International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 16, No. 3, September 2025, pp. 1496~1504
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v16.i3.pp1496-1504

The road feeling control system on the steer by wire system uses fuzzy logic control based on swarm optimization

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Article Info

Article history:

Received Sep 28, 2024
Revised May 8, 2025
Accepted May 25, 2025

Keywords:

Fuzzy logic control
MQPSO
Optimal torque control
Road feeling
Steer by wire

ABSTRACT

This paper presents an optimal control system for enhancing road feel in a steer-by-wire (SbW) system using fuzzy logic control (FLC) optimized with modified quantum particle swarm optimization (MQPSO). The objective is to improve the driver experience by providing realistic torque feedback, thereby replicating the steering sensations typically generated by road conditions. This feedback is essential for conveying information about vehicle dynamics and road surface variations through opposing torque applied to the steering interface. An artificial intelligence-based control system utilizing FLC was developed to manage the road feel feedback within the SbW system. The inputs to the FLC include steering angle, vehicle speed, and steering ratio, as well as key physical factors such as inertia and friction, all of which influence the generation of steering torque. The FLC parameters were optimized using MQPSO to achieve a more accurate and responsive road feel torque output. A Simulink model was constructed to simulate the proposed system. The simulation results demonstrate that the optimized FLC significantly improves the performance of the steering motor torque feedback mechanism. This study contributes to the advancement of steer-by-wire technology by proposing an optimal torque control framework and highlighting the effectiveness of integrating FLC with MQPSO in enhancing road feel dynamics.

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1. INTRODUCTION

The steer-by-wire (SbW) system has emerged as a prominent research topic in the development of future vehicles, primarily due to its elimination of the mechanical linkage between the steering wheel and the front wheels [1], [2]. This is important to provide steering feel caused by road conditions [3]. The demand for road feel reflects the driver's need for improved vehicle maneuverability and tactile feedback related to vehicle motion and road surface characteristics. Such feedback allows drivers to perceive changes in road conditions intuitively, without compromising comfort [4]-[6]. The quality of road feel is largely determined by the interplay of three primary torque components: inertial torque, which arises from the acceleration or deceleration of rotating masses and may delay system response to driver input [7] friction Torque, caused by internal mechanical resistances (e.g., bearings, joints, gears), potentially producing a "dead zone" where small steering inputs yield no corresponding wheel movement or feel unnaturally light [8] and road torque, generated from tire–road interactions and representing reactive forces from the road surface [9]. In SbW systems, such feedback must be synthesized artificially due to the absence of a mechanical connection.

Therefore, the objective of this research is to develop and characterize an artificial road feel that adaptively conveys road dynamics to the driver, thereby enhancing both perception and driving performance.

Several studies have simulated road feel control using mathematical algorithms influenced by parameters such as vehicle speed, front wheel angle, torque, and steering angle. These inputs are used to derive the desired road feel characteristics, aiming to produce realistic and informative steering feedback [1], [10]-[13]. An innovative artificial steering feel system based on proportional integral derivative (PID) control has been developed to enhance torque control, demonstrating high effectiveness and performance [3]-[6]. Artificial intelligence (AI)-based control systems offer advantages in performing tasks more rapidly, consistently, and comprehensively. Among these, fuzzy logic control (FLC) has proven to be a reliable AI technique for managing nonlinear systems [14]. However, determining the appropriate parameters for FLC in practical applications remains a challenge. Consequently, optimization methods are required to effectively tune FLC parameters [15], [16].

Particle swarm optimization (PSO) is a behavior-based optimization method known for its simplicity and rapid convergence, inspired by the social behavior of living organisms such as flocks of birds or schools of fish [2], [17]. To further enhance global optimality, a position update mechanism based on quantum mechanics was introduced, leading to the development of quantum-behaved particle swarm optimization (QPSO) [18], [19]. Subsequently, additional modifications were made to the local attractor parameters to improve global convergence accuracy, resulting in the modified quantum particle swarm optimization (MQPSO) method [17], [20].

Based on this background, the research problem addressed in this study is how to design a control system capable of generating a realistic road feel in a steer-by-wire (SbW) system using fuzzy logic control (FLC) optimized with MQPSO. The primary objective is to achieve optimal control of steering motor torque by integrating vehicle dynamics—including steering angle, vehicle speed, and steering ratio—while also accounting for inertia, road friction coefficient, and motor torque, in order to simulate the real-world performance of the SbW system.

