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# Improved Road Handling Performance with Fuzzy Logic Controller for a Coach Bus

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*Abstract:* - The present study investigates the effects of semi-active suspension systems controlled by skyhook, balance and fuzzy logic controllers on ride quality and road handling performances of a coach bus. The suspension dynamics are constructed as 7 DOF full vehicle models in MATLAB using Simulink toolbox. To compare the performances of different models, some virtual tests are carried out at a constant vehicle speed on a step input in Simulink and their tire deflections, suspension travels and body motions such as bouncing and pitching oscillations are evaluated. The results show that the fuzzy logic controller (FLC) developed in this study improves road handling performance of a coach bus while maintaining its comfort level.

*Keywords:* - Suspension system, vehicle model, fuzzy logic controller, ride quality, road handling.

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## 1. INTRODUCTION

The suspension system is one of the most important parts of a coach bus in terms of passenger comfort and safety [1]. Its main objective is to improve the quality of the ride and passenger comfort while providing the driver good road handling. It also prevents the occurrence of mechanical and structural failures caused by the road surface roughness related vibrations [2-4]. Excessive levels of vibrations are also harmful to the health of passengers. Therefore, suspension systems are used to isolate vibration transmission between the road surface and the vehicle body by reducing or eliminating the dynamic forces related to the road based excitation [5].

Until 1990, the passive suspension systems with fixed damping and stiffness ratios had been very popular [8]. Since the road-induced vibrations have unpredictable waveforms, typically a suspension system is forced to struggle with the broadband excitation spectra. These passive suspension systems do not have the capability to respond to both the higher damping requirements at resonance zones and the lower damping requirements at high frequency zones [2,6,7]. It is clear that passive suspension systems are not adequate for all road and driving conditions. Thus, semi-active suspension systems were proposed by Karnopp in early 1970's [6,8]. These systems have adaptive parameters for variable excitation and response characteristics.

In the automotive industry, especially after 1990s, the semi-active suspension systems have attracted

more attention due to their small energy requirement similar to passive systems and their high performance similar to the active systems [2,8-10]. Balance control for vibration shock isolation, skyhook damping control strategy and ground-hook control theories were studied by Alanoly-Sankar (1987), Karnopp et al. (1990) and Ivers-Miller (1994), respectively [6,8-12].

To achieve a better performance, some different control strategies have been investigated in recent years. Fuzzy Logic (FL), introduced by Zadeh (1965) [13], has been used as a control strategy for vehicle suspension systems by Rao & Prahlad (1997) [16]. From this moment, FL has become a significant part of these investigations since it represents human's heuristic knowledge.

The main purpose of this article is to develop a Fuzzy Logic Control (FLC) system, whose rules are based on the algorithms of skyhook and balance strategies. It aims to meet the road handling requirements of these comfort-oriented semi-active strategies. FLC, developed in this study, has three inputs called as body vertical velocity, suspension velocity and suspension travel to determine the damping coefficients of all suspension units in the system.

All 7-DOF full vehicle models are simulated in MATLAB/Simulink environment. The simulations are performed to compare the performances of these suspension systems in terms of the body motions, tire deflections and suspension travels of the models.

## 2. 7-DOF COACH BUS MODEL

In order to study the performances of the suspension systems, it is necessary to build a realistic simulation model for most accurate results. The model adopted for this study is based on a 7 DOF coach model that allows investigation of base-induced excitations and their effects on the full vehicle model. The schematic drawing of the bus is illustrated in Fig. 1 where each wheel is replaced by an equivalent suspension system model.

