International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 10, October 2026)

Air Powered Pneumatic Bumper Car with Intelligent Braking

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***Abstract*— Low-speed front collisions usually happen because the driver reacts a moment too late, and an ordinary passive bumper does very little to soften the hit once it occurs. This paper presents a low-cost prototype of a bumper car that combines ultrasonic obstacle sensing, staged automatic braking and a pneumatically actuated bumper. An HC-SR04 ultrasonic sensor measures the gap to the obstacle ahead, and an Arduino UNO places that reading in one of four zones: safe, warning, braking and critical. In the warning zone the controller lowers the motor speed through PWM on an L293D driver and sounds a buzzer. In the braking zone the drive motors are brought to a stop. In the critical zone a relay energises a solenoid valve, compressed air reaches two pneumatic pistons, and the bumper is pushed forward to take up the impact. The wiring and control logic were checked in a Tinkercad circuit simulation, where an LED stands in for the pneumatic stage. The work shows that braking and active impact protection, which earlier studies mostly treat separately, can be joined in one embedded system built from inexpensive parts. Such a system suits bumper-car rides, teaching laboratories and slow-moving campus or industrial vehicles.**

***Keywords*— Arduino UNO, automatic emergency braking, collision mitigation, pneumatic bumper, ultrasonic sensor, vehicle safety**

I. Introduction

Many collisions in parking lots, factory aisles, college campuses and amusement rides take place at low speed, yet they still damage vehicles and injure people. The common thread in most of them is time. An obstacle appears, the driver needs a noticeable fraction of a second to see it and react, and during that interval the vehicle keeps rolling forward. By the time the brake is applied, the remaining gap is often too short.

Modern passenger cars handle this problem with forward collision warning and autonomous emergency braking (AEB). Field data show that these functions lower both the number and the severity of rear-end crashes [8]. However, production AEB depends on radar, cameras and powerful processors, which puts it out of reach for small vehicles and low-budget platforms. The bumper itself, on the other hand, has hardly changed. It is a fixed, passive part that only starts to work after contact has already been made.

The idea behind this project is to protect the vehicle in two layers. The first layer tries to avoid the collision altogether by slowing the vehicle and then braking as the obstacle gets closer. The second layer accepts that braking may not always be enough. When contact becomes unavoidable, compressed air pushes the bumper forward a short time before impact, so that the collision energy is spread over a longer stroke. A related idea, pairing AEB with an external airbag, has been shown to give a clear safety benefit in a recent cost-benefit study [9]. Our aim is to achieve a similar effect with a much simpler and cheaper pneumatic mechanism.

The main contributions of this work are: (i) a four-zone braking strategy that runs on an 8-bit Arduino UNO using only one ultrasonic sensor; (ii) an electro-pneumatic bumper that is deployed automatically by the same controller; and (iii) a verified circuit and control flow that can be built from widely available low-cost parts. Section II reviews related work, Section III describes the proposed system, Section IV explains the hardware, Section V presents the control algorithm, Section VI discusses the simulation results and limitations, and Section VII concludes the paper.

II. Literature Review

Ultrasonic sensing has been a popular choice for short-range collision avoidance because the sensors are cheap and easy to interface. Ahmed et al. [1] built an automatic braking system in which an ultrasonic sensor measures the distance to the vehicle ahead and a controller applies the brake once that distance falls below a set limit. Their results confirmed that distance-triggered braking can stop frontal collisions at low speed, but the system offers no protection if the brake reacts too late. Krishnan [2] combined ultrasonic ranging with Li-Fi communication between vehicles, which improves awareness of nearby vehicles but is still limited to detection and warning.

A larger body of work deals with the decision logic of AEB. Hamid et al. [3] used a potential-field method to rate the risk of a frontal crash and trigger emergency braking. Guo et al. [6] proposed a model predictive controller with a variable time headway, so that the braking point adapts to the driving situation.

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Wang et al. [4] went further and coordinated steering with braking, letting the vehicle steer around an obstacle when braking alone cannot avoid it. These methods perform well, but they need accurate vehicle models, multiple sensors and considerable computing power, which is difficult to fit into a low-cost embedded platform. Dixit et al. [7] stressed that emergency braking must be modelled and tested under varied conditions before it can be trusted, and the survey by Rajendar and Kaliappan [5] gives an overview of the sensors and algorithms currently used in AEB.

