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DESIGN AND EXPERIMENTAL VALIDATION OF A SENSOR-BASED SAFETY-ENHANCED BRAKING SYSTEM FOR LOW-COST AUTOMOTIVE APPLICATIONS

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ABSTRACT

In recent times, automobile depends upon the active and passive safety systems to enhance the safety features due to increased rate of accidents. The causes of the accidents are increasing nowadays and therefore the fatality rate also increases. The automotive safety system had developed widely in costlier vehicles but unfortunately not in low end vehicles. The statistics describe that the safety systems in the low-cost vehicles are as par with high-cost vehicles and hence the fatality rate is also more than the high-cost vehicles. The causes of accidents were investigated by many researchers and they highlighted that the several road accidents were caused by inattention of drivers and in specific 77% fatality were mainly due to drivers' fault during regular driving. In this work, research was carried out to reduce the fatality rate and damages in emergency condition. The proposed research is to make the vehicle to come to stopping position by activating the braking system at the time of emergency. Ultrasonic sensor senses the obstacles and object present ahead of the vehicle. A new hydraulic actuator is developed and is connected with the brake pedal and actuator, it is actuated when signal from the control unit, press the brake pedal to slow down the vehicle in critical situations. The experimental setup is used for the testing the proposed system and to evaluate the performance of control algorithm with sensor-based technology. The safety enhances braking system is implemented for the proposed system by adding the actuator on the brake pedal without any change in the existing brake system. The concept of this research is to reduce the severity of injury, fatality in emergency condition.

I. INTRODUCTION

The automotive safety system had developed widely in costlier vehicles only but unfortunately not in low end vehicles. The causes of the accidents are widely investigated and the fatality rate is increased day by day; drivers fault only 77%. The statistics describes that safety systems in the low-cost vehicles are lower than the high-cost vehicles and therefore fatality rate also is more than the high-cost vehicles in the event of collision. Every safety feature cannot be incorporated in low end (cost) vehicles and the research is focused on what kind of safety system can be used to reduce the fatality rate in the low-cost vehicles.

The age factors also considered and analyzed for the causes of collision. The fatality rate is encountered day by day due to vehicle and human population and the important concern is not following the rules and regulation is one of the major issues. In the emergency braking (autonomous) vehicle safety systems which the sensors to observe the proximity of vehicles before and detects things wherever the relative speed and distance between the host and target vehicles counsel that a collision is close at hand. In such a scenario, emergency braking may be mechanically applied to avoid the collision or a minimum of to mitigate its effects. A recent study suggests that if all cars feature the system, it'll cut back accidents by up to 27 % and life says to 8000 lives per annum. The investigation carried out to decrease the fatality rate and literature points out some causes of collisions in past five years. There the different cases such as drivers fault, over speed, alcohol consumption during driving the vehicle, abnormal health issues, pedestrian crossing and mechanical error in India.

The investigation of road crashes reveals that driver's fault is the most important causes of collisions such as driver's fault of other vehicle, vehicle defects, Climate condition of road, pedestrians' fault, Vehicle defects, Condition of Road, Passenger fault Vehicle light or poor light, Unknown causes. The percentage of harmed fatality and collided rate is listed in the table. The maximum percentage of driver's fault is listed in the table and it shows that not only inattention of the drivers or slackness of the drivers shown in the Figure 1 [1-3]. The IR used for monitoring the drowsiness and eye blink during driving and the system is used to prevent the accident and ultrasonic sensor generator that functions to generate the sound waves and the timing instruction means for generating the signal into waves. This signal creates or generates the signal into ultrasonic waves based on the instruction. Transmitter waves the waves to find out the object or obstacles present in ahead of the vehicle. The range obstacle depends upon the sensor senses the road surface and distance measured by the sensor.

If the sensor senses the object and it shows the distance between the driving vehicle and object. The signal is amplified and compares with the reference signal of the amplifier. The magnitude of reference signal is controlled and maintains the ratio between the reference signal and the amplified signal [4],[5]. The brake is a device and it inhibits the motion of the vehicle by gripping the energy from the dynamic system using hydraulic actuator. The design and analysis of piston rod is theoretically measured and experimentally tested. The most popular accustomed retardation the vehicle or to forestall the motion and largely accomplished because of friction. The function of the braking system is to decrease or decelerate the vehicle velocity by pressing or pressing the brake pedal and brake pads or discs against the rotor attached to the wheel, where the vehicle forces to slow down due to friction [6].

