

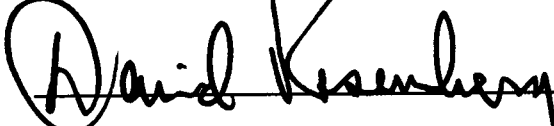
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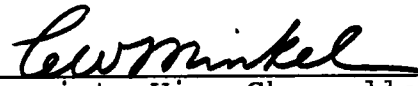
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VEHICLE STEERING ASSISTANCE IN EXTREME SITUATIONS USING A
FUZZY LOGIC CONTROLLER

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Gary Lindsay Brown

May 1994

DEDICATION

This thesis is dedicated to my loving wife,
Stephanie Raco-Brown,
whose inspiration and patience are sewn within each page.

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ABSTRACT

An innovative approach to vehicle control is presented which utilizes a relatively new control technique based upon fuzzy set theory. Within this paper, a Fuzzy Logic Controller (FLC) is developed which when combined with front and rear independent steering (FRIS) provides the driver greater control of his vehicle by minimizing undesirable spin caused by icy road conditions.

This study first develops a nonlinear mathematical model of a rubber tired vehicle which employs FRIS. The model is simulated using road-tire slip disturbances which mimic icy road conditions in order to observe the vehicle's dynamic characteristics. A FLC is then developed which monitors the vehicle's yaw rate error (spin) and road-tire slip ratios. Based on these two inputs, the FLC computes both a front and rear steering compensation angle. These compensation angles are summed with the driver's requested steering angle and fed to the vehicles steering mechanism.

With the FLC integrated into the mathematical vehicle model, simulations are again performed. Simulation results show that vehicle spin is considerably reduced with the FLC as compared to the uncompensated vehicle. The results further support the use of FRIS to enhance driver's safety while also re-enforcing FLC methods as an effective control technique.

TABLE OF CONTENTS

SECTION	PAGE
1. INTRODUCTION	1
2. AN INTRODUCTION TO FUZZY CONTROL THEORY	5
3. MATHEMATICAL MODEL FOR VEHICLE STEERING CONTROL	16
4. FUZZY LOGIC CONTROLLER DESIGN	34
5. SIMULATION OF A FLC BASED STEERING SYSTEM	47
6. CONCLUSION	54
LIST OF REFERENCES	56
APPENDIXES	60
APPENDIX A. PROGRAM LISTING OF VEHICLE MODEL	61
APPENDIX B. PROGRAM LISTINGS OF FUZZY LOGIC CONTROLLER	97
APPENDIX C. LIST OF ABBREVIATIONS	102
VITA	104

LIST OF TABLES

TABLE	PAGE
3-1. Vehicle's Nomenclature.	19
3-2. Nominal parameters for simulations.	26
3-3. Simulation scenario descriptions.	28
4-1. Summary of required sensor inputs.	37
4-2. Matrix representation of the rule set for front steering compensation.	43
4-3. Matrix representation of the rule set for rear steering compensation.	43

LIST OF FIGURES

FIGURE	PAGE
2-1. Fuzzy set terminology.	8
2-2. Basic structure of a fuzzy logic controller. . . .	11
2-3. SUP-MIN composition principle.	13
2-4. An iterative approach in the development of a fuzzy logic controller.	15
3-1. Schematic of the vehicle.	18
3-2. Road-tire friction coefficient as a function of wheel slip ratio.	22
3-3. Scenario 1 simulation without controller.	29
3-4. Scenario 2 simulation without controller.	30
3-5. Scenario 3 simulation without controller.	31
3-6. Scenario 4 simulation without controller.	32
4-1. Block diagram of a system using a FLC.	38
4-2. Yaw rate error's membership function.	40
4-3. Front and rear slip membership functions.	41
4-4. Front and rear steering compensation membership functions.	45
5-1. Scenario 1 simulation with the FLC.	48
5-2. Scenario 2 simulation with the FLC.	49
5-3. Scenario 3 simulation with the FLC.	50
5-4. Scenario 4 simulation with the FLC.	51

1. INTRODUCTION

As a branch of the Intelligent Vehicle-Highway Systems (IVHS) alliance, the Advance Vehicle Control Systems (AVCS) is encouraging research and development in the area of in-vehicle safety systems. Examples of such systems include 1) perceptual enhancements such as infrared imaging, head-up display, and advanced technology headlights; 2) collision avoidance instructions by means of obstacle detection, blind spot monitoring and driver vigilance behavior; and 3) enhanced vehicle control which includes variable assist steering, automatic braking and lane tracking control [22]. Although the first two systems provide a greater awareness of threatening situations they still put the responsibility of any evasive maneuvers with the driver and therefore are subject to error. The third promotes a more autonomous system integrated within the vehicle which minimizes driver interaction in threatening situations while increasing safety. An autonomous approach is preferable over visual or audio systems due to the fact that the possibility of human error or misjudgment is minimized. This paper examines one aspect of autonomous vehicle control enhancements through steering compensation in order to minimize the chances of collisions when presented extremely hazardous road conditions.

Many papers have examined autonomous steering of vehicles

[1], [2], [5], [8], [9], [19], [23], [24], [25], [26]. Most of these papers develop autonomous steering control which ensures the vehicle tracks the center of the road lane. These studies typically assume the vehicle employs a sensor which tracks external road markers to minimize lateral position and yaw rate deviations. The primary goal of these systems is to eliminate any need for human steering control provided the road and vehicle employ an integrated tracking controller. These studies typically assume the vehicle is controlled through conventional front wheel steering.

Unlike the fully autonomous steering control studies referenced above, this paper will develop a controller which will provide steering assistance to the driver when presented situations which generally increase the risk of collision. For example, when a driver is entering a turn where the road is slick the vehicle may start to spin out of control due to the lack of traction between the road and tires. The driver in this situation typically attempts to steer his vehicle such that spin is minimized while achieving maximum traction. With vehicles today, whether the driver is successful in gaining control of the vehicle is solely dependent upon his skill and reaction time.

This paper presents an innovative approach to minimizing vehicle spin in threatening situations by developing a steering control system which independently controls both front and rear tires. Front and rear independent steering

of a vehicle is relatively new [6], [10]. One particular study has shown favorable results with a system which controlled front and rear independent steering on a mathematical modeled vehicle [19]. However, this study used relatively innocuous environmental disturbances and assumed the vehicle to autonomously track external road guides. The system developed in this paper will not totally eliminate the driver's steering control nor will the system depend upon external tracking sensors. The controller will specifically be designed to ensure vehicle control is maintained when subjected to road-tire disturbances which simulate extreme icy road conditions.

In order to eliminate the necessity for external road guides or beacons, the controller will continuously calculate the drivers desired yaw rate by monitoring his steering wheel angle. The vehicle's actual yaw rate will be sensed by an angular velocity sensor. Yaw rate error (vehicle spin) is then calculated by taking the difference between the desired yaw rate and the actual yaw rate of the vehicle. The controller will minimize undesirable vehicle spin by independently controlling both front and rear steering angles of the vehicle. Front and rear steering compensation will only occur when the controller detects a difference between the driver's requested yaw rate and the vehicle's actual yaw rate.

One of the primary problems with the development of

vehicle steering controllers is that vehicle dynamics are highly nonlinear making designs difficult [21]. Although there have been successful controllers designed based on feedback feedforward techniques using a linearized model of the vehicle [19], these controllers generally have limitations when subjected to all possible road conditions and environments. There exists a relatively new technique in controller design which does not necessitate an exact model of the vehicle or require assumptions concerning system dynamics. This relatively new procedure takes advantage of fuzzy set theory in order to develop what's referred to as a fuzzy logic controller. The controller in this study is developed using fuzzy logic techniques.

This paper is divided into 6 Sections. Section 2 will introduce the concepts of fuzzy set theory as it pertains to the development of a fuzzy logic controller. A nonlinear model of the vehicle dynamics is presented in Section 3. The model is simulated without a controller under extreme road-tire conditions to establish the necessary fuzzy logic control variables which will minimize the vehicles spin. Section 4 develops a fuzzy logic controller. The controller is integrated into the vehicle's model. Simulation results of the vehicle with and without the controller are illustrated in Section 5. Conclusions are presented in Section 6.

2. AN INTRODUCTION TO FUZZY CONTROL THEORY

The application of fuzzy set theory for the implementation of fuzzy logic controllers (FLCs) is growing rapidly. One of the first applications of fuzzy set theory to the control problem was presented in a paper by Mamdani [18]. Since then several papers have shown exceptional results when fuzzy logic was used to control a given plant. For instance, when fuzzy control methods were compared to proportional-integral-derivative (PID) controllers, fuzzy controllers perform equivalently if not better when evaluating steady state error, settling time and response time [13]. Lin and Sheu [16] demonstrated that the combination of a FLC with conventional linear state feedback-control enhanced performance in a nonlinear system.

FLC is based from fuzzy set theory which was first introduced by Zadeh in 1965 [27]. Since its introduction, fuzzy set theory has gone through substantial theoretical development and correspondingly been applied to numerous applications. Maier and Sherif [17] tabulated some of the applications where fuzzy set theory is presently being applied.

Fuzzy set theory is based on a recognition that certain sets or subsets have imprecise boundaries. Unlike the usual set theory which defines an item as either a member or not a member of a set (i.e., $u \in X$ or $u \notin X$), fuzzy set theory

supports membership descriptions when sets are not always so well defined. Maier and Sherif state [17], "Fuzzy sets or subsets are those ill-specified and non-distinct collections of objects with un-sharp boundaries in which the transition from membership to non membership in a subset of a reference set is gradual rather than abrupt".

Since fuzzy set theory is relatively new to most engineering disciplines a brief description of basic fuzzy set terminology and operators follow. More formal descriptions of fuzzy set theory are described in [11], [12], [17], [27] and as it applies to fuzzy control in [4], [7], [14], [15].

Fuzzy Set Terminology

Universe of discourse is defined as all the possible values that a variable can assume. If U is a collection of objects denoted by $\{u\}$, U is called the universe of discourse and u represents an element of U .

A fuzzy set is characterized by a membership function $\mu(u)$ which takes values in the interval $[0,1]$. A fuzzy set X of a universe of discourse U is defined as a mapping $\mu_x(u): U \rightarrow [0,1]$. A fuzzy set may be viewed as a generalization of an ordinary set whose membership function only takes two values $\{0,1\}$. For example, given a membership value $\mu_x(u) = 0.5$ implies that u is a member of X to a degree of 0.5 where zero represents a null membership and one is a complete membership. When the universe of

discourse U is continuous a fuzzy set X can be expressed as

$$X = \int_U \mu_X(u) / u. \quad (2.1)$$

If U is discrete, then fuzzy set X is represented as

$$X = \sum_{i=1}^n \mu_X(u_i) / u_i. \quad (2.2)$$

Support of a fuzzy set is described as the crisp set of all points u in U such that $\mu(u) > 0$.

The crossover point is defined as the element u in U at which $\mu(u) = 0.5$. A fuzzy singleton is a fuzzy set whose support is a single point in U such that $\mu(u) = 1.0$. Figure 2-1 illustrates some of the fuzzy set terminology.

Fuzzy Set Operators

If X and Y are two fuzzy sets in U with membership functions μ_X and μ_Y , respectively, the following basic operators are described.

Union: The union of fuzzy sets X and Y is represented by $X \cup Y$ or $X + Y$ whose pointwise membership function $\mu_{X \cup Y}$ is described as

$$\mu_{X \cup Y}(u) = \max[\mu_X(u), \mu_Y(u)] \quad \text{for all } u \in U. \quad (2.3)$$

Intersection: The intersection of fuzzy sets X and Y is denoted by $X \cap Y$ or $X.Y$ whose pointwise membership function $\mu_{X \cap Y}$ is described as

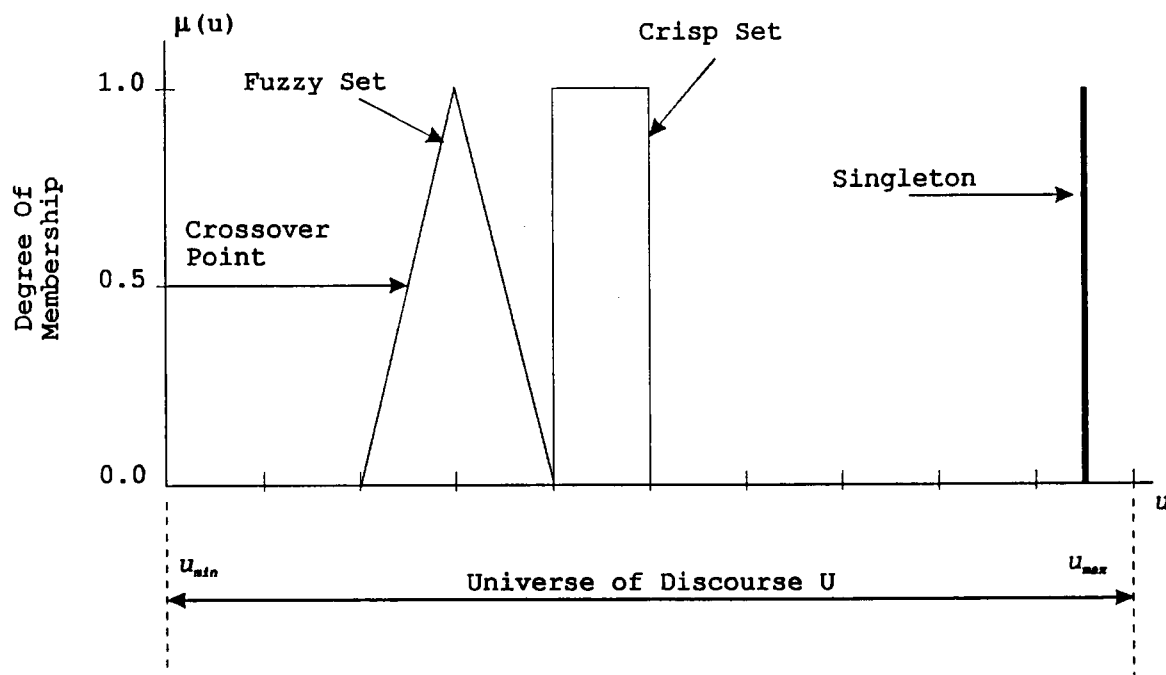


Figure 2-1. Fuzzy set terminology.

$$\mu_{X \cap Y}(u) = \min[\mu_X(u), \mu_Y(u)] \quad \text{for all } u \in U. \quad (2.4)$$

Complement: The complement of fuzzy set X is denoted by $\bar{X}$ or ΓX whose pointwise membership function $\mu_{\bar{X}}$ is describe by

$$\mu_{\bar{X}}(u) = 1 - \mu_X(u) \quad \text{for all } u \in U. \quad (2.5)$$

Some distinctions between fuzzy set theory and probability theory should be clarified. The primary difference between the two theories is probability deals with randomness of future events, whereas fuzzy set theory deals with the imprecision of current or past events. As stated by Maiers and Sherif [17], "Randomness deals with the uncertainty regarding the occurrence or nonoccurrence of some event, while the imprecision of fuzzy sets deals with the membership or nonmembership of an object in a set with imprecise boundaries". Although both disciplines address uncertainties, fuzzy theory deals with the uncertainty resulting from boundary conditions. Probability theory addresses the uncertainty that results from random behavior which generally dissipates with increasing information.

The advantages of applying fuzzy set theory to a control problem stems from the ability of developing a controller in a way as to mimic logical human thought. The FLC process assigns linguistic variables, similar to human expression, which facilitate imprecise boundaries of a subset. In essence, the FLC provides an algorithm which can convert the

linguistic control strategy based on expert knowledge into an automatic control strategy.

There are four principle components within a FLC. They are 1) the fuzzification interface; 2) knowledge base; 3) decision making logic; and 4) defuzzification interface. The basic structure of a FLC system is illustrated in Figure 2-2.

The fuzzification interface converts 'crisp' input data into linguistic values which are labels of fuzzy sets. This process requires measuring the values of the inputs, normalizing the inputs over the universe of discourse and applying the corresponding linguistic label.

The knowledge base consists of a data base and a linguistic control rule base. The data base provides the definitions of the linguistic control rules while the rule base characterizes the control policy in linguistic control terms. A fuzzy rule is typically written with the following structure

*IF x is Negative_Large (NL) AND y is Positive_Large (PL)
THEN u is Negative_medium_large (NML)*

where x and y are fuzzy input variables and u is the fuzzy output variable. NL, PL and NML are linguistic values which describe fuzzy subsets in the universe of discourse X, Y and U, respectively.

The decision making logic simulates human reasoning based on fuzzy concepts and fuzzy control actions. This procedure

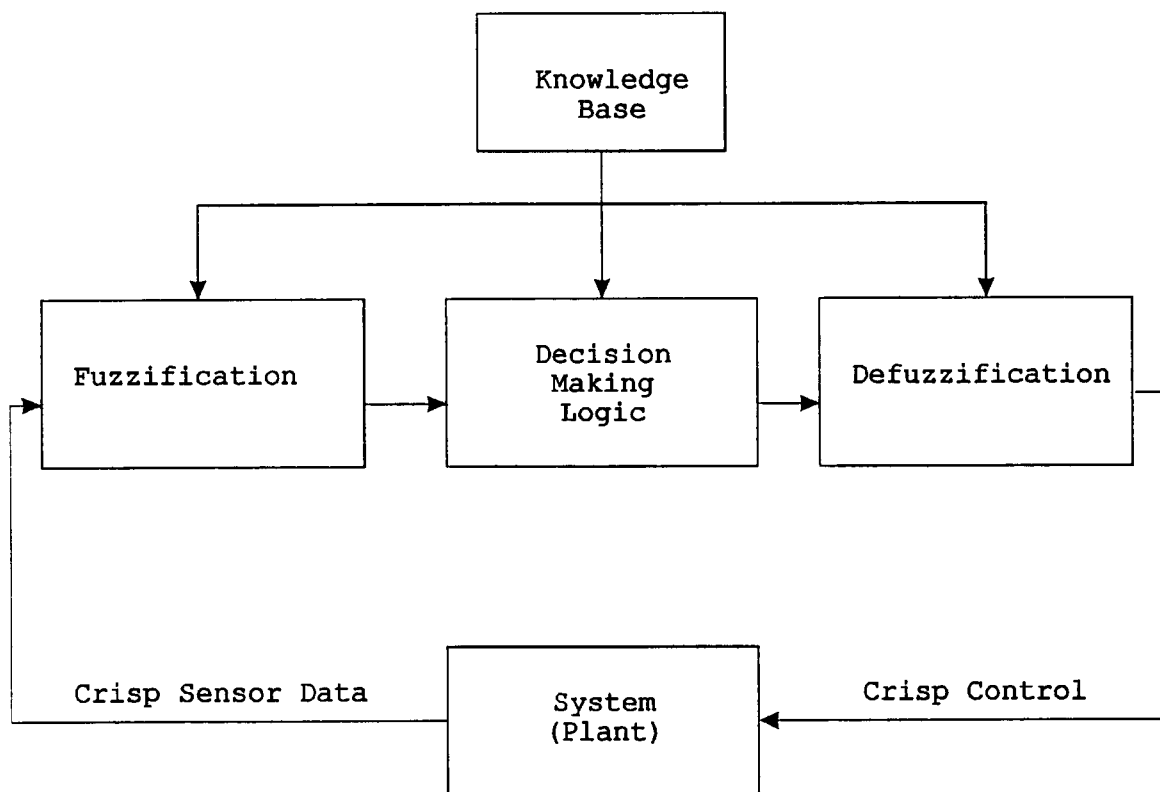


Figure 2-2. *Basic structure of a fuzzy logic controller.*

is often referred to as the inference process or fuzzy composition principle. Although several composition principles exist, the one used in most FLC systems today is known as the SUP-MIN. Figure 2-3 illustrates the SUP-MIN principle using two stated rules.

The defuzzification process converts the fuzzy output variable into a crisp control action. Typically, the defuzzification process is performed by either the center-of-gravity or the height methods. The center-of-gravity, otherwise known as the centroid method, selects the crisp output value by calculating the center of gravity of the output membership function. The centroid defuzzification method is expressed as

$$U_{crisp} = \frac{\int_U u \cdot \mu(u) du}{\int_U \mu(u) du} . \quad (2.6)$$

For the height method, each output membership function for each rule is evaluated. The crisp output is then calculated by taking the average of the individual centroids weighted by their heights. The height defuzzification process is expressed as

$$U_{crisp} = \frac{\sum_{i=1}^n u_i \cdot \mu(u_i)}{\sum_{i=1}^n \mu(u_i)} . \quad (2.7)$$

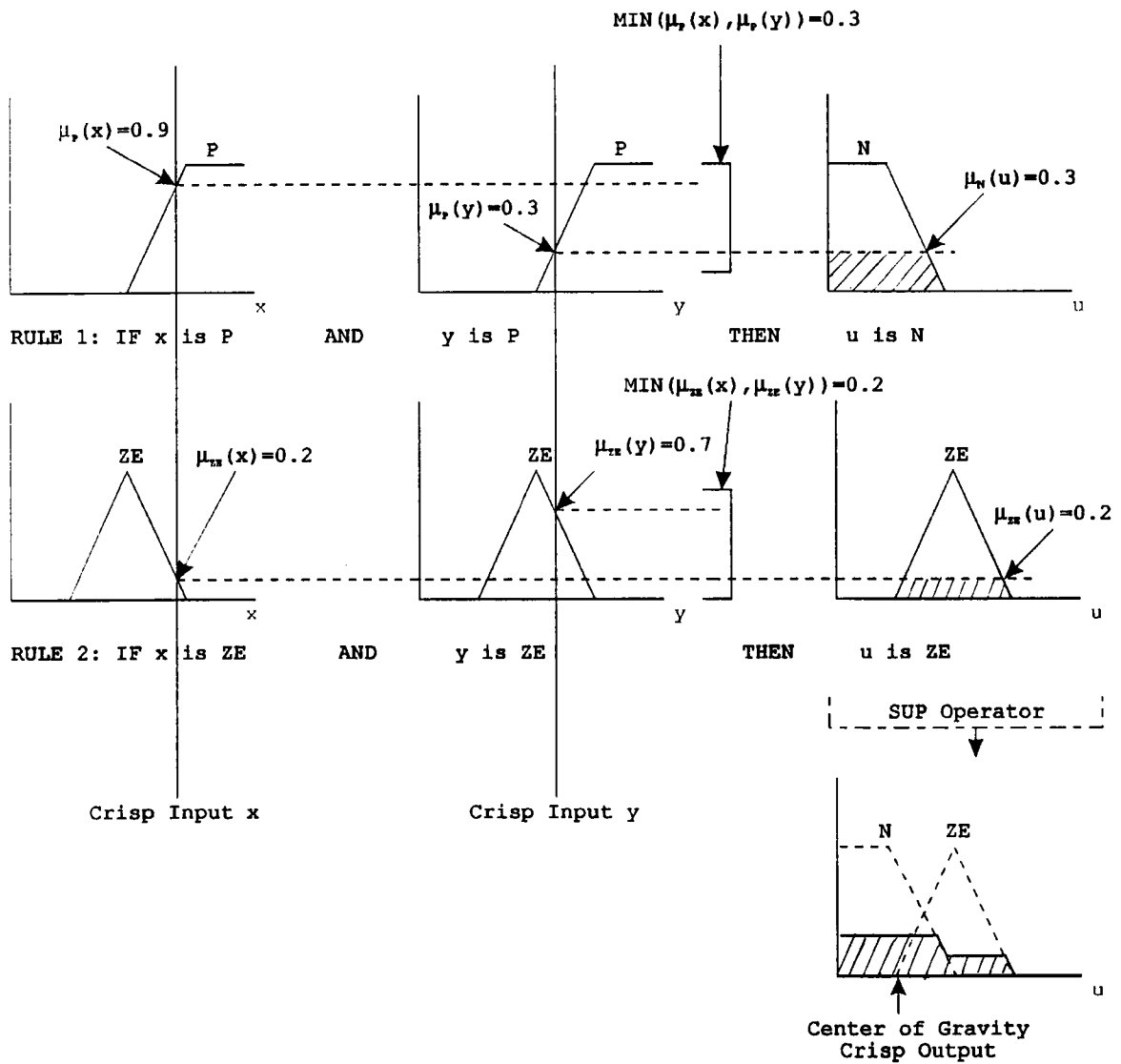


Figure 2-3. SUP-MIN composition principle.