Studies of real crashes support the value of these systems. Kusano and Gabler [8] estimated that forward collision warning, brake assist and autonomous braking together can noticeably reduce injuries in rear-end crashes. Ju et al. [9] looked at the problem from another angle and showed that adding an external airbag to AEB brings extra benefit, because it cushions the impacts that braking alone cannot prevent. Table I summarises these works. The gap that stands out is that almost all low-cost designs stop at braking, while active impact protection appears only in expensive automotive research. This paper tries to close that gap at the prototype level.

TABLE I
SUMMARY OF RELATED WORK

Ref.	Approach	Gap Addressed Here
[1]	Ultrasonic distance-based automatic braking	No impact protection if braking fails
[2]	Li-Fi and ultrasonic collision detection	Detection and warning only
[3]	Potential-field risk rating for AEB	Braking only; no bumper action
[4]	Combined steering and braking control	Needs full vehicle control system
[6]	MPC with variable time headway	Too complex for a low-cost MCU
[7]	Modelling and testing of AEB	No active bumper mechanism
[8]	Crash-data study of FCW, BA and AEB	Braking-based protection only
[9]	External airbag combined with AEB	Costly airbag; pneumatic option unexplored

III. PROPOSED SYSTEM

A. Problem Statement

Existing low-cost safety systems either warn the driver or apply the brakes, and they stop there. When an obstacle appears suddenly and the stopping distance is too short, the vehicle still hits the obstacle at full force through a rigid bumper.

A practical system is needed that can sense the obstacle, slow and stop the vehicle automatically, and soften the impact when a collision cannot be avoided, all at a cost that small vehicles can afford.

B. Objectives

The objectives of the project are: (a) to detect obstacles in front of the vehicle continuously; (b) to reduce speed and apply braking automatically as the danger increases; (c) to deploy a pneumatic bumper before a likely collision; (d) to lower the impact felt by the vehicle and its occupants; and (e) to achieve all of this with an Arduino-based design built from low-cost components.

C. System Architecture

Fig. 1 shows the block diagram. The Arduino UNO sits at the centre. On its input side it receives a regulated supply and the echo signal from the HC-SR04 sensor. On its output side it drives three groups of devices: the L293D motor driver that powers the four DC drive motors, a buzzer and LED for warnings, and a relay module that switches the pneumatic circuit. A single 12 V battery powers the whole vehicle. One branch of it feeds the voltage regulator for the electronics, and the other feeds the air compressor. The compressor supplies air to a solenoid valve, and when the relay opens this valve, air flows into two pneumatic pistons mounted behind the bumper.

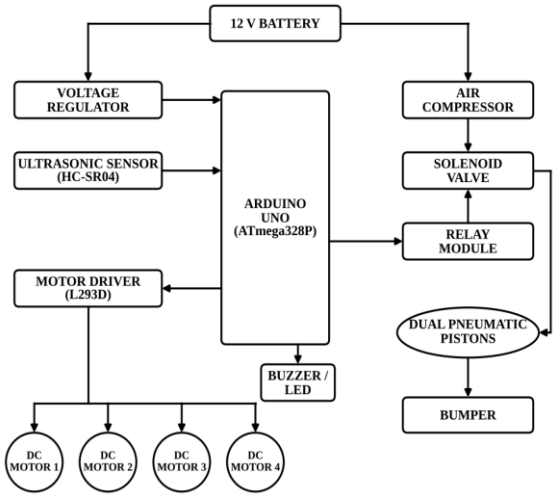


Fig. 1. Block diagram of the pneumatic bumper car

IV. HARDWARE DESIGN

A. Obstacle Sensing Unit

The HC-SR04 module has a transmitter and a receiver working at 40 kHz.

International Journal of Recent Development in Engineering and Technology
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A 10 µs pulse on the TRIG pin makes the module send out a short burst of ultrasound, and the ECHO pin then stays high for as long as the sound takes to reach the obstacle and return. The module covers roughly 2 cm to 400 cm [10]. Since the measured time t covers the path both ways, the distance d is

$$d = (v \times t) / 2 \qquad (1)$$

where v is the speed of sound, about 343 m/s at 20 °C. With t in microseconds and d in centimetres, (1) reduces to $d = 0.0343t/2$, or roughly $t/58$. The speed of sound rises with air temperature, so a temperature sensor could be added later for better accuracy outdoors. To ignore the odd false echo, the program takes the median of three consecutive readings before acting on them.

B. Control Unit

An Arduino UNO, based on the ATmega328P running at 16 MHz, acts as the controller [12]. It has 14 digital I/O pins, six of which can produce PWM, which is enough for this design. Two pins handle the sensor, four pins set the direction inputs of the L293D, two PWM pins set the motor speed through the enable inputs, and the remaining pins drive the relay, the buzzer and the indicator LED.