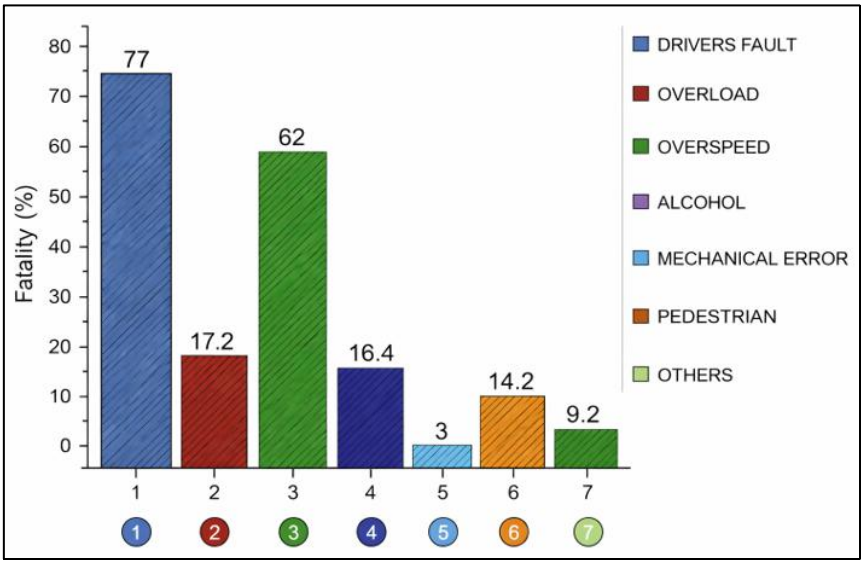

Figure 1: Causes of Road Accidents.
Source: Authors, (2026).

This study developed and tested a system inside the passenger car that checks how alert a driver is. The system can detect signs of fatigue driving, which can help prevent accidents caused by drowsiness [7]. The authors created a more advanced system for monitoring driver behavior, with additional safety features. Testing showed that this system can reduce the risk of accidents by identifying unusual driving behavior in real time [8]. This work introduced a braking system that includes a delay valve for cars. The analysis found that this system makes braking faster and more stable, helping to prevent skidding during sudden stops [9]. This paper examined how metal surfaces and rubber materials affect damping in tools used for boring. The results showed that choosing the right materials can significantly reduce tool vibrations, improving the quality of the machining process [10]. The research looked at the properties of bio-composites made from Aloe vera and hemp fibers.

The findings showed that these materials have better strength and can handle heat well, making them suitable for eco-friendly applications [11]. This work compared different methods of joining GFRP composites, such as riveting, bonding, and mixing. The hybrid method was found to be stronger and more durable than the others, making the joints more effective [12]. This paper looked at how a five-point seat belt helps during crashes. The study found that this type of seat belt greatly reduces movement and injury risk compared to regular seat belts [13]. The work examined how IoT is used in the car industry, including smart monitoring, regular maintenance, and better connectivity. The study showed that IoT improves car performance, increases safety, and enhances the driving experience [14]. This paper looked at ways to produce both energy and clean water using solar power with a special still. The results showed that this method is more efficient and produces more water than traditional systems [15].

The paper talks about an automatic braking system that uses a hydraulic device. The findings showed that this system can stop the car on its own to prevent collisions, without the driver needing to take any action [16]. This research introduced a health monitoring system for cars that checks the driver's condition in real time. The study explained how continuous monitoring can improve road safety by detecting early signs of tiredness or other health problems [17]. The paper examined rider fatigue on motorcycles through an online survey with experienced riders. The results showed common patterns of fatigue, which highlighted the need for monitoring systems to help prevent accidents caused by decreased alertness. The study presented a safety-focused driver condition monitoring system connected to vehicle controls, aimed at reducing the risk of accidents. Testing showed that the system could identify unsafe driving situations and help prevent accidents automatically and performed computational fluid dynamics (CFD) analysis on a simplified car model with side vortex generators using the RANS turbulence model [18],[19]. The study looked at a new design for the intake manifold for automobile that run on various types of design intake [20].

