Smart Controller-Based Vehicle Collision Avoidance System: Implementation in Rural Road Networks

Jyoti
P.hD Research Scholar
Department of Computer Science and Applications
Baba Mastnath University
Rohtak, Haryana, India
Email:

Dr. VK Shrivastava
Professor
Department of Computer Science and Applications
Baba Mastnath University
Rohtak, Haryana, India
Email:

Abstract- This study focuses on designing and testing a collision avoidance management system tailored for rural road conditions in India. Rural roads often face challenges such as narrow single-lane pathways, mixed traffic, and limited infrastructure, making accidents more frequent. To address these issues, a fuzzy logic controller was implemented, using key parameters such as velocity, distance, and angle to predict and prevent potential collisions. The system was tested under both single-lane and double-lane scenarios, simulating real-world rural traffic conditions. Results demonstrated that the fuzzy controller effectively identified collision risks and provided adaptive responses, such as speed regulation and steering adjustments, thereby enhancing safety. The study highlights the potential of intelligent control systems in reducing accidents and improving mobility in rural areas where conventional safety technologies are often absent.

Keywords: Smart Controllers, Collision Avoidance, Autonomous Systems, Safety Management etc.

I. INTRODUCTION

Road safety has become a pressing concern in India, particularly in rural areas where infrastructure is often underdeveloped and traffic conditions are unpredictable. Narrow single-lane and double-lane roads, mixed traffic involving motorized and non-motorized vehicles, and limited enforcement of safety regulations contribute to a high incidence of accidents. Traditional collision avoidance systems designed for urban highways are often unsuitable for rural contexts due to cost, complexity, and lack of adaptability. This has created a need for intelligent, low-cost, and context-specific solutions that can enhance safety and reduce accidents in rural road networks [1].

Smart controllers, especially those based on fuzzy logic, offer a promising approach to managing vehicle collision risks in such environments. Unlike rigid rule-based systems, fuzzy controllers can handle uncertainty and variability in traffic conditions by processing parameters such as velocity, distance, and angle. This allows the system to make adaptive decisions in real time, such as adjusting speed or steering to avoid potential collisions. The flexibility of fuzzy logic makes it particularly suitable for rural traffic scenarios, where unpredictability is common and conventional algorithms may fail to respond effectively [2].

The implementation of a Vehicle Collision Avoidance Management System using a smart controller focuses on simulating and testing scenarios in both single-lane and double-lane rural roads. In single-lane conditions, the system addresses head-on collision risks, while in double-lane setups, it manages overtaking and side-angle collision possibilities. By integrating real-time data on vehicle velocity, distance between vehicles, and angular positioning, the controller provides timely corrective actions to minimize accident risks [3].

This research contributes to the broader discourse on intelligent transportation systems by tailoring advanced technology to rural contexts. It demonstrates how smart controllers can bridge the gap between modern vehicular safety innovations and the practical needs of rural India. The study not only highlights the technical feasibility of fuzzy logic-based collision avoidance but also underscores its potential to improve road safety, reduce fatalities, and enhance mobility in regions where conventional safety infrastructure is limited [4].

II. RELATED WORK

Xu et al. (2025) [5] examined advances in vehicle safety and crash avoidance technologies. The objective was to evaluate modern innovations in crash prevention systems and vehicle safety mechanisms. Findings revealed that integration of sensor fusion, predictive algorithms, and automated braking significantly reduced accident risks. The conclusion emphasized that technological advancements provided robust frameworks for enhancing vehicular safety. Future scope suggested application in fully autonomous driving systems and integration with intelligent transportation infrastructures.

Aoki et al. (2024) [6] focused on the objective of developing an Advanced Driver Assistance System (ADAS) capable of preventing collisions with oncoming vehicles emerging from occluding areas at intersections in left-hand traffic. The methodology involved designing an ADAS that relies on on-board sensors rather than infrastructure-based communication systems, thereby overcoming limitations of designated

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intersection coverage. Hazardous speed criteria of the ego vehicle were calculated to identify high-risk collision scenarios, and speed control assistance was provided to guide the vehicle out of dangerous speed regions. Simulation results demonstrated that the proposed system significantly reduced collision risks compared to conventional Autonomous Emergency Braking Systems (AEBS). Findings confirmed that the sensor-based ADAS offered effective collision avoidance even under occlusion conditions. The scope of this research extends to enhancing safety in real-world intersections without dependence on external infrastructure.