C. Drive and Braking Unit

The L293D contains four half-H drivers, arranged as two full H-bridges, and each output can supply up to 600 mA [11]. One bridge drives the two left motors and the other drives the two right motors, so the four-wheel chassis is controlled as two sides. Speed is set by changing the PWM duty cycle on the enable pins. For braking, the controller keeps the enable pin high and pulls both inputs of a bridge to the same logic level. This shorts the motor terminals through the driver and gives a fast stop instead of a slow coast, which is the braking action used in this project.

D. Pneumatic Bumper Unit

A 12 V air compressor charges the air line. The solenoid valve is normally closed, so no air reaches the pistons during normal driving. Because the valve coil needs more current than an Arduino pin can supply, it is switched through a relay module, with a flyback diode across the coil to protect the circuit from voltage spikes. When the relay closes, the valve opens and air pushes two pistons that are mounted symmetrically behind the bumper. The bumper moves forward by the stroke length of the pistons and is then held there by the trapped air.

The benefit comes from the impulse relation

$$F_{avg} \times \Delta t = m \times \Delta v \qquad (2)$$

For a given vehicle mass m and change in velocity Δv, the average force F_{avg} falls as the contact time Δt grows. The air column inside the pistons behaves like a spring with built-in damping. It lets the bumper give way over the full stroke instead of stopping dead, which stretches the collision over a longer time and lowers the peak force passed on to the chassis.

E. Power Supply

The 12 V battery supplies the compressor, the solenoid valve and the motor side of the L293D directly. A voltage regulator brings this down to 5 V for the Arduino, the sensor and the relay module. In the Tinkercad simulation, a 9 V battery stands in for the motor supply. Table II lists all the components and their roles, and Fig. 2 shows the simulated circuit.

TABLE II
COMPONENTS AND THEIR ROLES

Component	Role in the System
12 V battery	Main power source
Voltage regulator	Regulated 5 V for the electronics
Arduino UNO	Central controller
HC-SR04 sensor	Measures distance to the obstacle
L293D driver	Motor speed, direction and braking
DC motors (4)	Drive the car as two side pairs
Air compressor	Produces compressed air
Solenoid valve	Lets air into the pistons on command
Relay module	Switches the solenoid valve
Pneumatic pistons (2)	Push the bumper forward
Bumper	Takes the physical impact
Buzzer	Audible warning
LED	Shows bumper activation (simulation)

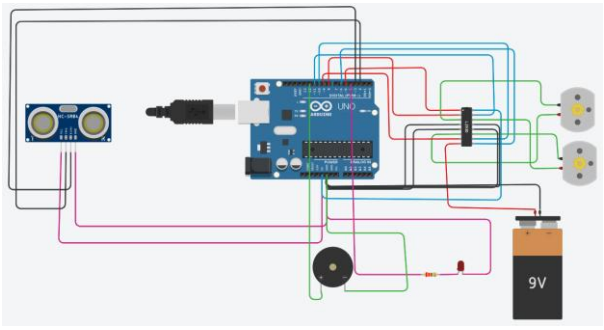


Fig. 2. Circuit of the system simulated in Tinkercad

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V. Working And Control Algorithm

The controller works on the principle that the response should grow stronger as the obstacle gets closer. Each reading of the sensor is placed in one of the four zones shown in Table III, and the controller then performs the action assigned to that zone. The thresholds given here are chosen for a small, slow prototype and can be changed in the program to suit a different vehicle.

TABLE III
Distance Zones and System Response

Zone	Distance	System Response
Safe	d > 50 cm	Full speed; buzzer off
Warning	30 < d ≤ 50 cm	Speed lowered by PWM; slow beep
Braking	15 < d ≤ 30 cm	Motors stopped; continuous buzzer
Critical	d ≤ 15 cm	Relay on, bumper deployed; LED on

1) Obstacle Detection: The sensor is triggered in every cycle of the main loop, and the distance is worked out from (1). The HC-SR04 needs about 60 ms between measurements so that late echoes do not disturb the next reading, which fixes the loop period.

2) Speed Reduction and Braking: As the obstacle enters the warning zone, the PWM duty cycle is lowered so the car slows down gently. If the obstacle keeps getting closer and enters the braking zone, the controller applies the fast-stop condition on the L293D and the buzzer sounds continuously.

