Performance Comparison of Different Fuzzy Logic Controllers on Vehicle-Caravan Systems

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ABSTRACT

Active control techniques in Vehicle-Caravan (VC) systems are designed to prevent instability modes. This study used Fuzzy Logic Controllers (FLCs), developed using the differential braking method, to prevent instability modes in a VC system and increase yaw stability. Four different FLC-based controllers were designed for the VC system: type-1 Mamdani, type-1 Sugeno, simplified type-2, and Interval Type-2 (IT2). FLC-based controllers are used in VC systems due to nonlinear characteristics. This study showed that unstable situations can be prevented with FLCs according to the inputs obtained from a single IMU sensor placed in the caravan. The performance of the controllers developed in MATLAB/Simulink was assessed using CarSim. Experimental studies showed that the skidding that occurs after the Double Lane Change (DLC) maneuver is prevented by FLC-based controllers and the yaw stability is increased.

Keywords-fuzzy logic controller; type-2 fuzzy sets; vehicle-caravan; differential braking

I. INTRODUCTION

Vehicle and trailer applications that are towed over a connection point are frequently preferred to increase vehicle carrying capacity and create different usage options. Among these options, caravans are among the most common. Despite the advantages of such uses, caravans complicate the dynamics of the VC system [1-4], and instability modes such as swing, folding, snaking, and jackknifing can occur in VC systems.

Active control techniques are used in VC systems against instability modes [5-24]. Active control techniques can be used in both the towing vehicle and the caravan system. Active Steering Control (ASC) and Active Differential Braking (ADB) are active control techniques used in vehicle-caravan systems. In ASC, a moment is created in the center of gravity to prevent skidding by giving a steering angle to the front or rear wheels [9], while the mechanism of the front or rear wheel must be arranged accordingly to use ASC. In the case of understeer in the ADB braking system, braking is applied to the right or left wheels, and a torque is applied in the opposite direction to the yaw moment that occurs around the center of gravity to damp the swing [7, 9, 16-21]. The ADB system is often preferred, as it does not require much extra hardware compared to the ASC. Various studies have been carried out using the ADB control method, and different control techniques have been used to determine the braking rate to be applied in the ADB.

Model-based and model-independent methods are used in active control techniques developed using ADB in VC systems. The Model Predictive Control (MPC) controller was developed to increase the lateral stability of the trailer system and prevent the occurrence of unstable situations [7, 21-22]. Examining the performance of the braking controller using the Linear Quadratic Regulator (LQR) technique showed that stable responses were produced [4, 6, 22]. Model-based controllers have the disadvantage that the system model can be used after modeling with different degrees of freedom according to the application area. The VC system has been modeled with different degrees of freedom, demonstrating the accuracy of different tests [1, 4, 23-24]. Another requirement of the model-based controller is that the state variables must be measured directly or obtained by estimation methods. It is not always desirable to perform these operations. At this point, for the reasons stated, model-independent control techniques are used instead of model-based controllers.

This study used the fuzzy logic method as a model-independent control technique, as there is no need for a system model if it is used as an active control technique in the VC system. Several studies used the FLC technique in VC systems, showing that unstable states were prevented [9, 21-24]. Such studies usually compare the proposed controller with other control techniques or when the controller is turned off. This study investigated the performance of different FLC controllers for VC systems. At first, the VC system was modeled with 3 degrees of freedom to obtain the system model required for the model-based controller and better understand the system dynamics. Then, the FLC design used in the ADB method was carried out. FLC controllers were designed using Type-1 Mamdani, Type-1 Sugeno, simplified Type-2, and Interval Type-2 (IT2) methods, and their performance was investigated using the Double Lane Change (DLC) test.

II. VEHICLE-CARAVAN MODELING

To better understand the forces and moments on the VC system, the system model needs to be derived. In the case of using model-independent controller methods, the system dynamics should be understood to form the rule base. Therefore, the VC system is modeled with three degrees of freedom: vehicle lateral velocity (m/s), vehicle yaw rate (rad/s), and hitch angle (rad). Figure 1 shows the free-body diagram of the VC system. Wheels on the same axle in the vehicle and caravan were assumed to have the same slip angle, and the visualization was carried out on a single wheel. The symbols used in the equations are the vehicle lateral speed (V), yaw rate (r), longitudinal speed (U), hitch angle (ψ), steering angle (δ), caravan lateral speed (v'), yaw rate (r'), longitudinal speed (U') and wheel lateral forces ($f_i a_i$).

