The purpose of this chapter is to present the basics of passive and semiactive damping, and to discuss their role in previous research studies involving the control of vehicle suspension dynamics. In the first section, an overview of vehicle suspension damping is presented. Next, the basic background information necessary for understanding passive and semiactive damping is discussed. The semiactive damping control methods that are included in this discussion are on-off skyhook, continuous skyhook, on-off groundhook, and fuzzy logic control. To conclude the chapter, a review of several pertinent publications is presented.

2.1 Overview of Vehicle Suspension Damping

The issue of vehicle suspension damping is the conflict between vehicle safety and ride comfort. The safety of a vehicle is typically measured by the vertical motion of the vehicle tires (wheel hop) and by the rotational motions of the vehicle body, such as the roll and pitch of the vehicle during cornering and braking. These measures are also considered as road handling and stability characteristics by providing information on the vehicle tire contact to the road and the location of the vehicle’s center of gravity. The degree of ride comfort of a vehicle is obtained by evaluating the displacements and accelerations of the vehicle body. This provides a measure of the movement and forces transmitted to the vehicle passenger, which cause discomfort.

Two common types of vehicle suspension dampers are passive and semiactive dampers. With each of these dampers, the magnitude of damping is dependent on the relative velocity across the damper. The force versus velocity curves of each type of damper, however, are not identical. Examples of the typical curves for a passive and a semiactive damper are shown in Figure 2.1.
In passive dampers, the magnitude and direction of the force exerted by the damper depend only on the relative velocity across the damper. In semiactive dampers, however, although the direction of the force exerted by the damper still depends on the relative velocity across the damper, the magnitude of the damping force is adjustable. The force exerted by a semiactive damper is accomplished by adjusting the damper’s fluid flow through an orifice. The advantage of semiactive over passive damping is the ability of semiactive dampers to control the magnitude of the damper force through any one of numerous possible damping control schemes. Slight disadvantages of semiactive dampers are their cost and the amount of power that is required for the operation of the damper controller and its associated components.

A third type of damping typically used in the control of vehicle suspension dynamics is referred to as active damping. In active damping, an actuator is used to generate the desired force in any direction, regardless of the relative velocity across it. While this provides more damping control, the amount of power required to generate the actuator force is much greater (orders of magnitude greater) than that required to adjust the control valve of the semiactive damper. Another disadvantage of active damping compared to semiactive damping deals with the failure modes of each. If the failure of a semiactive damper occurs, the result is a passive damper; however, an undesired force in an active damper could pull the tire away from the road, causing problems with vehicle handling and safety. Active damping will not be covered in this research.
2.2 Passive Damping

One of the methods of damping to be discussed for this research is what is commonly referred to as passive damping. In passive damping, the damper has a pre-defined curve in units of force/velocity. A change in the relative velocity across the damper, $v_{rel}$, thus changes the force output exerted by the damper, $F_d$. This concept is shown in Figure 2.2.

In actual applications, the slope of the force versus velocity curve is nonlinear, and tends to decrease as the velocity increases (in either the positive or negative direction). However, in the passive damper model used for this research, the slope of the curve is held constant. As the relative velocity on the damper increases, the force exerted on the damper increases linearly with a slope equivalent to the damper value.

2.3 Semiactive Damping

In semiactive damping, the damper is adjustable and may be set to any value between the damper-allowable maximum and minimum. The damper value is adjusted by a controller that may be programmed to any number of control schemes. In the succeeding paragraphs, the semiactive damping control schemes that were studied via computer simulation for this research are presented. These control schemes include on-off skyhook, continuous skyhook, on-off groundhook, and fuzzy logic damping control. For simplicity, these control policies will be explained using the quarter-car, two-degree-of-freedom
vehicle model of Figure 2.3. In Chapter 3, however, these policies will be applied to a roll-plane, four-degree-of-freedom model that is used in this research.