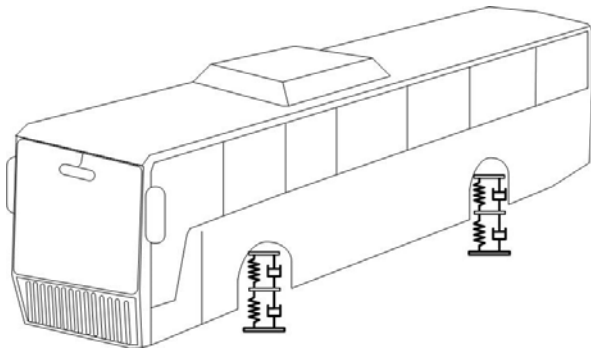


Figure 1. A full vibrating coach bus model

In this model, the motions of the vehicle's body and wheels can be constructed in addition to artificial road profiles. These motions include the body bounce  $X$ , the body rolling  $\Phi$ , the body pitching  $\Theta$ , the wheel hops  $x_1, x_2, x_3, x_4$  and the independent road excitations  $y_1, y_2, y_3$  and  $y_4$ . Hence, the modelled full vehicle has 7 degrees of freedom ( $X, \Phi, \Theta, x_1, x_2, x_3, x_4$ ) for which the motion equations are provided in Appendix A [3,6]. The motion parameters and other dimensional details of the vehicle vibration model are shown in Fig. 2.

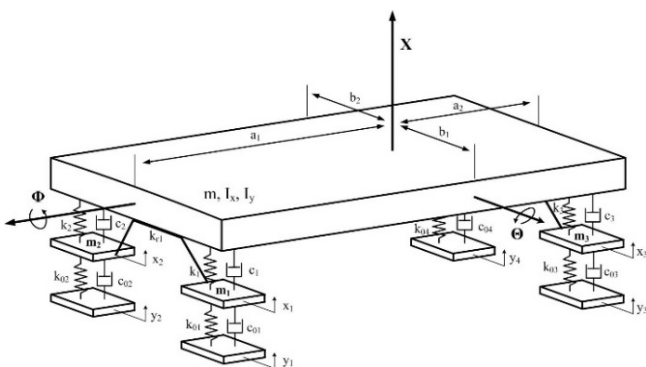


Figure 2. A passive vehicle model

The mathematical model of the vehicle is adapted from Jazar [3] which defines a 7 DOF vehicle model. This is then adapted to a specific coach bus used as a passenger carrier. The motion equation of the model is provided in Eq. 1 below.

$$M\ddot{X} + C\dot{X} + KX = F \quad (1)$$

where  $X$  is the state vector defined as

$$X = [x \ \Phi \ \Theta \ x_1 \ x_2 \ x_3 \ x_4]^T \quad (2)$$

## 3. SEMI-ACTIVE STRATEGIES

It is widely known that passive suspension models fail to meet the requirements for all road and driving conditions. On the other hand, it has been reported that the active control techniques are mainly too expensive both for initial investment and for running costs. Therefore, semi-active systems are the best in terms of system performance and cost effectiveness [6, 8]. In this article, the skyhook and the balance damping control strategies, well-known as comfort-oriented semi-active suspension techniques, are simulated.

The schematic drawing of a SDOF semi-active damping control model is illustrated in Fig. 3. In this figure, " $X$ " and " $X-Y$ " represent the body vertical displacement and the suspension travel, respectively.

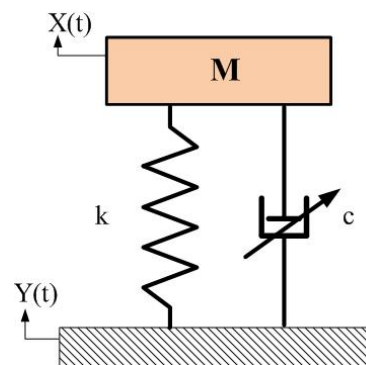


Figure 3. SDOF semi-active damping control model

In 7 DOF full bus model depicted in Fig.2, the term of  $(X + a_m\theta + b_n\phi)$  is the mathematical expression of body vertical motion for each suspension unit where  $1 \leq m, n \leq 2$  and  $m, n \in \mathbb{N}$  and  $x_i$  represents a tire deflection where  $1 \leq i \leq 4$  and  $i \in \mathbb{N}$ . Hence a suspension travel " $X-Y$ " can be defined as  $(X + a_m\theta + b_n\phi - x_i)$ .