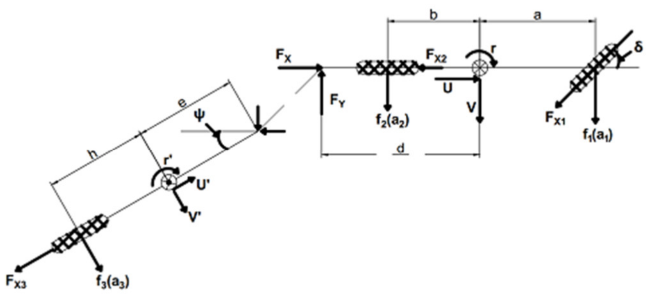

Fig. 1. The free-body diagram of a 3 DOF vehicle-caravan model.

The equations of motion on the vehicle are given by:

$$m_1(\dot{U} - V.r) = -F_{X1}.cos\delta - F_{X2} + F_X \quad (1)$$

$$m_1(\dot{V} - U.r) = f_1(a_1) + f_2(a_2)\delta + F_{X1}.sin\delta - F_Y \quad (2)$$

$$I_1\dot{r} = a.f_1(a_1) - b.f_2(a_2) + a.F_{X1}.sin\delta + d.F_Y \quad (3)$$

Similarly, the equations of motion on the caravan are given by:

$$m_2(\dot{U}' - V'.r') = -F_{X3} - F_X.cos\psi - F_Y.sin\psi \quad (4)$$

$$m_2(\dot{V}' - U'.r') = f_3(a_3) - F_X.sin\delta + F_Y.cos\psi \quad (5)$$

$$I_2\dot{r}' = -h.f_3(a_3) - e.F_X.sin\psi + e.F_Y.cos\psi \quad (6)$$

The VC is a system that is connected via the hitch point. In this case, their velocities and accelerations at the connection point are considered equal. Therefore, if the hitch angle, longitudinal and lateral velocity, and yaw rate are known, the longitudinal and lateral velocity of the caravan can be determined by:

$$U' = U.cos\psi - (V - dr)sin\psi \quad (7)$$

$$V' = U.sin\psi + (V - dr)cos\psi - e.r' \quad (8)$$

The equations of motion specified in (1)-(6) are nonlinear expressions. If a model-based controller is developed for the VC system, the equations of motion should be linearized. For this, the longitudinal velocity U is assumed constant, and (1) is ignored. Using the small angle approximation, it was assumed that cosy=1 and sinψ=ψ. In addition, for the initial condition, it is necessary to act according to the case $\dot{\psi} = r - r'$. To complete the equations of motion of the VC system, the lateral tire forces generated by the tires must also be modeled. Using the linear tire model, it can be expressed as follows:

$$f_i(a_i) = C_i a_i \quad (9)$$

The slip angles on the tires can be calculated by:

$$a_1 = \frac{V+ra}{U} - \delta_f \quad (10)$$

$$a_2 = \frac{V-rb}{U} \quad (11)$$

$$a_3 = \frac{[V - r(d+e+h) + (e+h)\dot{\psi}]}{U} + \psi \quad (12)$$

After linearizing the motion equations of the VC system under the above-mentioned assumptions, they can be expressed in state-space form for the controller. In this case, the expression for the VC system is:

$$M\{\dot{x}\} + D\{x\} + F\delta = 0 \quad (13)$$

The state variable used in the VC system can be determined by:

$$\{x\} = \{V\ r\ \dot{\psi}\ \psi\} \quad (14)$$

The M, D, and F matrices mentioned in (13) are shown in [6].