Goudarzi & Hassanzadeh (2024) [7] examined the objective of improving safety and reliability in self-driving vehicles by addressing instability in car-following behavior controlled by human drivers. The methodology incorporated hazard warning systems into adaptive control frameworks, with “time to contact” used as a key indicator of potential collisions. Various techniques including image processing, machine learning, deep learning, and sensor-based approaches were classified and analyzed to determine their effectiveness in collision prediction and prevention. Results highlighted the importance of integrating alarms and adaptive systems to mitigate unavoidable collision risks. Findings emphasized that advanced computational methods enhance obstacle detection and response reliability. The scope of the study includes identifying challenges, future research directions, and unresolved problems in collision avoidance systems for autonomous driving.

Yoo et al. (2024) [8] addressed the objective of improving emergency avoidance path planning in autonomous driving systems. The methodology involved integrating prediction data of surrounding vehicle paths into the artificial potential field (APF) method and optimizing quintic Bézier curve control points using sequential quadratic planning. Simulations were conducted using IPG CarMaker 12.0.1 and MATLAB/Simulink 2022b to validate the proposed approach. Results revealed that the integration of prediction data and curve optimization improved efficiency and stability in path planning, overcoming the local minimum problem associated with gradient descent in conventional APF methods. Findings confirmed that the enhanced approach generated safer and more reliable avoidance strategies. The scope of this research extends to advancing autonomous driving safety by embedding predictive intelligence into path planning algorithms.

Dong et al. (2024) [9] addressed the objective of developing an active collision avoidance method for autonomous vehicles that goes beyond emergency braking. The methodology involved designing a model predictive control (MPC)-based trajectory tracking control derived from vehicle dynamics, integrating MPC with adaptive cruise control (ACC) for braking strategies, and incorporating active steering based on a safety distance model. An obstacle avoidance function was constructed by considering vehicle–obstacle distance and relative speed, while nonlinear model predictive control (NMPC) was applied for path planning. To accelerate computation and enhance safety, the alternating direction multiplier method (ADMM) was employed. The algorithm was tested on the Simulink and CarSim co-simulation platform across static and dynamic obstacle scenarios. Results demonstrated effective collision avoidance through braking, with strong stability and robustness in steering maneuvers at high speeds. Findings confirmed that vehicles could return to the desired path after obstacle avoidance, validating the efficiency of the proposed algorithm. The scope of this research extends to improving autonomous vehicle safety in complex, high-speed environments through advanced predictive control strategies.

Kim et al. (2024) [10] focused on the objective of developing and validating a collision avoidance algorithm for unmanned surface vehicles (USVs). The methodology involved designing a catamaran-type USV equipped with multiple sensors integrated into a guidance, navigation, and control system. Thrusters on the port and starboard sides enabled turning maneuvers, while the robot operating system streamlined communication of sensor data such as position, orientation, and situational awareness. The collision risk index (CRI) method was applied to calculate risk based on obstacle distance and waypoint angle, guiding the USV along paths with minimized risk. Noise from two-dimensional LiDAR data was filtered using k-dimensional tree and Euclidean distance methods to ensure accurate obstacle identification. The algorithm was benchmarked against artificial potential field and safety zone methods in an artificial tank environment. Results highlighted the superior time efficiency and optimality of the CRI-based approach compared to its counterparts. Findings validated the effectiveness of CRI in real-world free-running tests. The scope of this study extends to enhancing maritime safety by providing robust, sensor-driven collision avoidance solutions for autonomous surface navigation.

Lin et al. (2024) [11] addressed the objective of improving path planning and collision avoidance for unmanned surface vehicles (USVs). The methodology involved developing an adaptive differential evolution algorithm integrated with the analytic hierarchy process (AHP-ADE). Enhancements included the introduction of an elite archive strategy and adaptive adjustment of the scale factor (F) and crossover factor (CR) to balance global and local search capabilities, thereby preventing premature convergence and improving accuracy. The collision risk index (CRI) model was optimized and combined with the quaternion ship domain to enhance precision in collision risk calculations. Evaluation factors such as the improved CRI model, International Regulations for Preventing Collisions at Sea, and optimal collision avoidance distance were incorporated into a fitness function, with weights determined through AHP. Results from MATLAB simulations demonstrated that the AHP-ADE algorithm outperformed the improved particle swarm algorithm in safety, economy, and operational efficiency. Findings confirmed superior performance in multiple ship encounter scenarios. The scope of this research extends to providing a robust and efficient framework for USV autonomous navigation in complex maritime environments.