2. METHOD

2.1. FLC control system design

A simulation model for the road feel control system in a steer-by-wire (SbW) configuration was designed using FLC implemented in MATLAB Simulink. The control system architecture includes inputs such as vehicle speed, steering angle, and steering ratio (SR), with the output being the motor current that generates torque on the steering wheel, as illustrated in Figure 1. The FLC generates torque output based on a set of predefined rules aimed at replicating the road feedback perceived by the driver. The parameters of the membership functions—such as scaling factors and gain multipliers—are optimized using the modified quantum particle swarm optimization (MQPSO) algorithm.

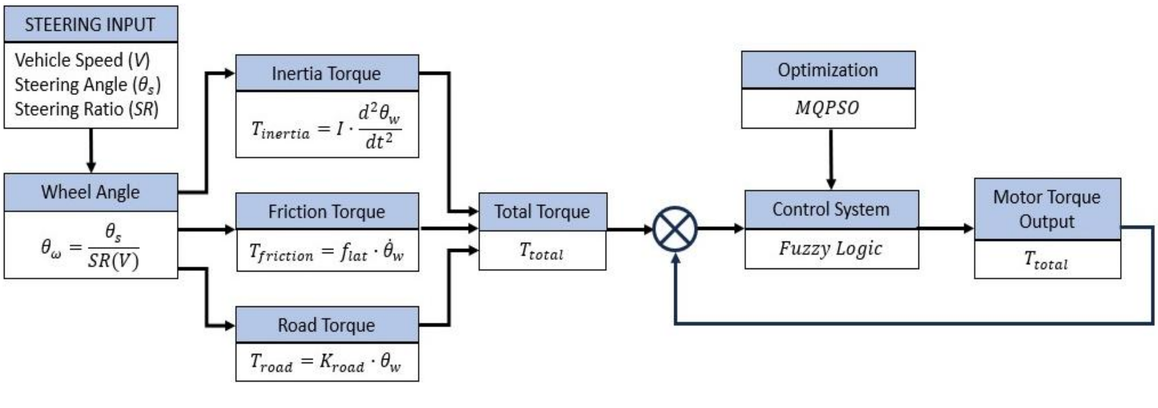

Figure 1. Block diagram of the road feeling control system

2.1.1. Control system input

The control system input is the steering signal, defined by a mathematical relationship between vehicle speed (V), steering angle (θ_s), and front wheel angle (θ_w). This relationship indicates that vehicle speed influences the steering ratio (SR) between the steering and front wheel angles [21]. At low speeds, a lower SR yields a larger steering angle, enhancing maneuverability, while at high speeds, a higher SR results in a smaller steering angle, thereby improving stability. This study adopts a simple, linearly varying SR model as a function of vehicle speed [22] expressed as (1) and (2).

$$SR(V) = aV + b \qquad \text{(a and b are constants)} \tag{1}$$

$$\theta_w = \frac{\theta_s}{SR(V)} \tag{2}$$

The steering input is mathematically transformed into three primary torque components:

i) Inertial torque model:

Inertial torque represents the resistance to changes in rotational motion within the system, as in (3).

$$T_{inertia} = I \cdot \frac{d^2\theta_w}{dt^2} \tag{3}$$

Where (I) is the moment of inertia and angular acceleration, which is the second derivative of the wheel angle. This torque influences the system's responsiveness to steering inputs [7].

ii) Friction torque model

Friction torque ($T_{friction}$) arises from resistive forces between the tires and the road surface [8] and can be expressed as (4).

$$T_{friction} = f_{Lateral} \cdot r_w \tag{4}$$

e $f_{lateral}$ is the friction force, which depends on the friction coefficient and the normal force, and r_w are the spokes of the wheel. Friction torque is an important factor in vehicle stability and control.

iii) Road torque model

Road torque (T_{road}) reflects resistive forces due to tire–road interaction [9] and is approximated by (5):

$$T_{road} = K_{road} \cdot \theta_w \tag{5}$$

where K_{road} is a representative constant for road conditions and tire characteristics. The total torque acting on the system is the sum of all three components, expressed as (6) and (7).

$$T_{total} = T_{inertia} + T_{friction} + T_{road} \tag{6}$$

$$T_{total} = I \cdot \ddot{\theta}_w + f_{Lateral} \cdot r_w + K_{road} \cdot \theta_w \tag{7}$$

Where: $f_{lateral}$ is the lateral friction force; I is the steering system inertia; $\ddot{\theta}_w$ is the angular acceleration of the wheel $\dot{\theta}_w$ is the angular speed of the wheel; θ_w is the front wheel angle. Inertial and friction torques determine the torque required to turn the wheels, while road torque contributes to the feedback felt by the driver. The total torque serves as the input to the FLC to generate a realistic road feel.

