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# A Sensor-Aided Pneumatic Bumper Activation System to Reduce the Impact Force During a Vehicle Crash

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## Abstract

Vehicle accidents have become the most significant problem on roads within South Africa. These accidents could result in mild to severe damage to the vehicles (sometimes purchased expensively) and/or in the loss of human life. Given the advances in pneumatics technology and automation, and the need to boost the safety capacities of vehicles to resist and limit damage to frontal collisions, this study proposes a sensor-aided pneumatic bumper activation system to reduce the impact force during a vehicle crash. We develop and analysed system-based model build-up to improve crashworthiness. The proposed system consists of a sensor transmitter, receiver unit, control unit, and bumper, and the proposed design is validated through simulation studies. The most important finding from this study was the improvement of crashworthiness in the case of a full-frontal collision between a vehicle and a barrier through the combination of the vehicle dynamics control systems with an extendable bumper. As obstacles approach the vehicle, with a control signal in place, the electronic circuit instantly activates the bumper to absorb the impact and keep it from getting too close to the vehicle's body. When the extendable bumper is deployed, the occupant's longitudinal displacement and acceleration are greatly reduced. The cost of high-end cars can be reduced by adopting this concept and providing equivalent levels of safety. Also, the importance of pneumatics technology in automation, modern machine shops, and space robots is emphasized.

**Keywords**:
vehicle dynamics, crashworthiness, pneumatic system, extendable bumper, simulation

## 1.Introduction
### Background
Safety is an integral part of life. Accident cases are reported daily on the major roads in all parts of developed and developing countries Garethiya et al. (2015). Steele and Dullabh (2024) showed the criticality of bad roads leading

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to fatal road accidents in South Africa. These accidents often result in the loss of human life. As such, more attention is required in the research and development of an efficient car driving-aiding system (Pradeep et al. 2021), (Cárdenas et al. 2024). Accident prevention systems come in diverse mechanisms. The purpose of these mechanisms is to improve the braking response time, thus making it possible to keep a safe distance between two vehicles (Prabhu et al. 2021). As noted by Nair et al.(2024) different safety systems have been implemented on modern cars through the immense development of the automobile industry. These systems include emergency brake assist, dynamic stability and traction control, electronic brake distribution, anti-lock braking system, blind spot information, night vision, driver distraction detection, alcohol detection and prevention systems etc. For example, Airbags, though costly provide some levels of safety but may not be effective in preventing damage or death in certain accidents. Safety is the sole matter of prime importance; it cannot be compromised for cost (Wada, 2009), (Nair et al. 2024).

In all braking systems, the input signal is given directly from the driver by applying the brake pedal. Mondal and Nandi (2023) indicated this as a crucial human interface in the braking system. Therefore, the braking of vehicles is highly manual operated and mostly dependent on the driver's intuition at applying the brakes. If the driver fails to respond when an obstacle is in front of his vehicle or fails to apply proper braking force on the brake pedal, chances of losing control of his vehicle are high and will most definitely lead to an accident. Urgent application of brakes may also result in imbalance by skidding the tyres of the vehicle (Pisal et al.2017). As noted by Srinivasa (2015) and (Jan et al.2024), studies have shown that current bumpers used in automobiles are rigid types. These bumpers consist of a specific capacity and the range of their accidental force is high, which leads to the failure of the bumper and thus these forces are transferred towards the passengers. Therefore, this system does not reduce the damage to either the vehicle or passengers. According to Pisal et al. (2017), it is necessary to automatically control brakes through electronic devices to overcome these unwanted effects.

Pneumatic braking systems are often widely used in commercial vehicles due to their properties, flexibility and cost-effectiveness therefore often reducing drivers' costs (Wei et al. 2023). Accident prevention systems have been established throughout the years to integrate diverse approaches towards achieving increased safety of automobiles on the road. Dileepan et al. (2017) revealed that accidents can greatly be avoided rather than prevented with an automatic pneumatic brake and bumper system. Research on pneumatic systems has previously been done such that Engineers have been able to gather diverse mechanisms (hydraulic, pneumatic, and mechanical systems) that are connected to the brakes. Shubham (2019) and (Wei et al. 2023) pointed out that these mechanisms need to take braking input from the operator to stop the vehicle. If the operator fails, an accident will then be caused.

This research focuses on studying and proposing a pneumatic automatic bumper system that will work simultaneously with a pneumatic brake to effectively minimize or avoid vehicle accidents. Essentially the study attempts to design intelligent control systems and electronic models. which will be divided into system and mechanical designs. It will focus on the design of a belt drive, input shaft, governor, and the selection of bumper material. Our design seeks to prioritise effectiveness due to minimal space requirements to implement a safety system. These requirements will further reduce modifications in a convectional system increasing the system's adaptability. Thus, re-engineering using simplified models and an intelligent control system based on electronic automotive bumper activation should be introduced.

