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DESIGN, SIMULATION AND CONTROL OF A NOVEL HYDRAULIC BRAKING SYSTEM

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ABSTRACT
A novel automatic braking system is designed in this research to decrease vehicles accidents caused by obstacles. A safer automatic braking system that can handle less driver attention to the driving is developed. The proposed system is operated by means of three parts; the sensing part, the control unit, and the actuator used. A proper hydraulic mechanism is used to operate and control the braking system automatically, this system can operate the brake pedal according to the control unit signals. The system senses the distance between obstacles and the vehicle using an ultrasonic sensor, then an electric pump provides a fluid flow and pressure value through the use of two solenoid valves which control the direction of brake fluid in the hydraulic braking system. In case the driver does not push the brake pedal manually in the right time, the system automatically stops the vehicle without the driver input. A vehicle model was developed and simulated. Braking distance, time analysis, vehicle, wheel and wheel slip models were produced mathematically, and the vehicle dynamics were simulated in SimMechanics. The open loop dynamics gave a far slip ratio value from the desired value. Reversely, in the closed loop dynamics simulation the slip ratio value followed the reference signal in an accepted manner. The system was experimentally assisted in terms of braking time, and the performance was acceptable. The errors between the measured and theoretical braking time and the theoretical braking time were nearly one and two percent.

KEYWORDS
Hydraulic brake; Control program; Ultrasonic sensor; SimMechanics.

INTRODUCTION
In conventional vehicles, there are many types of braking system mechanisms such as hydraulic, mechanical, and pneumatic systems. These braking mechanisms are activated directly by the driver through hitting the brake pedal which is completely a manual operation. But, in case the driver couldn't see obstacles in front of the

vehicle, or couldn't apply a suitable braking force to the brake pedal, the driver may lose the control of the vehicle causing an accident. That is why the intelligent braking systems have appeared recently. Intelligent braking systems such as pre-crash safety system with pedestrian collision avoidance and automatic braking system with a pneumatic pumper have been developed in latest research. These systems are based on controlling the vehicle speed using a proper actuator and control unit.

The hydraulic brake system is used in vehicles in addition to the mechanical and pneumatic brake systems. The main braking system in most passenger vehicles and light trucks are hydraulic brake system. In hydraulic brake a fluid is used to transmit force at the brake application. In pneumatic brake a compressed air is used to get the required braking force at each wheel. The medium used to transmit the power is the main difference between hydraulic and pneumatic brake systems. In hydraulic brake liquid/oil is used to transmit power, whereas in pneumatic brake compressed gas (generally air) is used to transmit power. Due to that difference there are many differences between the two systems. So, the hydraulic braking system will be used in this work as, [1 - 3], the hydraulic braking system generates a high brake force with less brake failure chances when compared to the mechanical braking. Hydraulic system possesses equality of braking action on the wheels. Mechanical braking system has very high tear and frictional wear due to the presence of numerous moving parts, which are much less in hydraulic system. Design complexity in case of mechanical braking was very high which is reduced with the introduction of hydraulic braking system as it has simple and easily assembled design with less maintenance requirements.

Many research works investigated the development of automatic brake system, such as Eung Soo Kim, [4], that designed and fabricated an auto-braking system for pre-crash safety. This system was designed to keep a constant distance between the front car and driver car. It was fabricated using FPGA (field-programmable gate array) and VHDL (very high-speed integrated circuit hardware description language). The sensors embedded in vehicle detect the road environment such as driver's vehicle velocity, distance between the front vehicle and surrounding vehicles using infrared and ultrasonic sensors. It displays the distance between the two vehicles, and the speed of the driver's vehicle. The brake pedal is actuated by a servo motor, and it is controlled by PWM (pulse width modulation) signal, which differs according to the distance between the front car and driver’s car.