The results from computer simulations showed that the stronger front structure could absorb more energy during a collision, reducing the chances of injuries to the people inside. There were also studies on engines design along with a technique on analysis process and these studies found that analysis techniques [21],[22]. Recent developments in automotive and two-wheeler engineering show a clear shift toward making vehicles safer, lighter, and more reliable through better design and control strategies. Studies on heavy vehicle chassis indicate that modifying structural geometry and selecting suitable materials can effectively improve strength and durability while reducing overall weight, which directly supports better vehicle efficiency and service life [23]. In a similar direction, research on two-wheelers demonstrates that the use of advanced materials along with ANSYS-based optimization leads to noticeable improvements in suspension performance and ride comfort under real operating conditions [24]. Improvements have also been reported in vehicle subsystems such as air conditioning, where optimized micro-channel heat exchanger designs enhance heat transfer and overall system effectiveness [25]. Safety-oriented research further emphasizes the importance of monitoring and control systems in reducing road accidents.

Driver condition monitoring systems are shown to be effective in identifying fatigue and unsafe driving behavior, helping to prevent accidents caused by human error [26]. Automatic emergency braking systems using hydraulic actuators provide an additional layer of protection by reducing collision impact and improving braking response in critical situations [27]. To support these intelligent systems, secure handling of sensor and control data is essential for reliable operation [28]. Studies integrating driver monitoring with safety-enhanced braking systems report improved accident prevention capability, particularly in real-time driving scenarios [29]. Advanced braking system designs for passenger vehicles continue to contribute to improved stopping performance and occupant safety [30]. Repeated structural evaluations confirm the benefits of optimized chassis design [31], while rider fatigue analysis highlights the need for assistive and safety technologies in motorcycles to improve rider endurance and overall road safety and study shows the measuring devices used for analysising the output results from motorised accurancy is due to sensors [32],[33].

II. MATERIALS AND METHODS

The materials and methods used to sense the object detection by using ultrasonic sensor which is placed in bumper and brake the wheels for preventing the accidents. The research is carried to analyze the condition of the driver by using sensor-based technology which is placed in bumper. The sensor analyzes object range for the driver. The ultrasonic sensor is used for the proposed system for better accuracy in sensing and sends signal to the data acquisition system. When the object is detected and the receiver end sends the signal to the micro controller. The microcontroller actuates the hydraulic actuator to press the brake pedal and the experimental test rig is designed and to examine the proposed system. The model is designed with 8051 microcontroller and an ultrasonic-sensor. The sensor transmits sound waves when the object detects at the ahead of the ultrasonic sensor, the sound waves are reflected back and the receiver will detect the waves. Approximately speed of the sound waves 341m/s in air. Ultrasonic sensor uses the velocity of the sound in air; time taken to the sensor to transmit and receive the waves to estimate the distance-object location. Specifications of ultrasonic sensor is Input voltage - 5 V (DC), Current – 2Ma, O/p voltage- 5v , Detection - 3 cm to 1000cm, Dimensions- 4.5 x 2 x2 cm, I/p trigger signal – 11 us TTL impulse, Keil IDE software, echo signal –o/p TTL PWM signal and 8051 microcontroller is used in Arduino nano with ATMEGA 328 has 3KB of SRAM & 1KB OF EEPROM, 14 digital pins on the Arduino nano used as an input & output by using the different modes like pin mode, digital read and digital write functions.

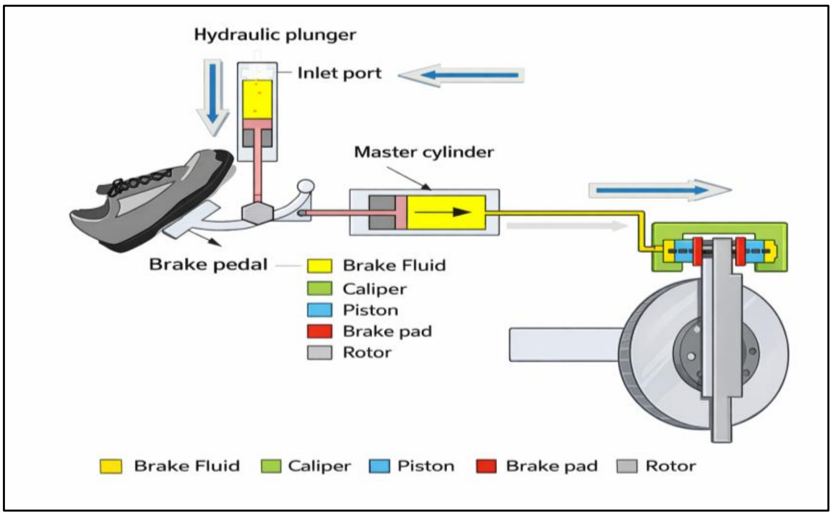

Figure 2: Layout of proposed braking system.
Source: Authors, (2026).