## 2.Literature Review

This section provides the central important theoretical review of a pneumatic bumper with an automated brake system. It gives insight into the knowledge and outlays the challenges in the current intelligent vehicle system. The current increment centred on public awareness of safety-related issues and the increasing legislative requirements have increased the pressure on vehicle manufacturers to improve rather than minimize crashworthiness. The collision avoidance system is an automobile safety system designed to reduce imminent and the possibility of an accident. A general conception or approach of mechatronics (Isermann 2000) has shown a reflection on all principles, components, regulations, sensors, etc. thus can lead to improvements in implementing the intelligent control system. Studies on collision avoidance systems have been made and it is efficient and provides the greatest security to users during bad weather conditions (Garethiya et al. 2015). Bad weather condition makes it difficult to operate a vehicle compared to normal conditions. Research has shown that generally, most accidents have occurred during bad weather conditions. Studies have proposed system architecture to avoid early accidents caused by the weather's asynchronous speed among vehicles (Kushal 2017).

The focus of the collision avoidance system is on controlling the steering manoeuvring system and vehicle warning systems that interfere with the vehicle drivers to activate braking systems (Garethiya et al. 2015). In both moving and stationary vehicles, brake support and a warning were provided for collisions with other vehicles. In

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terms of vehicle dynamics on vehicle collision, very little research existed. Mastandrea and Vangi(2005) took it upon themselves to investigate the influence that the brake force has on vehicle impact dynamics in low-speed rear-end collisions. The results obtained confirmed that in high-quality simulations at low speeds, the vehicle impact dynamics could not neglect the braking force. Reducing the risk of incompatibility and improving frontal vehicle-to-obstacle or vehicle-to-vehicle collision depends on the effect the brake brings, and the vehicle dynamics control during the collision (Dileepan et al. 2017). Their proposed system was able to prove that there is a slight improvement in the vehicle deformation that exists when brakes are applied during a crash. However, the implementation of this strategy did not achieve the goal, the statistics of vehicle accidents increased with the system having been put into action. Other researchers then designed a system that helps drivers stop the car automatically through the construction of an electronic circuit (Prabhu et al. 2021). The design of this circuit is such that, a signal is produced to the vehicle's braking system depending on the distance between the vehicle and obstacle, ensuring a safe braking distance.

Nishi et al. (2005), presented the usage of laser beams as their approach to collision avoidance. The system operates in a manner that estimates a vehicle's position in a second and then projects it onto the road surface via laser beams. The system took off slowly due to the expensive cost of lasers and its demand for good power supply for continuous operation. Implementing the system in ordinary and utility vehicles was almost impossible. An extendable and retractable bumper was presented by Wang (2005) for frontal designs of vehicles and retracts after the impact. Our proposed system partly extends the design by incorporating sensor dynamics, and pneumatic principles and uses simulations to study the effectiveness of our design.

Today the implementation of a proper system, an automatic bumper system can be effective on the accident rates. Therefore, our proposed model: a simple AC motor with belt drive to rotate the wheel disc, V-belts and pulleys will be used to rotate the brake drum with a reduction of 1:4 which will be created in this project, will stop the vehicle by applying brake for the distance of 0.5m in 1sec with the aid of an enhanced bumper.

A pre-crashing system is demanded, a simple, normal closed limit switch that will send electrical current when the driver stands from his seat. When the driver on the seat, his weight will press down the limit switch and then it will be in open mode. In this study, mathematical methods will be used to solve static friction in the braking system; its power evaluation and required measurement methods of this pneumatic system will have to be introduced. Based on these proposed methods, the distribution of power supply into the system will be analysed.The validation of the applicability of the proposed methods will be acquired from the analysis of the pneumatic efficiency of the compressor. The model of the system will be simulated using MATLAB software. This project will focus on designing an enhanced pneumatic bumper working simultaneously with a controlled pneumatic brake system using electronic devices and reducing the impact force during a collision.

## 3. Model Description

The research aim is to design and develop a control system based on an intelligent electronically controlled automotive pneumatic system to reduce impact force during vehicle collisions.
The following are the objectives to be dealt with:

To design a PID controller, which will result in a controlled system output.
To model a simple AC motor that drives compressed air into the actuator.
Design and model an actuator to extend and retract the bumper.

Pneumatics, as a technology, has for the longest time played a huge role in the performance of mechanical works. The proposed system is a pneumatic bumper activation system that will be aided by a sensor. According to Wada (2009), to reduce automotive, rear-end collisions, it is vital to assess the need for deceleration aid as soon as feasible and commence the help originally. The bumper system is actuated by pneumatic power in the intended system. The actions of the various components in the prototype are controlled by a microcontroller in this system. The microprocessor uses the signals from the sensor unit to measure the distance between the vehicle and the obstacle. The compressed air is then transferred to the pneumatic cylinder, which pushes the bumper forward. The compressed air is sent via the flow channels by the solenoid valve, and the compressed air is guided by the flow control valve. With the bumper extended, the length of the extension which is 0.5m will become a crumple zone which will absorb the impact force.

The application of pneumatics will produce smooth operation. Techniques can be modified and developed according to their application in the system. The reliability of this system will be ensured through simulation. The components will be evaluated individually. The system is solely dependent on the aid of the sensor, the sensor integrated is capable of detecting under all climatic conditions, which implies that the system will be functional and perform as intended at all times.