Firoz Syed, [5], presented an intelligent mechatronic braking System. The main target of the system is to run automatic braking when the sensor senses obstacles. The developed braking system automatically breaks the vehicle the control signal is received. The system includes an ultrasonic wave emitter provided on the front portion of the car and emitting ultrasonic waves frontward in a predetermined distance. An ultrasonic receiver is also placed on the front portion of the car that cooperatively receives the reflected ultrasonic wave signal. The reflected wave (detected pulse) measures the distance between the obstacle and the vehicle. Then a microcontroller (ATMEGA32) is used to control the speed of the vehicle based on the detected pulse information to push the brake pedal and apply the brake to the car for safety purpose.

P. Poongodi PPG, [6], studied the need for safety of vehicles by reducing the impact of a crash by applying a smooth or partial braking with the help of PIC 16F877a microcontroller. The driver's risk of sensing the object from a particular distance and being unable to notice it within a certain limit is considered. Once a similar situation is faced the acceleration of the vehicle will be directly controlled without any disturbing to the safe throttle (actuation mechanism) of the vehicle, the developed machine controls the pedal acceleration when the brake is not activated manually within the sensed braking distance.

K. Chirantana, [7], has proposed a technology of collision warning with automatic braking system for electric cars, this system is used to reduce vehicle speed and stop it when the distance between driver's vehicle and front vehicle becomes limited. This system warns the driver in case of collision existence and along with brake support for collisions with other vehicles. Collision detection is done by using ultrasonic sensor and stop indication using a flashing LED and LCD. When an ultrasonic sensor detects the subject such as vehicle or pedestrian, it sends the signal to a microcontroller which sends a signal to the brake circuit. The brake circuit consists of a servo motor and lever that is connected to the brake pedal, when servo motor received the signal from the microcontroller, the arm of the brake pedal is actuated by the brake.

R. S. Krishnaveni, [8], has designated a brake system using an intelligent vicinity adapter for vehicles. The main objective of this system is to help the driver to slow down the vehicle at breaking speed in order to prevent accidents. The main components of this system are ultrasonic sensor, IR sensor, microcontroller (ATmega328P) and servo motor. The distance between the driver vehicle and the object is measured by the ultrasonic sensor. Moreover, the happening of side scrape on the vehicle could be prevented, this can be done using IR sensor which detects break beam and also indicates the interruption of passenger's head and hand through a window and door during vehicle motion. The ultrasonic sensor detects distance, then it sends signals to the microcontroller, microcontroller processed signals to control the servo motor. Servo motor rotates the brake pedal and control the speed of vehicle according to it.

S. Wasnik, [9], has suggested using a pneumatic automated bumper. The objectives of this system are to decrease the rate of the car accident, increases the response of the braking system, and increases the sureness of people who are afraid of accidents. The main components of this system are IR sensor, solenoid valve, pneumatic cylinder, composer and a control unit. When the obstacle found in front of the vehicle, the IR sensor sends the signal to the control unit, which sends the signal to the solenoid valve, solenoid valve consists of one input and two outputs, the input is connected to the composer and the two outputs are connected to the wheel cylinder, when the solenoid valve receives the signal from the control unit it is activated and the brake is applied, whenever the driver does not hit the brake.

In this research, a new hydraulic brake system has been developed, it depends on using a pump and two solenoid valves to control the pressure value and direction of brake oil. This system does not prevent the driver from controlling the brake manually, it works in both manual and automatic modes in parallel. It is controlled

by a simple and inexpensive control system. The main goals of this study are to create an ultrasonic sensor-based safety car braking system and a vehicle that requires less human attention while driving. This paper contains six sections; the first is the introduction section where a brief background and literature review are presented about the problem, the second section draws the mathematical modelling of the brake system, the third section presents the proposed braking system and the working principle, the fourth section shows the Simulink model development and dynamics simulation. The fifth section introduces the experimental work, the last section is the conclusion. Then references are attached.