In Figure 2.3, one-quarter of a vehicle is represented. The mass of this portion of the vehicle body (sprung mass) and one tire (unsprung mass) is defined respectively by $m_b$ and $m_t$, with their corresponding displacements defined by $z_b$ and $z_t$. The suspension spring, $k_s$, and damper, $c_s$, are attached between the vehicle body and tire, and the stiffness of the tire is represented by $k_t$. The relative velocity across the suspension damper of this model is defined by:

$$v_{rel} = \dot{z}_b - \dot{z}_t$$  \hspace{1cm} (2.1)

2.3.1 On-Off Skyhook Control

In on-off skyhook control, the damper is controlled by two damping values. Illustrated in Figure 2.4, these are referred to as high-state and low-state damping.
Figure 2.4. Semiaactive Damping - On-Off Control

The determination of whether the damper is to be adjusted to either its high state or its low state depends on the product of the relative velocity across the suspension damper and the absolute velocity of the vehicle body mass attached to that damper, as illustrated in Figure 2.5. If the product is positive or zero, the damper is adjusted to its high state; otherwise, the damper is set to the low state. For the quarter-car model of Figure 2.3, this concept is summarized by:

\[
\dot{z}_b \times v_{rel} \geq 0; \quad c_s = \text{high state} \tag{2.2a}
\]

\[
\dot{z}_b \times v_{rel} < 0; \quad c_s = \text{low state} \tag{2.2b}
\]
The logic of the on-off skyhook control policy is as follows. When the relative velocity of the damper is positive, the force of the damper acts to pull down on the vehicle body mass; when the relative velocity is negative, the force of the damper pushes up on the mass. Thus, when the absolute velocity of the body mass is negative, it is traveling downwards and the maximum (high state) value of damping is desired to push up the mass, while the minimum (low state) value of damping is desired to continue pulling down on the mass. However, if the absolute velocity of the body mass is positive and the mass is traveling upwards, the maximum (high state) value of damping is desired to pull down the mass, while the minimum (low state) value of damping is desired to further push the mass upwards. The on-off skyhook semiactive policy emulates the ideal body displacement control configuration of a passive damper “hooked” between the body mass and the “sky,” as shown in Figure 2.6.
2.3.2 Continuous Skyhook Control

In continuous damping, there exist a “high” state and a “low” state of damping as in the on-off damping control policy described previously. In continuous control, however, the damping values are not limited to these two states alone; they may exist at any value within the two states. As illustrated in Figure 2.7, the high and low states serve as the maximum and minimum damping values, respectively, with the intermediate (shaded) area as all possible damping values between the maximum and minimum.

An extension of the on-off skyhook control policy was used as one method of continuous control. As in on-off skyhook control, Equations (2.2a) and (2.2b) still apply, except for the definition of the high-state and low-state damping. In on-off skyhook control, the high
and low states were defined as constant damping values. As shown in Equation 2.3, in continuous skyhook control, the low state remains defined by a constant damping value, while the high state is set equal to a constant gain value multiplied by the absolute velocity of the vehicle body attached to the damper, not to exceed the corresponding high and low state limits.

\[ \dot{z}_b \times v_{rel} \geq 0; \quad c_s = \max\{\text{low state}, \min[(\text{Gain} \times \dot{z}_b), \text{high state}]\} \]  
\[ \dot{z}_b \times v_{rel} < 0; \quad c_s = \text{low state} \]  

\(2.3a\)  
\(2.3b\)

### 2.3.3 On-Off Groundhook Control

As illustrated in Figure 2.4 for on-off skyhook control, in on-off groundhook control, the damper is also controlled by two damping values referred to as high-state and low-state damping. The determination of whether the damper is to be adjusted to either its high state or its low state depends on the product of the relative velocity across the suspension damper and the absolute velocity of the vehicle tire mass attached to that damper. As shown in Figure 2.8, if the product of the relative damper and absolute tire velocities is negative or zero, the damper is adjusted to its high state; if this product is positive, the damper is adjusted to its low state. For the quarter-car model of Figure 2.3, this concept is summarized by:

\[ \dot{z}_r \times v_{rel} \leq 0; \quad c_s = \text{high state} \]  
\[ \dot{z}_r \times v_{rel} > 0; \quad c_s = \text{low state} \]  