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The system's operational requirements are as follows:

- The proposed system relies on compressed air, which must be available in sufficient quantity and at a pressure that matches the system's capacity. The reciprocating compressor is an important required feature of any system. With the use of a pneumatic system, the system should be able to extend and retract the bumper during a collision.
- A pressure of 6kg/sq mm to 8kg/sq mm is required as a medium of working to develop a maximum braking force of 50kN. Control actuation can be done manually, either by pneumatic or electrical actuation.
- Thermoplastic Polyester Elastomer (TPEE) is the appropriate material for the extendable bumper, due to the great elongation at low temperatures. TPEE combines rubber and engineering plastic characteristics. The strong elasticity and stiffness of the material are the most important properties. As a result of these qualities, high durability against fatigue and massive deformation cycles is possible. This plastic is a block co-polymer with crystalline rigid polyester and a non-crystalline soft polyester or polyether molecular structure. To fulfil the project's aim, this is the required material to be used.
- During the service of a vehicle with the system integrated, the personnel working on the vehicle should be trained to do so and ensure that they follow the inspection and maintenance documents, which show how the bumper system should be maintained.
- The primary performance measure of the system is for the bumper to extend to 0.5m as soon as another vehicle is detected. The 0.5m length should be capable of absorbing more impact energy due to the additional crush distance available.

(a) System functional specifications.

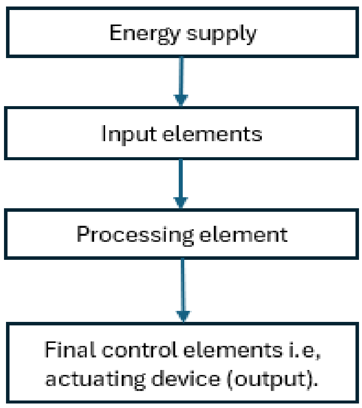


Figure 1. Pneumatic system flow chart.

(b) Air spring, single chamber cylinder

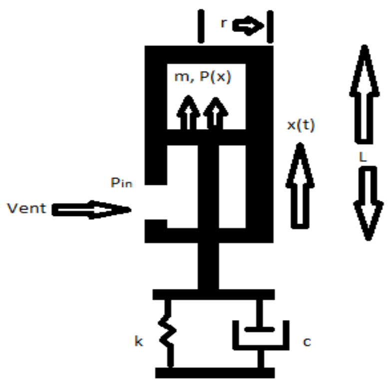


Figure 2. Single chamber cylinder.

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The performance requirements of the system are:

1. Maximum response time- This will ensure the system's uninterrupted user experience.
2. Pressure and flow rate- The relationship of these variables will ensure that the system operates as intended.
3. Load of the cylinder- The capacity of the load will influence the control of the cylinder.

Force factor and speed of the cylinder's piston- The force exerted on the cylinder will determine the push and pull effect required and will also influence the speed of the cylinder's piston

The cylinder is air-sprung therefore k denotes the spring rate and cX(t) is the position of the cylinder as a function of time, L is the length of the cylinder, m is the mass of the cylinder, $P_{in}$ is the exertion of force upon the cylinder.

(c) The proposed system with a controller

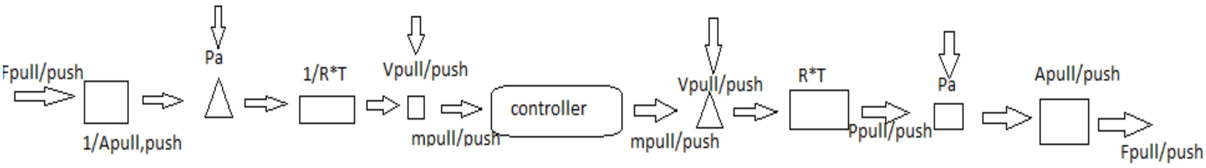


Figure 3. Proposed system with a controller

The generated force F, acting upon the piston, is proportional to its area A. The pressure difference is given by $\Delta pi = pi - p\alpha$ . Where $P_i$ denotes the absolute inner pressure of the chamber and the mass flowing out of the chamber going into the ambience with pressure which is $p_a$.

The pneumatic cylinder's behaviour is separated into two directions; this is for pushing and pulling afterwards.

## 3.1 Solution Approach

According to the author Wada (2009), to reduce automotive, rear-end collisions, it is vital to assess the need for deceleration aid as soon as feasible and commence the help originally.
Pneumatic power is used in the proposed system to activate the bumper system. To detect the impediment, the suggested system employs an infrared sensor mounted on the bumper. A microcontroller in this system directs the operations of the numerous prototype components. The signals from the ultrasonic sensor unit are used by the CPU to calculate how far the vehicle is from the obstruction. After that, the pneumatic cylinder receives compressed air and forces the bumper forward. The flow control valve directs the compressed air as it is sent through the flow channels by the solenoid valve.

Studies on collision avoidance systems have been made and it is efficient and provides the greatest security to users during severe weather conditions (Garethiya et al.,2015). Severe weather conditions make it difficult to operate a vehicle as compared to normal conditions. Research has shown that most accidents have occurred during severe weather conditions. Studies have proposed system architecture to avoid early accidents caused by the weather as well as due to asynchronous speed among vehicles (Kushal 2017). Fernandez et al., (2011) , implemented a model-based system. The system detects objects or obstacles using a sonar sensor; thus, this sensor produces sound waves and receives waves that are reflected from the obstacle. Avoidance algorithms are also received in this system as basic reflexes of the system.

