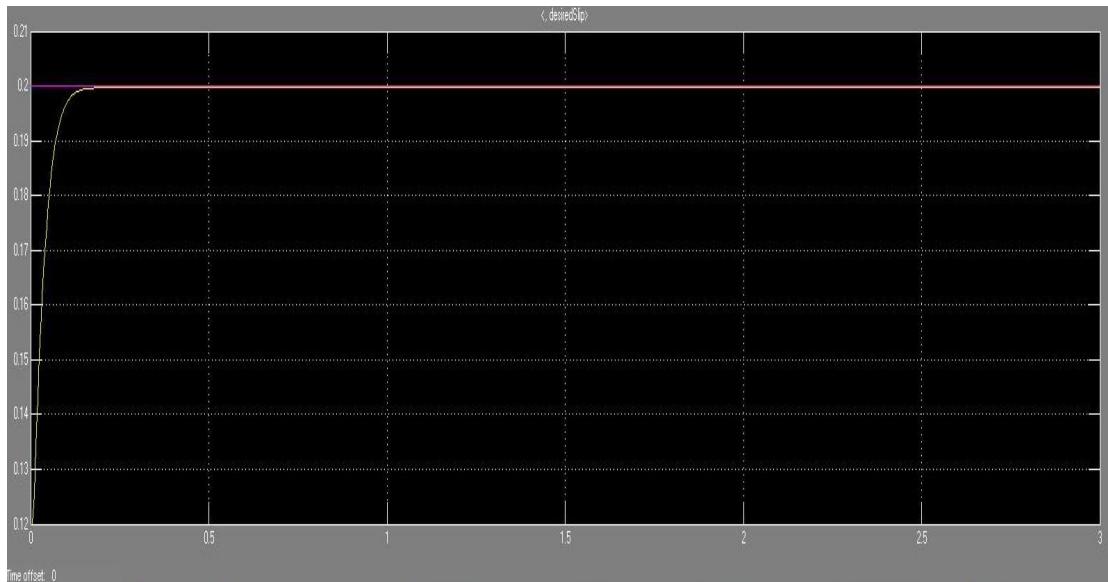


Figure 6.2c Slip ratio vs time in case of fuzzy controller.

From the graph of figure 6.2c we can see the curves for the desired wheel slip and actual wheel slip in case of the fuzzy controller. We can clearly see that in case of the fuzzy controller the settling time is approximately 0.25 seconds before it achieves the required slip.

Thus when compared to that of the PID controller we can clearly see that the settling time for fuzzy controller slip ratio is much less. Thus the system comes to stabilize quicker in case of the fuzzy logic based controller. Thus from the above comparisons, we can conclude that the fuzzy controller is more robust and a better control scheme when compared to the traditional PID control scheme.

CHAPTER 7

CONCLUSIONS

In this project an attempt has been made to understand the effects of using a linear and a non linear control scheme for designing an Anti Lock Braking System. For the linear control scheme the traditional Proportional Integral Derivative based controller was used and for the non linear scheme a simple Fuzzy Logic Controller was used. The system was modeled with simple quarter vehicle dynamics. A fixed wheel slip ratio was used as a criterion for the control work. This fixed ratio of 0.2 has been known to produce good results in ABS systems and the design region has been centered around the same value. From the simulations results it was observed that the fuzzy logic based control approach is a more robust approach. The stopping time was reduced by 0.25 seconds when compared to the PID control scheme at an initial longitudinal velocity of 40 Km/hr. Also the settling time for the wheel slip ratio was much less in case of the fuzzy controller. Thus it was observed that the fuzzy controller was a better control strategy as compared to the traditional PID based control scheme. The fuzzy based controller also showed superior tracking capacity when compared with the PID based controller scheme. It should be noted that the results were simulated under dry asphalt road conditions. It should also be noted that only longitudinal braking has been considered.

Under these specific conditions the fuzzy logic based controller has shown a better response and stability. In this present work a non linear vehicle model has been considered. The effectiveness of the fuzzy based controller may not be ideal in different road conditions or severe braking and turning conditions. A more intelligent approach is needed when studying these conditions. As a future scope of the work,

neural network systems or neuro-fuzzy systems may be employed for better control over varying road conditions. Also, real time implementation of the control logic is needed with an on board microcontroller mounted over a small scaled model of the vehicle system.

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APPENDIX

Quarter Car Vehicle Parameters

```
clear all  
close all  
clc  
disp('Loading parameters for QuarterCar.mdl');
```

$g = 9.81$; % gravity

% Controller parameters

$T_s = 0.005$; % Sample rate of discrete controller

$K_p = 1200$;

$K_i = 100000$;

$K_d = 0$;

$dPole = 1000$; % Pole of non-idealized derivative

% Vehicle parameters

$W_r = 0.32$; % wheel radius

$J = 1$; % wheel moment

$v_0 = 40$; % initial velocity

$m = 450$; % quarter car mass

$m_0 = m$; % Initial mass

% Pacejka model for dry asphalt 11.1 m/s

roadCoeffs = [1.2801 23.99 0.52];

% Actuator parameters

actuatorPole = 70;

actuatorSat = 4000;

actuatorDelay = 0.005;

% Reference signal

lambda_ref = 1.5;