MATHEMATICAL MODELING OF BRAKE SYSTEM

Braking distance and time analysis

Let the vehicle acceleration a is constant, and V_i represents the initial velocity, the final velocity is V_f, the travel time by car is t, and the travel distance is D. Considering the four principal kinematic equations in [10]. Hence, the theoretical final velocity is found by:

$$V_f = V_i + at \tag{1}$$

The travelled distance by the car D is found by:

$$D = V_i t + \frac{1}{2} at^2 \tag{2}$$

The final velocity can be found using:

$$V_f^2 = V_i^2 + 2aD \tag{3}$$

Using the equations (1), (2), and (3), the travel distance DT can be computed as:

$$D_T = \frac{V_f^2 - V_i^2}{2a} \tag{4}$$

The stopping distance Ds (the traveled distance by car before direct stopping) as the car finally stops (V_f is zero) can be computed as:

$$D_s = \frac{-V_i^2}{2a} \tag{5}$$

In vehicles with traditional braking system, the longitudinal deceleration a represents one of the main parameters of the braking system, which can be computed with the formula:

$$a = \phi_x g \tag{6}$$

As ϕ_x is the longitudinal coefficient of adherence of the tires with the running path, and g is the gravitational acceleration (g = 9.81 m/s^2). In the situation of actual cars, the maximum coefficient of adherence has the value φx = 1– 1.2, [11], if braking operation takes place on a running path with dry asphalt, situation when the deceleration of old cars with tires produced at the present moment can reach values in the range 7.35- 9.3 [m/s^2]. From equations (1) and (4) one can get the time formula as:

$$t = \frac{2\,D}{(V_f + V_i)} \tag{7}$$

The stopping time can be also computed as:

$$t_S = \frac{2\,D_S}{(V_i)} \tag{8}$$

Figure 1 shows the plot of stopping time and stopping distance variation with vehicle speed at ϕx=0.8 based on the produced formula as in equation (8). As the vehicle speed increases both the stopping time and stopping distance increase also.

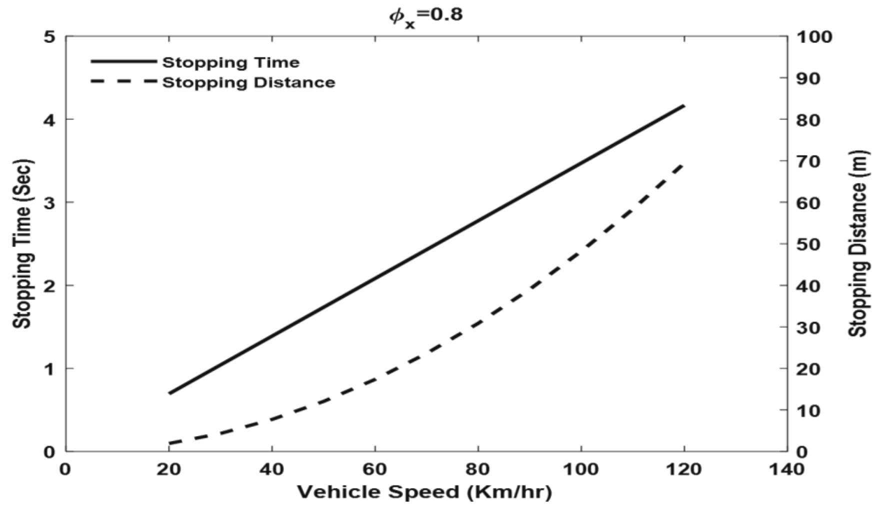


Fig. 1 Stopping time and stopping distance variation with vehicle speed at ϕx = 0.8.

In case of two vehicles; one follows the other and based on an earlier work [12-15], the collision avoidance distance (DCA, br) required by braking is set to be equal to the difference between host vehicle braking distances Dhv, br and preceding vehicle braking distance DPV, br, using equation (4).