From the Figure 2. The proposed model is activated by using solenoid valve and the signal from the sensor for activating the plunger. The brake pedal is connected to hydraulic cylinder or double acting cylinder which contains forward movement and retracting movement. The pump is used to pump the fluid from the reservoir to press the brake pedal. The selection of actuator or plunger for compressing the brake pedal for the passenger car braking system from hydraulic actuator or pneumatic actuator for the proposed research. The investigation or study on this both cases is classified according to their advantages. The disadvantages of pneumatic cylinder are less efficient than the linear methods.The compressor and the air delivery limitations describe that the lower pressure will have lower speed and forces.

The compressor must run continuously for operating the pressure even the work is not done. For accurate control or efficiency, it requires proportional valves & regulators but it increases the cost and complexity. Therefore, the air is available easily it may be contaminated by oil or lubrication leads to maintenance and downtime. The advantage of hydraulic actuators over the pneumatic actuators is suited for many applications and they can deliver the forces 25 times than the pneumatic cylinders of same size. The operating pressure 4000psi and the minimum load applied on the plunger is 300N to 1600N for pressing the load. Plunger 0.6 inches of piston rod used for forward and return stroke. The length or stroke of the piston rod is 169mm.

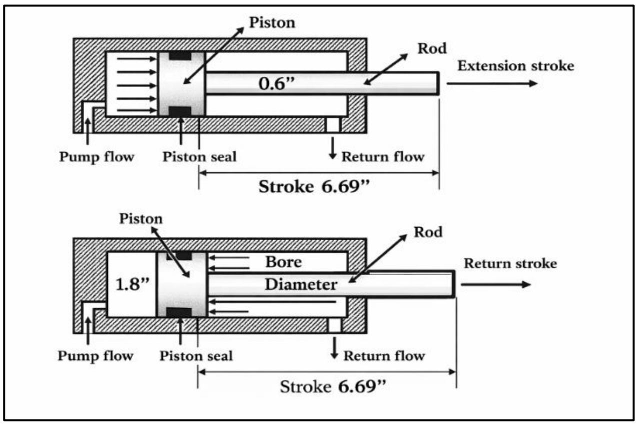

Figure 3(a): Schematic diagram Hydraulic Actuator.
Source: Authors, (2026).

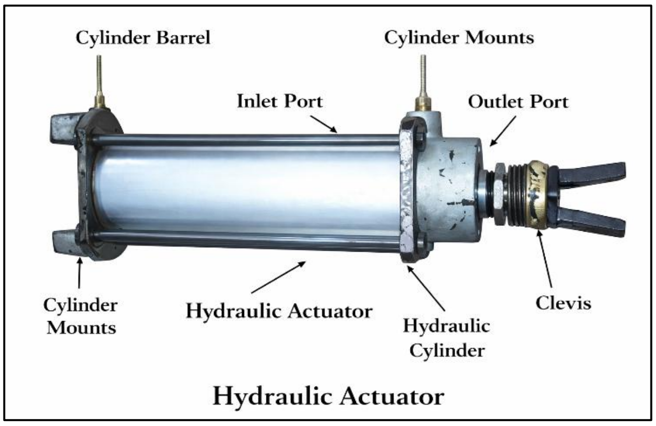

Figure 3(b): Developed model of Hydraulic Actuator.
Source: Authors, (2026).

From the Figure 3a and 3b. The maximum pressure for 70bar is used for analyzing the piston rod. The hydraulic pump flows the constant flow of hydraulic fluid through the solenoid valve to the inlet port. The inlet port pressurized the piston rod to press pedal. The inlet pressure for compressing limit is 30 bar acts inside the cylinder in all directions uniformly. The pressure on the piston provides force to press the brake pedal and it is calculated by using area of cylinder by (3.14 x r^2) by considering the diameter of the cylinder.