### 3.1. On-Off Skyhook Strategy

The Skyhook suspension control technique is based on balancing the real and imaginary dampers illustrated in Fig. 4. This balancing act is defined as keeping real and imaginary dampers in such a way that they do not reduce each other's damping effects. If the velocities of the real and imaginary dampers are in the same direction, their damping forces support each other. Otherwise, overall damping capacity of the system decreases [8-11]. On-off skyhook strategy are mathematically expressed in Eq. 3 below.

$$c = \begin{cases} c_{\max} & \dot{X}(\dot{X} - \dot{Y}) \geq 0 \\ c_{\min} & \dot{X}(\dot{X} - \dot{Y}) < 0 \end{cases} \quad (3)$$

$$c = \begin{cases} c_{\max} & (X - Y)(\dot{X} - \dot{Y}) \geq 0 \\ c_{\min} & (X - Y)(\dot{X} - \dot{Y}) < 0 \end{cases} \quad (4)$$

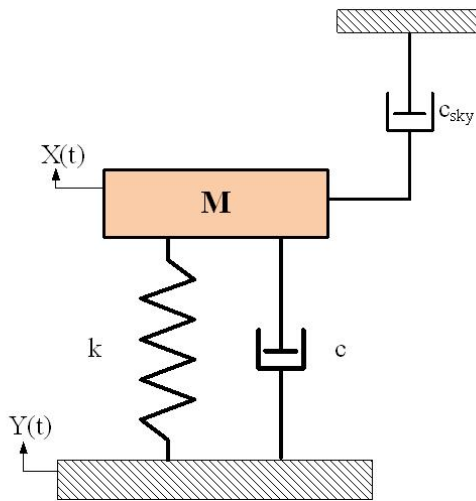


Figure 4. SDOF skyhook model

### 3.2. On-Off Balance Strategy

The principle of balance control strategy is based on the analysis of spring and damping force contributions to the acceleration response of the sprung mass in a suspension unit. It is evident from Fig. 5 that the acceleration level of sprung mass increases while the spring and the damping forces have same sign [7].

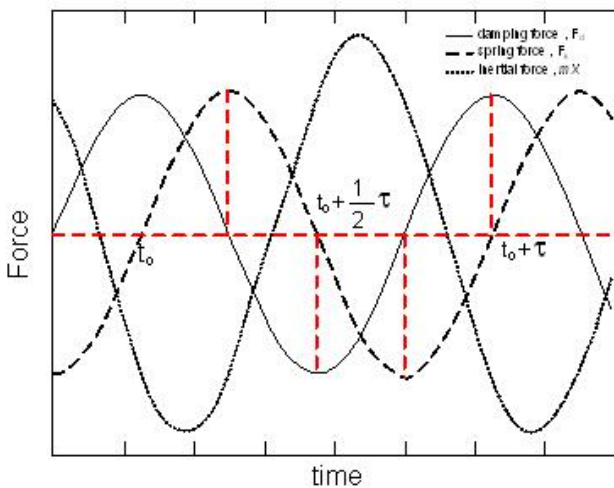


Figure 5. The forces of a passive SDOF system [7].

According to the balance control logic, the damping force level should be reduced in order to attenuate the acceleration level of sprung mass in each suspension unit if the spring and damping forces are in the same directions. Mathematical expression of this approach is seen in Eq. 4.

## 4. FUZZY LOGIC CONTROLLER

Fuzzy Logic Control (FLC) has been widely used in active and semi-active suspension systems in recent years. Unlike the other control systems, an FLC is based on some inference rules instead of mathematical model of the system [12,15,23,24].