A. Active Trailer Differential Braking System

The equations of motion must be updated to use the active control differential braking method in the VC system. In this case, the moments around the center of gravity of the caravan are the following:

$$I_2\dot{r}' = -h.f_3(a_3) - e.F_X.sin\psi + e.F_Y.cos\psi + \Delta M_z \quad (15)$$

In this case, (13) needs to be updated, as:

$$M\{\dot{x}\} + D\{x\} + C_b u + F\delta = 0 \quad (16)$$

$$u = \Delta M_z \quad (17)$$

No changes were made in the M, D, and F matrices used in (16), which was formed because of the equations updated with the ATDB method. The C_b matrix added to this set of equations is shown in [6].

III. FUZZY LOGIC CONTROLLER DESIGN

The controller design was developed based on fuzzy logic to prevent instability modes in the VC system. Fuzzy logic systems are often used for systems that contain nonlinear or time-varying expressions. These nonlinear dynamics and uncertainties can be modeled with the fuzzy set approach. Fuzzy logic systems expressed as Type-2 have emerged as a solution to problems experienced in correctly determining the membership function. Type-2 fuzzy logic systems are preferred in the modeling of the system or in cases where there are uncertainties and nonlinear characteristics arising from the variability of use cases [22-23]. Figure 2 shows the FLC designed for the VC system.

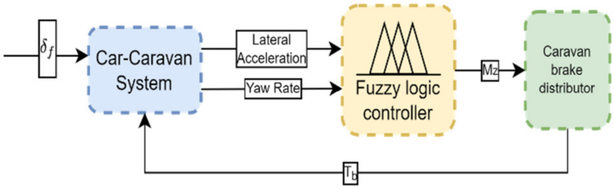

Fig. 2. Block diagram of the fuzzy logic controller scheme.

FLC determines the braking rate only based on data from the Inertial Measurement Unit (IMU) on the caravan. The Type-2 fuzzy logic system includes the type-reducer operator, unlike Type-1. Figure 3 shows the schematic design of the Type-2 FLC designed to prevent unstable situations that may occur in the caravan system.

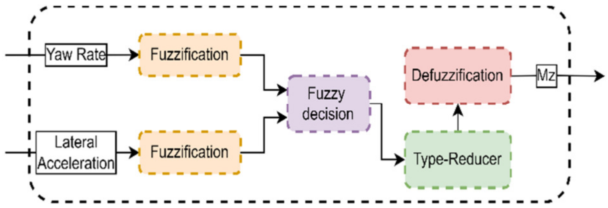

Fig. 3. Scheme of Type-2 the fuzzy logic controller.

Apart from this, the methods used in the Type-1 fuzzy logic system were used similarly. FLC design was carried out in MATLAB/Simulink [23]. In IT-2 FLC, input values of yaw rate and lateral acceleration are created when determining the braking rate to prevent skidding. Figure 4 shows the membership functions used in the fuzzification of the IT-2 FLC input values.

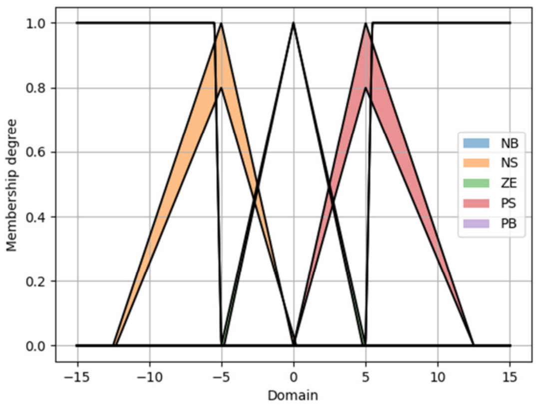

Fig. 4. Input membership function of yaw rate.

Figure 5 shows the membership function of the lateral acceleration, which is another input value used in the FLC. The input yaw rate membership function used in the IT-2 FLC was set to fuzzification yaw rates between -15 deg/s and 15 deg/s. The lateral acceleration input was adjusted to fuzzification values between -3 m/s^2 and 3m/s^2. Figure 6 shows the crisp membership function output of the IT2-FLC.