III. EXPERIMENTAL FRAMEWORK FOR TESTING THE PROPOSED MODEL

The proposed model and the experimental model consist of hydraulic actuator, DC motor, reservoir, hydraulic pump, solenoid valve, hydraulic hoses, rotating disc, and pressure gauge with vacuum booster and power supply shown in the Figure 4. The motor rpm is calculated by using tachometer for sensing the speed of the motor. The chain sprocket which is connected to the disc of the wheel. The wheel disc is the rotating disc or consider as wheel. The max rpm for the motor is 4000 rpm and this dc motor rpm are used instead of engine power supply. The pressure is measured by the pressure gauge for sensing the pressure or by calculating the theoretical value of the pressure in the cylinder acts on the piston. When these sensors are triggered the signal and the control unit actuates solenoid. The solenoid which is a hydraulic valve connected to the hydraulic pump and control unit. The static prototype model is used for testing the hydraulic cylinder working during the signal from the control unit. The hydraulic cylinder presses the foot pedal according to the output from the control unit. The control unit senses the wheel speed or motor speed for measuring the theoretical calculation of stopping distance in static model. The pedal force is measured for load and pressure calculation to compress the brake pedal. Therefore, the pedal force, theoretical stopping distance, hydraulic cylinder activation, sensing time and duration of response time are measured.

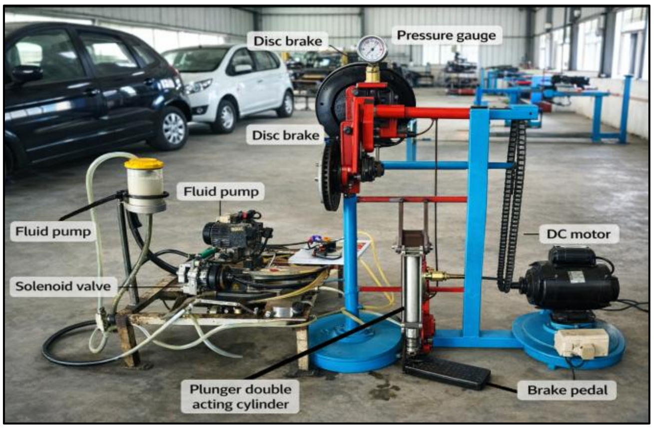

Figure 4: Experimental model of developed system.
Source: Authors, (2026).

The hydraulic pump tends to compress the pressure of maximum 14 bar for compressing the pedal. The reservoir consists of 3000ml volume of oil for storing capacity. The volume of the cylinder is calculated on the basis of fluid inside the cylinder. The stopping distance calculated theoretically for the prototype model by calculating the thinking time and braking distance. Stopping distance is based on response time of the driver which is max response time of driver is two seconds depends on the age factor. The calculated stopping distance by considering motor rpm to speed. The pedal force and pressure in master cylinder is calculated in prototype model. Prototype model used for testing the plunger activation with respect to the sensor response time. The response time of the sensor is one second for the complete activation of the system. The prototype system is tested for the pedal force, hydraulic pressure on the piston rod and stopping distance calculation. Thus, the pedal force is estimated by using

$$F_{in} = L_p \; X \; F_{app} \quad (N) \tag{1}$$

Where,
L_p = *Pedal ratio*
F_{app} = *Applied force*

$$L_p = \frac{d_{app}}{d_{in}} \tag{2}$$

(X) d_{app} = *15 inches*
(Y) d_{in} = *3 inches*
Pedal ratio is 5: 1

(i) To calculate the thinking distance [3]

$$d = (v \; x \; r) / 3.6 \tag{3}$$

d = thinking distance in meters
v = velocity in km/h
r = time (reaction) in seconds

$$d = (V \; x \; r) / 3600$$
$$= (100 \; x \; 1.5) / 3600$$
Reaction distance = 41.6 meters

(ii) To calculate the braking distance [3]

$$d = V^2 / 2x\mu xg \tag{4}$$

d = braking distance (m)
v = velocity in km/h
μ = cof (0.5)
g = Acceleration m/s^2

Example – calculating the speed of vehicle is in 100 km/h on dry asphalt:

$$d = (100/3.6)^2 / (2x \; 0.8x9.81)$$

Braking distance = 49 meters braking distance
Stopping distance = **thinking distance + braking distance**= 41.6 + 49**= 90.6 m.**