Although FLC techniques are gaining more respect, there are some drawbacks. Unlike conventional control methods (i.e., Bode, Root-locus), there is no formal procedure for the design and analysis of the fuzzy control system. As Figure 2-4 illustrates, the most efficient means of developing a fuzzy logic controller involves an iterative design approach where the rule-base and/or membership functions are adjusted until an optimal response is obtained. There must also be an expert which can describe linguistically the control rules which will govern the inference process. This expert typically is a human which inherently is subject to error or lacks the necessary experience to adequately describe a complete rule base.

For the engineer, the question whether fuzzy logic is an adaptable technique to his given control problem is somewhat subjective. As stated in [3], [14], [16], there are situations when FLC techniques are extremely beneficial. To summarize, FLCs are often superior to conventional control approaches when the system is highly nonlinear, the control mechanism can accurately be described in linguistic terms or if the system is difficult or impossible to define.

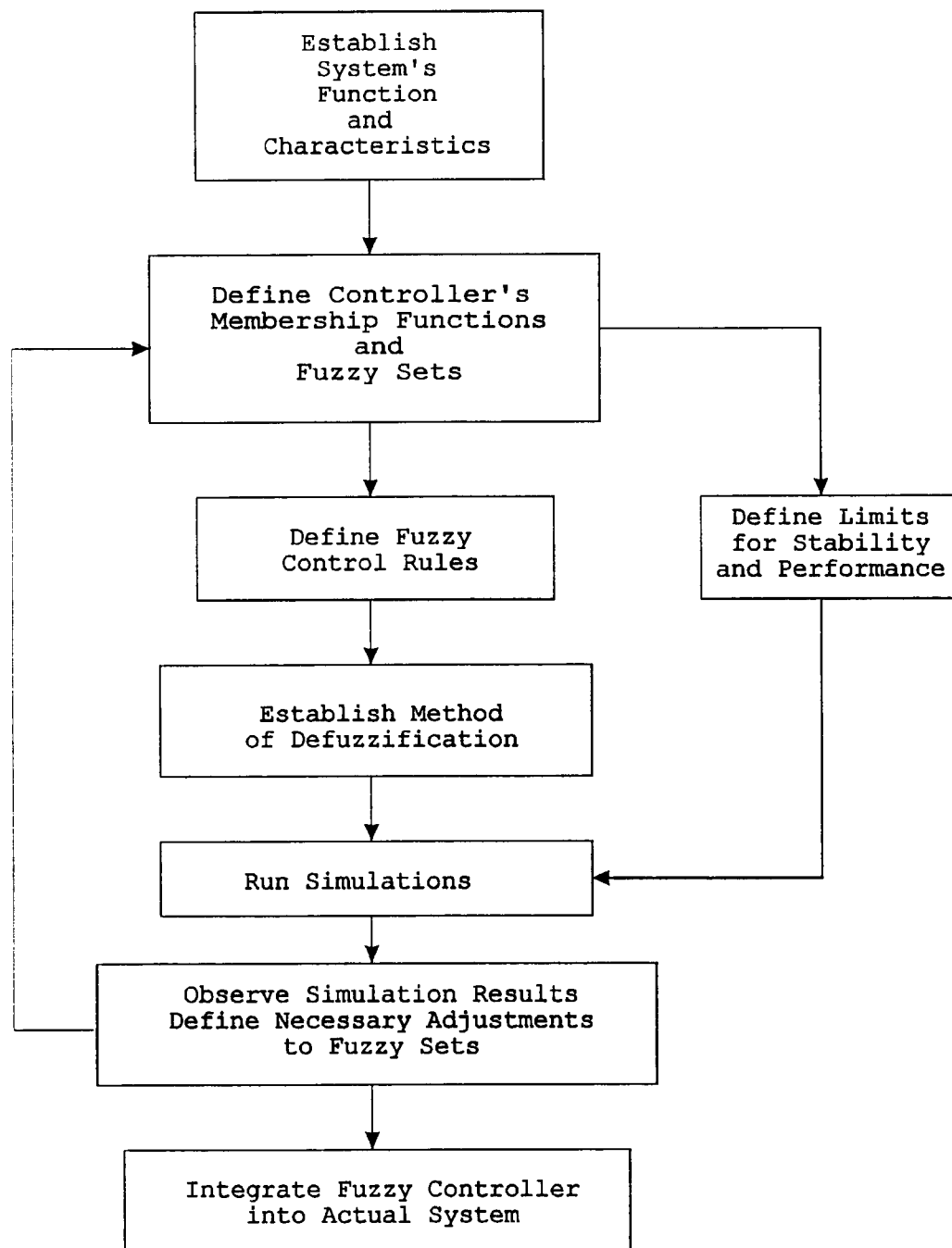


Figure 2-4. *An iterative approach in the development of a fuzzy logic controller.*

3. MATHEMATICAL MODEL FOR VEHICLE STEERING CONTROL

Rigorous mathematical models have been developed which predict the nonlinear dynamic characteristics of rubber-tired vehicles [19], [23], [25]. Past developments range in complexity from an eleven-degree-of-freedom (11-DOF) [20] to simple 2-DOF models [1], [24]. As Shladover et al. [26] explains, less complex models are adequate when studying the vehicles handling characteristics when the importance of roll steer is not a concern, however, a complete model of the dynamics should be used when evaluating the performance of a controller in a system.

Past automated steering control studies have typically used a nonlinear 3-DOF model for controller development [1], [19], [24], [25], [26]. The 3-DOF model is first linearized in order to design a controller using conventional techniques. The controllers performance is then evaluated using the more complex nonlinear model. This procedure works well for systems which are not greatly affected by the linearized assumptions.

In this section, a nonlinear 3-DOF vehicle model is developed. The model is similar to the one presented by Matsumoto and Tomizuka [19] with slight modifications. Modifications to their nonlinear mathematical model were necessary in order to develop a controller which responds to wheel slip ratios and yaw rate errors. Specifically, the

model developed in this study uses a look-up table which relates wheel slip ratios to road-tire friction coefficients in order to calculate the vehicle's lateral and longitudinal tire force. Matsumoto and Tomizuka established a relationship between each wheel's cornering stiffness and wheel slip angle in order to calculate the vehicle's lateral and longitudinal tire force. The cornering stiffness factor was estimated by a recursive least squares algorithm. The look-up table presented in this paper avoided complicated estimations while ensuring the nonlinear relationship between wheel slip ratios and tire forces were accurately modeled.

Since simulations will subject the vehicle with disturbances which mimic icy road conditions, steering angle, wheel slip angle and vehicle slip angle variances will significantly affect the vehicle's dynamics. In previous vehicle steering control studies [19], [24], [25], [26], these variances are assumed to be small allowing the controller to be developed around a linearized vehicle model. A linearized model is unnecessary in this study since fuzzy logic techniques will be used to develop a controller.

Figure 3-1 provides an illustration of the forces acting on the vehicle's dynamics. The mathematical model of the vehicle will be subjected to selected hazardous road conditions where the driver's steering maneuvers and

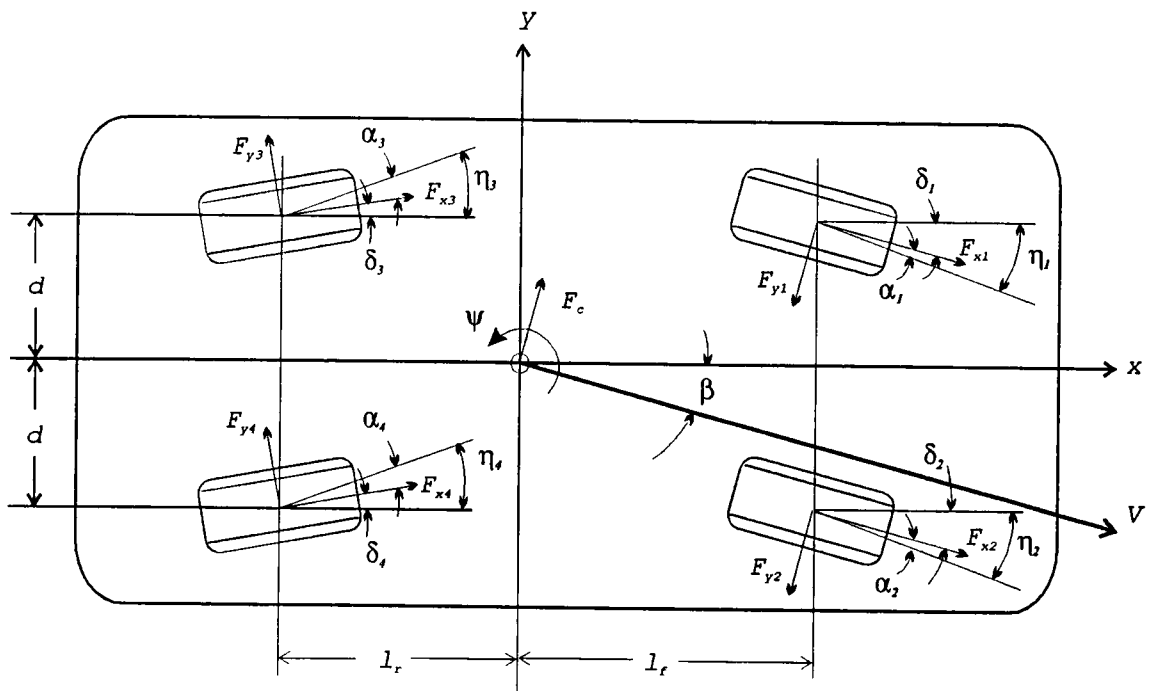


Figure 3-1. Schematic of the vehicle.

response time is vital. The vehicle's dynamics will be observed in order to establish fuzzy control variables for the development of a fuzzy logic controller. The intent of the controller is to minimize undesirable vehicle spin by means of front and rear steering compensation. The controller will simultaneously steer the two front and rear wheels, while monitoring wheel traction and requested steering wheel angles, in order to achieve the driver's desired vehicle path.

The vehicle's mathematical model will include lateral, longitudinal and yaw motions about the center of mass. Table 3-1 defines the vehicle's dynamic nomenclature.

Table 3-1. Vehicle's Nomenclature

Symbol	Description	Symbol	Description
d	distance from vehicle center line to one half a tire tread	I	moment of inertia in yaw motion
g	acceleration of gravity	M	vehicle mass
h	height from roadway to vehicle's center of mass	V	vehicle velocity
l_f	distance from center of mass to front axle	α_i	wheel slip angle
l_r	distance from center of mass to rear axle	β	vehicle side slip angle
x	longitudinal position	δ_i	steering angle
y	lateral position	ρ	radius of curvature
F_{x_i}	longitudinal tire force	ψ	yaw angle
F_{y_i}	lateral tire force		

By utilizing the road-tire forces acting on the vehicle's lateral motion, lateral accelerations can be represented as

$$\ddot{y} = \frac{F_{lat_1} + F_{lat_2} + F_{lat_3} + F_{lat_4} + F_c \cos \beta}{M} \quad (3.1)$$

where y denotes lateral position and M the mass of the vehicle. F_c represents the centrifugal force and β denotes the vehicles side slip angle. F_{lat_1} through F_{lat_4} are the lateral road-tire interaction forces whose subscripted numbers represent the individual wheel position as defined in Figure 3-1.

The lateral road-tire interaction forces F_{lat_i} are expressed as functions of longitudinal and lateral tire forces F_{x_i} and F_{y_i} , respectively.

$$F_{lat_i} = F_{y_i} \cos \delta_i + F_{x_i} \sin \delta_i \quad (\text{for } i = 1 \text{ through } 4) \quad (3.2)$$

Where δ_i represents the wheels steering angle.

Longitudinal acceleration $\ddot{x}$, follows the same derivation as lateral deviation where

$$\ddot{x} = \frac{F_{lon_1} + F_{lon_2} + F_{lon_3} + F_{lon_4} + F_c \sin \beta}{M}, \quad (3.3)$$

Longitudinal road-tire interaction forces F_{lon_i} is expressed as

$$F_{lon_i} = F_{x_i} \cos \delta_i - F_{y_i} \sin \delta_i \quad (\text{for } i = 1 \text{ through } 4). \quad (3.4)$$

Yaw motion is represented by the following moment

equation

$$I\ddot{\psi} = l_f(F_{lat_1} + F_{lat_2}) - l_r(F_{lat_3} + F_{lat_4}) - d(F_{lon_1} + F_{lon_3}) + d(F_{lon_2} + F_{lon_4}) \quad (3.5)$$

where ψ is yaw angle and I is the moment of inertia in the yaw motion. The distance from the center of mass to the front and rear axle are represented by l_f and l_r , respectively, while d represents the distance from the vehicles x-axis center line to half a tire tread.

Lateral tire force F_{y_i} is a function of the lateral road-tire friction coefficient μ_{y_i} , vehicle mass per wheel M_{w_i} and the acceleration of gravity g , expressed as

$$F_{y_i} = -M_{w_i}\mu_{y_i}g. \quad (3.6)$$

Similarly, longitudinal tire force F_{x_i} is expressed as

$$F_{x_i} = M_{w_i}\mu_{x_i}g \quad (3.7)$$

where μ_{x_i} represents the longitudinal road-tire friction coefficient. μ_{y_i} and μ_{x_i} are related to the slip ratio λ_i as shown in Figure 3-2.

The slip ratio is defined as

$$\lambda_i = \begin{cases} \frac{V_{w_i} - V_i}{V_{w_i}} & (V_{w_i} \geq V_i) \\ \frac{V_{w_i} - V_i}{V_i} & (V_{w_i} < V_i) \end{cases} \quad (\text{for } i = 1 \text{ through } 4) \quad (3.8)$$

where V_{w_i} is the wheel traveling velocity and V_i represents

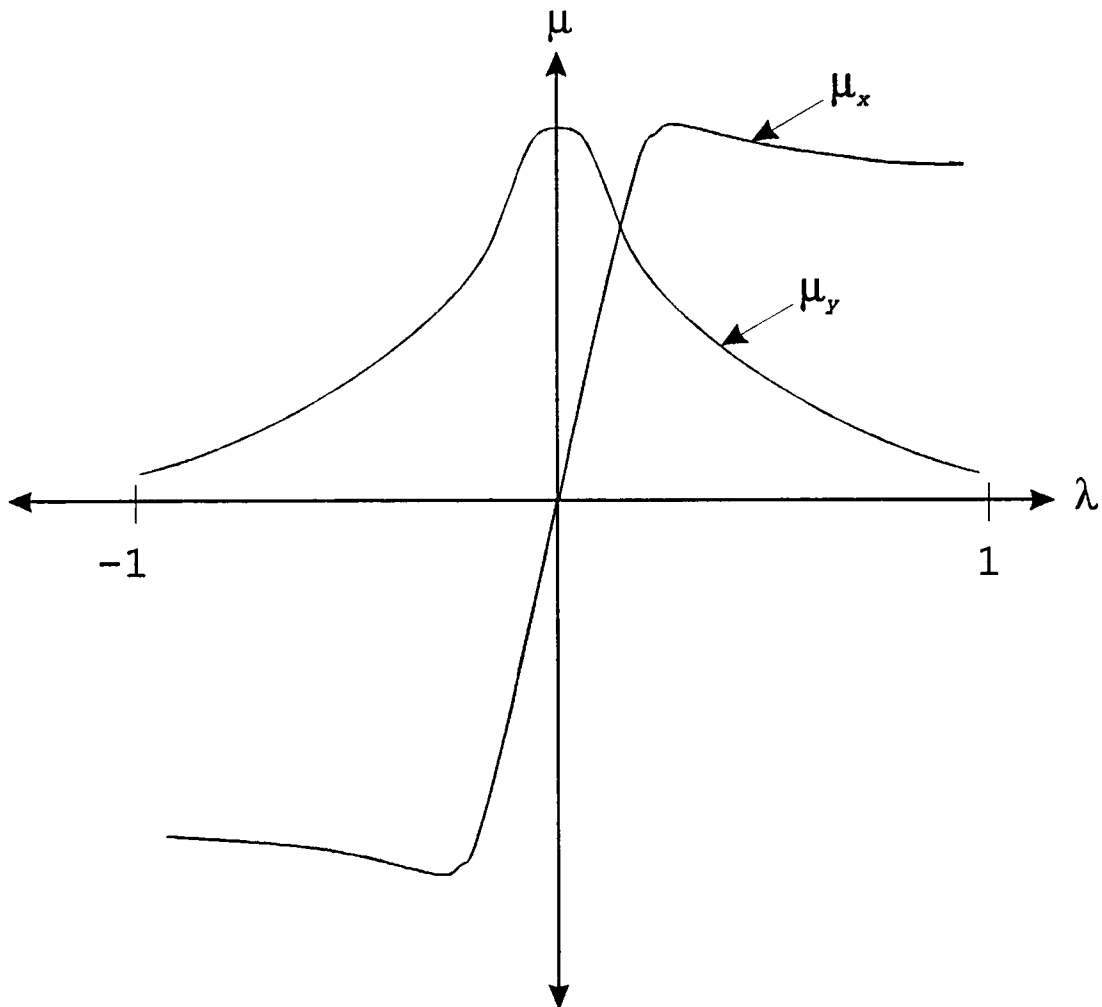


Figure 3-2. Road-tire friction coefficient as a function of wheel slip ratio.

Source: Matsumoto, N., and Tomizuka, M., "Vehicle lateral velocity and yaw control with two independent inputs," *Proceedings of the 1990 American Control Conference*, San Diego, CA., pp. 1868-1875, May 1990.

the vehicle's velocity in the wheel traveling direction relative to each wheel. With a slip ratio of zero, maximum longitudinal and lateral tire force is obtained. Note that wheel traveling velocity V_{w_i} and vehicle velocity V_i are interchanged in the denominator based upon the their relative velocities. This expression is represented as such in order to keep the magnitude of the slip ratio's less than one.

The vehicle's velocity relative to each wheel's traveling direction may slightly vary depending on the vehicles yaw rate and each wheel's slip angle. Relative to each wheel's traveling direction, the vehicle's velocity is represented by

$$\left. \begin{aligned} V_1 &= \sqrt{(\dot{x} - d\dot{\psi})^2 + (\dot{y} + l_f\dot{\psi})^2} \cos\alpha_1 \\ V_2 &= \sqrt{(\dot{x} + d\dot{\psi})^2 + (\dot{y} + l_f\dot{\psi})^2} \cos\alpha_2 \\ V_3 &= \sqrt{(\dot{x} - d\dot{\psi})^2 + (\dot{y} - l_r\dot{\psi})^2} \cos\alpha_3 \\ V_4 &= \sqrt{(\dot{x} + d\dot{\psi})^2 + (\dot{y} - l_r\dot{\psi})^2} \cos\alpha_4 \end{aligned} \right\} \quad (3.9)$$

Where α_i represents the wheel slip angle. α_i can be expressed as

$$\alpha_i = \eta_i - \delta_i \quad (\text{for } i = 1 \text{ through } 4). \quad (3.10)$$

Here η_i represents the direction of the wheel velocity. η_i for each wheel is expressed as

$$\left. \begin{aligned} \eta_1 &= \arctan \left(\frac{\dot{y} + l_f \dot{\psi}}{\dot{x} - d \dot{\psi}} \right) \\ \eta_2 &= \arctan \left(\frac{\dot{y} + l_f \dot{\psi}}{\dot{x} + d \dot{\psi}} \right) \\ \eta_3 &= \arctan \left(\frac{\dot{y} - l_f \dot{\psi}}{\dot{x} - d \dot{\psi}} \right) \\ \eta_4 &= \arctan \left(\frac{\dot{y} - l_f \dot{\psi}}{\dot{x} + d \dot{\psi}} \right) \end{aligned} \right\} \quad (3.11)$$

Assuming little difference between the two front wheel's traveling velocity V_{w_f} , front slip ratio λ_f can be represented as

$$\lambda_f = \lambda_1 = \lambda_2 = \begin{cases} \frac{V_{w_f} - V_f}{V_{w_f}} & (V_{w_f} \geq V_f) \\ \frac{V_{w_f} - V_f}{V_f} & (V_{w_f} < V_f) \end{cases} \quad (3.12)$$

where V_{w_f} represents front wheel traveling velocity and V_f the vehicle velocity in the front wheel traveling direction. Note that V_f assumes little difference in the vehicle's velocity exists between the two front wheels (i.e., $V_1 = V_2 = V_f$).