Several researchers agreed that the addition of sensors into the intelligent system will help reduce the number of vehicle accidents. A passive infrared sensor was then studied. It will be reliable for the detection of humans or animals. It is guaranteed that this technique can save lives (Kushal 2017). A variety of sensors are required as equipment for a pre-crash detection system. Vehicle parameters such as speed, gas, engine temperature, and eye-blink and alcohol sensors are being scanned continuously. In an instance where the driver is found to be under the influence of alcohol, the sensor warns and turns the buzzer on, thus possibly avoiding an accident from occurring. These studies also covered the design of an eye blink sensor which will monitor the number of times the operator's eye blinks. Should the eye blink decrease, it will mean the driver is sleepy thus the buzzer will go on (Rajesh 2017).

Challenges related to the passive IR sensor arose, due to the limitations of this sensor. Due to interferences, it would encounter because of sunlight, it made its application difficult. Garethiya et al. (2015) employed the usage

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of raspberry pi and ultrasonic sensors, with the reference being the stationary or moving object, the sensors would measure the distance with the aid of waves. The detection of obstacles is not affected by as many factors as compared to when using infrared sensors. A designed project on the differences between infrared sensors and ultrasonic sensors is currently in existence. This project confirmed that ultrasonic sensor works better than infrared sensors. These infrared sensors will therefore provide values that will fluctuate in variant light conditions. With the ultrasonic sensors, it obtains an estimated distance through the time interval between the obstacle and itself.

Various implementations may be taken when an intelligent control vehicle system detects that a collision is unavoidable. The activation of instant braking which is based on the behaviour of the vehicle's driver and the relative position of the obstacle is used as a reference in the Brake Assistance System (BAS) (Tamura et al., 2001) and the Collision Mitigation Brake System (CMBS) (Sugimoto and Sauer 2005). The implementation, development, and usage of ADAS (Advance Driver Assistant System), in existing vehicles are still far away from the goal of the study which is to prevent vehicle collisions. This system aims to reduce rather than avoid vehicle frontal collisions. After a collision enhancing crash energy absorption and minimizing the vehicle's frontal deformation requires two types of smart front-end structures, these are extendable and fixed.

## 3.2 Experimentation and Data

The analysis developed in the previous parts is validated in this section by presenting of simulation data. The simulation was performed using MATLAB software. The table below lists the values of the parameters used in block diagram simulation. The Parameters selected were chosen following a random trial-and-error and also to reflect the realities of the system.

Table 1. Parameters used in the Matlab simulation.

| Parameter | Mass | Radius | Resistance | Length/Position | Henrys (Km) | Henrys (Kb) | Emf constant (Kf) | Energy of work (J) |
|---|---|---|---|---|---|---|---|---|
| Value | 1.6 kg | 0.015 m | 2.0 ohm | 0.5 m | 0.1 N.m. s | 0.1 N.m. s | 0.2 N.m. s | 0.02 Kg.$m^2/s^2$ |

Figure 4 is the block diagram representing the main system of the design of pneumatic automatic bumper activation. The system will further be broken down into sub-systems to allow analysis of all variables.