2.1.2. Control system output

The motor torque, as the output of the FLC, is designed to replicate the natural feedback torque typically experienced by the driver through a mechanical linkage. The objective is to generate motor torque that emulates authentic road feel. A DC motor is used for this purpose, and its behavior is represented by a transfer function derived from its electrical and mechanical characteristics. The relationship between the motor torque and the motor torque constant in a DC motor is simplified [23] as in (8).

$$T_{motor} = K_T \cdot I_m \tag{8}$$

Where: T_{motor} is the motor torque (Nm); K_T is the motor torque constant (Nm/A); I_m is the current through the motor (A).

2.2. FLC optimization system design

MQPSO is employed to optimize the membership function (MF) parameters of the FLC, aiming to minimize the error between the desired and actual feedback torque. By incorporating quantum behavior, MQPSO enhances the global search capability of conventional PSO, enabling faster convergence and improved avoidance of local minima compared to PSO and QPSO [24], [25]. In this study, MQPSO is used to determine the optimal FLC parameters through a learning process applied to a vehicle model. The algorithm begins by generating a random initial population of particles, referred to as a swarm. Each particle represents a set of three control parameters—ΔER, ΔDE, and ΔOT—related to the position and width of the MFs. The particles are iteratively evaluated and updated until a predefined maximum number of iterations is reached. Throughout this process, the system minimizes error changes, and convergence is achieved when particles reach their optimal positions, indicating the best performance of the control system [25]. The optimization is governed by MQPSO equations that update particle velocity (vi), position vector (xi), and local attractor (pi) as in (9), (10), and (11).

$$v_i(t+1) = wv_t(t) + c_1r_1 - \left(pbest_t - x_t(t)\right) + c_2r_2 - \left(pbest_t - x_t(t)\right) \quad (9)$$

$$x_i(t+1) = p_i \pm \alpha|gbest - x_i(t)| * \ln(1u)\, u \approx U(0.1) \quad (10)$$

$$p_i = \beta \text{ x } pbest_i + (1-\beta) \text{ x } gbest_i \quad (11)$$

With: t = Iteration; c_1 = Social constant of acceleration 1; c_2 = Cognitive constant of acceleration 2; r_1 (t) = random number 1; r_2 (t) = random number 2; $pbest_i$ (t) = Local best position; $gbest_i(t)$ = Global best position. Optimization stages are as follows:

i) Step 1: Initialize parameters: Optimization parameters using MQPSO [26] is: the number of particles was determined to be 30; maximum iterations at 30; contraction–expansion coefficient (β) specified maximum 1.0 and minimum 0.4; the optimized variables are $\Delta_i = (\Delta_{ER}\,;\, \Delta_{DE}\,;\, \Delta_{OT})$.
ii) Step 2: Initialize swarm / current position: Initialize swarm / current position randomly (randomly)
iii) Step 3: Evaluate population initialization: Each particle is evaluated to obtain the fitness of each particle using the integral time-weighted absolute error (ITAE) criterion [27].
iv) Step 4: Evaluate the new particles: At this stage, each new particle is re-evaluated in every iteration using the ITAE as the fitness function. The global best position is continuously updated across iterations until the maximum iteration is reached. If the global best fitness converges, the corresponding particle position—indexed by the best global fitness—is considered to have reached the optimal value (Δi).

3. RESULTS AND DISCUSSION

Software-in-the-loop simulation (SILS) is conducted using MATLAB/Simulink, with test scenarios including variations in steering input (sine wave and double lane change) and vehicle speed. The structure of the FLC-MQPSO-based road feeling control system is illustrated in Figure 2. The SILS test results of the FLC-MQPSO optimal control system obtained the best convergence, fitness, three optimal FLC parameter values, and C-RMS error are MQPSO reaches convergence in the 6th iteration, fitness function: 13112e+04 (ITAE), and the optimal control system performance error is expressed in a C-RMS error of 0.000999.