Similarly, rear slip ratio can be represented as

$$\lambda_r = \lambda_3 = \lambda_4 = \begin{cases} \frac{V_{w_r} - V_r}{V_{w_r}} & (V_{w_r} \geq V_r) \\ \frac{V_{w_r} - V_r}{V_r} & (V_{w_r} < V_r) \end{cases} \quad (3.13)$$

where V_{w_r} represents rear wheel traveling velocity and V_r

the vehicle velocity in the rear wheel traveling direction. Note that V_r assumes little difference in the vehicle's velocity exists between the two rear wheels (i.e., $V_3 = V_4 = V_r$)

Since μ_{y_i} is approximately proportional to the wheel slip angle α_i , and a nonlinear function dependent upon the tires slip ratio λ_i as shown in Figure 3-2, μ_{y_i} can be expressed as

$$\mu_{y_i} \approx f_i(\lambda_i) \alpha_i \quad (\text{for } i = 1 \text{ through } 4). \quad (3.14)$$

Therefore, F_{y_i} can then be represented as

$$F_{y_i} = -M_{w_i} f_i(\lambda_i) \alpha_i g. \quad (3.15)$$

Since the relationship between the radius of curvature ρ and the vehicle velocity V satisfy

$$V = \rho (\psi + \beta), \quad (3.16)$$

the centrifugal force can be expressed as

$$F_c = \frac{MV^2}{\rho} = MV(\psi + \beta). \quad (3.17)$$

An approximation for the vehicle mass per wheel M_{w_i} is expressed as

$$\left. \begin{aligned}
 M_{w_1} &= \frac{l_f}{2(l_f + l_r)} \left(M - \frac{hF_c}{dg} \right) \\
 M_{w_2} &= \frac{l_f}{2(l_f + l_r)} \left(M + \frac{hF_c}{dg} \right) \\
 M_{w_3} &= \frac{l_r}{2(l_f + l_r)} \left(M - \frac{hF_c}{dg} \right) \\
 M_{w_4} &= \frac{l_r}{2(l_f + l_r)} \left(M + \frac{hF_c}{dg} \right)
 \end{aligned} \right\} \quad (3.18)$$

Here h is the height from the road way to the center of the vehicle's mass.

Using equations (3.1), (3.2), (3.3), (3.4), (3.5), (3.7), (3.10), (3.11), (3.15), (3.16), (3.17) and (3.18) a nonlinear model of the vehicle's dynamics was developed. A listing of the model's program is included in Appendix A. The vehicles nominal parameters were chosen from [19]. The vehicles nominal simulation parameters are listed in Table 3-2.

Table 3-2. *Nominal parameters for simulations.*

Parameter	Value
d	0.252 m
g	9.81 m/sec
h	0.08 m
l_f	0.392 m
l_r	0.392 m
I	5.0 kg/m ²
M	50.0 kg
V	2.0 m/sec
ρ	3.0 m

Several 'scenarios' were simulated on the modeled vehicle. Input disturbance were generated by varying front and rear wheel slip ratios over time. Slip ratio disturbances were chosen in order to observe the vehicle's yaw angle characteristics when subjected to slick road conditions. The vehicle's velocity V , wheel steering angle δ_i and the road's radius of curvature ρ were held constant. A look-up table was used for the lateral and longitudinal road-tire friction coefficients based on Figure 3-2.

Yaw rate error ψ_{err} is the observed output of the simulations. ψ_{err} is defined as

$$\psi_{err} = \psi_c - \psi_{obs} \quad (3.19)$$

where ψ_c and ψ_{obs} are the commanded and observed yaw rate, respectively. ψ_c represents the yaw rate of the vehicle without lateral slip (side slip angle β is zero). From equation (3.16), with β equal to zero, commanded yaw rate is expressed as

$$\dot{\psi}_c = \frac{V}{\rho}. \quad (3.20)$$

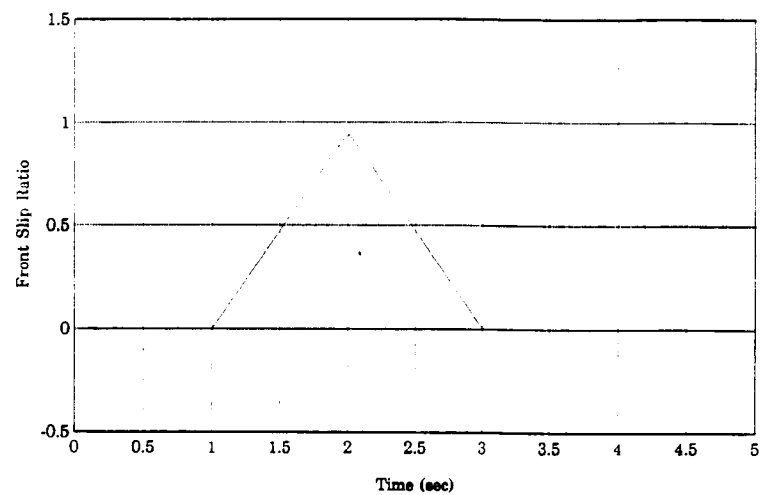
ψ_{obs} is the actual simulation yaw rate of the vehicle.

Of the many scenarios simulated, four illustrate the system's 'worst case' response with the given conditions. In each scenario, it was assumed that the vehicle was turning in a clockwise rotation. A description of the four

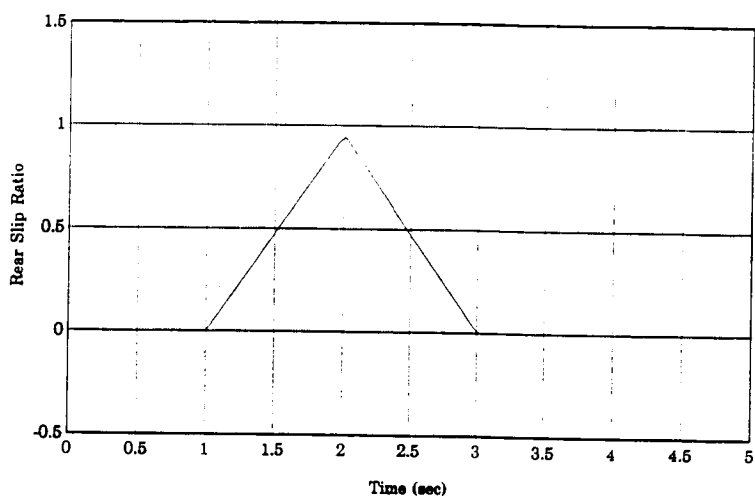
scenarios is provided in Table 3-3. Simulation results are shown in Figures 3-3 through 3-6 for scenarios 1 through 4, respectively.

Table 3-3. Simulation scenario descriptions.

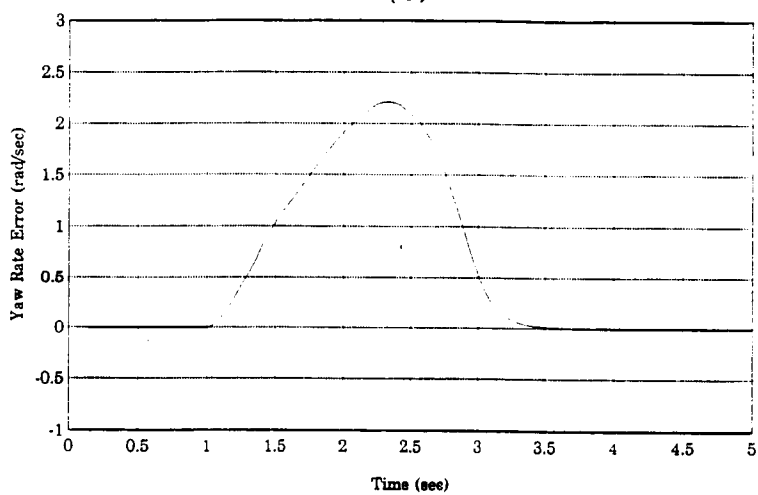
Scenario	Figure	Disturbance Descriptions
1	3-3 (a)	t = 1 sec. front wheel slip ratio begins to linearly increase (acceleration). t = 2 sec. front wheel slip ratio peaks at +0.95 and begins to linearly decrease. t = 3 sec. front wheels retain full traction.
	3-3 (b)	t = 1 sec. rear wheel slip ratio begins to linearly increase (acceleration). t = 2 sec. rear wheel slip ratio peaks at +0.95 and begins to linearly decrease. t = 3 sec. front wheels retain full traction.
2	3-4 (a)	t = 1 sec. front wheel slip ratio begins to linearly decrease (skidding). t = 2 sec. front wheel slip ratio peaks at -0.95 and begins to linearly increase. t = 3 sec. front wheels retain full traction.
	3-4 (b)	t = 1 sec. rear wheel slip ratio begins to linearly decrease (skidding). t = 2 sec. rear wheel slip ratio peaks at -0.95 and begins to linearly increase. t = 3 sec. rear wheels retain full traction.
3	3-5 (a)	t = 1 sec. front wheel slip ratio begins to linearly decrease (skidding). t = 2 sec. front wheel slip ratio peaks at -0.30 and begins to linearly increase. t = 3 sec. front wheels retain full traction.
	3-5 (b)	t = 1 sec. rear wheel slip ratio begins to linearly decrease (skidding). t = 2 sec. rear wheel slip ratio peaks at -0.30 and begins to linearly increase. t = 3 sec. rear wheels retain full traction.
4	3-6 (a)	t = 1 sec. front wheel slip ratio begins to linearly decrease (skidding). t = 2 sec. front wheel slip ratio peaks at -0.95 and begins to linearly increase. t = 3 sec. front wheels retain full traction.
	3-6 (b)	No disturbances on rear wheels (slip ratio = 0).



(a)

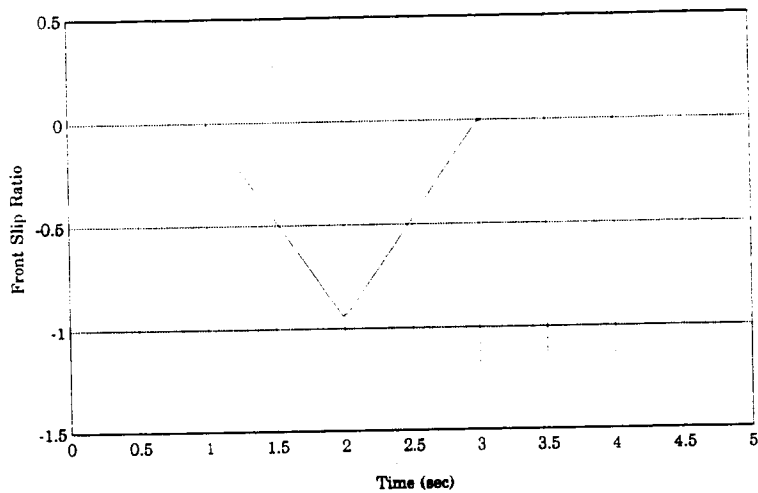


(b)

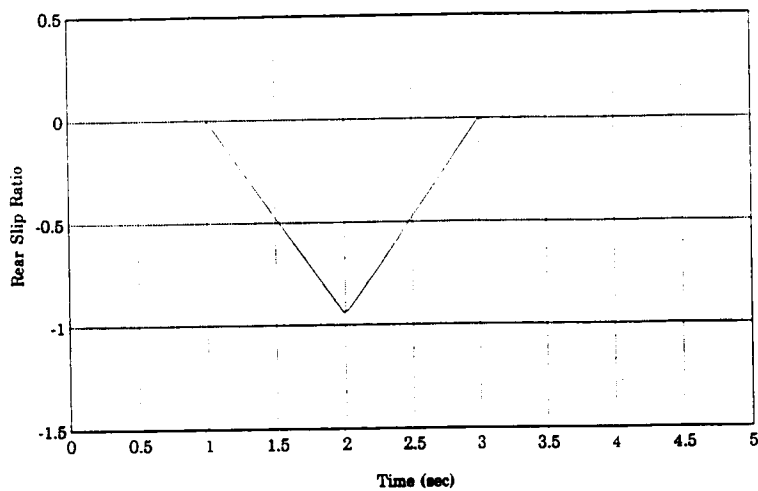


(c)

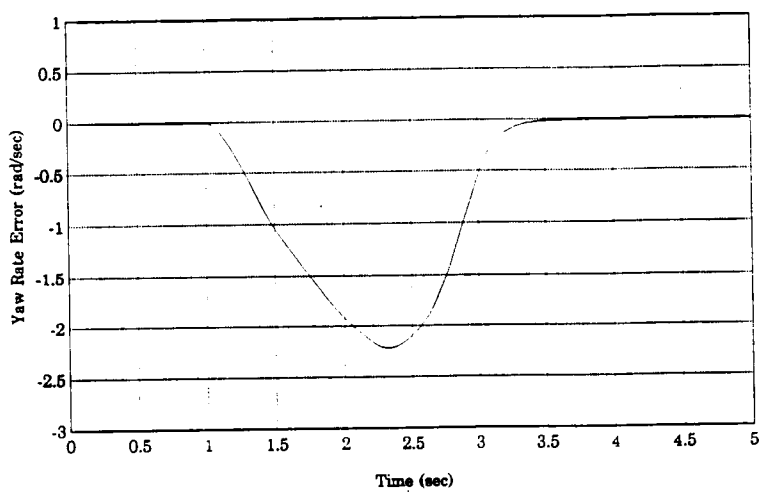
Figure 3-3. Scenario 1 simulation without controller. (a) and (b) illustrate forced disturbances on front and rear wheels, respectively. (c) shows effect on yaw rate error.



(a)



(b)



(c)

Figure 3-4. Scenario 2 simulation without controller. (a) and (b) illustrate forced disturbances on front and rear wheels, respectively. (c) shows effect on yaw rate error.

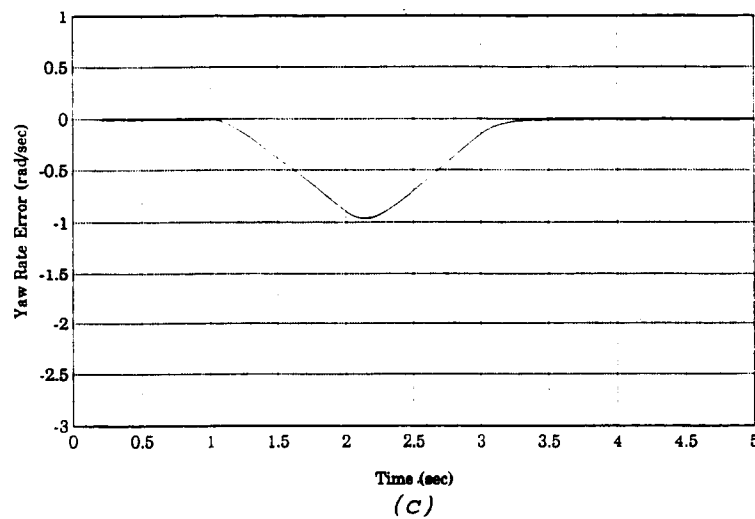
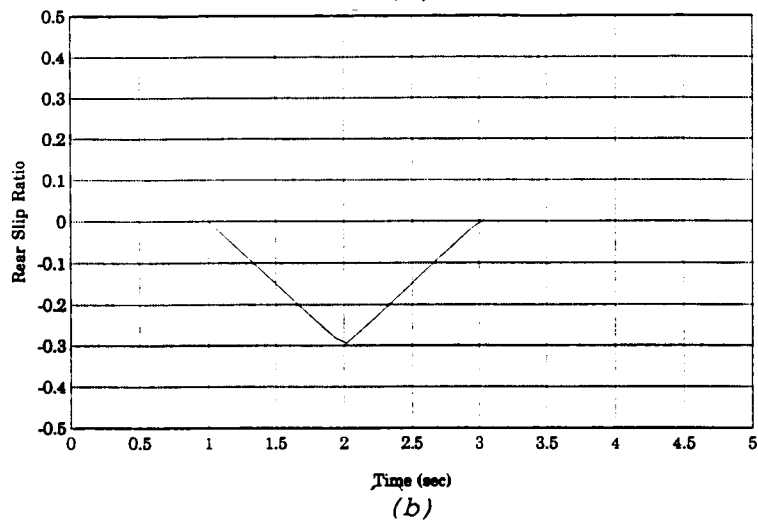
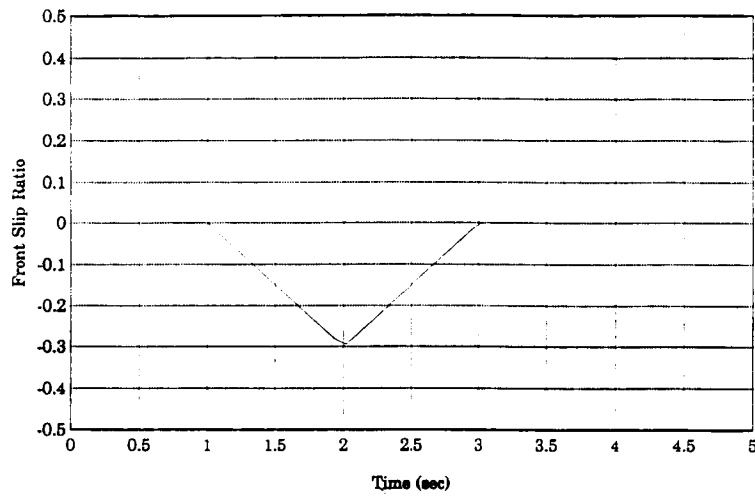


Figure 3-5. Scenario 3 simulation without controller. (a) and (b) illustrate forced disturbances on front and rear wheels, respectively. (c) shows effect on yaw rate error.

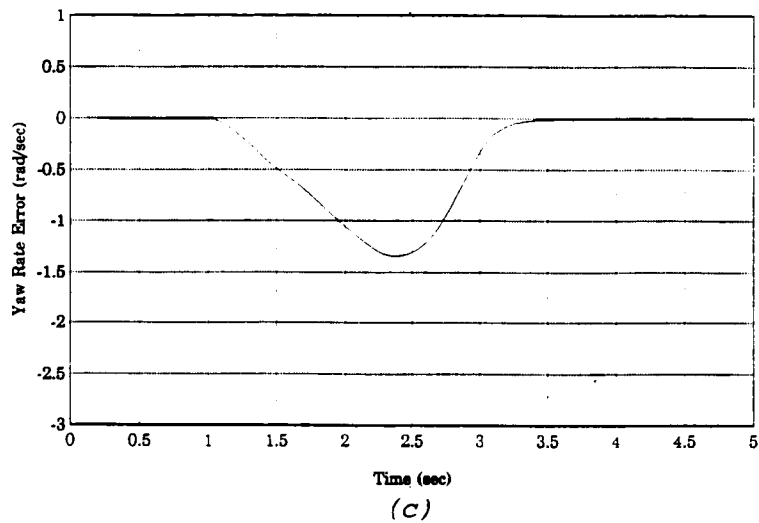
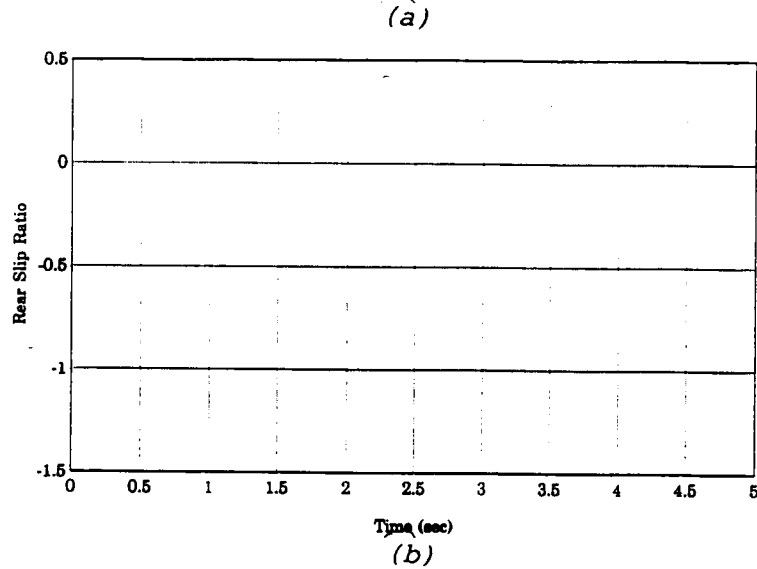
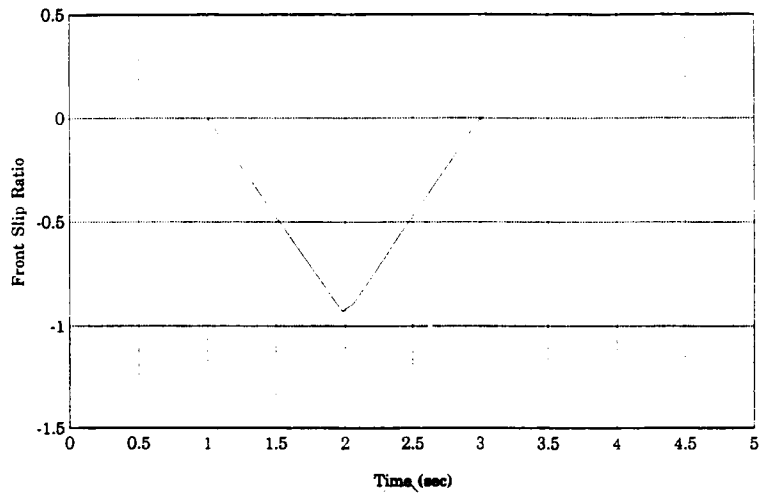


Figure 3-6. Scenario 4 simulation without controller. (a) and (b) illustrate forced disturbances on front and rear wheels, respectively. (c) shows effect on yaw rate error.

The results of the simulation are reasonable. As Figure 3-3 (a) through (c) illustrates, while front and rear wheels are increasing in acceleration (front and rear slip ratios positive), the vehicle would spin in a clockwise rotation (observed yaw rate would be negatively increasing). Correspondingly, yaw rate error would be positively increasing provided vehicle velocity V and road curvature ρ are positive. Since the vehicle's velocity was held constant, yaw rate error would continue to increase as front and rear slip ratio's increase. When front and rear slip ratio's begin to decrease, yaw rate error would also decrease as the illustrations demonstrate.

Figure 3-4 (a) through (c) illustrate the scenario when both front and rear wheel slip ratios are decreasing (vehicle skidding). The observed yaw rate would be positively increasing as the vehicle increased it's relative counterclockwise spin. As the observed yaw rate increased, yaw rate error would decrease. Similarly as front and rear slip ratio's decreased, the vehicle's counterclockwise spin and yaw rate error would decrease.