\(2.4a\)  
\(2.4b\)
The reasoning of the on-off groundhook control policy is similar to the on-off skyhook control policy, except that control is based on the unsprung mass. When the relative velocity of the damper is positive, the force of the damper acts to pull up on the tire mass; when the relative velocity is negative, the force of the damper pushes down on the tire mass. However, when the absolute velocity of the tire mass is negative, it is traveling downwards and the maximum (high state) value of damping is desired to pull the mass, while the minimum (low state) value of damping is desired to continue pushing down on the mass. But, if the absolute velocity of the tire mass is positive and the mass is traveling upwards, the maximum (high state) value of damping is desired to push down the mass, while the minimum (low state) value of damping is desired to further pull the mass upwards. The on-off groundhook semiactive policy emulates the ideal tire displacement control configuration of a passive damper “hooked” between the tire and the “ground,” as shown in Figure 2.9.
2.4 Fuzzy Logic Control

Fuzzy logic control of semiactive dampers is another example of continuous control illustrated in Figure 2.7. The output of the controller as determined by the fuzzy logic may exist anywhere between the high and low damper states. Fuzzy logic is used in a number of controllers because it does not require an accurate model of the system to be controlled. Fuzzy logic works by executing rules that correlate the controller inputs with the desired outputs. These rules are typically created through the intuition or knowledge of the designer regarding the operation of the system being controlled. No matter what the system, there are three basic steps that are characteristic to all fuzzy logic controllers. These steps include the fuzzification of the controller inputs, the execution of the rules of the controller, and the defuzzification of the output to a crisp value to be implemented by the controller. These steps will be explained in succeeding paragraphs.

2.4.1 Step One: Fuzzification

The first step of the fuzzy logic controller is the fuzzification of the controller inputs. This is accomplished through the construction of a membership function for each of the inputs. The possible shapes of these functions are infinite, though very often a triangular or trapezoidal-shape is used [1-2]. For simplicity, an example of a triangular-shaped membership function used to describe the controller input, x, is shown in Figure 2.10.
The number of memberships assigned may be any number of linguistic variables. The three linguistic variables assigned to the example of Figure 2.8 are Negative(N), Zero(Z), and Positive(P), and are correspondingly assigned values of -1, 0, and +1. Once the membership function is assigned for each input, the actual fuzzification of the inputs is performed. First, the input is read as a crisp value. Say, for example, that the input “x” is entered as -0.6. A line is drawn from the x axis at -0.6 to indicate its point of intersection with each component of the membership function, as detailed in Figure 2.11.

From the intersection of the x value of -0.6 drawn in Figure 2.11, it can be seen that this value crosses “Z” at a weighting function of 0.4 and crosses “N” at a weighting function of 0.6. In linguistic terms, an input of -0.6 is considered to be 40% Zero and 60% Negative. These are the fuzzified values of the crisp input, x. Once this process has been performed for all the inputs into the controller, the fuzzification step of the fuzzy logic
controller is complete and the rules of the controller are executed.

2.4.2 Step Two: Execution of Rules

In order to create the rule-base of the controller, the membership function of the output must first be defined. Take, for example, the triangular-shaped membership function for the output, $y$, shown in Figure 2.12.

![Figure 2.12. Triangular-Shaped Output Membership Function Example](image)

The linguistic variables assigned to the output are defined as: Small(S), Medium Small(MS), Medium(M), Medium Large(ML), and Large(L), and are given the values of 2, 4, 6, 8, and 10, respectively.

Now that the derivation of the controller output membership function is complete, the rule-base of the controller may be created. Suppose two inputs exist, $x_1$ and $x_2$, that are each defined by the membership function of Figure 2.10, and one output, $y$, defined by Figure 2.12. For each possible input combination of $x_1$ and $x_2$, a value for the output, $y$, is linguistically defined. An example of a possible rule-base is shown in Figure 2.13.
The rules of Figure 2.13 may also be described as a series of “IF-THEN” statements. For instance,

\[
\begin{align*}
\text{IF} & \quad x_1 = N \\
& \quad \text{and} \\
& \quad x_2 = N \\
\text{THEN} & \quad y = S
\end{align*}
\]

and

\[
\begin{align*}
\text{IF} & \quad x_1 = N \\
& \quad \text{and} \\
& \quad x_2 = Z \\
\text{THEN} & \quad y = MS
\end{align*}
\]

and so forth, until all the rules of the table are described. The table of Figure 2.13 has a total of 9 rules.