Verstraete & Muhammad (2024) [12] focused on the objective of reviewing pedestrian collision avoidance systems in autonomous vehicles over the past decade. The methodology involved classifying existing studies into five categories: pedestrian detection methods, collision avoidance approaches, actions, computing methods, and test methods. Results of the review provided a comprehensive overview of the techniques and technologies employed in pedestrian collision avoidance. Findings emphasized the diversity of approaches and the importance of integrating detection, decision-making, and testing frameworks to ensure safety. The scope of this review extends to democratizing autonomous vehicle technology by making pedestrian collision avoidance systems more accessible and reliable for widespread adoption.

A. Research Gap

Despite significant advancements in intelligent transportation systems, there remains a clear research gap in the application of smart controller-based collision avoidance technologies specifically tailored for rural road networks in India. Most existing studies focus on urban highways or advanced vehicular systems, often overlooking the unique challenges of rural environments such as narrow single-lane and double-lane roads, mixed traffic conditions, and limited infrastructure. Furthermore, while fuzzy logic controllers have been explored in general traffic management, limited empirical work has been conducted to validate their effectiveness using parameters like velocity, distance, and angle under rural scenarios. This gap highlights the need for context-specific research that adapts intelligent collision avoidance systems to rural India, ensuring affordability, simplicity, and practical applicability in regions where conventional safety technologies are often absent.

B. Research Objective

The primary objective of this study is to design, implement, and evaluate a smart controller-based vehicle collision avoidance management system using fuzzy logic for rural road networks in India. By focusing on traffic scenarios in single-lane and double-lane rural conditions, the research aims to analyze how parameters such as velocity, distance, and angle can be dynamically processed to predict and prevent potential collisions. The goal is to develop an adaptive, low-cost, and context-specific solution that enhances safety in rural areas where conventional road infrastructure and advanced vehicular technologies are limited. Ultimately, the study seeks to provide a validated framework that demonstrates the effectiveness of fuzzy controllers in reducing accident risks and improving mobility in rural India.

III. RESEARCH METHODOLOGY

Collision control in autonomous vehicles is crucial for ensuring the safety of passengers and pedestrians on the road. These vehicles can identify potential collisions and react within milliseconds, thus decreasing the frequency of traffic accidents. By integrating advanced sensors and artificial intelligence, autonomous vehicles can skillfully navigate complex traffic scenarios, thereby improving road safety for everyone. This research examines the mitigation of vehicular accidents in the nation's rural regions. A fuzzy controller is utilized to manage vehicle motion. The vehicles utilized are rear-wheel drive, including two rear wheels: one on the left and one on the right. The vehicle examined in this thesis is either a car or a bus, intended for simulation purposes. Each vehicle is outfitted with a series of sensors that gauge distances in its environment and ascertain the position of the target.

A. Description of Obstacle Avoidance Maneuver

An obstacle avoidance maneuver is a controlled action performed by a vehicle to prevent collision when an obstacle is detected in its path as shown in fig 1. In rural and hill curve areas, this maneuver is critical because obstacles may include livestock, pedestrians, or sudden road barriers, and the road geometry often limits visibility. The maneuver involves adjusting steering, braking, and acceleration in real time, guided by sensor inputs and smart controllers. The goal is to maintain stability while safely navigating around obstacles without leaving the designated lane or losing control on steep gradients.

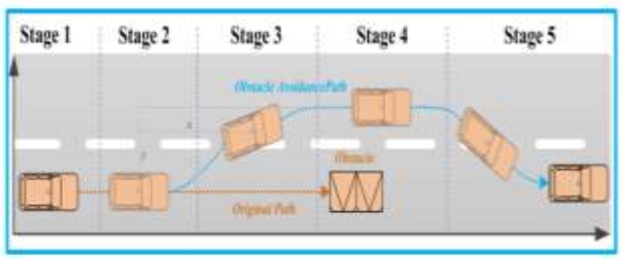

Fig 1: Obstacle Avoidance Process

Mathematically, the maneuver can be described using vehicle dynamics. If the vehicle is modeled with a bicycle model, the lateral displacement $y(t)$ and yaw angle $\psi(t)$ are governed by:

$$\dot{y}(t) = v \cdot \sin(\psi), \dot{\psi}(t) = \frac{v}{L} \cdot \tan(\delta)$$

where v is the vehicle speed, L is the wheelbase, and δ is the steering angle. During obstacle avoidance, the controller computes the required steering angle δ to shift the trajectory laterally by a safe margin while maintaining stability. The minimum safe distance to initiate the maneuver can be calculated using the stopping distance equation:

$$d_{\text{safe}} = v \cdot t_r + \frac{v^2}{2\mu g}$$

where t_r is the driver/controller reaction time, μ is the road friction coefficient, and g is gravitational acceleration. If the detected obstacle lies within d_{safe}, the system must combine braking with steering to avoid collision. In hill areas, the slope angle θ modifies the braking distance as:

$$d_{\text{brake}} = \frac{v^2}{2g(\mu \pm \sin\theta)}$$

showing that uphill and downhill conditions directly affect maneuver feasibility.