Where, V_h = host vehicle velocity, V_P = lead vehicle velocity, ah = host vehicle maximum deceleration rate, a_P = lead vehicle maximum deceleration rate, as shown in Figure 2. The braking distance can be calculated as:

$$D_{CA,br} = D_{h,br} - D_{p\,,br} \; = -\left(\frac{V_{ih}^2}{2a_h} - \frac{V_{iP}^2}{2a_P}\right) \tag{9}$$

Where, $D_{h,br}$ and $D_{p,\mathrm{br}}$ are the braking distance of the host and preceding vehicles respectively. If it is assumed that ah and aP are equal to a, equation (9) can be simplified as:

$$D_{CA,br} = \frac{-V_{ih}^2 + V_{iP}^2}{2a} \tag{10}$$

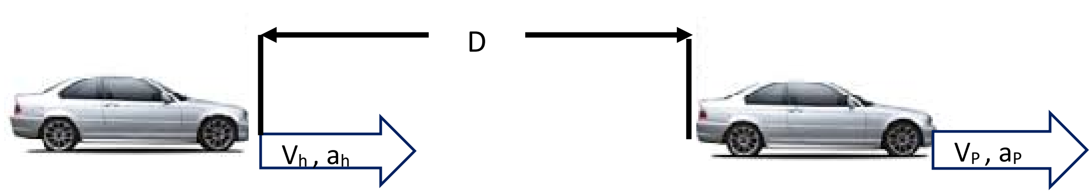


Fig. 2 Relative motion representation between the host and preceding vehicles.

Unluckily, equation (10) does not suit all situations. For example, this equation will not possess the actual Dhv, br required to avoid a collision with a previous vehicle when the initial velocity of host vehicle is higher than the velocity of the earlier vehicle, and the braking distance of the earlier vehicle is higher than the braking distance of the host vehicle. A case example is given to explain this. Let the host vehicle

is moving with a speed of 25 m/s (= 90 km/h). Preceding vehicle is moving with a speed of 17 m/s (= 61.2 km/h). If the preceding vehicle starts decelerating with 4 m/s2 and host vehicle is able to brake with 8 m/s^2, equation 5 would give following Dhv required to avoid collision with preceding vehicle by braking. The Dbr = -3.5 m/s^2, note that this means that host vehicle would not be required to start braking in order to avoid collision with preceding vehicle. It is clear that this is not the case in real life. The driver response time and system delay can easily be accounted for if required. The DCA required by braking is then:

$$D_{br} = -\left(\frac{V_{ih}^2}{2a_h} - \frac{V_{iP}^2}{2a_P}\right) + V_r t_r + V_r t_S \tag{11}$$

Where tr is the driver response time, t_s is the system output, and V_r is the corresponding relative velocity. The relative velocity can be computed as

$$V_r = V_{ih} - (V_{iP} + a_P(t_r + t_S)/2) \tag{12}$$

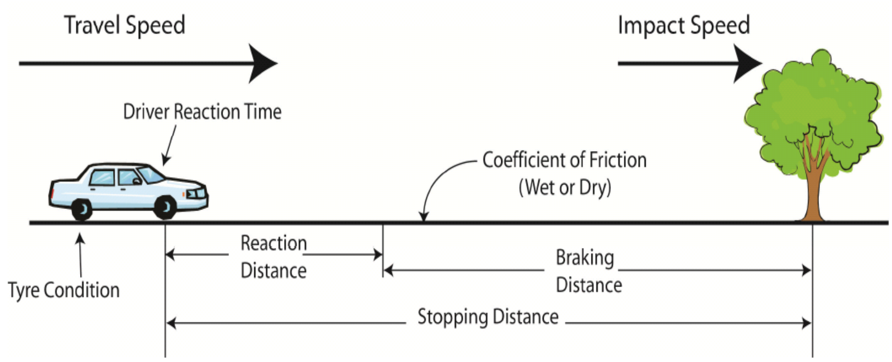


Fig. 3 Key factors in stopping distance.