Figure 3-5 is similar to Figure 3-4 with only the degree of disturbance on front and rear slip ratio's differing. Figure 3-6 illustrates the scenario when the front wheels are skidding and the rear wheels have full traction.

4. FUZZY LOGIC CONTROLLER DESIGN

The application of fuzzy logic control (FLC) techniques to vehicle guidance is gaining recognition. Hessburg and Tomizuka [8] shown that the use of a fuzzy rule-based controller applied to lateral guidance of a vehicle achieved "good" tracking results when integrated with automated highways. Altrock et al. [2] incorporated a fuzzy logic controller within a model car which sensed road obstacles and successfully steered around them.

Vehicle steering dynamics meet many of the conditions which support fuzzy logic as a control technique. The system is highly nonlinear, accurate sensor data is difficult to obtain due to the wide variety of external disturbances (i.e., road vibration, wind gusts, etc) and the control rules can be described by an 'expert' which in this case is a human.

The objective of the controller in this study is to provide automated steering assistance for the driver when presented situations which require precise maneuvering responses. Specifically, the controller will provide both front and rear steering compensation when sensor data detects an unacceptable spin (yaw rate error) of the vehicle. The concept is similar to anti-lock braking systems (ABS) in that the system will not eliminate the driver from control of his vehicle but will limit his

ability to over or under compensate a desired maneuver. Unlike the studies conducted in [9], [24], [25], [26], and [28] where a roadway reference system was used, the controller in this study will continually monitor the commanded yaw rate by sensing the driver's desired steering angle. When sensor data detects the vehicle is entering an undesirable spin, front and rear steering angle compensation (δ_{fc} , δ_{rc} , respectively) from the FLC are summed with the driver's desired steering angle. The summed steering angles then drive the steering actuators of the vehicle. It is a goal of the controller to respond fast enough in order to minimize or eliminate spin of the vehicle before the driver actual detects the spin himself.

The first step in developing a FLC is to define the required sensor data which will provide sufficient information for the appropriate output response. For the given system, the controller will be designed to minimize the vehicles yaw rate error (ψ_{err}) by providing front and rear steering compensation. Therefore, ψ_{err} will be required as an input to the FLC while front and rear steering compensation are the FLC's output variables. Note that this study assumes the vehicle has front and rear independent steering (FRIS) which was shown to have great potentials [6], [10], however, the concepts and methods presented can be adapted to the front two wheel steering

(FWS) vehicle.

Yaw rate error ψ_{err} was defined in equation (3.19).

Since the observed yaw rate ψ_{obs} in (3.19) cannot be directly calculated, an angular velocity sensor shall be mounted on the vehicle to sense the actual yaw rate ψ_{sen} .

Therefore,

$$\psi_{err} = \psi_c - \psi_{sen} \quad (4.1)$$

where ψ_c was previously given in (3.20).

Since ρ from equation (3.20) cannot be directly measured, the following relationship shall be used

$$\rho = -\frac{l_f}{\tan \delta_d} \quad (4.2)$$

where l_f is the length from the vehicle's center of gravity to the front axle and δ_d is the desired steering angle commanded by the driver.

In addition to yaw rate error ψ_{err} , front and rear wheel slip ratios will be monitored from sensor data. The slip ratios are necessary to determine the correct steering response which differs dramatically between whether the vehicle's tires are skidding (slip ratio less than zero) or accelerating (slip ratio greater than zero). Relationships for front and rear wheel slip ratio were defined in equations (3.9) and (3.10), respectively. From equations

(3.11), (3.12) and (3.13) the necessary sensor data required to calculate slip ratios are front wheel traveling velocity V_{w_f} , rear wheel traveling velocity V_{w_r} , longitudinal acceleration $\ddot{x}$ and lateral acceleration $\ddot{y}$.

Table 4-1 summarizes the necessary sensor data and the type of sensor required for the FLC. Figure 4-1 shows a block diagram of the system utilizing a FLC.

Table 4-1. *Summary of required sensor inputs.*

Sensor Input Nomenclature	Description	Sensor Type
v	vehicle velocity	speedometer
δ_d	driver's desired steering angle	potentiometer on steering mechanism
ψ_{sen}	sensed yaw rate of vehicle	angular velocity
V_{w_f}	front wheel traveling velocity	rotary encoder
V_{w_r}	rear wheel traveling velocity	rotary encoder
$\ddot{x}$	longitudinal acceleration	accelerometer
$\ddot{y}$	lateral acceleration	accelerometer

With the fuzzy logic input and output variables established, the universe of discourse for each variables membership function can be defined. The universe of discourse for yaw rate error ψ_{err} was established from simulations results of the vehicle in Section 3. From

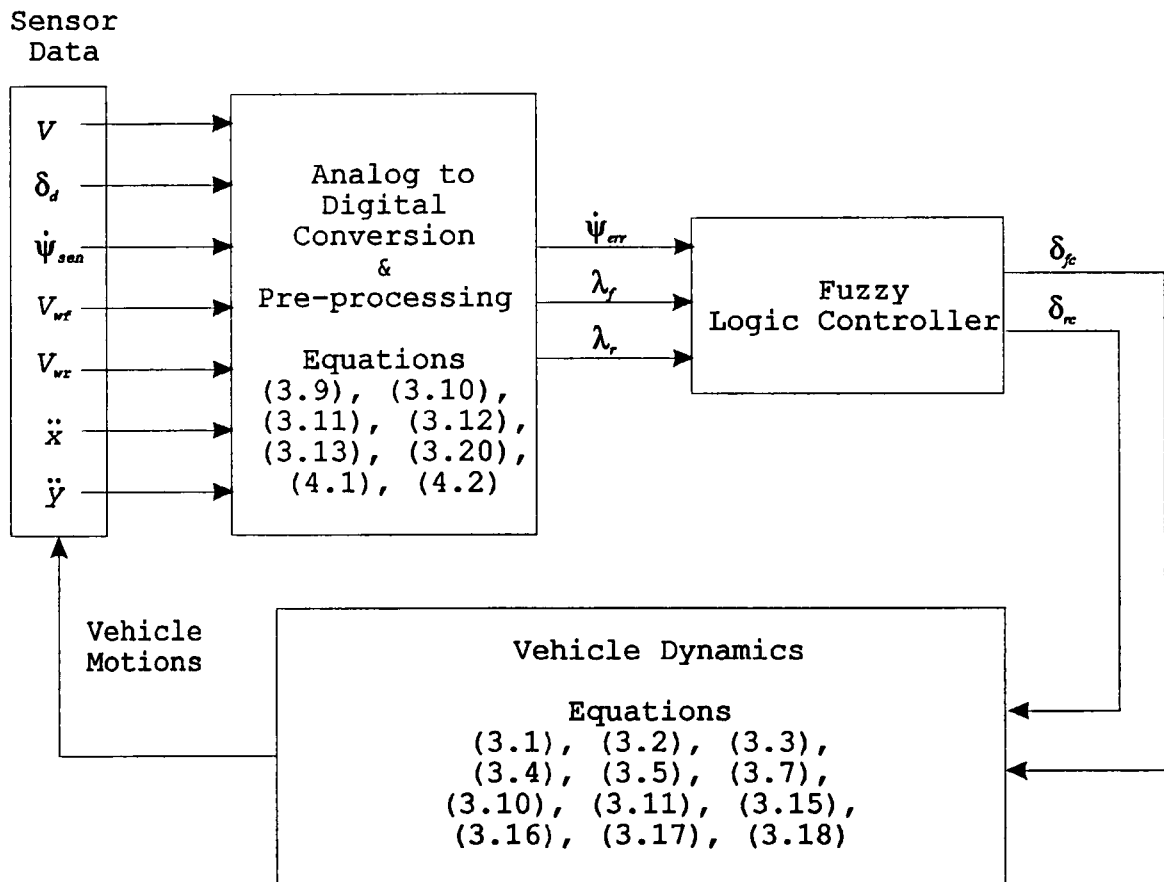


Figure 4-1. Block diagram of system using a FLC.

Figure 3-3 (c), a ψ_{err} of 2.2 radians per second was observed when both the front and rear wheels slip ratio were +0.95. A ψ_{err} of -2.2 radians per second was observed for the case when both the front and rear tires slip ratios were -0.95, Figure 3-4 (c). The universe of discourse for ψ_{err} will extend from -5.0 to +5.0 radians per second. Figure 4-2 illustrates ψ_{err} 's membership function after approximately ten (10) iterations of adjustments to the fuzzy set descriptions. The iterative procedure followed the flow chart previously illustrated in Figure 2-4. The fuzzy set descriptions Negative Large (NL), Negative Medium Large (NML), Negative Medium (NM), Positive Medium (PM), Positive Medium Large (PML) and Positive Large (PL) were first intuitively defined based upon the uncompensated simulations of the mathematical vehicle. As simulations were performed on the model with the FLC, the fuzzy descriptions were appropriately adjusted by the author until an optimal systems response was achieved.

The universe of discourse for the front and rear slip ratio's will range from -1.0 to 1.0. This range was chosen from Figure 3-2. Figure 4-3 illustrates front and rear slip ratio's membership functions after approximately twenty (20) iterations of adjustments. The increased number of iterations for this membership function was primarily due to the sensitivity of the system when the vehicle's lack of

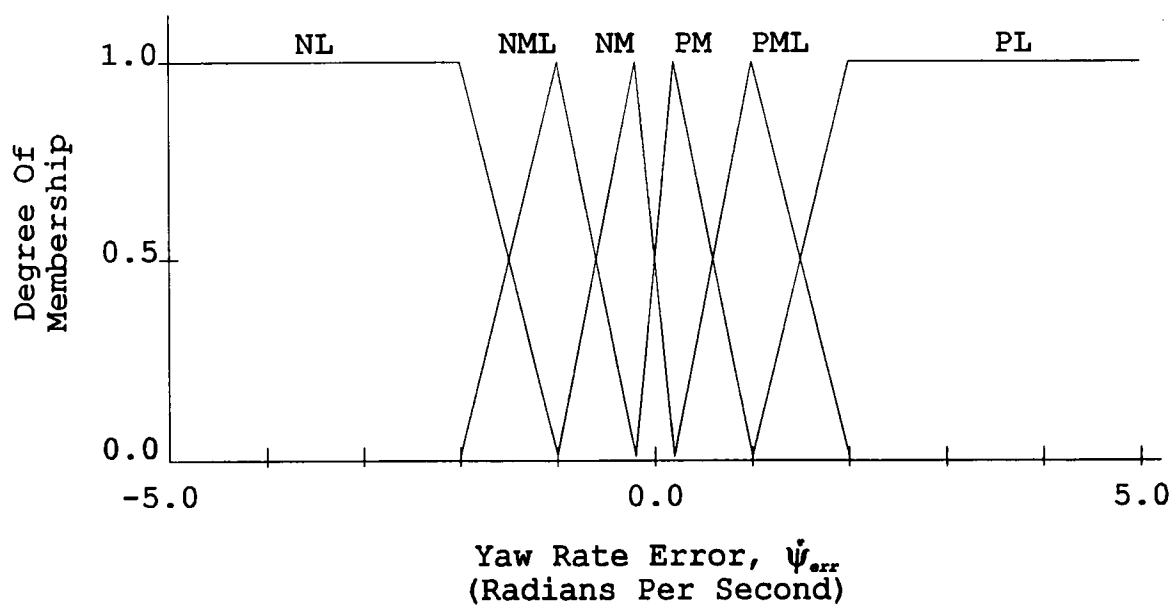


Figure 4-2. Yaw rate error's membership function.

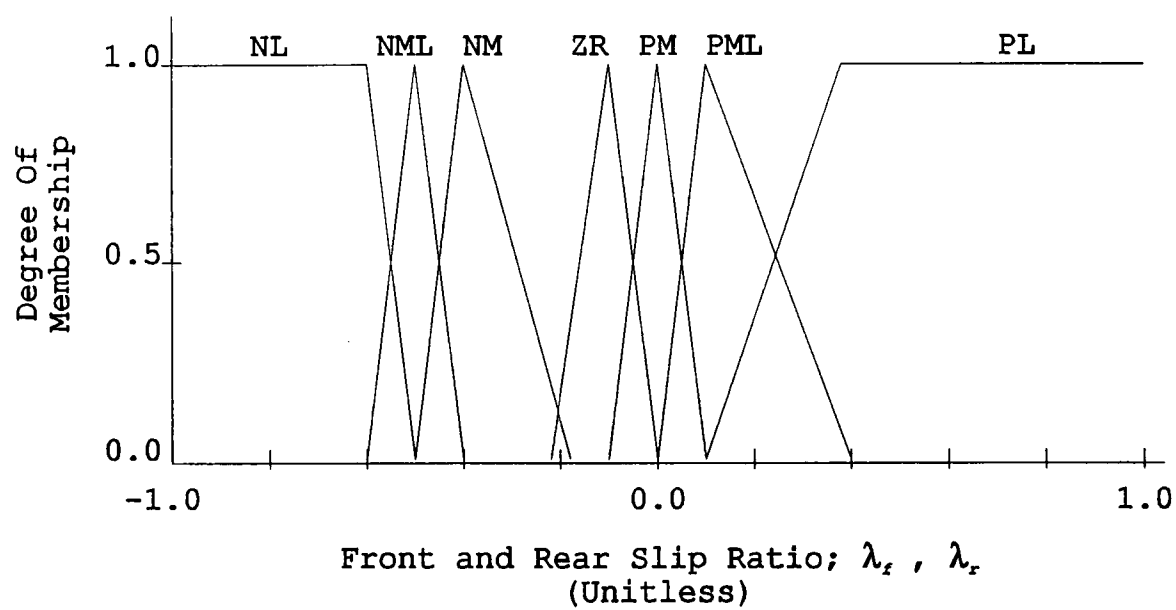


Figure 4-3. Front and rear slip membership functions.

road-tire traction, when skidding, substantially increased ψ_{err} 's magnitude. This occurred when the vehicle's front and rear slip ratio reached -0.2. Slight membership adjustments around this point greatly effected the systems overall response. Correspondingly, membership descriptions Negative Medium (NM) and Zero (ZR) had little crossover which implies the output control commands vary greatly in this area.

Tables 4-2 and 4-3 illustrate the rules for the front and rear steering compensation, respectively. Fuzzy input variables yaw rate error ψ_{err} and slip ratio determine the appropriate steering angle commands. Fuzzy rule evaluation will utilize the SUP-MIN composition principle. The shaded portion of the Tables represent the fuzzy commanded steering angle. Referring to Table 4-2, one of several rules used within the FLC is expressed as follows:

IF Yaw_Rate_Error is Negative_Large (NL)

AND Front_Slip is Negative_Large (NL)

THEN Command_Front_Steering_Angle is Positive_Large (PL)

Table 4-2. Matrix representation of the rule set for front steering compensation.

		ψ_{err} Fuzzy Input					
		NL	NML	NM	PM	PML	PL
Front Slip Fuzzy Input	NL	PL	PL	PM	NM	NML	NL
	NML	PML	PML	PM	NM	NML	NML
	NM	PM	PM	PM	NM	NM	NM
	ZR	NM	NM	NM	PM	PM	PM
	PM	NM	NM	NM	PM	PM	PM
	PML	NM	NM	NM	PM	PM	PM
	PL	NML	NML	NM	PM	PM	PML

Table 4-3. Matrix representation of the rule set for rear steering compensation.

		ψ_{err} Fuzzy Input					
		NL	NML	NM	PM	PML	PL
Rear Slip Fuzzy Input	NL	NL	NL	NM	PM	PML	PL
	NML	NML	NML	NM	PM	PML	PML
	NM	NM	NM	NM	PM	PM	PM
	ZR	PM	PM	PM	NM	NM	NM
	PM	PM	PM	PM	NM	NM	NM
	PML	PM	PM	PM	NM	NM	NM
	PL	PML	PML	PM	NM	NM	NML

Tables 4-2 and 4-3 were developed based upon simulation results of the mathematical vehicle model and to a greater extent of human intuition. Developing the rule base is where FLC techniques take advantage of human linguistic expression and reasoning. For example, intuitively most

drivers know to steer into a turn when their vehicle is spinning out of control. With fuzzy techniques, an equivalent linguistic expression for this controlled response is easily implemented. However, as discovered by the author, it is very important in the development of the FLC's rules that comprehensive simulations are performed on the compensated system before assuming the controller is complete especially if the rules are based from human 'expertise'. Although Tables 4-2 and 4-3 illustrate the rule base after only three (3) iterations of adjustments, one initial rule that the author believed was obvious, was found through simulations to be seriously flawed.

The membership function for the front and rear steering angle compensation (δ_{fc} , δ_{rc} , respectively) is shown in Figure 4-4. Since the fuzzy sets are singletons, the crisp outputs for front and rear steering angle compensation are generated using the height method which is a simplified case of the weighted average defuzzification method. Although this method was chosen primarily for it's ease of programming, it showed considerably favorable results. Therefore, more complex time consuming defuzzification algorithms were not explored.

Although the FLC presented in this section took several iterations of adjustments in it's overall development, it should be noted that these adjustments were not time consuming. This is primarily due to fuzzy's strength in

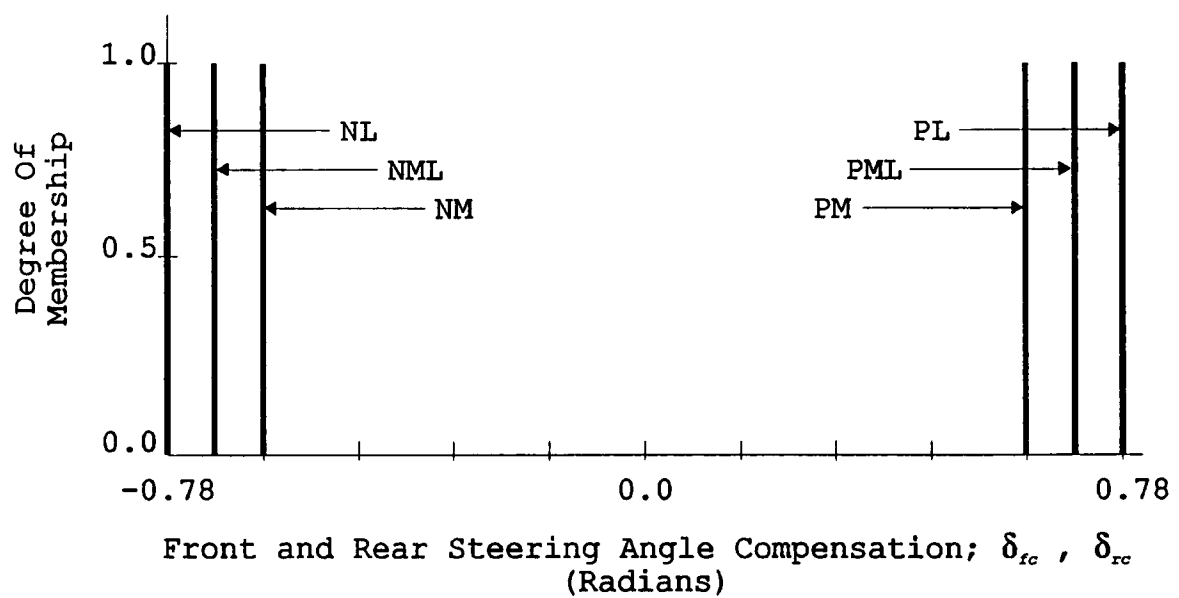


Figure 4-4. *Front and rear steering angle compensation membership functions.*

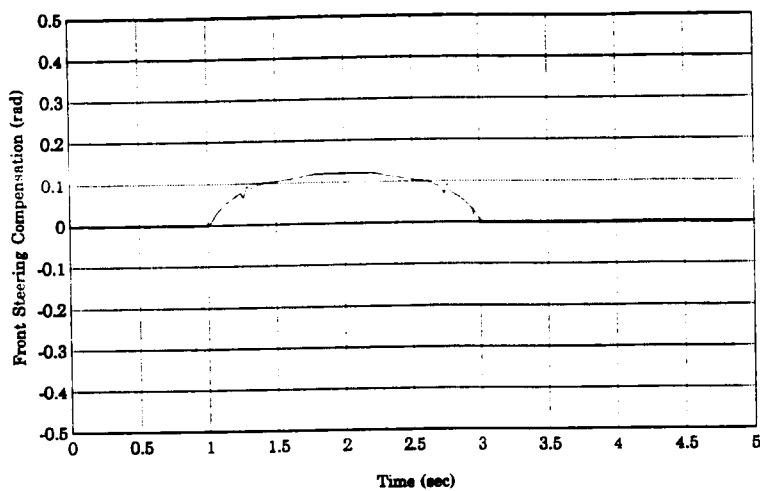
providing a controller development procedure which mimics human reasoning and expresses control rules in simple linguistic terms. The FLC development procedure also avoided the necessity of complex mathematics which is typically required when using conventional control techniques.

Appendix B lists the fuzzy logic programs which were developed using the software package f.i.d.e.TM by APTRONIXTM.

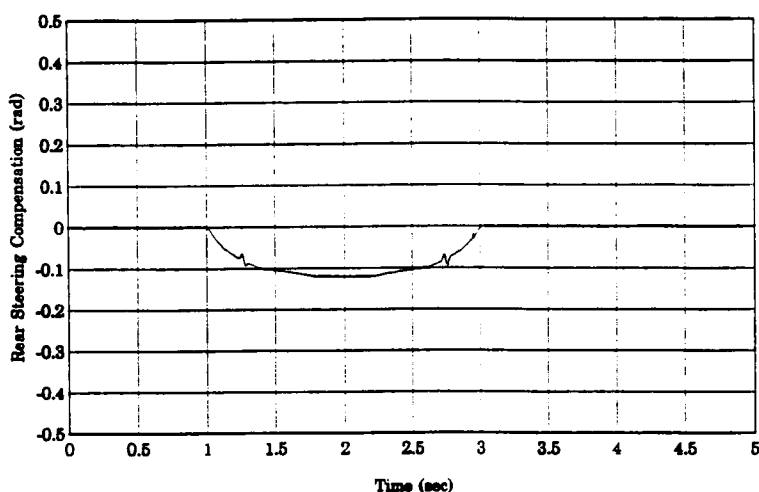
5. SIMULATION OF A FLC BASED STEERING SYSTEM

The fuzzy logic controller (FLC) generated in Section 4 was integrated into the nonlinear vehicle model developed in Section 3. The mathematical model of the system illustrated in Figure 4-1 was formulated using Table 3-2's nominal parameters. Simulations were performed on the system. Figures 5-1 through 5-4 illustrate simulation results which used front and rear slip disturbances identical to those previously shown in (a) and (b) of Figures 3-3 through 3-6, respectively. For each figure, part (a) shows the vehicle's defuzzified front steering angle compensation (δ_{fc}) while part (b) illustrates the defuzzified rear steering angle compensation (δ_{rc}). To examine the systems performance, part (c) plots yaw rate error's (ψ_{err}) response with and without the FLC.