B. Car Model and Road Geometry

$$\dot{x}(t) = v(t)\cos(\psi(t)), \dot{y}(t) = v(t)\sin(\psi(t))$$

The car's position $(x(t), y(t))$ changes according to its speed $v(t)$ and yaw angle $\psi(t)$. When $\psi = 0$, the car moves along the positive x-axis; as ψ changes, the velocity vector rotates accordingly. These are purely kinematic relations derived from projecting the velocity onto the global axes.

$$\dot{\psi}(t) = \frac{v(t)}{L}\tan(\delta(t)), \dot{v}(t) = a(t)$$

where x, y are position, ψ yaw angle, v speed, δ steering, a longitudinal acceleration, and L wheelbase. The yaw rate depends on speed v, wheelbase L, and steering angle δ. The $\tan(\delta)$ term comes from the bicycle-model geometry that approximates front/rear wheel behavior as a single front-steer axle. The longitudinal acceleration $a(t)$ governs speed changes due to throttle/brake. Together, these define how the vehicle turns and accelerates, assuming moderate steering angles and no tire saturation.

C. Car Model for Maneuver Planning

It models the host vehicle using the kinematic bicycle approximation, valid at moderate speeds and for rear-wheel-drive vehicles typical in rural contexts. The state is position (x, y), heading ψ, and speed v. The control inputs are steering angle δ and longitudinal acceleration a. Let L be the wheelbase.

Planar motion:

$$\dot{x} = v\cos\,\psi, \dot{y} = v\sin\,\psi$$

Heading dynamics (small slip assumption):

$$\dot{\psi} = \frac{v}{L}\tan\,\delta$$

Speed dynamics:

$$\dot{v} = a$$

Curvature-capable steering:

$$\kappa = \frac{\tan\delta}{L}, R = \frac{1}{\kappa}$$

where κ is path curvature and R is instantaneous turning radius.

Lateral acceleration (comfort/safety limit):

$$a_y = v^2\kappa$$

Bound a_y by friction and comfort limits:

$$a_y \leq \mu g, a_y \leq a_{y,\text{comfort}}$$

D. Function of Smart Controller

The smart controller in a vehicle collision avoidance system is primarily employed to manage the movement of vehicles under uncertain and dynamic rural road conditions. It integrates inputs from multiple sensors such as front, left, and right obstacle distances, and heading angle as well as wireless communication data from nearby vehicles. By processing this information, the controller continuously evaluates the risk of collision and determines appropriate maneuvers, including braking, steering, or speed adjustments. Its use ensures that vehicles can respond in real time to obstacles, hidden hazards, or oncoming traffic, thereby enhancing safety in environments where visibility and predictability are often limited.

Table 1: Function Details of Fuzzy Controller

Membership Function	ZMF (Z-shaped membership function)
Defuzzification	Weighted average
And Method	Product
Or Method	Probabilistic OR

(Source: MATLAB)

Table 1 shows the function details of the fuzzy controller. In the context of fuzzy sets, when there is exactly one element with a membership value of one, it is sometimes called the prototype or the archetypal element of the set. The generation of rules for a fuzzy inference system is frequently the most challenging stage in the design process.

IV. RESULTS OF SYSTEM

In the single-lane rural road simulation, the system demonstrated its effectiveness in maintaining safe distances between vehicles traveling in both the same and opposite directions. When vehicles moved in the same direction and the longitudinal gap fell below the threshold, the base station (BS) intervened to regulate speed and spacing, successfully preventing rear-end collisions. Similarly, when vehicles approached from opposite directions, the BS monitored the lateral clearance and adjusted positions to ensure adequate side distance. These results highlight that the integration of sensors, fuzzy control, and wireless communication allowed vehicles to respond dynamically to imprecise motion and unpredictable rural traffic conditions, thereby reducing collision risks in narrow single-lane environments. Figure 2 shows the original scene which is used in this system. It shows that one-way traffic in rural areas with two vehicles is moving in this scenario. It follows the concept of left moving vehicle as per Indian standards. Both vehicles never collide with each other.