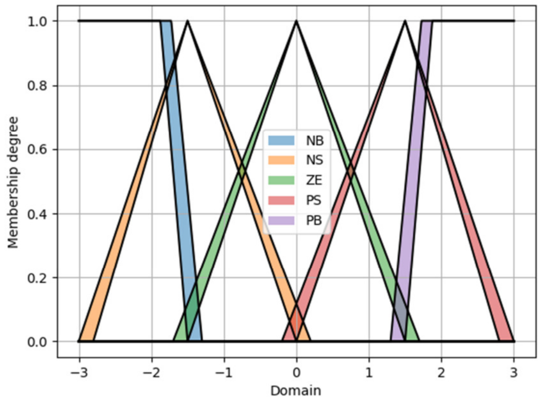

Fig. 5. Input membership function of lateral acceleration.

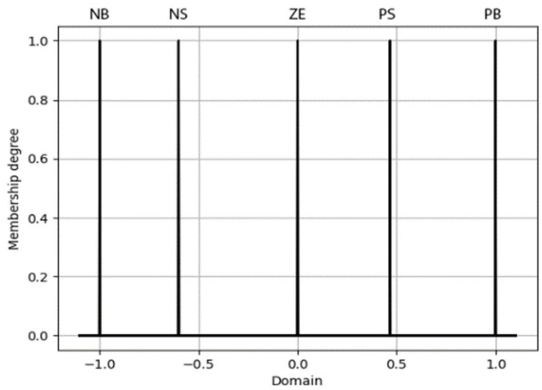

Fig. 6. Output membership function of differential brake.

As a result of the type-reducer mechanism, five different crisp outputs were produced by the defuzzification. These were: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB). Table I shows the rule-based relationship between inputs and outputs in IT-2 FLC.

TABLE I. FUZZY LOGIC CONTROLLER RULE BASE

Yaw Rate	Lateral Acceleration				
	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NB	NB
NS	NB	NB	NS	NB	NB
ZE	NB	NB	ZE	PS	PB
PS	PB	PB	PS	PB	PB
PB	PB	PB	PB	PB	PB

Figure 7 shows the control surface for the relationship between the input and the output membership functions used in the IT-2 FLC. The response surface, which is used to visualize the relationship between input and output membership functions outside of the rule table, increases the expert's command of the rule base.

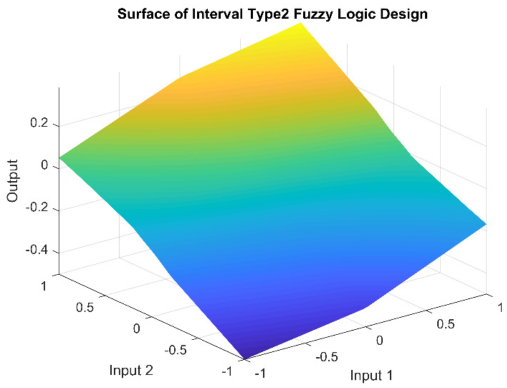

Fig. 7. Response surface of interval type 2 fuzzy logic controller.

IV. TESTS

The FLC-based yaw controller of the VC system was developed in MATLAB/Simulink in four variants: Type-1 Mamdani, Type-1 Sugeno, simplified Type-2 [24], and IT-2. The performance of the FLC controllers was evaluated with the DLC test and compared with the results of a separate test with the controller turned off. Figure 8 shows the steering angle applied for the DLC scenario performed at 80 km/h.

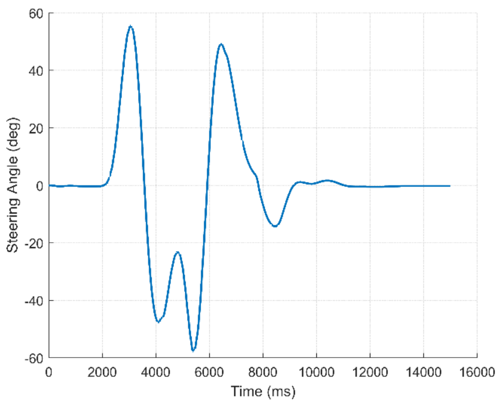

Fig. 8. Steering angle applied in the DLC test.