Multiplier factor for membership function:
- Error (ER) = 7.802928688626110
- Delta error (DE) = 2.571552150733341
- Output (OT) = 5.241155929013686

Convergence graph of the FLC control system optimization process using MQPSO, as shown in Figure 3. The test input variables consist of: steering ratio linear: $SR(V) = 0.1\,V + 12$; constant slip angle (0.05); coefficient of road friction (0.9).

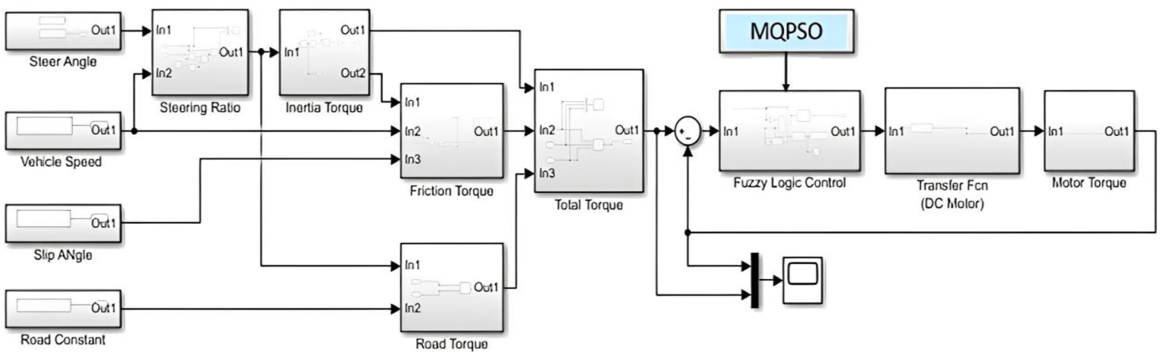

Figure 2. Structure of the FLC-MQPSO road feeling control system

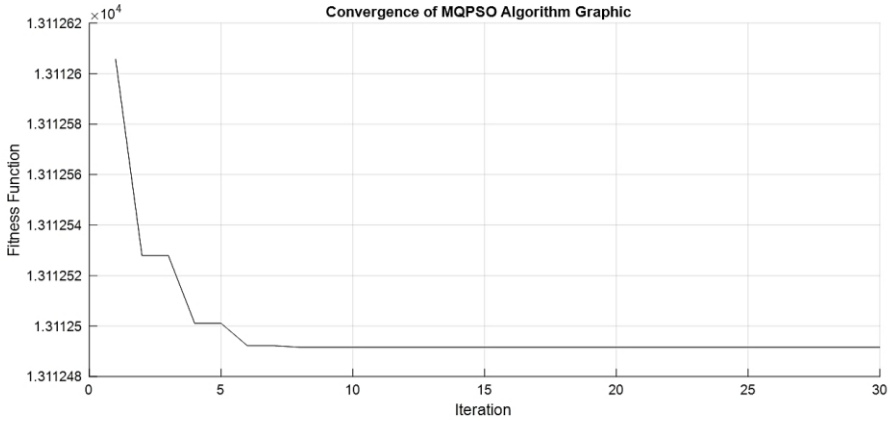

Figure 3. Convergence of FLC-MQPSO optimization

3.1. Test pattern I

The control system input uses a continuous steering angle in the form of a sine wave (SW) with an amplitude of 45°, representing the maximum steering angle. Vehicle speeds are varied at 25, 50, and 100 km/h. Figure 4 illustrates the system response, showing the relationship between the input steering angle and the resulting wheel angle, which is influenced by the steering ratio (SR) and vehicle speed. The test results show that with a continuous sine wave steering input of 45° amplitude and constant vehicle speeds of 25, 50, and 100 km/h, the steering angle remains unchanged, while the wheel angle—determined by the speed-dependent steering ratio SR(*V*) = 0.1 *V* + 12—varies. At 25 km/h, the wheel angle reaches a maximum amplitude of 3.103431°, which decreases to 2.045443° at 100 km/h, as presented in Table 1.

Next, the steering input is converted into inertial torque and additional torques—friction torque and road torque—which together form the total torque input to the FLC-MQPSO control system. This system then produces output in the form of motor torque, serving as road feeling feedback for the driver. Tests were conducted using the same steering input at three constant speeds: 25, 50, and 100 km/h, as shown in Figure 5.

Simulation results of the SbW road feeling torque control system demonstrate that the output torque is effectively regulated by the FLC-MQPSO method, achieving a C-RMS error of 0.000999. The torque differences between input and output are 0.12839 Nm at 25 km/h, 0.10622 Nm at 50 km/h, and 0.07898 Nm at 100 km/h. However, initial output torque exhibits a transient vibration, primarily influenced by the motor characteristics modeled through its transfer function, as detailed in Table 2.