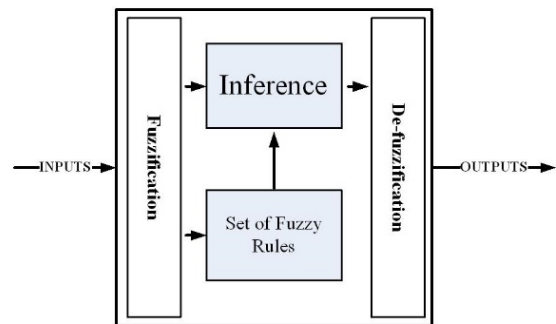


Figure 6. Block diagram of fuzzy logic controller

There are three main elements of an FLC system namely as fuzzification, inference rules and defuzzification blocks as depicted in Fig.6. The crisp values of inputs are converted into linguistic values in fuzzification stage. Then, fuzzy output values are created via inference rules. Finally, these fuzzy outputs are turned back into real-numbers in the defuzzification stage [13,15].

## 5. SIMULATION MODELS

In order to provide a basis for a reliable comparison, stiffness and damping coefficients as well as the vehicle parameters are set to the same values for all models. Moreover, none of the semi-active models are optimized for road handling and ride comfort characteristics. All parameters related to the models are included in Appendix B. The 7 DOF models constructed and benchmarked in this study are explained in the following sub-sections.

### 5.1. Model A

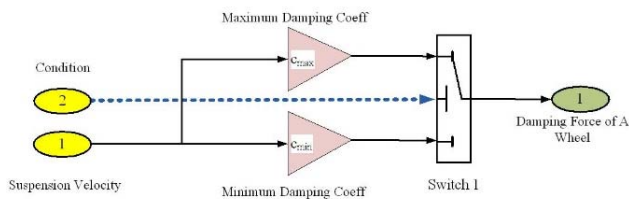
Model A is the simplest 7 DOF model equipped with the passive suspension units having constant damping and stiffness ratios for each wheel. The damping and stiffness ratios of all units are listed below in Table 1.

**Table 1:** Suspension parameters of Model A

Suspension Parameters of Passive System		
	Front Axle	Rear Axle
Damping Coeff (Ns/m)	10,000	18,000
Stiffness Coeff (N/m)	100,000	180,000

**5.2. Semi-Active Models**

Fig. 7 indicates the block diagram of an on-off semi-active model equipped with a skyhook or a balance controller. In this study, semi-active models have different conditions that determine their on-off status while running. The damping coefficient is taken as maximum for the on-state and minimum for the off-state.



**Figure 7.** Block diagram of a semi-active suspension unit

Moreover, stiffness and max and min values of damping coefficient used for semi-active model are listed in Table 2.

**Table 2:** Parameters of a semi-active suspension unit

Suspension Parameters of On-Off Semi-Active Control Systems			
		Front Axle	Rear Axle
Damping Coeff (Ns/m)	Min	5,000	9,000
	Max	10,000	18,000
Stiffness Coeff (N/m)		100,000	180,000

**5.2.1. Model B**

Model B is one of the semi-active 7 DOF models used in this study. Each suspension unit in this model is controlled by on-off skyhook damping control strategy.

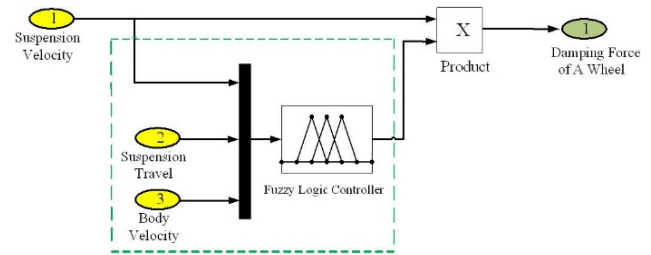
**5.2.2. Model C**

Model C is the other semi-active 7 DOF model having balance damping controllers

**5.2.3. Model D**

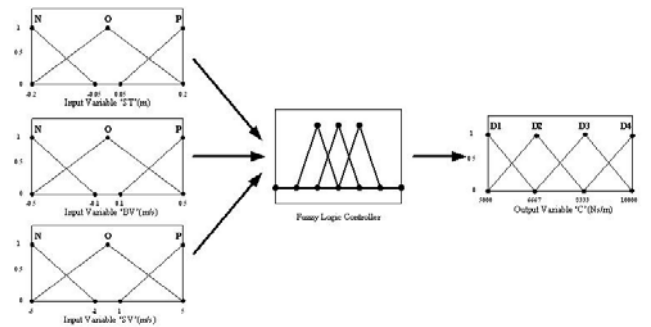
The FLC system developed in this study combines the techniques of skyhook and balance controllers. It produces damping coefficient as an output by analyzing the three inputs called as body vertical velocity, suspension velocity and suspension travel for each suspension unit. The inference rules of FLC