III. RESULTS AND DISCUSSIONS

The experimental testing for the proposed system is calibrated for the observation of sensor response time and actuator activation. The research is carried to analyze the hydraulic actuator, pedal force, pressure, stopping distance by testing in the test rig developed model to prevent the collision in emergency. The results and discussion point out the output of sensing efficiency of sensor and actuator response and automatic braking is applied during emergency situation. The table 1 describes the pedal force calculation for the proposed developed model. The pedal force is calculated by varying different force on the brake pedal to calculate the booster output force by using the actuator activation during testing in developed model. The Table 2 describes the booster force from the master cylinder when the pedal force is applied by actuator and it is calculated for differ force for accuracy and to examine for testing. The master cylinder dimensions are calculated and shown in the Table 2 and Figure 5 describes the variation of pedal force with applied weight on the pedal.

Table 1: Pedal force calculation.

S. No	Weight (kg)	Force (N)
1	20	196
2	17	166
3	15	147
4	10	98
5	5	49
6	4	39
7	2	19

Source: Authors, (2026).

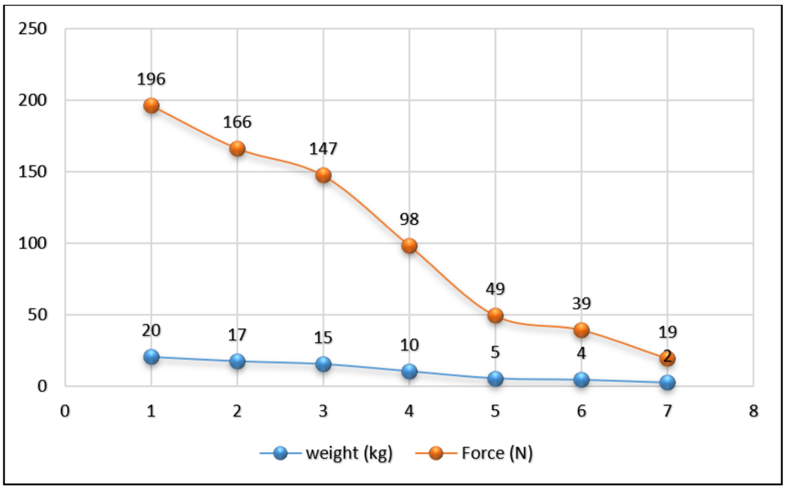

Figure 5: Pedal Force calculated based on weight applied.
Source: Authors, (2026).

Table 2: Output force from master cylinder.

S. No	Pedal force I/p (N)	Bore (mm)	Piston area (mm)	Master cylinder Pressure (bar)	O/p force from master cylinder(N)
1	196	2.54	22.3	14	785
2	166	2.54	22.3	12	667
3	147	2.54	22.3	10	589
4	98	2.54	22.3	7	393
5	49	2.54	22.3	3.46	196
6	39	2.54	22.3	2.77	157
7	19	2.54	22.3	1.39	79

Source: Authors, (2026).

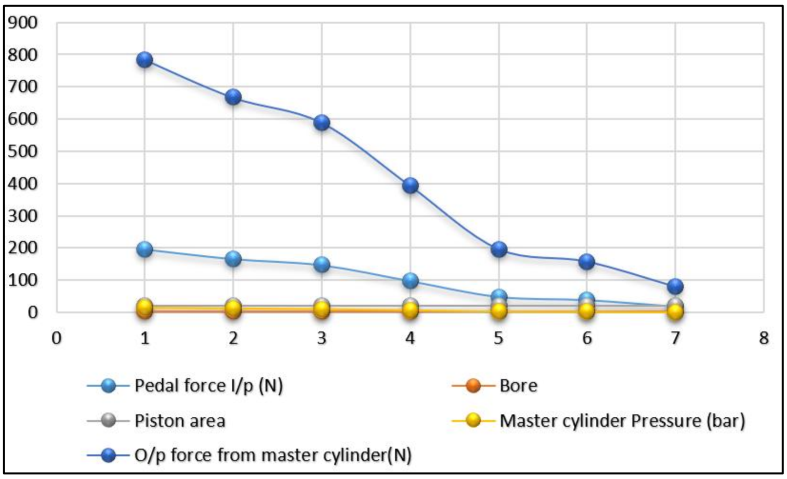

Figure 6: Effect of pedal force vs brake booster output force.
Source: Authors, (2026).