3.2. Test pattern II

The control system input is a continuous steering angle double lane change (DBL) with an amplitude of 40°, corresponding to a maximum steering angle of 40°. Vehicle speed is varied at 25, 50, and 100 km/h. Figure 6 illustrates the comparison between the DBL steering input and the resulting wheel angle, which changes according to the speed-dependent steering ratio SR(V) = 0.1 V + 12. The test results show that while the steering input maintains a constant amplitude of 40°, the wheel angle amplitude decreases with increasing vehicle speed. At 25 km/h, the wheel angle reaches a maximum amplitude of 2.7589°, which decreases to 1.8182° at 100 km/h, as summarized in Table 3.

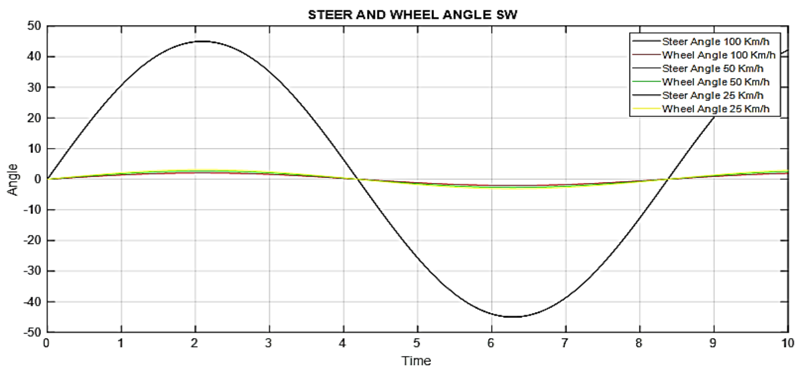

Figure 4. Steering and wheel input - continues steering angle sine wave

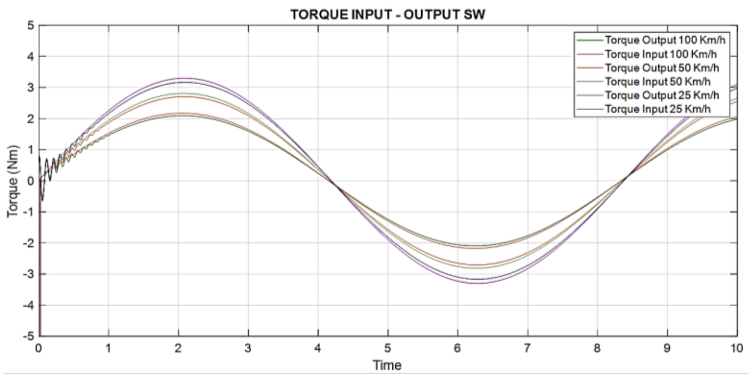

Figure 5. Input and output torque - continuous steering angle sine wave

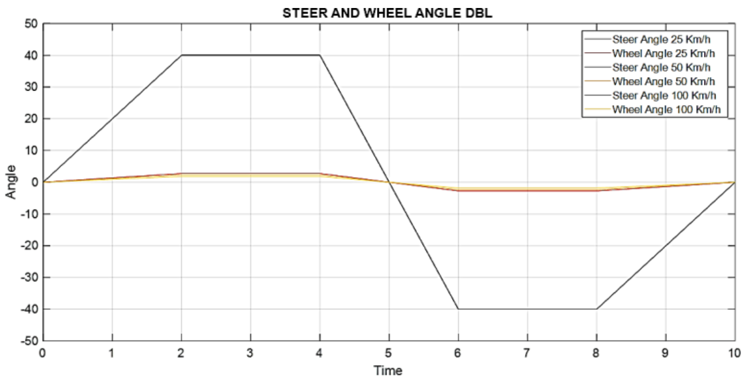

Figure 6. Steering and wheel input - continuous steering angle double lane change

Table 1. Steering and wheel input - continues steering angle sine wave

Peak	Speed 25 Km/h		Speed 50 Km/h		Speed 100 Km/h	
	Steering Angle (°)	Wheel Angle (°)	Steering Angle (°)	Wheel Angle (°)	Steering Angle (°)	Wheel Angle (°)
Max	44.99976	3.103431	44.99976	2.647044	44.99976	2.045443
Min	-44.99999	-3.103440	-44.99999	-2.647050	-44.99999	-2.045450