are based on the philosophy that the damping capacity of the system increases in case of overlapping the on-states of skyhook and balance conditions and decreases especially in case of coincidence of their off-states. As previously described, the aim of the FLC system is to meet road handling requirements while providing the comfort levels of both semi-active models. The block diagram of FL Strategy is illustrated in Fig. 8.



**Figure 8.** Block diagram of fuzzy logic controller

The membership functions of FLC system are indicated in Fig.9. N (Negative High), O (Neutral), P (Positive High) represent the linguistic values of the inputs. Moreover, each  $D_i$  ( $1 \leq i \leq 4$ ), is defined as a fuzzy value of the FLC system output.



**Figure 9.** Membership functions of FLC

Finally, the rulebase of FLC system has 27 rules expressed as a matrix in Table 4 in Appendix C.

**6. TEST RESULTS**

All test in this study are carried out at constant vehicle speed of 90 km/h to compare the models. Road profile kept fixed for all tests as step input with the height of 100 mm as illustrated in Appendix D.

**6.1. Ride Quality**

To evaluate the ride qualities of 7 DOF coach bus models, their body motions and acceleration levels are studied. Even though the overshoot levels of FLC Model are as high as those of the Passive Model one especially for body bounce and pitch motions as illustrated in Fig. 10. Besides, its body RMS acceleration level is close to the levels that other

semi-active models have. All models have almost same settling times. This result can be clearly seen in Fig. 10 below.

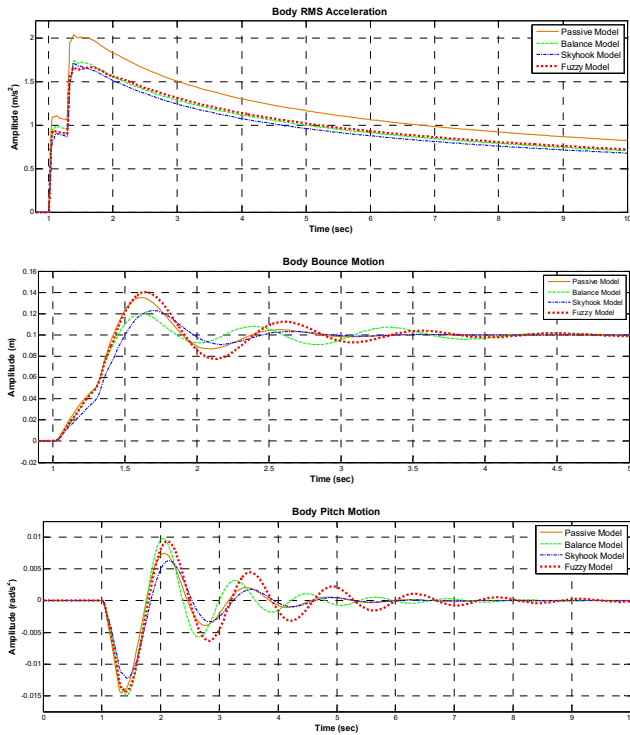


Figure 10. Body oscillations and acceleration levels

## 6.2. Road Handling

The road handling performances of the 7 DOF coach bus models are assessed for their tire deflections and suspension travels. Since the suspension units on the left and right sides of the models have similar results, only the left ones are shown in the Figs 11-12.