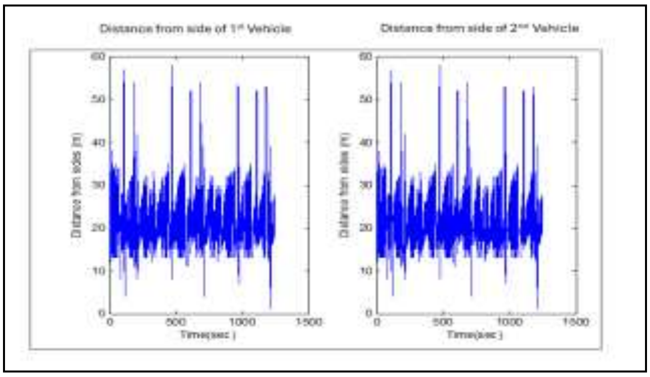

Fig 2: Distance of Both Vehicles from Wall

In Figure 2, the simulation illustrates the variation in side distances of two vehicles traveling in the same direction along a rural road. The x-axis represents time in seconds, while the y-axis denotes the measured distance from the side walls. Both vehicles are regulated by a fuzzy controller, which continuously adjusts their trajectories to maintain safe margins. The results show that the side distance fluctuates, reaching a maximum of about 70 feet, while the minimum value never approaches zero, ensuring that vehicles do not collide with the boundaries.

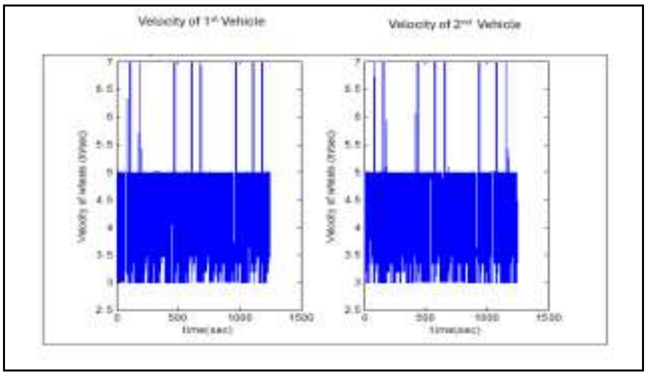

Fig 3: Velocity Comparison of Both Vehicles

In Figure 3, the velocity profile of two vehicles traveling in the same direction is presented, with time represented on the x-axis and velocity in meters per second on the y-axis. The simulation shows that the vehicles' speeds fluctuate between a minimum of 3 m/sec and a maximum of 7 m/sec, reflecting the dynamic adjustments made during motion. Both vehicles are regulated by a fuzzy controller, which continuously processes distance inputs to determine safe velocity levels. As the vehicles approach each other or encounter varying road conditions, the controller adapts their speeds to maintain safe separation and avoid collisions. The results confirm that, despite imprecise motion inputs, the fuzzy controller successfully ensures smooth velocity regulation, preventing the vehicles from hitting each other or any surrounding obstacles, thereby demonstrating the system's effectiveness in collision avoidance.

V. CONCLUSION

The research concludes that a fuzzy controller-based collision avoidance system is highly effective in managing traffic safety on rural roads. By integrating parameters such as velocity, distance, and angle, the system can dynamically assess risk and provide timely corrective measures. In single-lane scenarios, the controller proved efficient in managing head-on collision risks, while in double-lane conditions, it successfully handled overtaking and side-angle collision possibilities. The findings confirm that smart controllers can adapt to unpredictable rural traffic environments, offering a cost-effective and practical solution for enhancing road safety. This approach bridges the gap between advanced vehicular technologies and the pressing need for accident prevention in rural India.

VI. FUTURE SCOPE

The study opens avenues for further development and deployment of intelligent collision avoidance systems in rural contexts. Future research can expand the model by incorporating additional parameters such as road surface conditions, weather variations, and driver behavior patterns to enhance accuracy. Integration with Internet of Things (IoT) devices and vehicle-to-vehicle (V2V) communication could further strengthen predictive capabilities, enabling cooperative safety management across multiple vehicles. Policymakers and transport authorities may consider pilot projects to implement such systems in rural districts, thereby reducing accident rates and improving public confidence in road safety. Additionally, the framework can be extended to low-cost embedded systems, making it accessible for widespread adoption in rural India where affordability and simplicity are critical.

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