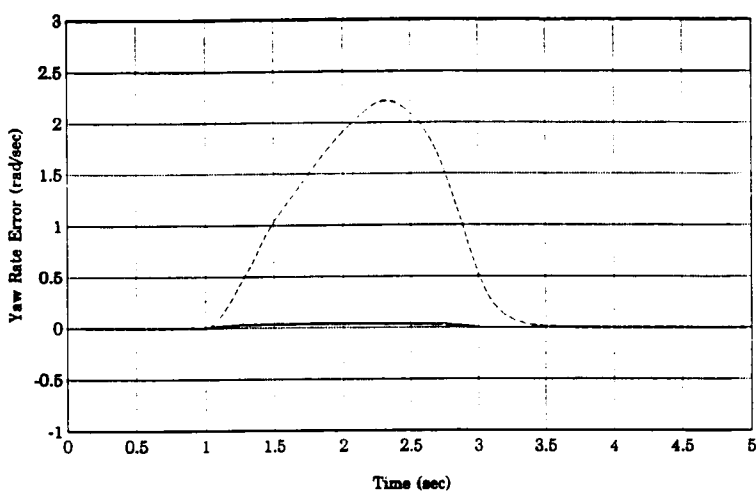
Figure 5-1 presents simulation results using scenario 1's front and rear slip disturbances as previously defined in Table 3-3. In this scenario, front and rear steering compensation commands the vehicle's wheels to turn opposite the motion of spin as illustrated in Figures 5-1 (a) and (b), respectively. Since the wheels are accelerating, the small positive coefficient of friction produces a beneficial longitudinal force which counters the vehicle's spin. As Figure 5-1 (c) illustrates, the FLC greatly reduces the



(a)



(b)



(c)

Figure 5-1. Scenario 1 simulation with the FLC. (a) and (b) illustrate front and rear steering compensation, respectively. (c) shows yaw rate error with (solid line) and without (dashed line) the FLC.

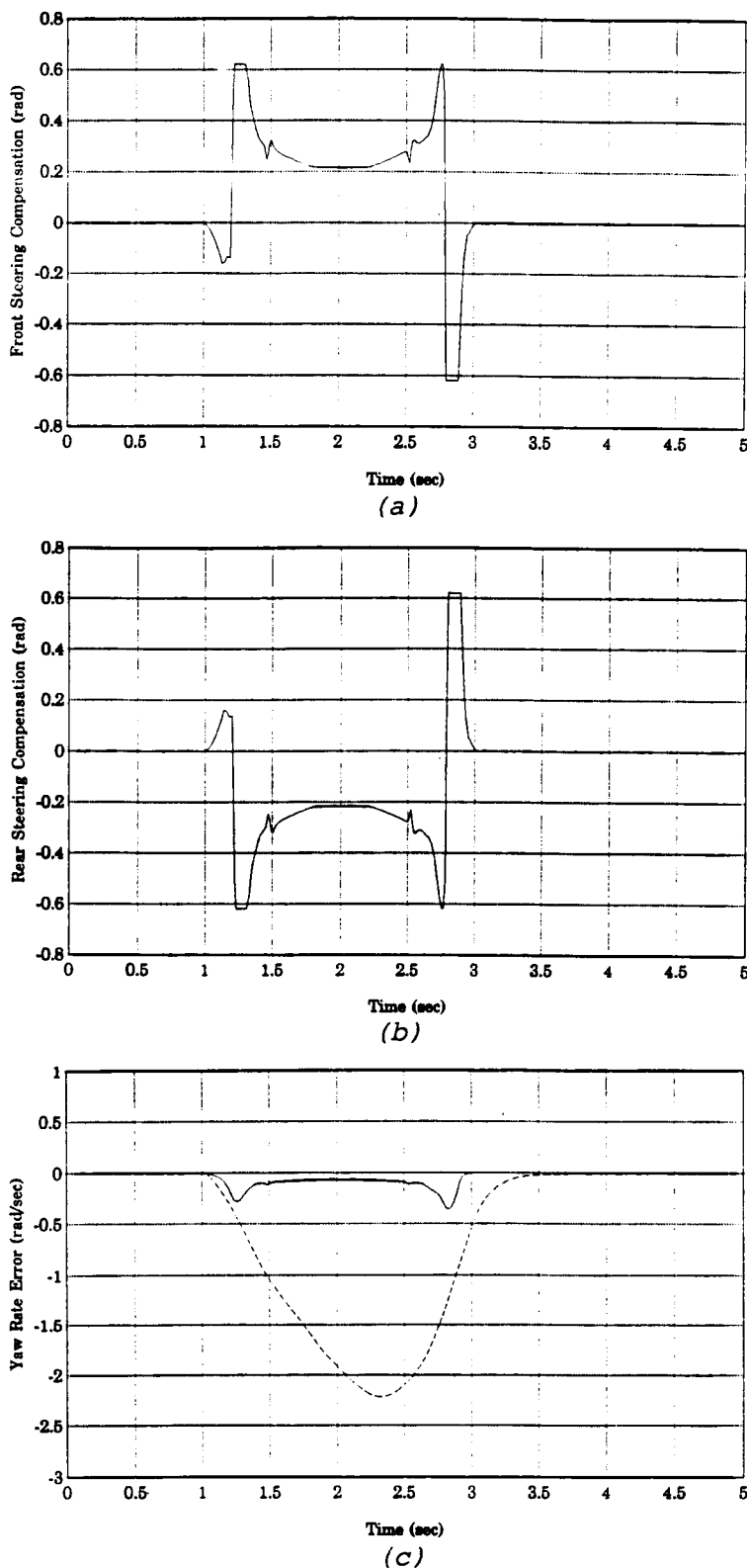
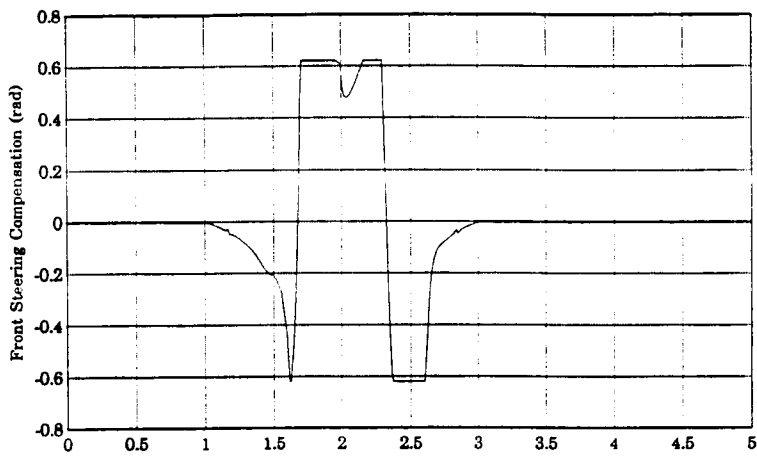
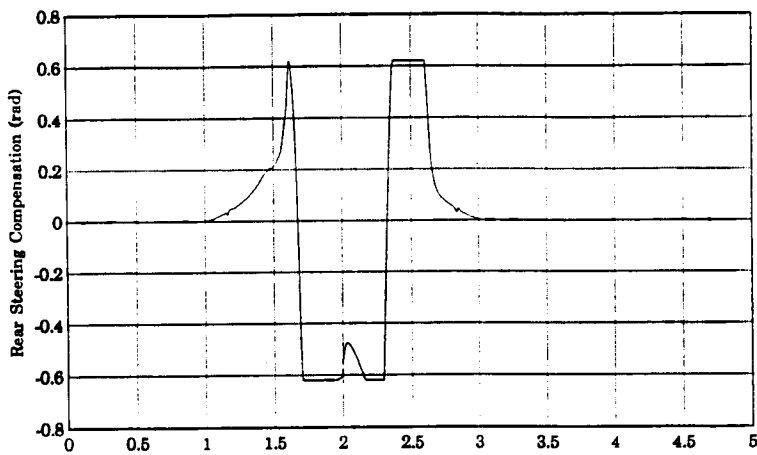


Figure 5-2. Scenario 2 simulation with the FLC. (a) and (b) illustrate front and rear steering compensation, respectively. (c) shows yaw rate error with (solid line) and without (dashed line) the FLC.



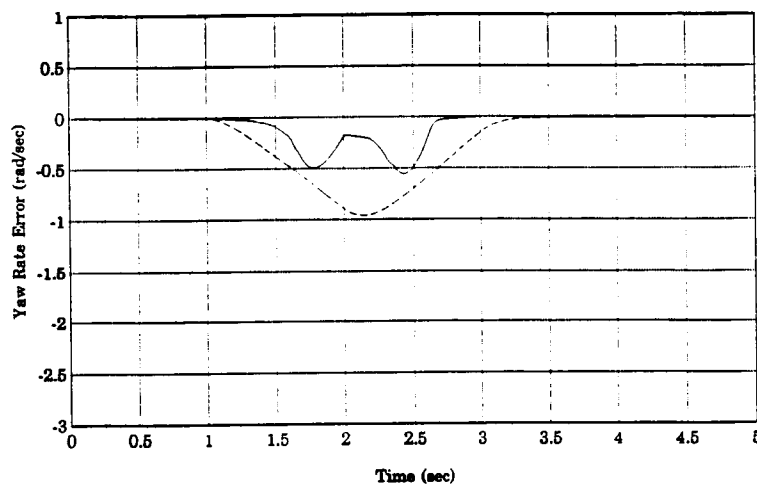
Time (sec)

(a)



Time (sec)

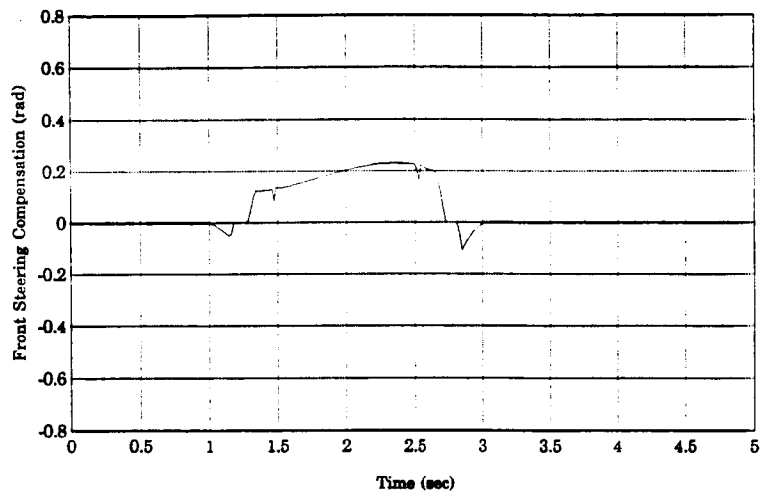
(b)



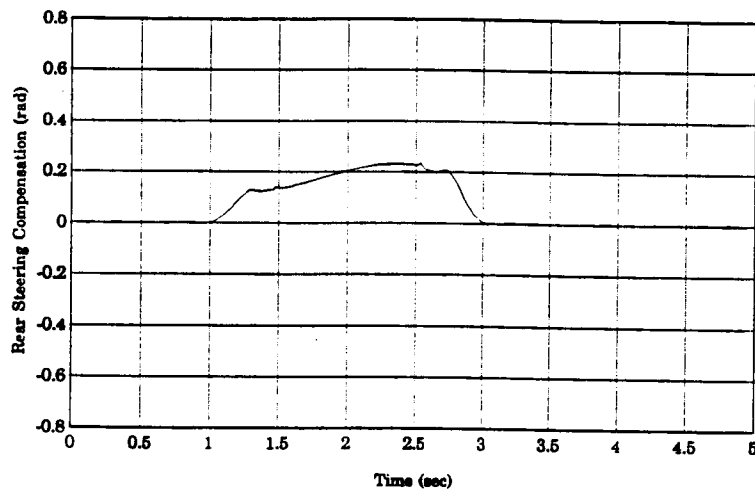
Time (sec)

(c)

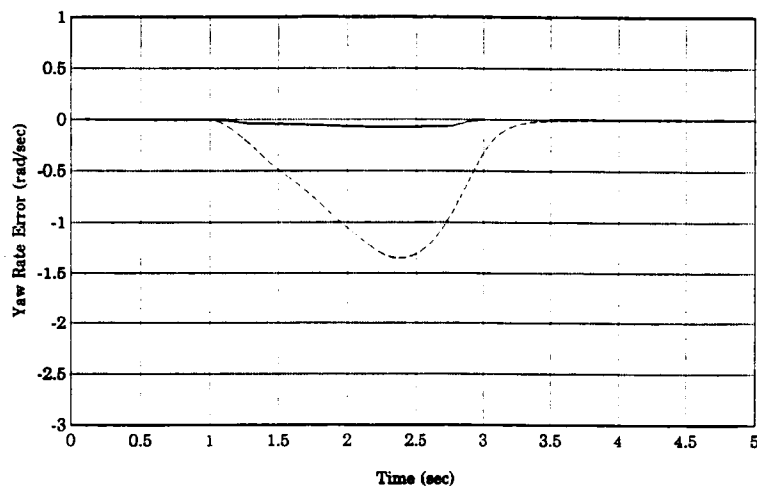
Figure 5-3. Scenario 3 simulation with the FLC. (a) and (b) illustrate front and rear steering compensation, respectively. (c) shows yaw rate error with (solid line) and without (dashed line) the FLC.



(a)



(b)



(c)

Figure 5-4. Scenario 4 simulation with the FLC. (a) and (b) illustrate front and rear steering compensation, respectively. (c) shows yaw rate error with (solid line) and without (dashed line) the FLC.

vehicle's yaw rate error. Without the controller, yaw rate error reached +2.2 rads/sec. With the controller, the maximum yaw rate error was +0.04 rads/sec.

Scenario 2's simulation results with the FLC are illustrated in Figure 5-2. Large fluctuations on front and rear steering angle compensation are observed in Figures 5-2 (a) and (b), respectively. When the vehicle first starts to skid (slip ratio greater than -0.2 and less than 0), the controller takes advantage of any lateral and longitudinal frictional forces and steers against (into) the spin. When slip ratios are less than -0.2, it becomes beneficial to steer in the direction of the spin taking advantage of any existing road-tire traction which would slow the speed of the rotation. As Figure 5-2 (c) illustrates, yaw rate error decreased from a maximum value of -2.2 rads/sec without a controller to approximately -0.35 rads/sec with the controller.

Figure 5-3 presents simulation results with the FLC using scenario 3's disturbances. Figures 5-3 (a) and (b) again illustrate large fluctuations on front and rear steering angle compensation, respectively. As discussed above, the fluctuations are a result of the required steering compensation commands when the vehicle is breaking with decreasing road-tire traction. Figure 5-3 (c) compares yaw rate errors with and without the FLC. Yaw rate error was reduced from a maximum of -0.9 rads/sec to -0.6 rads/sec.

Figure 5-4 illustrates scenario 4's response with the FLC integrated within the vehicle model. Since there was no slip with the rear wheels the fluctuations on front and rear steering angle compensation was less severe as compared to scenario's 2 and 3. Figures 5-4 (a) and (b) display front and rear steering compensation, respectively. Yaw rate error with and without the controller is illustrated in Figure 5-4 (c). As Figure 5-4 (c) demonstrates, yaw rate error is greatly reduced when only the front wheels are subjected to slick road conditions and the FLC is installed. In this scenario, yaw rate error previously peaked at -1.3 rads/sec without a controller and was reduced to -0.1 rads/sec with the controller.

6. CONCLUSION

This study evaluated the performance of a fuzzy logic controller (FLC) integrated with a nonlinear 3-DOF vehicle model to assist in minimizing a vehicle's yaw rate error, or spin, when subjected to hazardous road conditions. The mathematical vehicle model developed in this study was equipped with front and rear independent steering (FRIS). The controller's goal is to assist the driver in keeping control of his vehicle when subjected to slick road conditions through front and rear steering compensation. The automated steering compensation would only engage when externally mounted sensors detected the vehicle entered an undesirable spin.

The FLC was designed based upon simulations of a nonlinear 3-DOF vehicle model developed in Section 3. The controller used front and rear wheel slip ratios along with yaw rate error as its fuzzy input variables. Fuzzy control rules were established using fuzzy set theory's SUP-MIN composition principle. The defuzzification process calculated 'crisp' outputs using the height method.

Simulations of the steering controlled vehicle were performed over four scenarios. The scenarios attempted to convey the performance of the controlled vehicle over the most extreme road conditions. For the given conditions, the FLC achieved its goal by greatly reducing vehicle spin.

The FLC based steering control showed very favorable results, however, there were assumptions in the model which would affect the system's performance. The vehicle's velocity was held constant throughout the simulation which, in reality, would vary significantly. Steering actuator dynamics were not included in the model which would produce an additional time lag from the controller's called for steering angle compensation to the actual steering angle of the wheels. Wind gusts, road perturbations and powertrain control (acceleration, braking) would also affect the controllers performance.

Continued studies are recommended which should include evaluating the controllers performance over a more comprehensive vehicle model, implementing the controller on an experimental vehicle and observing the vehicles response given extreme road conditions.

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LIST OF REFERENCES

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APPENDIXES

APPENDIX A
PROGRAM LISTING OF VEHICLE MODEL

```
% Programmer: Gary L. Brown
% Program: SIMNOC.m
% Date: 10/1/93
% Description: This program models the dynamics of a vehicle
                in order to observe yaw rate, lateral
                acceleration and longitudinal acceleration.
                The program will be used for the development
                of a fuzzy logic controller which will
                provide steering assistance for the vehicle
                when spinning out of control.
```

Note this program was developed using
SIMULINK™ running under MATLAB™. SIMULINK™
uses a graphical block diagram programming
approach, therefore, the listing below will
appear somewhat cryptic.

```
%
function [ret,x0,str]=simnoc(t,x,u,flag);
%SIMNOC is the M-file description of the SIMULINK system
named SIMNOC.
% The block-diagram can be displayed by typing: SIMNOC.
%
% SYS=SIMNOC(T,X,U,FLAG) returns depending on FLAG certain
% system values given time point, T, current state vector,
X,
% and input vector, U.
% FLAG is used to indicate the type of output to be
returned in SYS.
%
% Setting FLAG=1 causes SIMNOC to return state derivatives,
FLAG=2
% discrete states, FLAG=3 system outputs and FLAG=4 next
sample
% time. For more information and other options see SFUNC.
%
% Calling SIMNOC with a FLAG of zero:
% [SIZES]=SIMNOC([],[],[],0), returns a vector, SIZES,
which
% contains the sizes of the state vector and other
parameters.
% SIZES(1) number of states
% SIZES(2) number of discrete states
% SIZES(3) number of outputs
% SIZES(4) number of inputs.
% For the definition of other parameters in SIZES, see
SFUNC.
% See also, TRIM, LINMOD, LINSIM, EULER, RK23, RK45, ADAMS,
GEAR.

% Note: This M-file is only used for saving graphical
information;
% after the model is loaded into memory an internal
```

```

model
%      representation is used.

% the system will take on the name of this mfile:
sys = mfilename;
new_system(sys)
simver(1.2)
if(0 == (nargin + nargout))
    set_param(sys,'Location',[0,0,36,36])
    open_system(sys)
end;
set_param(sys,'algorithm',      'Linear')
set_param(sys,'Start time',    '0.0')
set_param(sys,'Stop time',     '3')
set_param(sys,'Min step size',  '0.001')
set_param(sys,'Max step size',  '1')
set_param(sys,'Relative error','1e-5')
set_param(sys,'Return vars',   't,yrerr')

add_block('built-in/To Workspace',[sys, '/', 'To
Workspace22'])
set_param([sys, '/', 'To Workspace22'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'mat-name','fslip',...
    'buffer','1000',...
    'position',[210,241,240,269])

add_block('built-in/Sum',[sys, '/', 'Sum15'])
set_param([sys, '/', 'Sum15'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','++',...
    'position',[1975,200,1995,220])

add_block('built-in/Sum',[sys, '/', 'Sum14'])
set_param([sys, '/', 'Sum14'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','++',...
    'position',[2010,560,2030,580])

add_block('built-in/Sum',[sys, '/', 'Sum13'])
set_param([sys, '/', 'Sum13'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','++',...
    'position',[395,641,420,679])

add_block('built-in/Sum',[sys, '/', 'Sum12'])
set_param([sys, '/', 'Sum12'],...
    'Font Number',786433,...

```

```

'Drop Shadow',786432,...
'inputs','++',...
'position',[460,471,485,509])

add_block('built-in/Constant',[sys, '/', 'Constant8'])
set_param([sys, '/', 'Constant8'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Value','0',...
'position',[1740,290,1760,310])

add_block('built-in/To Workspace',[sys, '/', 'x'])
set_param([sys, '/', 'x'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'mat-name','x',...
'buffer','1000',...
'position',[1345,287,1395,303])

add_block('built-in/To Workspace',[sys, '/', ['y''4']])
set_param([sys, '/', ['y''4']],...
'Font Number',786433,...
'Drop Shadow',786432,...
'mat-name','y',...
'buffer','1000',...
'position',[1315,402,1365,418])

add_block('built-in/Constant',[sys, '/', 'Constant7'])
set_param([sys, '/', 'Constant7'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Value','-sa',...
'position',[1920,555,1940,575])

add_block('built-in/Constant',[sys, '/', 'Constant6'])
set_param([sys, '/', 'Constant6'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Value','sa',...
'position',[1890,220,1910,240])

add_block('built-in/Sum',[sys, '/', 'Sum10'])
set_param([sys, '/', 'Sum10'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'inputs','+-',...
'position',[2065,455,2085,475])

add_block('built-in/Sum',[sys, '/', 'Sum9'])
set_param([sys, '/', 'Sum9'],...
'Font Number',786433,...
'Drop Shadow',786432,...