For an obstacle as shown in Figure 3 ($V_{iP} = 0$), the DCA required by braking is

$$D_{br} = -\left(\frac{V_{ih}^2}{2a_h}\right) + V_{ih} t_r + V_{ih} t_S \tag{13}$$

For real vehicle and avoiding the driver as well as the system responses, the actual needed times are the actual braking time. The system braking distance can be calculated as:

$$D_{br} = -\left(\frac{V_{ih}^2}{2a_h}\right) \tag{14}$$

Also, the rate of change of the velocity with respect to distance travelled can be calculated using equation (3) as:

$$\frac{dV_f}{dD} = \frac{a}{\sqrt{V_i^2 + 2aD}} = \frac{a}{V_f} \tag{16}$$

The developed relations are plotted. Figure 4 shows vehicle speed versus distance travelled at ϕ = 0.8, as vehicle speed increases the distance travelled increases too. Figure 5 shows vehicle speed versus distance travelled at different road friction coefficient (ϕ), with the increase of road friction coefficient the stopping distance decreases for the same vehicle speed.

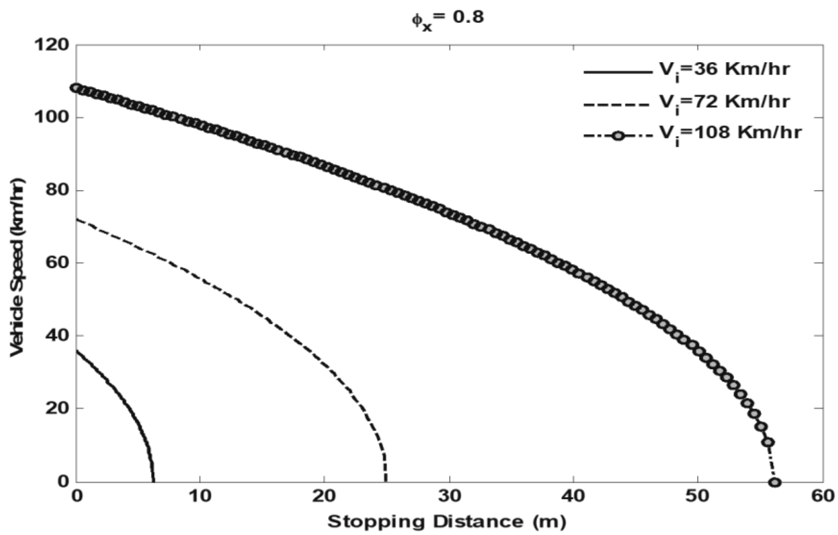


Fig. 4 Vehicle speed versus distance travelled at ϕ = 0.8.

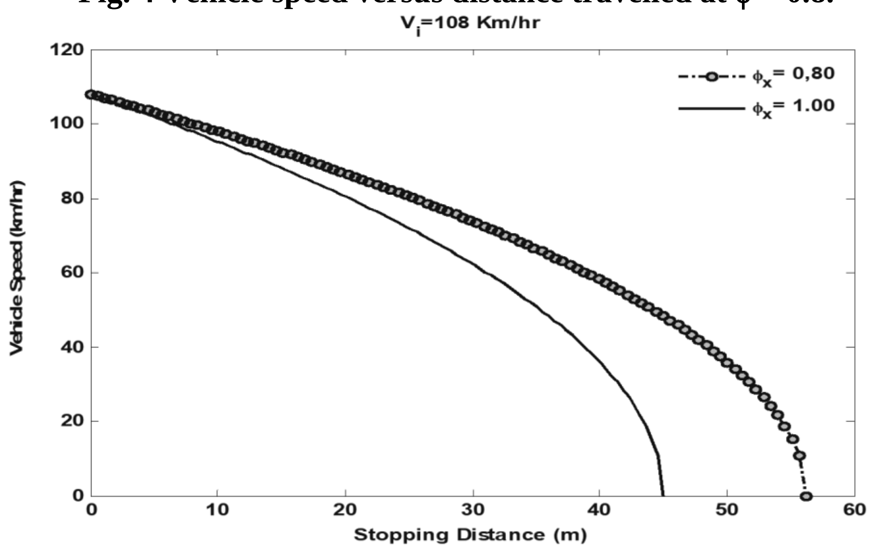


Fig. 5 Vehicle speed against stopping distance at different road friction coefficient (ϕ).