Now suppose that after fuzzification, \( x_1 \) is found to be 40% Zero and 60% Positive, and \( x_2 \)
is found to be 50% Zero and 50% Positive. In other words: $\mu_{x_1,N}=0$, $\mu_{x_1,Z}=0.4$, $\mu_{x_1,P}=0.6$, $\mu_{x_2,N}=0$, $\mu_{x_2,Z}=0.5$, and $\mu_{x_2,P}=0.5$. The rules are applied by assigning the output variable with the minimum (or maximum, depending on the defuzzification method to be applied) weighting function described by the rules. Applying the rule

\[
IF \\
\begin{align*}
  x_1 &= P \\
  and \\
  x_2 &= P \\
THEN \\
  y &= L
\end{align*}
\]

with the fuzzified values of $x_1$ and $x_2$, the rule becomes

\[
IF \\
\begin{align*}
  x_1 &= 0.6P \\
  and \\
  x_2 &= 0.5P \\
THEN \\
  y &= \min(0.6,0.5)L = 0.5L
\end{align*}
\]

In other words, $y(0.6P,0.5P)=0.5L$, where the output weighting function $\mu_y(x_1=P,x_2=P)=0.5$. Applying this procedure to the inputs defined by this example, the fuzzy outputs become:

\[
\begin{align*}
  y(0.0N,0.0N) &= 0.0S & y(0.0N,0.5Z) &= 0.0MS & y(0.0N,0.5P) &= 0.0S \\
  y(0.4Z,0.0N) &= 0.0M & y(0.4Z,0.5Z) &= 0.4M & y(0.4Z,0.5P) &= 0.4M \\
  y(0.6P,0.0N) &= 0.0L & y(0.6P,0.5Z) &= 0.5ML & y(0.6P,0.5P) &= 0.5L
\end{align*}
\]

These fuzzy outputs now go through the defuzzification process to determine a single, or crisp, controller output value.
2.4.3 Step Three: Defuzzification

Defuzzification is the process of taking the fuzzy outputs and converting them to a single or crisp output value. This process may be performed by any one of several defuzzification methods. Some common methods of defuzzification include the max or mean-max membership principles, the centroid method, and the weighted average method [1]. The weighted average method was used for this research. It should be noted that the weighted average method is valid only for symmetrically-shaped output membership functions.

The weighted average method for finding the crisp output value, $y^*$, is accomplished by taking the sum of the multiplication of each weighting function, $\mu_y$, with the maximum value of its respective membership value, $\overline{y}$, and dividing it by the sum of the weighting functions. This concept is presented in Equation (2.5).

$$
y^* = \frac{\sum \mu_y(\overline{y}) \times \overline{y}}{\sum \mu_y(\overline{y})}
$$

(2.5)

Applying the weighted average defuzzification method to the example discussed in Section 2.4.2, the crisp output, $y^*$, of the controller is calculated by:

$$
y^* = \frac{(0.4M + 0.4M + 0.5ML + 0.5L)}{(0.4 + 0.4 + 0.5 + 0.5)} = 7.67
$$

Recall from Figure 2.13 that the maximum values of the linguistic variables M, ML, and L were respectively defined as 6, 8, and 10. A crisp output of 7.67 is thus calculated and applied to the system being controlled. At this point, the current controller inputs are read, and the steps of the fuzzy logic controller are repeated.
2.5 Literature Review

While passive dampers for a vehicle suspension system (shock absorbers) have been in existence for many decades, the first semiactive damper was not patented until 1974 [3]. Since the issuance of this patent, there have been numerous simulation and experimental studies on the comparison between passive and semiactive damping. In the first part of the review, articles on semiactive control schemes, including on-off and continuous skyhook, will be examined [4-13]. Articles on semiactive dampers using fuzzy logic control will then be discussed [14-20].