```

```

        'inputs','+-',...
        'position',[2100,390,2120,410])

add_block('built-in/Sum',[sys, '/', 'Sum8'])
set_param([sys, '/', 'Sum8'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','+-',...
    'position',[2100,330,2120,350])

add_block('built-in/Sum',[sys, '/', 'Sum7'])
set_param([sys, '/', 'Sum7'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','-+',...
    'position',[2045,265,2065,285])

add_block('built-in/Fcn',[sys, '/', 'n4'])
set_param([sys, '/', 'n4'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','((u[2]-lr*u[3])/(u[1]+V))',...
    'position',[1980,450,2020,470])

add_block('built-in/Mux',[sys, '/', 'Mux3'])
set_param([sys, '/', 'Mux3'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','3',...
    'position',[1900,444,1930,476])

add_block('built-in/Mux',[sys, '/', 'Mux2'])
set_param([sys, '/', 'Mux2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','3',...
    'position',[1900,379,1930,411])

add_block('built-in/Fcn',[sys, '/', 'n3'])
set_param([sys, '/', 'n3'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','((u[2]-lr*u[3])/(u[1]+V))',...
    'position',[1975,385,2015,405])

add_block('built-in/Fcn',[sys, '/', 'n2'])
set_param([sys, '/', 'n2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','((u[2]+lf*u[3])/(u[1]+V))',...
    'position',[1975,325,2015,345])

```

```

add_block('built-in/Mux',[sys, '/', 'Mux1'])
set_param([sys, '/', 'Mux1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','3',...
    'position',[1900,319,1930,351])

add_block('built-in/Mux',[sys, '/', 'Mux'])
set_param([sys, '/', 'Mux'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','3',...
    'position',[1900,262,1930,298])

add_block('built-in/Fcn',[sys, '/', 'n1'])
set_param([sys, '/', 'n1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','((u[2]+1f*u[3])/(u[1]+V))',...
    'position',[1975,270,2015,290])

add_block('built-in/Fcn',[sys, '/', 'Fcn5'])
set_param([sys, '/', 'Fcn5'],...
    'orientation',2,...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','cos(u[1])',...
    'position',[1305,800,1345,820])

add_block('built-in/Fcn',[sys, '/', 'fcsin'])
set_param([sys, '/', 'fcsin'],...
    'orientation',2,...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','sin(u[1])',...
    'position',[1620,220,1660,240])

add_block('built-in/Product',[sys, '/', 'Product8'])
set_param([sys, '/', 'Product8'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[950,220,975,240])

add_block('built-in/Constant',[sys, '/', 'F_cetrifugall'])
set_param([sys, '/', 'F_cetrifugall'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Value','M*V*V/row',...
    'position',[855,216,925,254])

add_block('built-in/Constant',[sys, '/', 'F_cetrifugal'])

```

```

set_param([sys, '/', 'F_cetrifugal'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'Value', 'M*V*V/row',...
    'position', [1410, 638, 1480, 672])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspace14'])
set_param([sys, '/', 'To Workspace14'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'mat-name', 'Fc',...
    'buffer', '1000',...
    'position', [1530, 557, 1580, 573])

add_block('built-in/Product',[sys, '/', 'Product7'])
set_param([sys, '/', 'Product7'],...
    'orientation', 2,...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'inputs', '2',...
    'position', [1240, 790, 1265, 810])

add_block('built-in/To Workspace',[sys, '/', ['y''3']])
set_param([sys, '/', ['y''3']],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'mat-name', 'lry34',...
    'buffer', '1000',...
    'position', [1285, 707, 1335, 723])

add_block('built-in/To Workspace',[sys, '/', ['y''2']])
set_param([sys, '/', ['y''2']],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'mat-name', 'lfy12',...
    'buffer', '1000',...
    'position', [1285, 672, 1335, 688])

add_block('built-in/Product',[sys, '/', 'Product6'])
set_param([sys, '/', 'Product6'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'inputs', '2',...
    'position', [1325, 525, 1350, 545])

add_block('built-in/Constant',[sys, '/', '1//Inert'])
set_param([sys, '/', '1//Inert'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'Value', '1/I',...
    'position', [1270, 490, 1295, 520])

```

```

add_block('built-in/Note',[sys, '/', 'ux2'])
set_param([sys, '/', 'ux2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'position',[254,705,255,706])

add_block('built-in/Note',[sys, '/', 'uy2'])
set_param([sys, '/', 'uy2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'position',[256,550,257,551])

add_block('built-in/Note',[sys, '/', 'ux1'])
set_param([sys, '/', 'ux1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'position',[459,365,460,366])

add_block('built-in/Note',[sys, '/', 'uy1'])
set_param([sys, '/', 'uy1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'position',[456,300,457,301])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspacel3'])
set_param([sys, '/', 'To Workspacel3'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'mat-name','B',...
    'buffer','1000',...
    'position',[1740,432,1790,448])

add_block('built-in/Integrator',[sys, '/', 'Integrator6'])
set_param([sys, '/', 'Integrator6'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Initial','0',...
    'position',[1645,430,1665,450])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspacel2'])
set_param([sys, '/', 'To Workspacel2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'mat-name','Bd',...
    'buffer','1000',...
    'position',[1630,482,1680,498])

add_block('built-in/Fcn',[sys, '/', 'Fcn4'])
set_param([sys, '/', 'Fcn4'],...
    'Font Number',786433,...

```

```

'Drop Shadow',786432,...
'Expr','(V/row) - u[1]',...
'position',[1495,480,1535,500])

```

```

%      Subsystem 'X4Y4'.

```

```

new_system([sys,'/', 'X4Y4'])
set_param([sys,'/', 'X4Y4'],'Location',[1,88,536,443])

```

```

add_block('built-in/Note',[sys,'/', 'X4Y4/Fy2'])
set_param([sys,'/', 'X4Y4/Fy2'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'position',[320,65,321,66])

```

```

add_block('built-in/Inport',[sys,'/', 'X4Y4/uy4'])
set_param([sys,'/', 'X4Y4/uy4'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Port','1',...
'position',[120,25,140,45])

```

```

add_block('built-in/Inport',[sys,'/', 'X4Y4/ux4'])
set_param([sys,'/', 'X4Y4/ux4'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Port','3',...
'position',[75,275,95,295])

```

```

add_block('built-in/Inport',[sys,'/', 'X4Y4/m4'])
set_param([sys,'/', 'X4Y4/m4'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Port','2',...
'position',[75,225,95,245])

```

```

add_block('built-in/Product',[sys,'/', 'X4Y4/Product8'])
set_param([sys,'/', 'X4Y4/Product8'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'inputs','2',...
'position',[215,80,240,100])

```

```

add_block('built-in/Constant',[sys,'/', 'X4Y4/gravity1'])
set_param([sys,'/', 'X4Y4/gravity1'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Value','g',...
'position',[75,185,95,205])

```

```

add_block('built-in/Product',[sys,'/', 'X4Y4/Product6'])

```

```

set_param([sys, '/', 'X4Y4/Product6'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[155,190,180,210])

add_block('built-in/Product',[sys, '/', 'X4Y4/Product5'])
set_param([sys, '/', 'X4Y4/Product5'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[250,195,275,215])

add_block('built-in/Gain',[sys, '/', 'X4Y4/Gain2'])
set_param([sys, '/', 'X4Y4/Gain2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Gain','-1',...
    'position',[270,80,290,100])

add_block('built-in/Inport',[sys, '/', 'X4Y4/flsa'])
set_param([sys, '/', 'X4Y4/flsa'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Port','4',...
    'position',[190,290,210,310])

add_block('built-in/Product',[sys, '/', 'X4Y4/Product4'])
set_param([sys, '/', 'X4Y4/Product4'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[445,240,470,260])

add_block('built-in/Product',[sys, '/', 'X4Y4/Product3'])
set_param([sys, '/', 'X4Y4/Product3'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[400,305,425,325])

add_block('built-in/Sum',[sys, '/', 'X4Y4/sum2'])
set_param([sys, '/', 'X4Y4/sum2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','++',...
    'position',[520,275,540,295])

add_block('built-in/Sum',[sys, '/', 'X4Y4/Sum1'])
set_param([sys, '/', 'X4Y4/Sum1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...

```

```

        'inputs','+-',...
        'position',[440,145,460,165])

add_block('built-in/Fcn',[sys, '/', 'X4Y4/Fcn1'])
set_param([sys, '/', 'X4Y4/Fcn1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','sin(u[1])',...
    'position',[265,155,305,175])

add_block('built-in/Fcn',[sys, '/', 'X4Y4/Fcn'])
set_param([sys, '/', 'X4Y4/Fcn'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','cos(u[1])',...
    'position',[265,290,305,310])

add_block('built-in/Product',[sys, '/', 'X4Y4/Product2'])
set_param([sys, '/', 'X4Y4/Product2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[355,225,380,245])

add_block('built-in/Product',[sys, '/', 'X4Y4/Product1'])
set_param([sys, '/', 'X4Y4/Product1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[355,95,380,115])

add_block('built-in/Outport',[sys, '/', 'X4Y4/out_1'])
set_param([sys, '/', 'X4Y4/out_1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Port','1',...
    'position',[490,145,510,165])

add_block('built-in/Outport',[sys, '/', 'X4Y4/out_2'])
set_param([sys, '/', 'X4Y4/out_2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Port','2',...
    'position',[570,275,590,295])

add_block('built-in/Product',[sys, '/', 'X4Y4/Product9'])
set_param([sys, '/', 'X4Y4/Product9'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[160,35,185,55])

```

```

add_block('built-in/Inport',[sys, '/', 'X4Y4/alpha4'])
set_param([sys, '/', 'X4Y4/alpha4'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Port','5',...
    'position',[115,75,135,95])
add_line([sys, '/', 'X4Y4'],[190,45;190,85;210,85])
add_line([sys, '/', 'X4Y4'],[140,85;150,85;150,50;155,50])
add_line([sys, '/', 'X4Y4'],[145,35;155,40])
add_line([sys, '/', 'X4Y4'],[185,200;185,95;210,95])
add_line([sys, '/', 'X4Y4'],[100,285;205,285;205,210;245,210])
add_line([sys, '/', 'X4Y4'],[100,235;130,235;130,205;150,205])
add_line([sys, '/', 'X4Y4'],[245,90;265,90])
add_line([sys, '/', 'X4Y4'],[100,195;150,195])
add_line([sys, '/', 'X4Y4'],[185,200;245,200])
add_line([sys, '/', 'X4Y4'],[310,300;325,300;325,240;350,240])
add_line([sys, '/', 'X4Y4'],[325,300;410,300;410,255;440,255])
add_line([sys, '/', 'X4Y4'],[430,315;490,315;490,290;515,290])
add_line([sys, '/', 'X4Y4'],[475,250;500,250;500,280;515,280])
add_line([sys, '/', 'X4Y4'],[295,90;345,90;350,100])
add_line([sys, '/', 'X4Y4'],[310,90;310,147;390,147;390,245;440,245])
add_line([sys, '/', 'X4Y4'],[310,165;330,165;330,110;350,110])
add_line([sys, '/', 'X4Y4'],[330,165;330,310;395,310])
add_line([sys, '/', 'X4Y4'],[280,205;335,205;335,225;350,230])
add_line([sys, '/', 'X4Y4'],[335,225;325,225;310,230;310,320;395,320])
add_line([sys, '/', 'X4Y4'],[385,235;400,235;400,160;435,160])
add_line([sys, '/', 'X4Y4'],[385,105;410,105;410,150;435,150])
add_line([sys, '/', 'X4Y4'],[215,300;260,300])
add_line([sys, '/', 'X4Y4'],[225,300;225,165;260,165])
add_line([sys, '/', 'X4Y4'],[465,155;485,155])
add_line([sys, '/', 'X4Y4'],[545,285;565,285])

```

% Finished composite block 'X4Y4'.

```

set_param([sys, '/', 'X4Y4'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'position',[600,690,645,760])

```

% Subsystem 'X3Y3'.

```

new_system([sys, '/', 'X3Y3'])
set_param([sys, '/', 'X3Y3'],'Location',[1,88,536,443])

add_block('built-in/Inport',[sys, '/', 'X3Y3/uy1'])
set_param([sys, '/', 'X3Y3/uy1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...

```

```

        'Port','1',...
        'position',[105,20,125,40])

add_block('built-in/Inport',[sys, '/', 'X3Y3/ux3'])
set_param([sys, '/', 'X3Y3/ux3'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Port','3',...
    'position',[75,275,95,295])

add_block('built-in/Inport',[sys, '/', 'X3Y3/m3'])
set_param([sys, '/', 'X3Y3/m3'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Port','2',...
    'position',[75,225,95,245])

add_block('built-in/Product',[sys, '/', 'X3Y3/Product8'])
set_param([sys, '/', 'X3Y3/Product8'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[215,80,240,100])

add_block('built-in/Constant',[sys, '/', 'X3Y3/gravity1'])
set_param([sys, '/', 'X3Y3/gravity1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Value','g',...
    'position',[75,185,95,205])

add_block('built-in/Product',[sys, '/', 'X3Y3/Product6'])
set_param([sys, '/', 'X3Y3/Product6'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[155,190,180,210])

add_block('built-in/Product',[sys, '/', 'X3Y3/Product5'])
set_param([sys, '/', 'X3Y3/Product5'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[250,195,275,215])

add_block('built-in/Gain',[sys, '/', 'X3Y3/Gain2'])
set_param([sys, '/', 'X3Y3/Gain2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Gain','-1',...
    'position',[270,80,290,100])

```

```

add_block('built-in/Inport',[sys, '/', 'X3Y3/flsa'])
set_param([sys, '/', 'X3Y3/flsa'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Port','4',...
    'position',[190,290,210,310])

add_block('built-in/Product',[sys, '/', 'X3Y3/Product4'])
set_param([sys, '/', 'X3Y3/Product4'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[445,240,470,260])

add_block('built-in/Product',[sys, '/', 'X3Y3/Product3'])
set_param([sys, '/', 'X3Y3/Product3'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[400,305,425,325])

add_block('built-in/Sum',[sys, '/', 'X3Y3/sum2'])
set_param([sys, '/', 'X3Y3/sum2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','++',...
    'position',[520,275,540,295])

add_block('built-in/Sum',[sys, '/', 'X3Y3/Sum1'])
set_param([sys, '/', 'X3Y3/Sum1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','+-',...
    'position',[440,145,460,165])

add_block('built-in/Fcn',[sys, '/', 'X3Y3/Fcn1'])
set_param([sys, '/', 'X3Y3/Fcn1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','sin(u[1])',...
    'position',[265,155,305,175])

add_block('built-in/Fcn',[sys, '/', 'X3Y3/Fcn'])
set_param([sys, '/', 'X3Y3/Fcn'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','cos(u[1])',...
    'position',[265,290,305,310])

add_block('built-in/Product',[sys, '/', 'X3Y3/Product2'])
set_param([sys, '/', 'X3Y3/Product2'],...
    'Font Number',786433,...

```

```

'Drop Shadow',786432,...
'inputs','2',...
'position',[355,225,380,245])

add_block('built-in/Product',[sys,'/', 'X3Y3/Product1'])
set_param([sys,'/', 'X3Y3/Product1'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'inputs','2',...
'position',[355,95,380,115])

add_block('built-in/Outport',[sys,'/', 'X3Y3/out_1'])
set_param([sys,'/', 'X3Y3/out_1'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Port','1',...
'position',[490,145,510,165])

add_block('built-in/Outport',[sys,'/', 'X3Y3/out_2'])
set_param([sys,'/', 'X3Y3/out_2'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Port','2',...
'position',[570,275,590,295])

add_block('built-in/Product',[sys,'/', 'X3Y3/Product9'])
set_param([sys,'/', 'X3Y3/Product9'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'inputs','2',...
'position',[160,25,185,45])

add_block('built-in/Inport',[sys,'/', 'X3Y3/alpha3'])
set_param([sys,'/', 'X3Y3/alpha3'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Port','5',...
'position',[105,75,125,95])

add_line([sys,'/', 'X3Y3'],[190,35;200,35;200,85;210,85])
add_line([sys,'/', 'X3Y3'],[130,85;140,85;140,40;155,40])
add_line([sys,'/', 'X3Y3'],[130,30;155,30])
add_line([sys,'/', 'X3Y3'],[185,200;185,95;210,95])
add_line([sys,'/', 'X3Y3'],[100,285;205,285;205,210;245,210])
add_line([sys,'/', 'X3Y3'],[100,235;130,235;130,205;150,205])
add_line([sys,'/', 'X3Y3'],[245,90;265,90])
add_line([sys,'/', 'X3Y3'],[100,195;150,195])
add_line([sys,'/', 'X3Y3'],[185,200;245,200])
add_line([sys,'/', 'X3Y3'],[310,300;325,300;325,240;350,240])
add_line([sys,'/', 'X3Y3'],[325,300;410,300;410,255;440,255])
add_line([sys,'/', 'X3Y3'],[430,315;490,315;490,290;515,290])
add_line([sys,'/', 'X3Y3'],[475,250;500,250;500,280;515,280])
add_line([sys,'/', 'X3Y3'],[295,90;345,90;350,100])

```

```

add_line([sys, '/', 'X3Y3'], [310, 90; 310, 147; 390, 147; 390, 245; 44
0, 245])
add_line([sys, '/', 'X3Y3'], [310, 165; 330, 165; 330, 110; 350, 110])
add_line([sys, '/', 'X3Y3'], [330, 165; 330, 310; 395, 310])
add_line([sys, '/', 'X3Y3'], [280, 205; 335, 205; 335, 225; 350, 230])
add_line([sys, '/', 'X3Y3'], [335, 225; 325, 225; 310, 230; 310, 320; 3
95, 320])
add_line([sys, '/', 'X3Y3'], [385, 235; 400, 235; 400, 160; 435, 160])
add_line([sys, '/', 'X3Y3'], [385, 105; 410, 105; 410, 150; 435, 150])
add_line([sys, '/', 'X3Y3'], [215, 300; 260, 300])
add_line([sys, '/', 'X3Y3'], [225, 300; 225, 165; 260, 165])
add_line([sys, '/', 'X3Y3'], [465, 155; 485, 155])
add_line([sys, '/', 'X3Y3'], [545, 285; 565, 285])

```

% Finished composite block 'X3Y3'.

```

set_param([sys, '/', 'X3Y3'], ...
    'Font Number', 786433, ...
    'Drop Shadow', 786432, ...
    'position', [590, 565, 635, 635])

```

% Subsystem 'X2Y2'.

```

new_system([sys, '/', 'X2Y2'])
set_param([sys, '/', 'X2Y2'], 'Location', [1, 88, 536, 443])

add_block('built-in/Note', [sys, '/', 'X2Y2/Fy2'])
set_param([sys, '/', 'X2Y2/Fy2'], ...
    'Font Number', 786433, ...
    'Drop Shadow', 786432, ...
    'position', [320, 65, 321, 66])

add_block('built-in/Inport', [sys, '/', 'X2Y2/uy2'])
set_param([sys, '/', 'X2Y2/uy2'], ...
    'Font Number', 786433, ...
    'Drop Shadow', 786432, ...
    'Port', '1', ...
    'position', [105, 20, 125, 40])

add_block('built-in/Inport', [sys, '/', 'X2Y2/ux2'])
set_param([sys, '/', 'X2Y2/ux2'], ...
    'Font Number', 786433, ...
    'Drop Shadow', 786432, ...
    'Port', '3', ...
    'position', [75, 275, 95, 295])

add_block('built-in/Inport', [sys, '/', 'X2Y2/m2'])
set_param([sys, '/', 'X2Y2/m2'], ...
    'Font Number', 786433, ...
    'Drop Shadow', 786432, ...

```

```

        'Port','2',...
        'position',[75,225,95,245])

add_block('built-in/Product',[sys,'/', 'X2Y2/Product8'])
set_param([sys,'/', 'X2Y2/Product8'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[215,80,240,100])

add_block('built-in/Constant',[sys,'/', 'X2Y2/gravity1'])
set_param([sys,'/', 'X2Y2/gravity1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Value','g',...
    'position',[75,185,95,205])

add_block('built-in/Product',[sys,'/', 'X2Y2/Product6'])
set_param([sys,'/', 'X2Y2/Product6'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[155,190,180,210])

add_block('built-in/Product',[sys,'/', 'X2Y2/Product5'])
set_param([sys,'/', 'X2Y2/Product5'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[250,195,275,215])

add_block('built-in/Gain',[sys,'/', 'X2Y2/Gain2'])
set_param([sys,'/', 'X2Y2/Gain2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Gain','-1',...
    'position',[270,80,290,100])

add_block('built-in/Inport',[sys,'/', 'X2Y2/flsa'])
set_param([sys,'/', 'X2Y2/flsa'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Port','4',...
    'position',[190,290,210,310])

add_block('built-in/Product',[sys,'/', 'X2Y2/Product4'])
set_param([sys,'/', 'X2Y2/Product4'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[445,240,470,260])

```

```

add_block('built-in/Product',[sys,'/', 'X2Y2/Product3'])
set_param([sys,'/', 'X2Y2/Product3'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[400,305,425,325])

add_block('built-in/Sum',[sys,'/', 'X2Y2/sum2'])
set_param([sys,'/', 'X2Y2/sum2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','++',...
    'position',[520,275,540,295])

add_block('built-in/Sum',[sys,'/', 'X2Y2/Sum1'])
set_param([sys,'/', 'X2Y2/Sum1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','+-',...
    'position',[440,145,460,165])

add_block('built-in/Fcn',[sys,'/', 'X2Y2/Fcn1'])
set_param([sys,'/', 'X2Y2/Fcn1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','sin(u[1])',...
    'position',[265,155,305,175])

add_block('built-in/Fcn',[sys,'/', 'X2Y2/Fcn'])
set_param([sys,'/', 'X2Y2/Fcn'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'Expr','cos(u[1])',...
    'position',[265,290,305,310])

add_block('built-in/Product',[sys,'/', 'X2Y2/Product2'])
set_param([sys,'/', 'X2Y2/Product2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[355,225,380,245])

add_block('built-in/Product',[sys,'/', 'X2Y2/Product1'])
set_param([sys,'/', 'X2Y2/Product1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'inputs','2',...
    'position',[355,95,380,115])

add_block('built-in/Outport',[sys,'/', 'X2Y2/out_1'])
set_param([sys,'/', 'X2Y2/out_1'],...
    'Font Number',786433,...