Table 3: Stopping distance estimation.

Motor (rpm)	Speed (Km/hr)	Thinking distance (m)	Braking Distance (m)	Stopping distance (m)
130	10	4.1	0.4	4.5
250	20	8.3	2.1	10.2
380	30	12.5	4.6	17.2
500	40	16.5	8	24.5
620	50	20.3	12.2	33.5
750	60	25	18.2	43.2
850	70	29.1	24.4	53.4
980	80	33.3	32.1	65.4
1100	90	37.2	40	78.2
1250	100	41.5	49	90.5

Source: Authors, (2026).

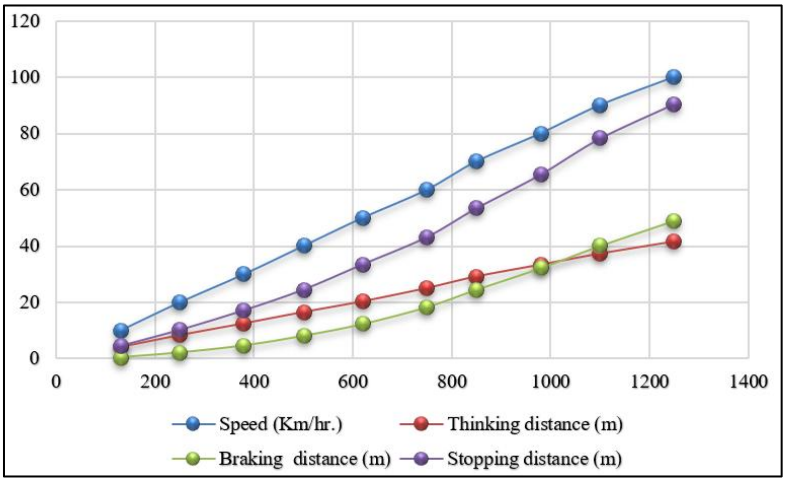

Figure 7: Effect of speed vs stopping distance.
Source: Authors, (2026).

The Table 3 describes the stopping distance calculation by using the experimental model for analyzing the thinking distance, stopping distance and braking distance. Figure 7 shows the effect of speed and stopping distance and it describes that for different speeds is calculated. Example say speed (10km/hr.) has the stopping distance 4.6 m with 4.1m reaction distance and 0.4 m braking distance. The graph 7 shows how vehicle speed affects thinking distance, braking distance, and total stopping distance. As speed increases, the thinking distance increases gradually due to the fixed reaction time of the driver. The braking distance increases more rapidly at higher speeds because greater kinetic energy must be dissipated by the braking system. As a result, the stopping distance, which combines both thinking and braking distances, rises sharply with speed. This clearly indicates that even small increases in speed can lead to a significant increase in the distance required to bring a vehicle to a complete stop, highlighting the critical role of speed management in vehicle safety.

IV. CONCLUSION

The developed system enables object detection while driving, making it applicable for both passenger and commercial vehicles. Designed to be cost-effective, it can also be implemented in budget-friendly vehicles priced below 5 lakhs. This system provides valuable support for drivers during prolonged driving and emergency situations. Experimental validation using a test rig confirmed the effectiveness of the automatic braking function in emergencies. The system successfully reduced vehicle speed, minimized collision impact, and additionally provided safety alerts—such as warning signals, alarm activation, and continuous stop-light blinking—to alert nearby traffic and prevent rear-end collisions.

V. AUTHOR’S CONTRIBUTION

Conceptualization: C. Dineshkumar, P R Hemavathy, A Arockia Julias.
Methodology: C. Dineshkumar, P R Hemavathy, A Arockia Julias.
Investigation: Mohamed Jaheen, Mohammed Harris.
Discussion of results: C. Dineshkumar, P R Hemavathy, A Arockia Julias.
Writing - Original Draft: Mohamed Jaheen, Mohammed Harris, Mohamed Sulthan.
Writing - Review and Editing: Mohammed Harris, Mohamed Sulthan.
Resources: M Mohammed Harris, N M Mohamed Sulthan, Mohamed Jaheen.
Supervision: C. Dineshkumar, P R Hemavathy, A Arockia Julias.
Approval of the final text: C. Dineshkumar, P R Hemavathy, A Arockia Julias.

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