2.5.1 Skyhook-Based Control Literature

Articles [4-9] detail the results of simulation-based studies. In an article presented by Karnopp et al. [4], the damping response of the single-degree-of-freedom system of Figure 2.14(a) is examined.

In the Karnopp study [4], the displacement, velocity, and acceleration transient responses of the sprung body are presented for semiactive on-off skyhook damping control with a pure-tone base excitation with natural frequencies of 0.5, 1.0, and 3.0 times the natural frequency of the system. These results show that the amplitudes of the transient response decrease with an increase in frequency. The frequency response of the system is then compared for the same system with passive and semiactive on-off skyhook damping,
showing that the transmissibility of the system is decreased when the semiactive damping is employed. In the second part of the study in [4], the frequency response of the two-damper, two-degree-of-freedom model of Figure 2.14(b) was also examined using passive and semiactive on-off skyhook damping. The output of this system is composed of a combination of the body heave and roll responses. The transmissibility of this system also shows a decrease when semiactive control is used.

Using the quarter-car model of Figure 2.3, Ahmadian and Marjoram [5] examine the frequency response of the body accelerations, tire deflections (wheel hop), and suspension deflections for a random input velocity of 0-25 Hz, using both passive and semiactive on-off skyhook damping. Two major conclusions were drawn from this report. In the first part of the study, the results for passive damping show increased coupling between the body and axle for an increase in damping. The results for semiactive damping, however, did not show increased coupling for an increase in damping. In another study using a single-degree-of-freedom model, Ahmadian [6] takes these results a step further. He shows that, for a sufficiently large damping ratio, a semiactive damper can provide isolation at all frequencies. This is in contrast to a passive damper, which can isolate only at frequencies larger than $\sqrt{2}$ times the natural frequency of the suspension, regardless of the magnitude of the damping.

The second part of the study in [5] deals with the effect of damping on the natural frequency of the tire, typically 10-12 Hz. With a passive damper, an increase in damping corresponds to higher body accelerations (less ride comfort), but less suspension deflection and more control of the wheel hop (better road handling). With the semiactive damper, however, an increase in damping showed improved ride, at the cost of increased wheel hop. Nagai et al. [7] confirm these results by showing a comparison of passive with semiactive damping, using both on-off and continuous skyhook control. This study shows that in response to a random input (at approximately 10 Hz) into the base of the quarter-car model, semiactive damping improves body accelerations while decreasing the tire to road contact force.
Another approach in examining the response of passive and semiactive damping is taken by Miller [8]. In this research, the quarter-car model response is measured for a random noise base excitation of less than 100 Hz. The system response is then measured for an increase in the damping ratio of a passive damper, and for an increase in the high state (with the low state held constant) and low state (with the high state held constant) of the on-off and continuous skyhook policies applied to a semiactive damper. At a single damping ratio, the semiactive damper caused reduction of the RMS values of body acceleration, but increased the suspension deflection and tire contact force. The results show, however, that at certain high state to low state damping ratios, both the on-off and continuous skyhook control policies can provide improvement in the RMS of the body acceleration and suspension travel while maintaining the same road-holding ability as passive damping. Using a full-car model with seven degrees of freedom, Lieh [9] also showed the effects of passive versus semiactive skyhook damping on body acceleration, suspension travel, and tire deflection. The trends of the Lieh’s study results agreed with the results of another study by Miller [8]. They both showed that for a given damping ratio, the body accelerations were improved when using semiactive damping, while the suspension and tire deflections were improved while using passive damping.

The above research approaches all detail the simulation responses of various vehicle suspension systems to passive and semiactive damping. They show that the transmissibility of a base-excited system is decreased when semiactive damping is used. They also show that while an increase in damping of a passive system results in higher body accelerations and lower suspension and tire deflections, the results of a semiactive system cause the opposite to occur. However, when the appropriate combination of the high and low states of a semiactive skyhook damper is used, compared with passive damping, the body acceleration and suspension deflection can decrease, while maintaining the same level of road contact.