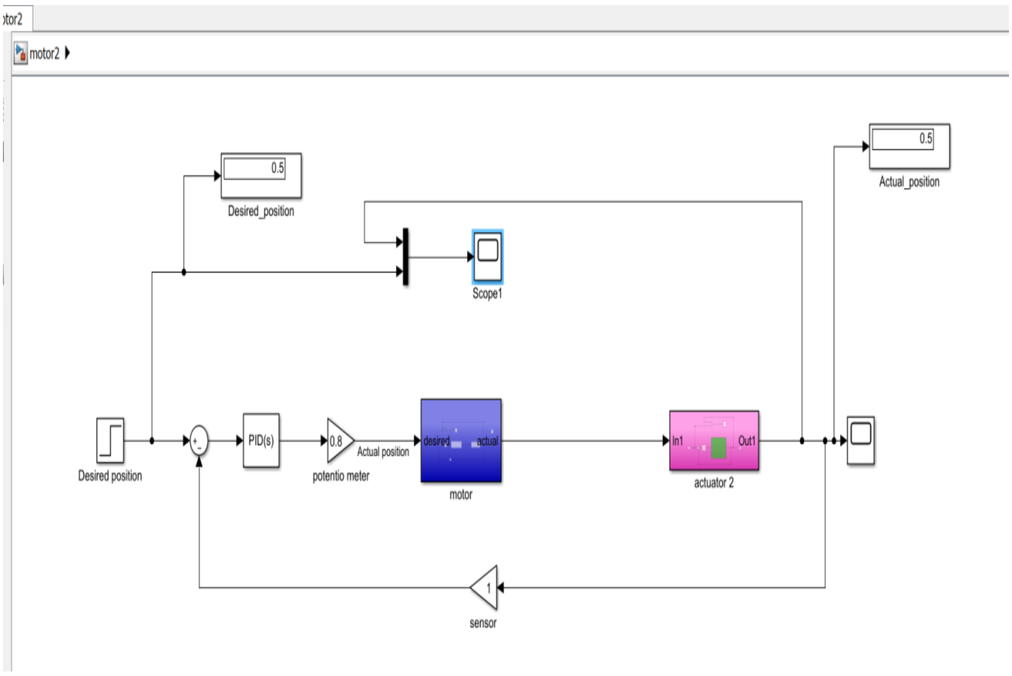


Figure 4. System Overview

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The design is based on the product's design and development technique. The requirement for an automatic pneumatic bumper system is therefore identified. For the development of the process, various theoretical concepts were defined.

Different inputs are used to conduct a thorough examination of the principles, and the trial-and-error procedure is used to select the appropriate rather most effective parameters for the controller. The effective parameters and design for the proper proportions are examined. The system will first be built in two dimensions, and then it will be modelled.

The figure below shows the MATLAB script that characterizes the system.

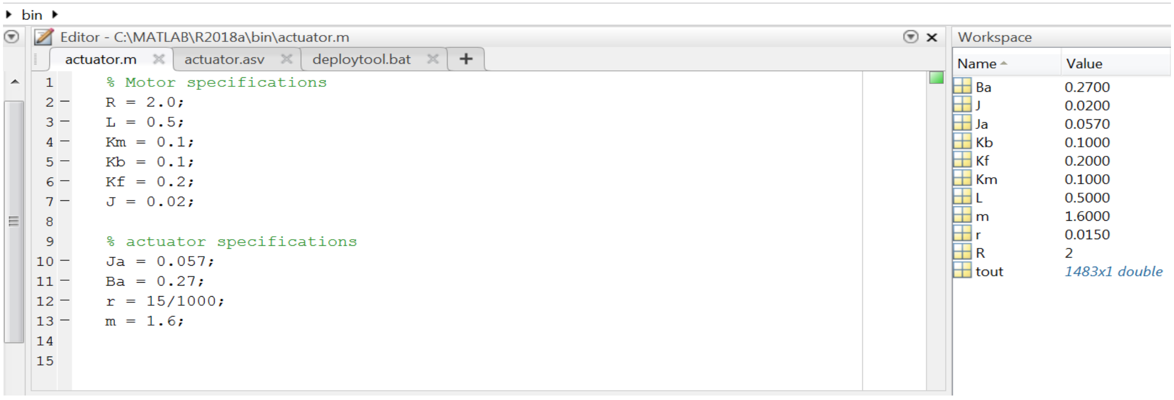


Figure 5. Matlab Scripts

### 3.3 PID Controller

A PID controller is used to build the feedback control with the help of the system. The controller technique's goal is to give the control the desired position of the extendable bumper before a collision and keep it there until it collides with another vehicle. While the sensor detects that a collision is unavoidable, 1 second before contact, the actuator and the extendable bumper will be triggered in this brief window of opportunity. The front spring forces are equal to zero prior collisions and at completion of the ride, the front-end springs are disengaged.
Table 2 shows the values of the proportional, integral, and derivative gains of the PID controller. An ad hoc approach was implemented in the attainment of these values. The values show trials implemented to reach the desired specifications.

Table 2. PID Control Values.

| **PID Ad hock Values** | | | |
|---|---|---|---|
| | Try one | Try two | Try three |
| Proportional (P) | 4.4 | 0 | 0 |
| Integral (I) | 0 | 0 | 0.5 |
| Derivative (D) | 0.001 | 1 | 0 |
| Filter coefficient (N) | 100 | 100 | 100 |

## 4.Results and discussion

Figure 6 below shows the step response of the extendable bumper system. The bumper extends to 0.5m and has a settling time of 12s. These values correspond with the designed steady-state characteristics. Despite, the system being sluggish and over-dumped, stability is achieved. During the frontal collision, the dynamic reaction and the crash response of the real pull and pull actuation are compared to the one desired by the system being simulated. This is actuation utilizing a cylinder and a flexible shaft. The block diagram depicts how the system was modelled, taking into consideration all aspects, including disruptions. When the extendable bumper is not extended, then the deformation increases right until it reaches its maximum amount, and therein decreases when the front-end springs