Table 2. Input and output torque - continuous steering angle sine wave

Peak	Speed 25 Km/h		Speed 50 Km/h		Speed 100 Km/h	
	Torque input (Nm)	Torque output (Nm)	Torque input (Nm)	Torque output (Nm)	Torque input (Nm)	Torque output (Nm)
Max	3.169113	3.29750	2.706669	2.812889	2.095623	2.174607
Min	-3.169333	-3.29749	-2.706490	-2.812880	-2.095510	-2.174610

Table 3. Steering and wheel input - continuous steering angle, double lane change

Peak	Speed 25 Km/h		Speed 50 Km/h		Speed 100 Km/h	
	Steering angle (°)	Wheel angle (°)	Steering angle (°)	Wheel angle (°)	Steering angle (°)	Wheel angle (°)
Max	40	2.758621	40	2.352941	40	1.818182
Min	-40	-2.758620	-40	-2.352940	-40	-1.818180

Subsequently, the steering input is converted into inertial torque, friction torque, and road torque, which together form the total torque input to the FLC-MQPSO control system. This total torque is used to generate motor torque as road feeling feedback for the driver. The system was tested using identical steering inputs at constant vehicle speeds of 25, 50, and 100 km/h, as illustrated in Figure 7. The simulation results of the SbW road feeling torque control system demonstrate that the output torque can be effectively controlled by FLC-MQPSO, with a C-RMS error of 0.000999. The torque differences between input and output are 0.420266 Nm at 25 km/h, 0.420144 Nm at 50 km/h, and 0.428196 Nm at 100 km/h. However, a torque vibration is observed at the onset of opposing torque generation by the motor, which is primarily influenced by motor characteristics represented by the transfer function in this simulation, as detailed in Table 4.

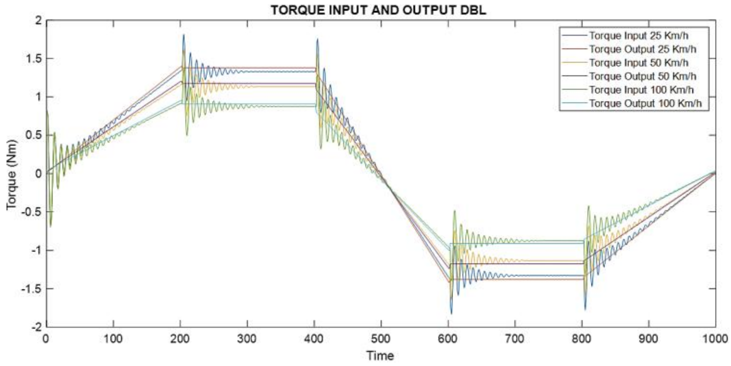

Figure 7. Input and output torque-continuous steering angle double lane change

Table 4. Input and output torque - continuous steering angle double lane change

Peak	Speed 25 Km/h		Speed 50 Km/h		Speed 100 Km/h	
	Torque input (Nm)	Torque output (Nm)	Torque input (Nm)	Torque output (Nm)	Torque input (Nm)	Torque output (Nm)
Max	1.816818	1.396552	1.626026	1.205882	1.382741	0.954545
Min	-1.832530	-1.413790	-1.645400	-1.235290	-1.402880	-1.000000

4. CONCLUSION

At small steering angles, the required steering torque is relatively low due to minimal resistance. As the steering angle increases, the resistance on the front wheels also increases, resulting in a higher torque demand. Conversely, at higher vehicle speeds, the required steering torque for the same steering angle tends to decrease. Overall, greater steering angles necessitate greater torque to counteract resistance and maintain directional control.

ACKNOWLEDGMENTS

We express our gratitude for the support of the Directorate of Research and Community Service, the Directorate General of Research Strengthening and Development of the Ministry of Research, Technology and Higher Education of the Republic of Indonesia which has funded this research.

FUNDING INFORMATION

The source of funding for this research is provided by the Directorate of Research, Technology, and Community Service (DRTPM), Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, through a Fundamental Research competition grant. The research is officially funded based on Decree Number 0459/E5/PG.02.00/2024 and Agreement/Contract Number 109/E5/PG.02.00.PL/2024.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Gatot Subiyakto						✓	✓	✓		✓	✓	✓	✓	✓
Purbo Suwandono					✓	✓	✓	✓	✓	✓		✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [FH], upon reasonable request.

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