Experimentally, research does exist regarding the experimental responses of actual systems
These studies range in complexity from hardware-in-the-loop simulations [10] to actual vehicle-installed damper studies [11]. In research presented by Ivers and Miller [12], a quarter-car test rig is used to compare the passive and semiactive skyhook damping (both on-off and continuous) response with a simulated quarter-car model. These tests show that although the test rig results are not identical to those of the model simulations, they do exhibit similar trends. Ivers and Miller have also presented a paper in which they review the hardware, sensor, and data acquisition techniques that are necessary to obtain accurate experimental responses [13].

2.5.2 Fuzzy Logic Control Literature
Although fuzzy logic was first developed by Zadeh in 1965 [14], it has been only in more recent years that it has been applied to vehicle suspension dynamic control [15-20]. While most of this research is simulation-based [15-18], there has been some experimental research [19-20].

In an article by Titli and Roukieh [15], the results for a simulation study on the response of a quarter-car model with passive and semiactive fuzzy logic-controlled damping are presented. In this research, the objective of the fuzzy logic controller design was to improve the compromise between ride comfort, as measured by body displacement, and road handling, as measured by tire displacement, that is commonly acknowledged with a passive damper. In this design, the controller is actually composed of three sub-components: a “comfort” controller, a “handling” controller, and a fuzzy supervisor. Each of the two controller sub-components consists of two inputs, described by seven linguistic variables each, for a total of 49 rules in each rule-base. The comfort controller uses the inputs of suspension deflection and body speed, while tire deflection and tire speed are the inputs into the handling controller.

For the fuzzy supervisor in [15], the inputs include vehicle speed and acceleration, braking pressure, steering angle, and body height. The supervisor then uses each of these inputs to create a weighting factor for handling and another one for comfort, thus multiplying each
controller output by the corresponding factor and adding the results to present a single system output. The results were then examined for a step input into the model base, and the supervisor parameters were held constant. The transient responses for the body and wheel displacements were found to have an approximate 50\% reduction in percent overshoot with the fuzzy logic controller than with passive damping.

Although the results achieved by the Titli and Roukieh study [15] were promising, a controller by Al-Holou et al. [16] requires fewer inputs, significantly fewer rules (and therefore fewer computations), and yields equally promising results when compared with passive damping. This research studies the responses of a quarter-car model with a sinusoidal base excitation. The fuzzy logic controller design of this study consists of two inputs, body velocity and suspension velocity. Each input is thus described by three linguistic variables each, corresponding to a total of nine rules in the rule-base. The RMS values of body acceleration and tire deflection were used for showing the compromise in ride comfort and road handling, respectively. When compared with passive damping, the fuzzy logic controller results showed significant improvements in both areas. However, when compared with on-off skyhook damping, only slight improvement of the body acceleration was noted, and the results for tire deflection were slightly worse.

Other researchers [17,19] also used the quarter-car model to validate their fuzzy logic designs. In the article by Lieh and Li [17], the peak body acceleration is shown to be lowered when the fuzzy logic controller is used, as compared with both passive and on-off skyhook damping. The displacement response of the body mass of a quarter-car, fuzzy logic damping-controlled test rig showed acceptable similarity with simulation-generated responses in a research paper by Titli et al. [19]. They also showed nearly 40 percent reduction in percent overshoot when compared with passive damping.

A few of the articles used models other than the quarter-car to validate the fuzzy logic damping control. Jones et al. [18] used a 47-degree-of-freedom model to illustrate the feasibility of fuzzy logic control of a full-vehicle model suspension system. A simple fuzzy
controller consisting of four inputs (vertical and lateral acceleration, vehicle forward speed, and steering rate) and eight rules was designed and tested via simulations. Although the results did not show acceptable responses to large road inputs, they did practically eliminate the percent overshoot of the vehicle sprung mass roll angle, yaw rate, and lateral acceleration to a step steering input.

In summary, when compared with passive damping, the semiactive fuzzy logic controller was found to significantly reduce the percent overshoot of the transient responses. When these responses were compared with the responses generated using semiactive skyhook damping, fuzzy logic was found to decrease the body acceleration, but at the cost of wheel hop.