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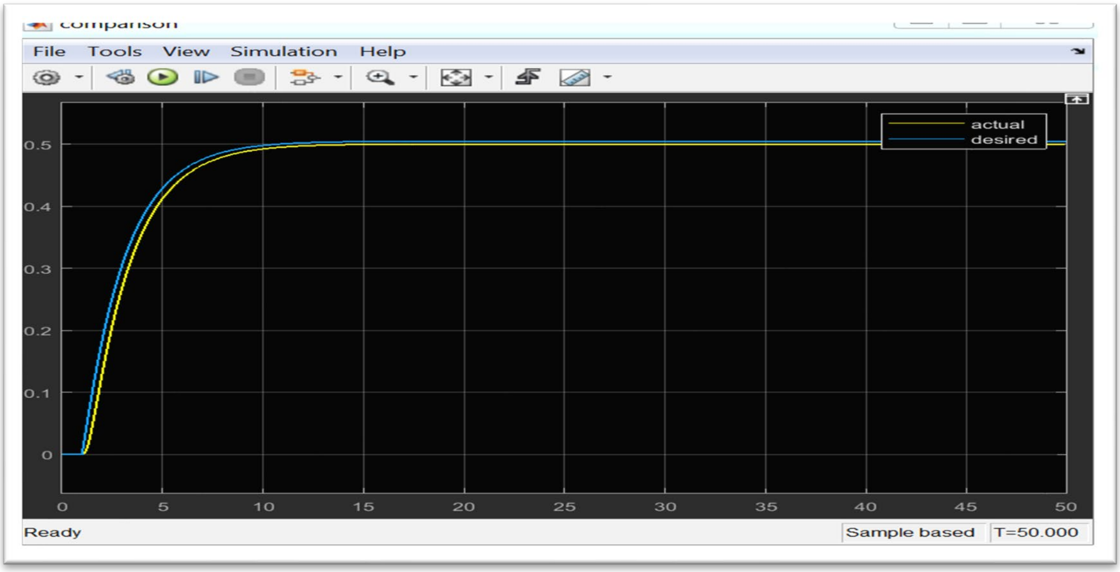


Figure 6. Position(m) vs time (s) graph

are rebounded. The model is such that when the extendable bumper is used, the front-end deformation grows steadily until it reaches a specific point this being in 50 seconds. The extendable bumper is entirely deformed and the deformation then rapidly climbs to its maximum value, and then gradually decreases due to the rebound effect. The primary benefit of an extendable bumper is the capacity to absorb more impact energy due to the additional crush distance available, which is 0.5m

Figure 8 shows the scope of the input and the output of the actuator. Angular velocity sends the input signal into the system. The graph shows the response of the subsystem with the step input being angular velocity and that of the main system being voltage. The output of the scope is given by Output = (Error * gain). The scope is the functionality that the system will provide.

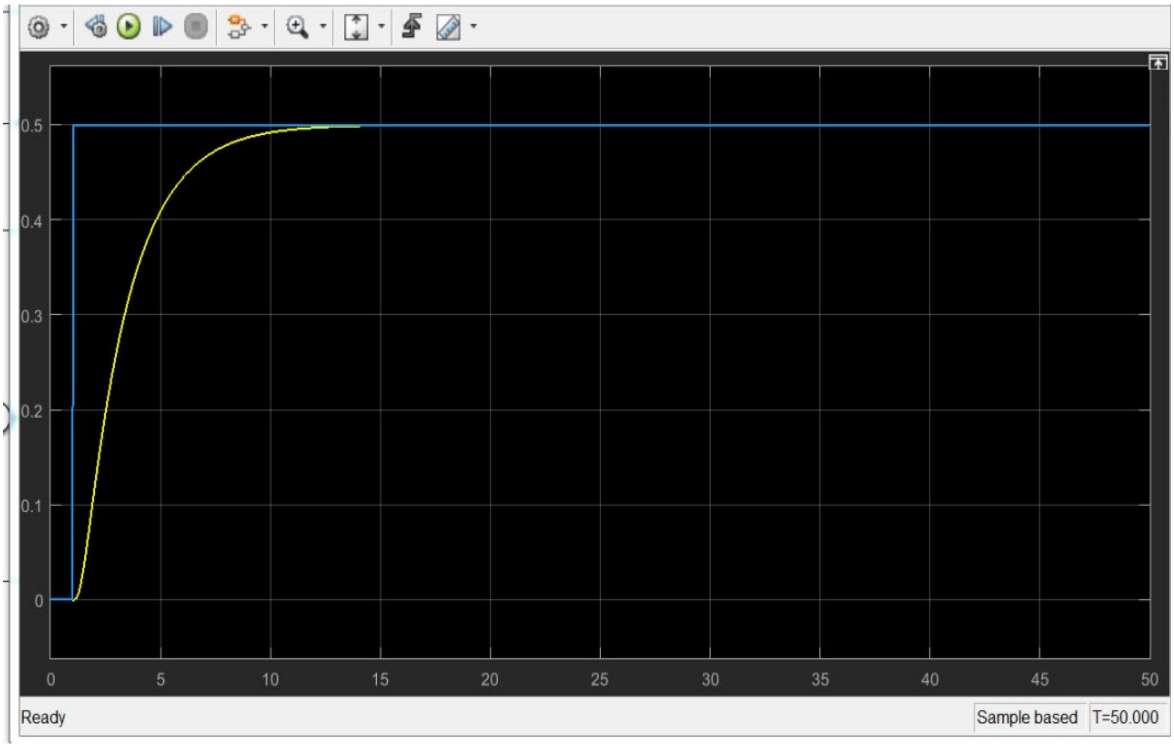


Figure 7. Position (m) vs time(s). Comparison of actual scope and desired scope.