### 6.2.1. Dynamic Tire Deflection

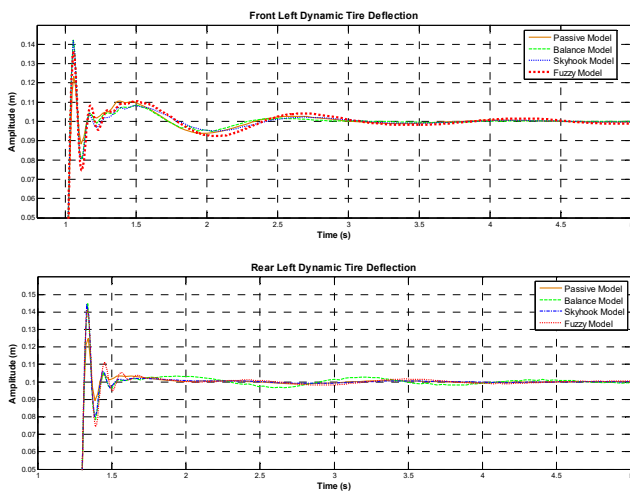


Figure 11. Tire deflections of left wheels

Although Passive Model has the lowest overshoot levels in the bump tests as shown in Fig. 11, the

overshoot levels of FLC Model are lower than these of the other semi-active models. In other words, FLC Model is better than the other semi-active ones in terms of tire deflection characteristics. All models have almost same settling times.

### 6.2.1. Suspension Travel

The vibration characteristics of the suspension system is determined by the wheel motion in the first stage of its oscillation (from  $t=0$  to 1.5) while it is under the dominant influence of the body motion in the second stage (from  $t=1.5$  to 7). Just like the case seen in Fig. 11, Fig. 12 also shows that Passive Model has the lowest overshoot levels and the suspension travel characteristics of FLC Model are better than these of the other semi-active models. A suspension unit of a vehicle should provide both good vibration isolation and a small “rattle space” which is the acceptable limit for suspension deflection. It can be concluded from Fig. 11 and 12 that FLC Model requires smaller rattle space than the other semi-active models do.

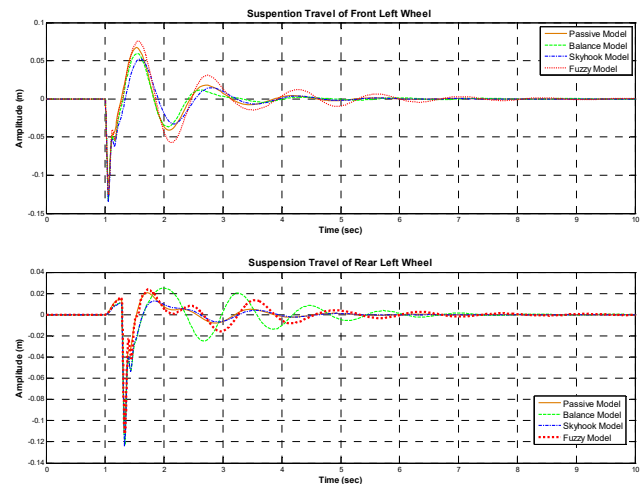


Figure 12. Suspension travels of left wheels

## 7. CONCLUSIONS

In this paper, a new FLC control technique applied to a 7 DOF full coach bus model is proposed. The suspension travel, body vertical and suspension velocities are treated as the input variables of FLC to provide better compromise between the ride quality and road handling requirements.

The suspension system performance of this new model is compared with the passive, the on-off skyhook and the balance damping control strategies. The following conclusions are drawn based on the results of the tests carried out on a bump with the height of 100 mm.

- The minimum tire deflections and rattle space requirements are observed in the passive model;

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hence, the passive model has a clear superiority over the other models in terms of road handling performance.

- Our data clearly suggests that the ride quality of FLC Model is as well as these of Skyhook and Balance Models.

- The FLC strategy proposed in this study is the best strategy providing both higher ride quality and higher road handling performance.

In conclusion, FLC control technique ensures better reconciliation between the body and tire displacements than other damping strategies.

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