The results obtained for the closed and open conditions of the controller were compared. The IT-2 FLC results were used in the controller test, and Figure 9 shows changes in caravan yaw rate, lateral acceleration, and hitch angle in the DLC test. Figure 9(a) shows the caravan yaw rate in the CV system, where a maximum of 37 deg/s was obtained when the controller was off and 24 deg/s when IT-2 FLC was active, showing a 35% improvement. Figure 9(b) shows the lateral acceleration value on the caravan, showing a maximum value of 0.63 g when the controller was off and 0.57 g when it was active. IT-2 FLC exhibited 10% more stable behavior when comparing lateral accelerations. Figure 9(c) shows the angle change that occurred at the hitch point between the vehicle and the caravan, showing a maximum change of 14.7 deg when the controller was off and a maximum change of 6.46 deg when IT-2 FLC was active.

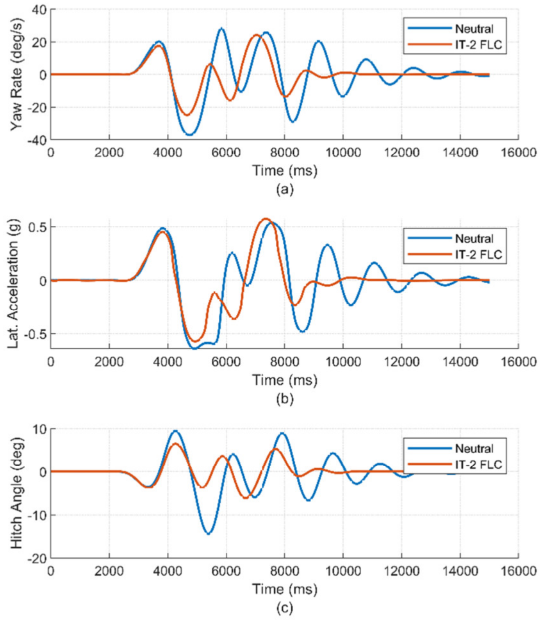

Fig. 9. Performance of active control technique based on the IT-2 FLC for DLC: (a) Yaw rate, (b) lateral acceleration; and (c) hitch angle.

A comparison of the performance of different FLC-based controllers designed to prevent instability modes that may occur in the VC system was performed with the DLC maneuver. Figure 8 shows the steering angle applied for the DLC maneuver. The controllers determined the braking rate to prevent the instability modes after this input. The yaw was prevented due to the applied braking force. Figure 10 shows the results of the controller performance comparison.

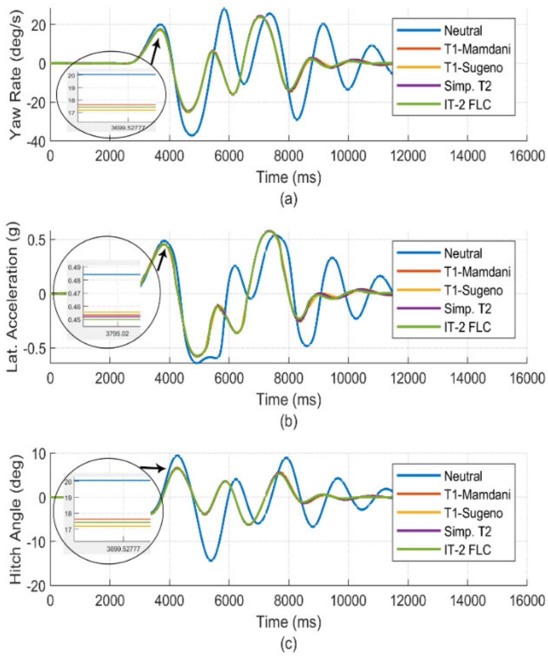

Fig. 10. Performance of active control technique based on different FLC for DLC: (a) Yaw rate, (b) lateral acceleration; and (c) hitch angle.

The change in yaw rate was 65 deg/s when the controller was off and 31.5 deg/s when the FLC-based controller was active. According to the hitch angle data, FLC-based controllers were 51.5% more successful. In terms of lateral acceleration, peak-to-peak was 0.893 g when the controller was off and 0.686 g when the FLC-based controller was active. In terms of lateral acceleration, the FLC-based controller was 23% better. In terms of hitch angle, a 23.85 deg change was observed when the controller was off and a 10.6 deg swing occurred when it was active. According to the data obtained, the FLC-based controllers were successful at a rate of 55.5%. These results show that FLC-based controllers successfully prevent instability modes in the VC system.