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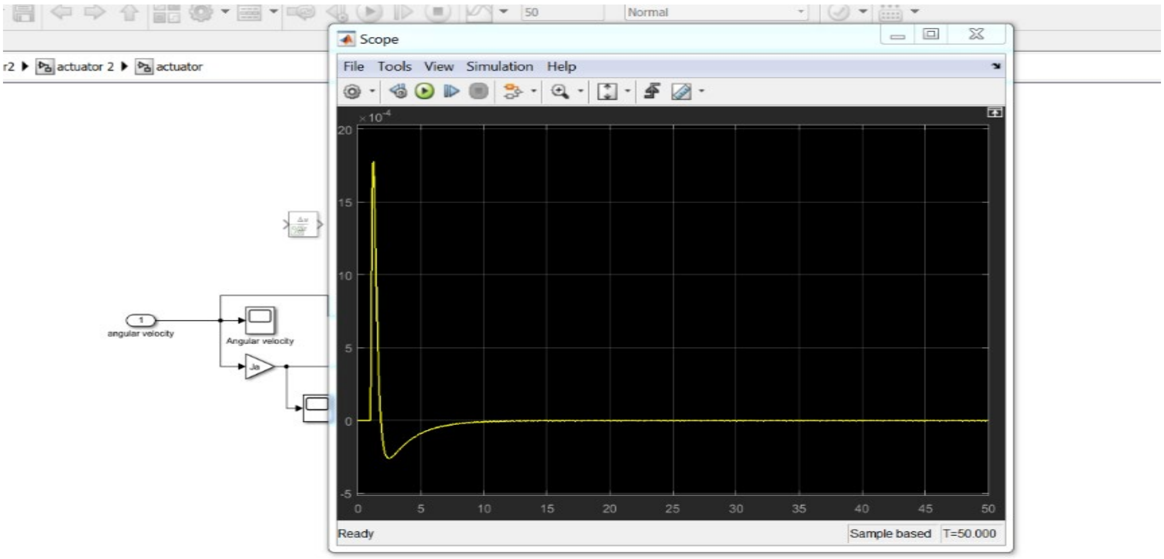


Figure 8. Scope vs time graph

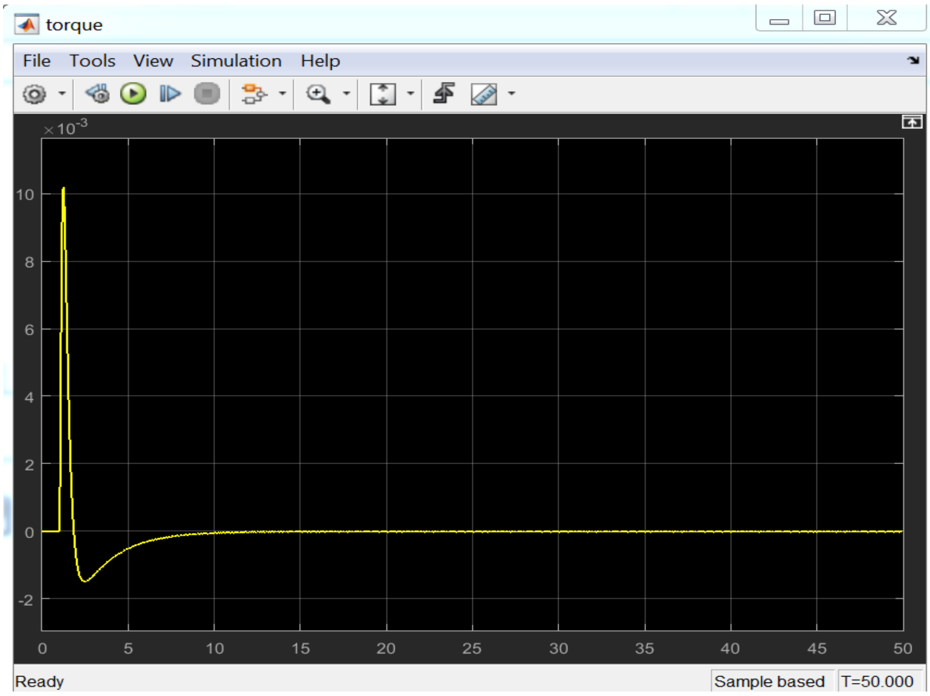

Figure 9. Torque vs. time graph

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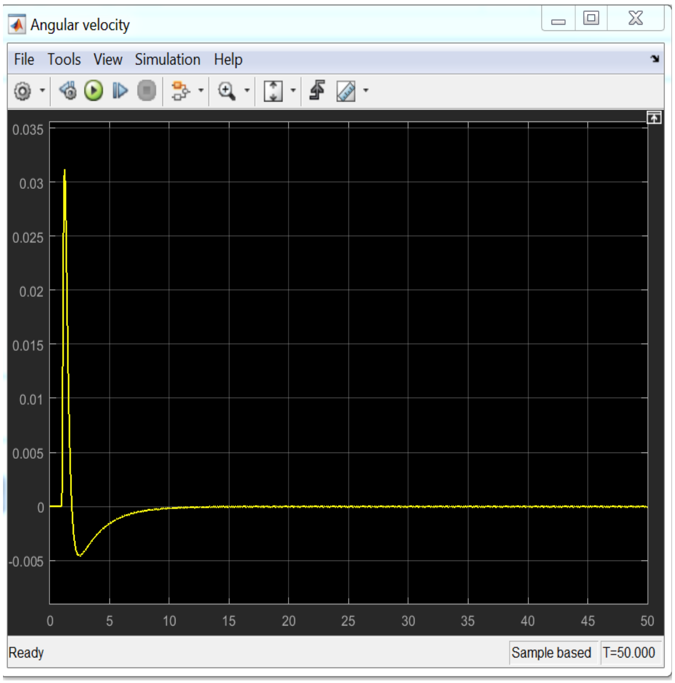