```

```

'Drop Shadow',786432,...
'Port','1',...
'position',[490,145,510,165])

add_block('built-in/Outport',[sys,'/', 'X2Y2/out_2'])
set_param([sys,'/', 'X2Y2/out_2'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Port','2',...
'position',[570,275,590,295])

add_block('built-in/Product',[sys,'/', 'X2Y2/Product9'])
set_param([sys,'/', 'X2Y2/Product9'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'inputs','2',...
'position',[150,25,175,45])

add_block('built-in/Inport',[sys,'/', 'X2Y2/alpha2'])
set_param([sys,'/', 'X2Y2/alpha2'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Port','5',...
'position',[105,80,125,100])
add_line([sys,'/', 'X2Y2'],[130,90;135,90;135,40;145,40])
add_line([sys,'/', 'X2Y2'],[180,35;190,35;190,85;210,85])
add_line([sys,'/', 'X2Y2'],[130,30;145,30])
add_line([sys,'/', 'X2Y2'],[185,200;185,95;210,95])
add_line([sys,'/', 'X2Y2'],[100,285;205,285;205,210;245,210])
add_line([sys,'/', 'X2Y2'],[100,235;130,235;130,205;150,205])
add_line([sys,'/', 'X2Y2'],[245,90;265,90])
add_line([sys,'/', 'X2Y2'],[100,195;150,195])
add_line([sys,'/', 'X2Y2'],[185,200;245,200])
add_line([sys,'/', 'X2Y2'],[310,300;325,300;325,240;350,240])
add_line([sys,'/', 'X2Y2'],[325,300;410,300;410,255;440,255])
add_line([sys,'/', 'X2Y2'],[430,315;490,315;490,290;515,290])
add_line([sys,'/', 'X2Y2'],[475,250;500,250;500,280;515,280])
add_line([sys,'/', 'X2Y2'],[295,90;345,90;350,100])
add_line([sys,'/', 'X2Y2'],[310,90;310,147;390,147;390,245;440,245])
add_line([sys,'/', 'X2Y2'],[310,165;330,165;330,110;350,110])
add_line([sys,'/', 'X2Y2'],[330,165;330,310;395,310])
add_line([sys,'/', 'X2Y2'],[280,205;335,205;335,225;350,230])
add_line([sys,'/', 'X2Y2'],[335,225;325,225;310,230;310,320;395,320])
add_line([sys,'/', 'X2Y2'],[385,235;400,235;400,160;435,160])
add_line([sys,'/', 'X2Y2'],[385,105;410,105;410,150;435,150])
add_line([sys,'/', 'X2Y2'],[215,300;260,300])
add_line([sys,'/', 'X2Y2'],[225,300;225,165;260,165])
add_line([sys,'/', 'X2Y2'],[465,155;485,155])
add_line([sys,'/', 'X2Y2'],[545,285;565,285])

```

```

%      Finished composite block 'X2Y2'.

set_param([sys, '/', 'X2Y2'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'position', [590, 430, 635, 500])

add_block('built-in/Fcn', [sys, '/', 'Fcn3'])
set_param([sys, '/', 'Fcn3'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'Expr', 'lr/(2*(lf+lr))*(M+(h*u[1]))/(d*g)',...
    'position', [1535, 800, 1575, 820])

add_block('built-in/Fcn', [sys, '/', 'Fcn2'])
set_param([sys, '/', 'Fcn2'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'Expr', 'lr/(2*(lf+lr))*(M-(h*u[1]))/(d*g)',...
    'position', [1535, 745, 1575, 765])

add_block('built-in/Fcn', [sys, '/', 'Fcn1'])
set_param([sys, '/', 'Fcn1'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'Expr', 'lf/(2*(lf+lr))*(M+(h*u[1]))/(d*g)',...
    'position', [1535, 690, 1575, 710])

add_block('built-in/Fcn', [sys, '/', 'Fcn'])
set_param([sys, '/', 'Fcn'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'Expr', 'lf/(2*(lf+lr))*(M-(h*u[1]))/(d*g)',...
    'position', [1535, 645, 1575, 665])

add_block('built-in/To Workspace', [sys, '/', 'To Workspace'])
set_param([sys, '/', 'To Workspace'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'mat-name', 'ml',...
    'buffer', '1000',...
    'position', [1640, 647, 1690, 663])

add_block('built-in/Integrator', [sys, '/', 'Integrator'])
set_param([sys, '/', 'Integrator'],...
    'Font Number', 786433,...
    'Drop Shadow', 786432,...
    'Initial', '0',...
    'position', [1165, 295, 1185, 315])

add_block('built-in/Integrator', [sys, '/', 'Integrator1'])
set_param([sys, '/', 'Integrator1'],...

```

```

'Font Number',786433,...
'Drop Shadow',786432,...
'Initial','0',...
'position',[1280,295,1300,315])

add_block('built-in/Integrator',[sys, '/', 'Integrator2'])
set_param([sys, '/', 'Integrator2'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Initial','0',...
'position',[1170,400,1190,420])

add_block('built-in/Integrator',[sys, '/', 'Integrator3'])
set_param([sys, '/', 'Integrator3'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Initial','0',...
'position',[1280,400,1300,420])

add_block('built-in/Integrator',[sys, '/', 'Integrator4'])
set_param([sys, '/', 'Integrator4'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Initial','yawdint',...
'position',[1360,590,1380,610])

add_block('built-in/Integrator',[sys, '/', 'Integrator5'])
set_param([sys, '/', 'Integrator5'],...
'Font Number',786433,...
'Drop Shadow',786432,...
'Initial','0',...
'position',[1455,590,1475,610])

add_block('built-in/To Workspace',[sys, '/', ['x'']])
set_param([sys, '/', ['x'']],...
'Font Number',786433,...
'Drop Shadow',786432,...
'mat-name','xd',...
'buffer','1000',...
'position',[1265,252,1315,268])

add_block('built-in/To Workspace',[sys, '/', ['y'']])
set_param([sys, '/', ['y'']],...
'Font Number',786433,...
'Drop Shadow',786432,...
'mat-name','yrnc',...
'buffer','1000',...
'position',[1265,357,1315,373])

add_block('built-in/To Workspace',[sys, '/', ['yaw'']])
set_param([sys, '/', ['yaw'']],...
'Font Number',786433,...

```

```

        'Drop Shadow',786432,...
        'mat-name','yawd',...
        'buffer','1000',...
        'position',[1425,542,1475,558])

add_block('built-in/To Workspace',[sys,'/', 'To Workspace1'])
set_param([sys,'/', 'To Workspace1'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'mat-name','m2',...
    'buffer','1000',...
    'position',[1755,692,1805,708])

add_block('built-in/To Workspace',[sys,'/', 'To Workspace2'])
set_param([sys,'/', 'To Workspace2'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'mat-name','m3',...
    'buffer','1000',...
    'position',[1725,747,1775,763])

add_block('built-in/To Workspace',[sys,'/', 'To Workspace3'])
set_param([sys,'/', 'To Workspace3'],...
    'Font Number',786433,...
    'Drop Shadow',786432,...
    'mat-name','m4',...
    'buffer','1000',...
    'position',[1775,802,1825,818])

%      Subsystem 'X1Y1'.

new_system([sys,'/', 'X1Y1'])
set_param([sys,'/', 'X1Y1'],'Location',[1,88,536,443])

add_block('built-in/Note',[sys,'/', 'X1Y1/Fy1'])
set_param([sys,'/', 'X1Y1/Fy1'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'position',[321,65,322,66])

add_block('built-in/Inport',[sys,'/', 'X1Y1/uy1'])
set_param([sys,'/', 'X1Y1/uy1'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'Port','1',...
    'position',[105,20,125,40])

add_block('built-in/Inport',[sys,'/', 'X1Y1/ux1'])
set_param([sys,'/', 'X1Y1/ux1'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...

```

```

        'Port','3',...
        'position',[75,275,95,295])

add_block('built-in/Inport',[sys, '/', 'X1Y1/m1'])
set_param([sys, '/', 'X1Y1/m1'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'Port','2',...
    'position',[75,235,95,255])

add_block('built-in/Product',[sys, '/', 'X1Y1/Product8'])
set_param([sys, '/', 'X1Y1/Product8'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','2',...
    'position',[215,80,240,100])

add_block('built-in/Constant',[sys, '/', 'X1Y1/gravity1'])
set_param([sys, '/', 'X1Y1/gravity1'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'Value','g',...
    'position',[75,185,95,205])

add_block('built-in/Product',[sys, '/', 'X1Y1/Product6'])
set_param([sys, '/', 'X1Y1/Product6'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','2',...
    'position',[155,190,180,210])

add_block('built-in/Product',[sys, '/', 'X1Y1/Product5'])
set_param([sys, '/', 'X1Y1/Product5'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','2',...
    'position',[250,195,275,215])

add_block('built-in/Gain',[sys, '/', 'X1Y1/Gain2'])
set_param([sys, '/', 'X1Y1/Gain2'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'Gain','-1',...
    'position',[270,80,290,100])

add_block('built-in/Inport',[sys, '/', 'X1Y1/flsa'])
set_param([sys, '/', 'X1Y1/flsa'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'Port','4',...
    'position',[190,290,210,310])

```

```

add_block('built-in/Product',[sys, '/', 'X1Y1/Product4'])
set_param([sys, '/', 'X1Y1/Product4'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','2',...
    'position',[445,240,470,260])

add_block('built-in/Product',[sys, '/', 'X1Y1/Product3'])
set_param([sys, '/', 'X1Y1/Product3'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','2',...
    'position',[400,305,425,325])

add_block('built-in/Sum',[sys, '/', 'X1Y1/sum2'])
set_param([sys, '/', 'X1Y1/sum2'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','++',...
    'position',[520,275,540,295])

add_block('built-in/Sum',[sys, '/', 'X1Y1/Sum1'])
set_param([sys, '/', 'X1Y1/Sum1'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','+-',...
    'position',[440,145,460,165])

add_block('built-in/Fcn',[sys, '/', 'X1Y1/Fcn1'])
set_param([sys, '/', 'X1Y1/Fcn1'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'Expr','sin(u[1])',...
    'position',[265,155,305,175])

add_block('built-in/Fcn',[sys, '/', 'X1Y1/Fcn'])
set_param([sys, '/', 'X1Y1/Fcn'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'Expr','cos(u[1])',...
    'position',[265,290,305,310])

add_block('built-in/Product',[sys, '/', 'X1Y1/Product2'])
set_param([sys, '/', 'X1Y1/Product2'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','2',...
    'position',[355,225,380,245])

add_block('built-in/Product',[sys, '/', 'X1Y1/Product1'])
set_param([sys, '/', 'X1Y1/Product1'],...
    'Font Number',720897,...

```

```

        'Drop Shadow',720896,...
        'inputs','2',...
        'position',[355,95,380,115])

add_block('built-in/Outport',[sys, '/', 'X1Y1/out_1'])
set_param([sys, '/', 'X1Y1/out_1'],...
        'Font Number',720897,...
        'Drop Shadow',720896,...
        'Port','1',...
        'position',[495,145,515,165])

add_block('built-in/Outport',[sys, '/', 'X1Y1/out_2'])
set_param([sys, '/', 'X1Y1/out_2'],...
        'Font Number',720897,...
        'Drop Shadow',720896,...
        'Port','2',...
        'position',[570,275,590,295])

add_block('built-in/Product',[sys, '/', 'X1Y1/Product9'])
set_param([sys, '/', 'X1Y1/Product9'],...
        'Font Number',720897,...
        'Drop Shadow',720896,...
        'inputs','2',...
        'position',[155,25,180,45])

add_block('built-in/Inport',[sys, '/', 'X1Y1/alpha1'])
set_param([sys, '/', 'X1Y1/alpha1'],...
        'Font Number',720897,...
        'Drop Shadow',720896,...
        'Port','5',...
        'position',[80,65,100,85])
add_line([sys, '/', 'X1Y1'],[185,35;195,35;195,85;210,85])
add_line([sys, '/', 'X1Y1'],[105,75;140,75;140,40;150,40])
add_line([sys, '/', 'X1Y1'],[130,30;150,30])
add_line([sys, '/', 'X1Y1'],[185,200;185,95;210,95])
add_line([sys, '/', 'X1Y1'],[100,285;205,285;205,210;245,210])
add_line([sys, '/', 'X1Y1'],[100,245;130,245;130,205;150,205])
add_line([sys, '/', 'X1Y1'],[245,90;265,90])
add_line([sys, '/', 'X1Y1'],[100,195;150,195])
add_line([sys, '/', 'X1Y1'],[185,200;245,200])
add_line([sys, '/', 'X1Y1'],[310,300;325,300;325,240;350,240])
add_line([sys, '/', 'X1Y1'],[325,300;410,300;410,255;440,255])
add_line([sys, '/', 'X1Y1'],[430,315;490,315;490,290;515,290])
add_line([sys, '/', 'X1Y1'],[475,250;500,250;500,280;515,280])
add_line([sys, '/', 'X1Y1'],[295,90;345,90;350,100])
add_line([sys, '/', 'X1Y1'],[310,90;310,147;390,147;390,245;440,245])
add_line([sys, '/', 'X1Y1'],[310,165;330,165;330,110;350,110])
add_line([sys, '/', 'X1Y1'],[330,165;330,310;395,310])
add_line([sys, '/', 'X1Y1'],[280,205;335,205;335,225;350,230])
add_line([sys, '/', 'X1Y1'],[335,225;325,225;310,230;310,320;395,320])

```

```

add_line([sys, '/', 'X1Y1'], [385, 235; 400, 235; 400, 160; 435, 160])
add_line([sys, '/', 'X1Y1'], [385, 105; 410, 105; 410, 150; 435, 150])
add_line([sys, '/', 'X1Y1'], [215, 300; 260, 300])
add_line([sys, '/', 'X1Y1'], [225, 300; 225, 165; 260, 165])
add_line([sys, '/', 'X1Y1'], [465, 155; 490, 155])
add_line([sys, '/', 'X1Y1'], [545, 285; 565, 285])

```

```

%      Finished composite block 'X1Y1'.

```

```

set_param([sys, '/', 'X1Y1'], ...
    'Font Number', 720897, ...
    'Drop Shadow', 720896, ...
    'position', [585, 310, 630, 380])

```

```

add_block('built-in/Sum', [sys, '/', 'Sum'])
set_param([sys, '/', 'Sum'], ...
    'Font Number', 720897, ...
    'Drop Shadow', 720896, ...
    'inputs', '+++++', ...
    'position', [990, 277, 1010, 333])

```

```

add_block('built-in/Product', [sys, '/', 'Product'])
set_param([sys, '/', 'Product'], ...
    'Font Number', 720897, ...
    'Drop Shadow', 720896, ...
    'inputs', '2', ...
    'position', [1085, 295, 1110, 315])

```

```

add_block('built-in/Constant', [sys, '/', '1//Mass'])
set_param([sys, '/', '1//Mass'], ...
    'Font Number', 720897, ...
    'Drop Shadow', 720896, ...
    'Value', '1/M', ...
    'position', [1030, 320, 1055, 350])

```

```

add_block('built-in/Product', [sys, '/', 'Product1'])
set_param([sys, '/', 'Product1'], ...
    'Font Number', 720897, ...
    'Drop Shadow', 720896, ...
    'inputs', '2', ...
    'position', [1110, 400, 1135, 420])

```

```

add_block('built-in/Constant', [sys, '/', '1//Mass1'])
set_param([sys, '/', '1//Mass1'], ...
    'Font Number', 720897, ...
    'Drop Shadow', 720896, ...
    'Value', '1/M', ...
    'position', [1060, 440, 1085, 470])

```

```

add_block('built-in/Sum', [sys, '/', 'Sum1'])
set_param([sys, '/', 'Sum1'], ...

```

```

'Font Number',720897,...
'Drop Shadow',720896,...
'inputs','++++-',...
'position',[1005,377,1025,433])

add_block('built-in/Sum',[sys, '/', 'Sum2'])
set_param([sys, '/', 'Sum2'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'inputs','+--+ ',...
'position',[1275,573,1295,632])

add_block('built-in/Product',[sys, '/', 'Product2'])
set_param([sys, '/', 'Product2'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'inputs','2',...
'position',[1180,510,1205,530])

add_block('built-in/Product',[sys, '/', 'Product3'])
set_param([sys, '/', 'Product3'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'inputs','2',...
'position',[1195,585,1220,605])

add_block('built-in/Product',[sys, '/', 'Product4'])
set_param([sys, '/', 'Product4'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'inputs','2',...
'position',[1195,650,1220,670])

add_block('built-in/Product',[sys, '/', 'Product5'])
set_param([sys, '/', 'Product5'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'inputs','2',...
'position',[1195,720,1220,740])

add_block('built-in/Constant',[sys, '/', 'd'])
set_param([sys, '/', 'd'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'Value','d',...
'position',[1140,672,1165,698])

add_block('built-in/Constant',[sys, '/', 'lr'])
set_param([sys, '/', 'lr'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'Value','lr',...

```

```

        'position',[1120,602,1145,628])

add_block('built-in/Constant',[sys, '/', 'lf'])
set_param([sys, '/', 'lf'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'Value','lf',...
    'position',[1115,527,1140,553])

add_block('built-in/Sum',[sys, '/', 'Sum3'])
set_param([sys, '/', 'Sum3'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','++',...
    'position',[1085,497,1105,533])

add_block('built-in/Sum',[sys, '/', 'Sum4'])
set_param([sys, '/', 'Sum4'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','++',...
    'position',[1085,572,1105,608])

add_block('built-in/Sum',[sys, '/', 'Sum5'])
set_param([sys, '/', 'Sum5'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','++',...
    'position',[1080,637,1100,673])

add_block('built-in/Sum',[sys, '/', 'Sum6'])
set_param([sys, '/', 'Sum6'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'inputs','++',...
    'position',[1085,717,1105,753])

add_block('built-in/Note',[sys, '/', 'X1 '])
set_param([sys, '/', 'X1 '],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'position',[689,315,690,316])

add_block('built-in/Note',[sys, '/', 'Y1'])
set_param([sys, '/', 'Y1'],...
    'Font Number',720897,...
    'Drop Shadow',720896,...
    'position',[698,345,699,346])

add_block('built-in/To Workspace',[sys, '/', 'To Workspace8'])
set_param([sys, '/', 'To Workspace8'],...
    'Font Number',720897,...

```

```

'Drop Shadow',720896,...
'mat-name','Y3',...
'buffer','1000',...
'position',[715,606,745,634])

add_block('built-in/To Workspace',[sys, '/', 'To Workspace9'])
set_param([sys, '/', 'To Workspace9'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'mat-name','X3',...
'buffer','1000',...
'position',[905,566,935,594])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspacel0'])
set_param([sys, '/', 'To Workspacel0'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'mat-name','Y4',...
'buffer','1000',...
'position',[830,761,860,789])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspacel1'])
set_param([sys, '/', 'To Workspacel1'],...
'Font Number',720897,...
'Drop Shadow',720896,...
'mat-name','X4',...
'buffer','1000',...
'position',[1010,691,1040,719])

add_block('built-in/Constant',[sys, '/', 'fsa'])
set_param([sys, '/', 'fsa'],...
'Font Number',655361,...
'Drop Shadow',655360,...
'Value','sa',...
'position',[395,490,415,510])

add_block('built-in/To Workspace',[sys, '/', ['Y''1']])
set_param([sys, '/', ['Y''1']],...
'Font Number',655361,...
'Drop Shadow',655360,...
'mat-name','ydd',...
'buffer','1000',...
'position',[1165,447,1215,463])

add_block('built-in/To Workspace',[sys, '/', ['x''1']])
set_param([sys, '/', ['x''1']],...
'Font Number',655361,...
'Drop Shadow',655360,...
'mat-name','xdd',...
'buffer','1000',...