In addition to examining these variations, the forces occurring at the hitch point were observed, as they are included in the system dynamics that affect the lateral stability of the VC system. The longitudinal and lateral forces acting on the connection point affect the moments formed around the center of gravity. Additionally, the force acting on the connection point on the z-axis affects the dynamics that occur on the roll axis of the caravan. Figure 11 shows the longitudinal, lateral, and vertical forces at the connection point.

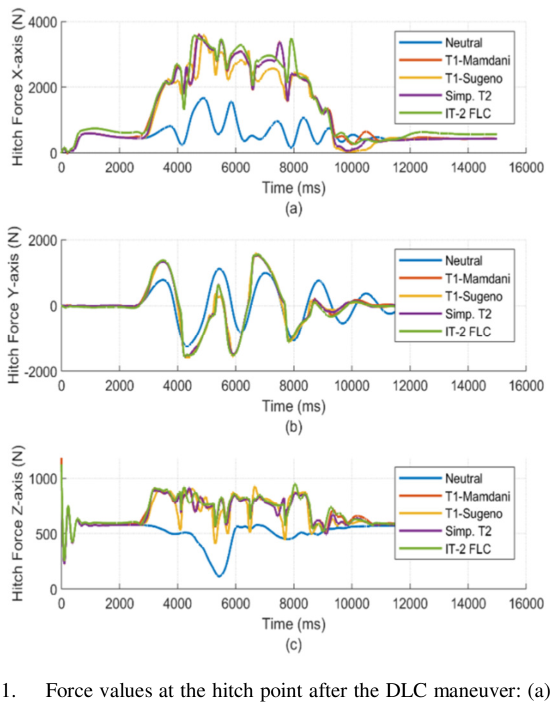

Fig. 11. Force values at the hitch point after the DLC maneuver: (a) x-axis hitch force, (b) y-axis hitch force, and (c) z-axis hitch force

Figure 11(a) shows the results obtained for the longitudinal force change at the hitch point. The lower longitudinal force when the controller was off was because no braking force was applied to the caravan tires. This value was 1600 N when the controller was off and increased to 3600 N when active. Figure 11(b) shows the variation in lateral force that occurred on the hitch. The reason for obtaining higher values with an active controller is the braking force applied by the tires. A force of 780 N was observed on the y-axis when the controller was off, while it was 1370 N when the FLC-based controller was active. When examining the braking forces applied by the FLC-based controller, it was observed that reactions were produced that prevented the formation of instability modes. Figure 11(c) shows the vertical forces that occurred at the hitch point. Like other axes, a value of 570 N was observed in the z-axis when the controller was off, and a 910 N was determined in the case of active FLC-based controllers. To detect instability modes that may occur on the roll axis, it is necessary to follow the vertical forces that occur at the hitch point. When examining the vertical forces at the hitch point after the DLC maneuver, it was observed that less force acted when the T1-Sugeno controller was active.

V. CONCLUSION

This paper presented an FLC-based yaw controller to prevent instability modes in a VC system, as these controllers are preferred due to the non-linear characteristics of VC systems. The performance of these controllers, developed in MATLAB/Simulink, was evaluated with the DLC maneuver applied in CarSim. Simulations were carried out when the controllers were active and offline, and the results were compared. The designed FLC-based controllers were: T1-Mamdani, T1-Sugeno, simplified T2, and IT-2. According to the results obtained, it was shown that different types of fuzzy logic-based systems prevent instability modes. The T1-Sugeno and IT-2 FLC controllers were more successful than the others, according to the yaw rate, lateral acceleration, changes in the hitch angle, and the force values formed at the hitch point. Various optimizations can be applied to the interval values of the membership functions to further improve the results of the IT-2 FLC. It was observed that different types of fuzzy controller systems performed close to each other. Therefore, the use of Type-1 and IT2 FLC is preferred, which were developed according to the constraints on the hardware to be used in the field test.

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