Figure 10. Angular acceleration vs. time graph

Figure 9 shows the torque vs. time graph. As expected, the graph shows a high start-up torque before settling at 0Nm after 10 seconds. This corresponds with the angular velocity vs. time graph which is also seen in Figure 10. The impact force is estimated during a vehicle accident, and the determined impact force is subsequently applied to the bumper materials. The vehicle's mass, as well as its initial and ultimate velocity, are considered when calculating the impact force. The angular velocity as a function of time is depicted in this graph. That is, if the angular velocity of an item changes with time, the angular motion of the body is described by the graph of angular velocity versus time. The area under the curve, computed by the integral of the function, gives the angular displacement of the moving body and the slope of the curve on this graph, derived by the derivative of the function, permits measuring the angular acceleration. Figure 11 shows the  Actuator Position and time graph.

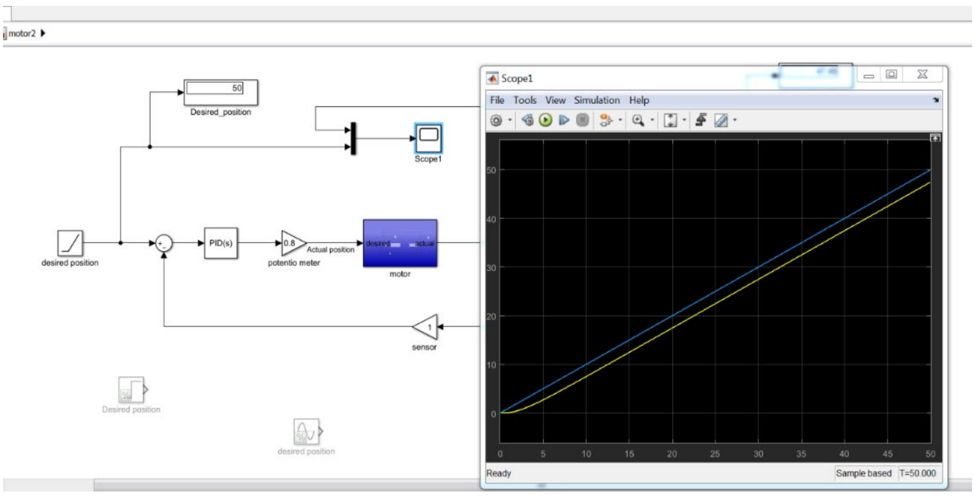


Figure 11.  Position vs time graph. (Impulse input: Actuator)

From the three inputs used, the step input gives the most accurate results. There are no overshoots therefore the desired output is obtained. These obtained step response results are the integral of the obtained impulse input. The Laplace transfer function of the obtained impulse response is the transfer function.

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## 5.Conclusion

The major goal of this system's design is to improve accident prevention techniques while also lowering the risk of accidents such as vehicle damage, human harm, etc.We discovered that our effort could achieve all the necessary goals. Cars with airbags have a high initial cost. We can cut the cost of high-end cars by adopting the Sensor-Aided Pneumatic Bumper Activation System and providing equivalent levels of safety. Airbags are useful for providing interior safety to passengers in vehicles, but in our proposal, we will give both internal and external safety to protect the vehicle from harm. As a result, we will lower the initial cost of cars while simultaneously providing additional benefits.Vehicle crash structures, vehicle dynamic control and extendable bumper systems are mostly part of the system introduced in this study. In addition, to capture the occupant dynamic response, a mathematical model has been constructed. Numerical models have shown that the extended bumper absorbs more collision energy than the typical structure at the same crash speed. Furthermore, it has been demonstrated with the programmed system's results that the extended bumper actuated by a cylinder reduces intrusions and aids in keeping vehicle deceleration below acceptable limits.

From the results obtained, the system has improved such that the controller introduced will be used to calculate the chance of collision. The extension of the bumper increases the time of impact and reduces the force of impact. Force is inversely proportional to time therefore when time increases, force will decrease. In so doing the injuries to the passengers will be reduced if not avoided. To improve on this study, combining numerous elements into this system to give greater protection through the intelligent braking system in real-time applications can be achieved. Some of the probable adjustments are as follows: A limit switch can be used to set the minimum speed at which the system will be activated. The bumper design can be improved to include external airbags. With a few tweaks, the project may be utilized with timer circuits to apply brakes and extend the bumper after a few milliseconds of delay, ensuring that the bumper does not extend until the vehicle is within crashing distance. Finally, comparative studies with other possible results using related techniques in the Literature will provide more insights into the efficacy of our designed system.

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