```

```

        'position',[1155,337,1205,353])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspace16'])
set_param([sys, '/', 'To Workspace16'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'mat-name','n4',...
    'buffer','1000',...
    'position',[2145,477,2195,493])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspace17'])
set_param([sys, '/', 'To Workspace17'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'mat-name','n3',...
    'buffer','1000',...
    'position',[2240,392,2290,408])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspace18'])
set_param([sys, '/', 'To Workspace18'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'mat-name','n2',...
    'buffer','1000',...
    'position',[2235,332,2285,348])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspace19'])
set_param([sys, '/', 'To Workspace19'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'mat-name','n1',...
    'buffer','1000',...
    'position',[2230,267,2280,283])

add_block('built-in/Constant',[sys, '/', 'ydesired'])
set_param([sys, '/', 'ydesired'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'Value','V/row',...
    'position',[1410,395,1435,425])

add_block('built-in/Sum',[sys, '/', 'Sum11'])
set_param([sys, '/', 'Sum11'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'inputs','--',...
    'position',[1460,399,1485,441])

```

```

add_block('built-in/To Workspace',[sys, '/', 'To
Workspace20'])
set_param([sys, '/', 'To Workspace20'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'mat-name','yrerr',...
    'buffer','1000',...
    'position',[1530,412,1580,428])

add_block('built-in/Look Up Table',[sys, '/', 'uy_table'])
set_param([sys, '/', 'uy_table'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'Input_Values','[-1 -0.75 -0.5 -0.25 -0.125 0 0.125 0.25 0.5
0.75 1]',...
    'Output_Values','[0.2 0.22 0.37 0.7 0.9 1 0.9 0.7 0.37 0.22 0.2]')
set_param([sys, '/', 'uy_table'],...
    'position',[195,295,240,335])

add_block('built-in/Look Up Table',[sys, '/', 'ux_table'])
set_param([sys, '/', 'ux_table'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'Input_Values','[-1 -0.75 -0.5 -0.375 -0.25 -0.125 0 0.125
0.25 0.375 0.5 0.75 1]',...
    'Output_Values','[-0.7 -0.75 -0.8 -1 -0.8 -0.5 0 0.5 0.8 1 0.8
0.75 0.7]')
set_param([sys, '/', 'ux_table'],...
    'position',[195,360,240,400])

add_block('built-in/Look Up Table',[sys, '/', 'uy_table1'])
set_param([sys, '/', 'uy_table1'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'Input_Values','[-1 -0.75 -0.5 -0.25 -0.125 0 0.125 0.25 0.5
0.75 1]',...
    'Output_Values','[0.2 0.22 0.37 0.7 0.9 1 0.9 0.7 0.37 0.22 0.2]')
set_param([sys, '/', 'uy_table1'],...
    'position',[200,550,245,590])

add_block('built-in/Look Up Table',[sys, '/', 'ux_table1'])
set_param([sys, '/', 'ux_table1'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'Input_Values','[-1 -0.75 -0.5 -0.375 -0.25 -0.125 0 0.125
0.25 0.375 0.5 0.75 1]',...
    'Output_Values','[-0.7 -0.75 -0.8 -1 -0.8 -0.5 0 0.5 0.8 1 0.8
0.75 0.7]')
set_param([sys, '/', 'ux_table1'],...
    'position',[200,705,245,745])

add_block('built-in/Constant',[sys, '/', 'rsa'])

```

```

set_param([sys, '/', 'rsa'],...
    'Font Number', 655361,...
    'Drop Shadow', 655360,...
    'Value', '-sa',...
    'position', [335, 640, 355, 660])

add_block('built-in/Look Up Table',[sys, '/', 'uy_table2'])
set_param([sys, '/', 'uy_table2'],...
    'Font Number', 655361,...
    'Drop Shadow', 655360,...
    'Input_Values', '[0 1 2 3 4 5 6 7 8 9 10]',...
    'Output_Values', '[0 0 FS 0 0 0 0 0 0 0 0]',...
    'position', [105, 295, 150, 335])

add_block('built-in/Clock',[sys, '/', 'Clock'])
set_param([sys, '/', 'Clock'],...
    'Font Number', 655361,...
    'Drop Shadow', 655360,...
    'position', [45, 305, 65, 325])

add_block('built-in/Look Up Table',[sys, '/', 'uy_table3'])
set_param([sys, '/', 'uy_table3'],...
    'Font Number', 655361,...
    'Drop Shadow', 655360,...
    'Input_Values', '[0 1 2 3 4 5 6 7 8 9 10]',...
    'Output_Values', '[0 0 RS 0 0 0 0 0 0 0 0]',...
    'position', [100, 550, 145, 590])

add_block('built-in/To Workspace',[sys, '/', 'To
Workspace21'])
set_param([sys, '/', 'To Workspace21'],...
    'Font Number', 655361,...
    'Drop Shadow', 655360,...
    'mat-name', 'rslip',...
    'buffer', '1000',...
    'position', [210, 486, 240, 514])

add_block('built-in/Constant',[sys, '/', 'fsal'])
set_param([sys, '/', 'fsal'],...
    'Font Number', 655361,...
    'Drop Shadow', 655360,...
    'Value', '0',...
    'position', [380, 450, 400, 470])

add_block('built-in/Constant',[sys, '/', 'rsal'])
set_param([sys, '/', 'rsal'],...
    'Font Number', 655361,...
    'Drop Shadow', 655360,...
    'Value', '0',...
    'position', [335, 680, 355, 700])

add_block('built-in/Constant',[sys, '/', 'Constant9'])

```

```

set_param([sys, '/', 'Constant9'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'Value','0',...
    'position',[1935,610,1955,630])

add_block('built-in/Constant',[sys, '/', 'Constant10'])
set_param([sys, '/', 'Constant10'],...
    'Font Number',655361,...
    'Drop Shadow',655360,...
    'Value','0',...
    'position',[1905,175,1925,195])
add_line(sys,[155,315;190,315])
add_line(sys,[170,315;170,250;205,255])
add_line(sys,[405,460;450,460;455,480])
add_line(sys,[420,460;420,435;335,435;335,400;365,400])
add_line(sys,[2000,210;2030,210;2030,270;2040,270])
add_line(sys,[2030,270;2030,345;2095,345])
add_line(sys,[1915,230;1950,230;1970,215])
add_line(sys,[1930,185;1955,185;1955,205;1970,205])
add_line(sys,[1960,620;1980,620;1980,575;2005,575])
add_line(sys,[2035,570;2045,570;2045,405;2095,405])
add_line(sys,[2045,470;2060,470])
add_line(sys,[1945,565;2005,565])
add_line(sys,[425,660;550,660;550,740;595,740])
add_line(sys,[550,660;550,615;585,615])
add_line(sys,[360,650;390,650])
add_line(sys,[490,490;560,485;585,480])
add_line(sys,[540,486;580,360])
add_line(sys,[420,500;455,500])
add_line(sys,[1765,300;1815,325;1895,325])
add_line(sys,[1815,325;1815,385;1895,385])
add_line(sys,[1815,385;1815,450;1895,450])
add_line(sys,[1815,325;1815,270;1895,270])
add_line(sys,[1305,305;1340,295])
add_line(sys,[1305,410;1310,410])
add_line(sys,[2025,460;2060,460])
add_line(sys,[2020,395;2095,395])
add_line(sys,[2020,335;2095,335])
add_line(sys,[2020,280;2040,280])
add_line(sys,[1670,440;1735,440])
add_line(sys,[1695,440;1695,230;1665,230])
add_line(sys,[1195,410;1275,410])
add_line(sys,[1235,410;1235,365;1260,365])
add_line(sys,[1235,365;1235,345;1830,345;1830,280;1895,280])
add_line(sys,[1830,345;1830,460;1895,460])
add_line(sys,[1830,395;1895,395])
add_line(sys,[1830,335;1895,335])
add_line(sys,[1935,460;1975,460])
add_line(sys,[1935,395;1970,395])
add_line(sys,[1935,335;1970,335])
add_line(sys,[1935,280;1970,280])

```

```

add_line(sys,[1300,810;1290,810;1285,805;1270,805])
add_line(sys,[1615,230;1045,230;1045,200;940,200;940,230;945
,225])
add_line(sys,[1480,230;1480,280;1500,280])
add_line(sys,[980,230;995,230;995,265;960,265;960,325;985,32
5])
add_line(sys,[995,255;1025,255])
add_line(sys,[1695,440;1695,625;1395,625;1395,810;1350,810])
add_line(sys,[930,235;945,235])
add_line(sys,[1485,655;1530,655])
add_line(sys,[1510,655;1510,565;1525,565])
add_line(sys,[1235,800;970,800;970,425;1000,425])
add_line(sys,[1510,655;1510,700;1530,700])
add_line(sys,[1510,700;1510,810;1530,810])
add_line(sys,[1510,780;1420,780;1420,795;1270,795])
add_line(sys,[1225,595;1225,715;1280,715])
add_line(sys,[1210,520;1245,520;1245,580;1270,580])
add_line(sys,[1245,580;1245,680;1280,680])
add_line(sys,[1355,535;1370,535;1370,580;1330,580;1325,600;1
355,600])
add_line(sys,[1300,605;1310,605;1310,540;1320,540])
add_line(sys,[1300,505;1310,505;1310,530;1320,530])
add_line(sys,[1540,490;1625,490])
add_line(sys,[1560,490;1560,440;1640,440])
add_line(sys,[1580,810;1770,810])
add_line(sys,[1650,810;1650,895;515,895;515,710;595,710])
add_line(sys,[1580,755;1720,755])
add_line(sys,[1620,755;1620,865;325,865;325,585;585,585])
add_line(sys,[1580,700;1750,700])
add_line(sys,[1710,700;1710,190;525,190;525,450;585,450])
add_line(sys,[1580,655;1635,655])
add_line(sys,[1600,655;1600,180;500,180;500,330;580,330])
add_line(sys,[1510,755;1530,755])
add_line(sys,[1190,305;1275,305])
add_line(sys,[1230,305;1230,260;1260,260])
add_line(sys,[1060,335;1070,335;1070,310;1080,310])
add_line(sys,[1015,305;1080,300])
add_line(sys,[635,330;795,330])
add_line(sys,[780,330;780,285;985,285])
add_line(sys,[640,450;865,445])
add_line(sys,[840,446;840,295;985,295])
add_line(sys,[640,585;900,580])
add_line(sys,[885,580;885,305;985,305])
add_line(sys,[650,710;1005,705])
add_line(sys,[940,706;940,315;985,315])
add_line(sys,[1140,410;1165,410])
add_line(sys,[1090,455;1090,415;1105,415])
add_line(sys,[1030,405;1105,405])
add_line(sys,[640,485;705,485])
add_line(sys,[685,485;685,395;1000,395])
add_line(sys,[1110,515;1175,515])
add_line(sys,[1145,540;1155,540;1155,525;1175,525])

```

```

add_line(sys,[635,365;710,365])
add_line(sys,[685,365;685,385;1000,385])
add_line(sys,[915,385;915,505;1080,505])
add_line(sys,[685,485;685,525;1080,525])
add_line(sys,[1110,590;1190,590])
add_line(sys,[640,620;710,620])
add_line(sys,[675,620;675,540;790,540;790,405;1000,405])
add_line(sys,[790,540;1055,540;1055,580;1080,580])
add_line(sys,[1150,615;1180,615;1180,600;1190,600])
add_line(sys,[1225,595;1270,595])
add_line(sys,[755,330;755,645;1075,645])
add_line(sys,[885,580;885,665;1075,665])
add_line(sys,[1105,655;1190,655])
add_line(sys,[1225,660;1240,660;1240,610;1270,610])
add_line(sys,[940,706;940,725;1080,725])
add_line(sys,[840,446;840,745;1080,745])
add_line(sys,[1110,735;1190,735])
add_line(sys,[1170,685;1180,685;1180,665;1190,665])
add_line(sys,[1180,685;1180,725;1190,725])
add_line(sys,[1225,730;1250,730;1250,625;1270,625])
add_line(sys,[1140,410;1140,455;1160,455])
add_line(sys,[1115,305;1160,305])
add_line(sys,[1130,305;1130,345;1150,345])
add_line(sys,[650,745;670,745;670,680;820,680;820,775;825,775])
add_line(sys,[820,680;820,600;1080,600])
add_line(sys,[955,600;955,415;1000,415])
add_line(sys,[1385,600;1450,600])
add_line(sys,[1400,600;1400,550;1420,550])
add_line(sys,[1400,550;1400,490;1490,490])
add_line(sys,[1400,490;1400,360;1845,360;1845,290;1895,290])
add_line(sys,[1845,345;1895,345])
add_line(sys,[1845,360;1845,405;1895,405])
add_line(sys,[1845,405;1845,470;1895,470])
add_line(sys,[2090,465;2195,465;2195,75;270,75;270,770;580,770;580,755;595,755])
add_line(sys,[2130,465;2130,485;2140,485])
add_line(sys,[2125,400;2185,400;2185,100;300,100;300,630;585,630])
add_line(sys,[2185,400;2235,400])
add_line(sys,[2125,340;2145,340;2145,115;330,115;330,545;575,545;575,495;585,495])
add_line(sys,[2145,340;2230,340])
add_line(sys,[2070,275;2105,275;2105,145;545,145;545,375;580,375])
add_line(sys,[2105,275;2225,275])
add_line(sys,[1440,410;1455,410])
add_line(sys,[1445,490;1445,430;1455,430])
add_line(sys,[1490,420;1525,420])
add_line(sys,[250,570;435,570;435,695;595,695])
add_line(sys,[435,570;585,570])
add_line(sys,[245,380;485,380;485,465;585,465])

```

```

add_line(sys,[480,380;480,345;580,345])
add_line(sys,[245,315;435,315;435,435;585,435])
add_line(sys,[435,315;580,315])
add_line(sys,[170,315;170,380;190,380])
add_line(sys,[70,315;100,315])
add_line(sys,[70,315;80,315;95,570])
add_line(sys,[150,570;195,570])
add_line(sys,[170,570;170,725;195,725])
add_line(sys,[170,570;170,500;205,500])
add_line(sys,[250,725;595,725])
add_line(sys,[475,725;475,600;585,600])
add_line(sys,[360,690;390,670])
% Return any arguments.
if (nargin | nargout)
    % Must use feval here to access system in memory
    if (nargin > 3)
        if (flag == 0)
            eval(['[ret,x0,xstr]=',sys,'(t,x,u,flag);'])
        else
            eval(['ret =', sys,'(t,x,u,flag);'])
        end
    else
        [ret,x0,str] = feval(sys);
    end
end
end

```

APPENDIX B
PROGRAM LISTINGS OF FUZZY LOGIC CONTROLLER

```

$Programmer: Gary L. Brown
$Date created: August 27, 1993
$Date last modified: October 15, 1993
$Filename: fsteera.fil
$Description: This program describes the inference process
               of the fuzzy logic controller which governs
               the front steering compensation actions.

```

Note that this program was developed using
fide™ fuzzy logic controller software
developed by APTRONIX™.

```

$
$ In this routine, the input variables are yaw rate error
$ (yre) and front slip (f_slip) where
$     yre = yaw_rate_desired - yaw_rate_measured
$
$ the output variable is front steering compensation (fstr)
$

```

```

$header
fiu tvfi (min max) *8;

```

\$The input variables and there membership functions

```

invar yre "radians/sec": -5()5 [
    YNL    (@-5.0,1,   @-2,1,   @-1,0),
    YNML   (@-2,0,    @-1,1,   @-0.2,0),
    YNM    (@-1.0,0,   @-0.2,1,  @0.2,0),
    YPM    (@-0.2,0,   @0.2,1,   @1,0),
    YPML   (@0.2,0,    @1,1,    @2,0),
    YPL    (@1,0,     @2,1,     @5,1)
];

invar f_slip "units": -1()1 [
    FS_NL   (@-1,1,     @-0.6,1,   @-0.4,0),
    FS_NML  (@-0.6,0,    @-0.5,1,   @-0.4,0),
    FS_NM   (@-0.5,0,    @-0.4,1,   @-0.19,0),
    FS_Z    (@-0.21,0,   @-0.1,1,   @0.0,0),
    FS_PM   (@-0.1,0,    @0.0,1,   @0.1,0),
    FS_PML  (@0.0,0,     @0.1,1,   @0.4,0),
    FS_PL   (@0.1,0,     @0.4,1,   @1,1)
];

```

\$ The output variable and its membership function

```

outvar fstr "radians": -0.78()0.78 * (
    SA_NL   =-0.78,
    SA_NML  =-0.70,
    SA_NM   =-0.62,
    SA_ZE   =0,
    SA_PM   =0.62,
    SA_PML  =0.70,
    SA_PL   =0.78);

```

\$rules describe the relations between input variable and output variables

```
if yre is YPL and f_slip is FS_NL then fstr is SA_NL;
if yre is YPL and f_slip is FS_NML then fstr is SA_NML;
if yre is YPL and f_slip is FS_NM then fstr is SA_NM;
if yre is YPL and f_slip is FS_Z then fstr is SA_PM;
if yre is YPL and f_slip is FS_PM then fstr is SA_PM;
if yre is YPL and f_slip is FS_PML then fstr is SA_PM;
if yre is YPL and f_slip is FS_PL then fstr is SA_PML;

if yre is YPML and f_slip is FS_NL then fstr is SA_NML;
if yre is YPML and f_slip is FS_NML then fstr is SA_NML;
if yre is YPML and f_slip is FS_NM then fstr is SA_NM;
if yre is YPML and f_slip is FS_Z then fstr is SA_PM;
if yre is YPML and f_slip is FS_PM then fstr is SA_PM;
if yre is YPML and f_slip is FS_PML then fstr is SA_PM;
if yre is YPML and f_slip is FS_PL then fstr is SA_PM;

if yre is YPM and f_slip is FS_NL then fstr is SA_NM;
if yre is YPM and f_slip is FS_NML then fstr is SA_NM;
if yre is YPM and f_slip is FS_NM then fstr is SA_NM;
if yre is YPM and f_slip is FS_Z then fstr is SA_PM;
if yre is YPM and f_slip is FS_PM then fstr is SA_PM;
if yre is YPM and f_slip is FS_PML then fstr is SA_PM;
if yre is YPM and f_slip is FS_PL then fstr is SA_PM;

if yre is YNM and f_slip is FS_NL then fstr is SA_PM;
if yre is YNM and f_slip is FS_NML then fstr is SA_PM;
if yre is YNM and f_slip is FS_NM then fstr is SA_PM;
if yre is YNM and f_slip is FS_Z then fstr is SA_NM;
if yre is YNM and f_slip is FS_PM then fstr is SA_NM;
if yre is YNM and f_slip is FS_PML then fstr is SA_NM;
if yre is YNM and f_slip is FS_PL then fstr is SA_NM;

if yre is YNML and f_slip is FS_NL then fstr is SA_PL;
if yre is YNML and f_slip is FS_NML then fstr is SA_PML;
if yre is YNML and f_slip is FS_NM then fstr is SA_PM;
if yre is YNML and f_slip is FS_Z then fstr is SA_NM;
if yre is YNML and f_slip is FS_PM then fstr is SA_NM;
if yre is YNML and f_slip is FS_PML then fstr is SA_NM;
if yre is YNML and f_slip is FS_PL then fstr is SA_NML;

if yre is YNL and f_slip is FS_NL then fstr is SA_PL;
if yre is YNL and f_slip is FS_NML then fstr is SA_PML;
if yre is YNL and f_slip is FS_NM then fstr is SA_PM;
if yre is YNL and f_slip is FS_Z then fstr is SA_NM;
if yre is YNL and f_slip is FS_PM then fstr is SA_NM;
if yre is YNL and f_slip is FS_PML then fstr is SA_NM;
if yre is YNL and f_slip is FS_PL then fstr is SA_NML;
end
```

```

$Programmer: Gary L. Brown
$Date created: August 27, 1993
$Date last modified: October 18, 1993
$Filename: rrsteera.fil
$Description: This program describes the inference process
               of the fuzzy logic controller which governs
               the rear steering compensation actions.

```

Note that this program was developed using
fide™ fuzzy logic controller software
developed by APTRONIX™.

```

$ In this routine, the input variables are yaw rate error
$ (yre) and rear slip (r_slip) where
$     yre = yaw_rate_desired - yaw_rate_measured
$
$ the output variable is rear steering compensation (rstr)
$

```

```

$header
fiu tvfi (min max) *8;

```

\$The input variables and there membership functions

```

invar yre "radians/sec": -5()5 [
    YNL    (@-5.0,1,    @-2,1,    @-1,0),
    YNML    (@-2,0,    @-1,1,    @-0.2,0),
    YNM     (@-1.0,0,    @-0.2,1,    @0.2,0),
    YPM     (@-0.2,0,    @0.2,1,    @1,0),
    YPML    (@0.2,0,    @1,1,    @2,0),
    YPL     (@1,0,    @2,1,    @5,1)
];

invar r_slip "units": -1()1 [
    RS_NL    (@-1,1,    @-0.6,1,    @-0.4,0),
    RS_NML    (@-0.6,0,    @-0.5,1,    @-0.4,0),
    RS_NM     (@-0.5,0,    @-0.4,1,    @-0.19,0),
    RS_Z      (@-0.21,0,    @-0.1,1,    @0.0,0),
    RS_PM     (@-0.1,0,    @0.0,1,    @0.1,0),
    RS_PML    (@0.0,0,    @0.1,1,    @0.4,0),
    RS_PL     (@0.1,0,    @0.4,1,    @1,1)
];

```

\$ The output variable and its membership function

```

outvar rstr "radians": -0.78()0.78 * (
    SA_PL    =0.78,
    SA_PML    =0.70,
    SA_PM     =0.62,
    SA_ZE     =0,
    SA_NM     =-0.62,
    SA_NML    =-0.70,
    SA_NL     =-0.78);

```

\$rules describe the relations between input variable and output variables

```
if yre is YPL and r_slip is RS_NL then rstr is SA_PL;
if yre is YPL and r_slip is RS_NML then rstr is SA_PML;
if yre is YPL and r_slip is RS_NM then rstr is SA_PM;
if yre is YPL and r_slip is RS_Z then rstr is SA_NM;
if yre is YPL and r_slip is RS_PM then rstr is SA_NM;
if yre is YPL and r_slip is RS_PML then rstr is SA_NM;
if yre is YPL and r_slip is RS_PL then rstr is SA_NML;

if yre is YPML and r_slip is RS_NL then rstr is SA_PML;
if yre is YPML and r_slip is RS_NML then rstr is SA_PML;
if yre is YPML and r_slip is RS_NM then rstr is SA_PM;
if yre is YPML and r_slip is RS_Z then rstr is SA_NM;
if yre is YPML and r_slip is RS_PM then rstr is SA_NM;
if yre is YPML and r_slip is RS_PML then rstr is SA_NM;
if yre is YPML and r_slip is RS_PL then rstr is SA_NM;

if yre is YPM and r_slip is RS_NL then rstr is SA_PM;
if yre is YPM and r_slip is RS_NML then rstr is SA_PM;
if yre is YPM and r_slip is RS_NM then rstr is SA_PM;
if yre is YPM and r_slip is RS_Z then rstr is SA_NM;
if yre is YPM and r_slip is RS_PM then rstr is SA_NM;
if yre is YPM and r_slip is RS_PML then rstr is SA_NM;
if yre is YPM and r_slip is RS_PL then rstr is SA_NM;

if yre is YNM and r_slip is RS_NL then rstr is SA_NM;
if yre is YNM and r_slip is RS_NML then rstr is SA_NM;
if yre is YNM and r_slip is RS_NM then rstr is SA_NM;
if yre is YNM and r_slip is RS_Z then rstr is SA_PM;
if yre is YNM and r_slip is RS_PM then rstr is SA_PM;
if yre is YNM and r_slip is RS_PML then rstr is SA_PM;
if yre is YNM and r_slip is RS_PL then rstr is SA_PM;

if yre is YNML and r_slip is RS_NL then rstr is SA_NL;
if yre is YNML and r_slip is RS_NML then rstr is SA_NML;
if yre is YNML and r_slip is RS_NM then rstr is SA_NM;
if yre is YNML and r_slip is RS_Z then rstr is SA_PM;
if yre is YNML and r_slip is RS_PM then rstr is SA_PM;
if yre is YNML and r_slip is RS_PML then rstr is SA_PM;
if yre is YNML and r_slip is RS_PL then rstr is SA_PML;

if yre is YNL and r_slip is RS_NL then rstr is SA_NL;
if yre is YNL and r_slip is RS_NML then rstr is SA_NML;
if yre is YNL and r_slip is RS_NM then rstr is SA_NM;
if yre is YNL and r_slip is RS_Z then rstr is SA_PM;
if yre is YNL and r_slip is RS_PM then rstr is SA_PM;
if yre is YNL and r_slip is RS_PML then rstr is SA_PM;
if yre is YNL and r_slip is RS_PL then rstr is SA_PML;
end
```

APPENDIX C
LIST OF ABBREVIATIONS

LIST OF ABBREVIATIONS

Advance Vehicle Control Systems	AVHS
Degree Of Freedom	DOF
Fuzzy Logic Controller	FLC
Intelligent Vehicle-Highway Systems	IVHS
Proportional-Integral-Derivative	PID

VITA

Gary Lindsay Brown was born in Detroit, Michigan on February 7, 1959. He attended elementary schools in the East Detroit Public School District and graduated from East Detroit High School in June, 1977. He received the degree of Bachelor of Science in Electrical Engineering in 1982 from Lawrence Institute of Technology in Southfield, Michigan. In January, 1989 he entered the University of Tennessee, Knoxville and in May, 1994 received a Master of Science degree in Electrical Engineering.

The author is presently employed as a Digital Design Manager with Raytheon's Missile Systems Division Bristol Operations in Bristol, Tennessee.