3) Bumper Deployment: If the distance still falls to 15 cm or less, for example because the obstacle itself is moving towards the car, the controller energises the relay. The solenoid valve opens, air drives the pistons and the bumper moves forward to meet the impact. The LED marks this event.

4) Reset: The bumper is retracted only after the path is clear again, that is, when the distance rises above 30 cm. This gap between the deployment and reset thresholds prevents the valve from switching on and off rapidly when an object hovers around the critical limit.

Fig. 3 gives the complete flow of the program. For a real vehicle, the critical distance must be larger than the distance the vehicle covers while the system reacts and brakes. This minimum safe distance can be estimated as

$$d_{\min} = v \times t_r + v^2 / (2a) \qquad (3)$$

where v is the vehicle speed, t_r the total reaction time of the system and a the braking deceleration. The thresholds in Table III should be scaled up using (3) whenever the design is moved to a faster or heavier vehicle.

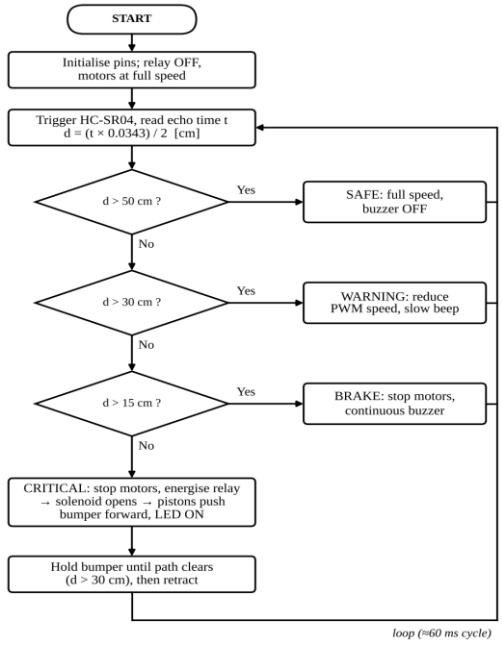


Fig. 3. Flowchart of the control algorithm

VI. Simulation Results And Discussion

The circuit of Fig. 2 was built and run in Tinkercad. During simulation, the distance seen by the HC-SR04 was changed step by step using the sensor slider while the motor outputs, the buzzer and the LED were observed. The simulation followed the intended sequence. Above 50 cm both motors ran at full speed. Between 50 cm and 30 cm the motor speed dropped and the buzzer beeped. Between 30 cm and 15 cm the motors stopped and the buzzer stayed on. At 15 cm and below, the LED that represents the pneumatic stage lit up together with the braking action. When the distance was raised again, the LED went off only after crossing 30 cm, which confirmed the reset logic.

A simple estimate shows that the timing is comfortable for a prototype. With a loop period of about 60 ms and an assumed speed of 0.5 m/s, the car moves only about 3 cm between two readings. The 15 cm critical zone therefore gives the controller several full sensing cycles to react before contact. The total cost stays low because every part is a standard hobby or automotive item, and the electronics can be assembled on a single board.

The design also has some limitations. A single ultrasonic sensor sees only a narrow cone in front of the car, so objects approaching at an angle may be missed, and soft materials such as cloth absorb ultrasound and return weak echoes. Once the bumper has been deployed, the compressor needs some time to refill the line before the bumper can act again. In addition, the reduction in impact force has not yet been measured on the physical prototype. Mounting an accelerometer on the chassis and comparing impacts with and without the pneumatic bumper is the natural next step.

VII. Conclusion And Future Scope

This paper presented an air-powered pneumatic bumper car with intelligent braking. Using one HC-SR04 sensor and an Arduino UNO, the system slows down, brakes and finally deploys a pneumatic bumper as an obstacle comes closer. The simulation confirmed that each stage is triggered at the correct distance and that the bumper resets safely. By combining braking with active impact protection in a single low-cost controller, the design addresses a gap that most budget collision-avoidance systems leave open.

Future work will focus on measuring the impact force on the hardware prototype, adding more sensors or a short-range radar to widen the detection area, and using vehicle speed to adjust the thresholds automatically based on (3). The bumper could also be fitted to the rear of the vehicle, and an IoT module could be added to log and report collision events.

Acknowledgment

The authors thank their guide, Prof. Amit Kumar Patil, for his guidance throughout this project, and their industry mentor, Mr. Vivek Dawange, President, Nexzu Mobility Limited, for his practical suggestions. The authors are also grateful to the Department of Electronics and Communication Engineering, MIT School of Engineering & Sciences, MIT ADT University, Pune, for providing the facilities needed for this work.

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