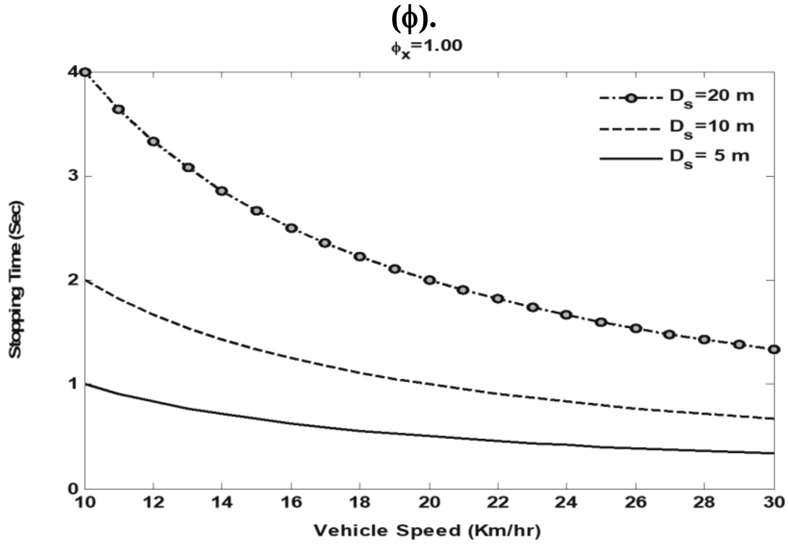


Fig. 6 Stopping time versus vehicle speed at different allowable stopping distance (Ds).

And Fig. 6 shows stopping time versus vehicle speed at different allowable stopping distance (Ds). Where the stopping distance decreases as the stopping time decreases with the increase of vehicle speed.

MATHEMATICAL MODELS OF VEHICLE, WHEEL, AND WHEEL SLIP

Vehicle model

Considering a moving vehicle in a straight direction under braking conditions as shown in Figure 7(a), the equations of equilibrium in the horizontal direction can be written as [16]:

$$F_f = F_i \tag{17}$$

Where Ff is the friction force between the wheel and ground, and Fi is the inertial force of the vehicle.

The equations of equilibrium for the vertical direction can be presented as:

$$N = W \tag{18}$$

Where N is the normal force (road reaction) and W is the vehicle weight.

The expressions of the friction force can be defined as [17]:

$$F_f = \mu \times N \tag{19}$$

Where μ represents the wheel-road friction coefficient.

The vehicle's weight is:

$$W = m_v \times g \tag{20}$$

Where mv is the total vehicle mass, so the frictional force can be presented by replacing (18) and (20) in (19):

$$F_f = \mu \times m_v \times g \tag{21}$$

The inertia force that can be produced between the vehicle mass mv and vehicle acceleration av can be defined as;

$$F_i = m_v \times a_v = m_v \times \frac{dv}{dt} \tag{22}$$

From equations (17), (21), and (22), the vehicle acceleration can be also calculated as:

$$\frac{dv}{dt} = \frac{1}{m_v} \times \mu \times m_v \times g \tag{23}$$

Wheel and wheel slip model

During braking, the driver applies a braking torque, T_b through the braking system to the wheels as shown in Figure 7(b). The friction force Ff between the wheel and the road creates an opposite torque with the wheel radius r_w to stop the vehicle, the braking torque must be equal to the friction force, and therefore, the equation of equilibrium for the wheel is written as, [18]:

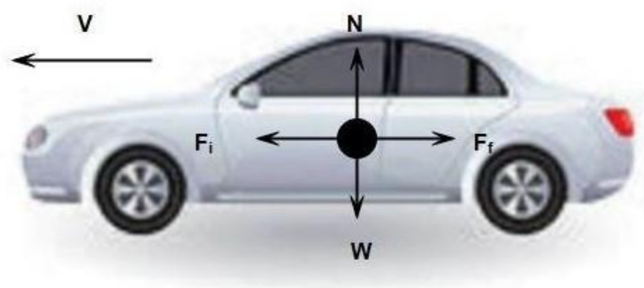
$$T_b - F_f \times r_w - J_w \frac{dw}{dt} = 0 \tag{24}$$

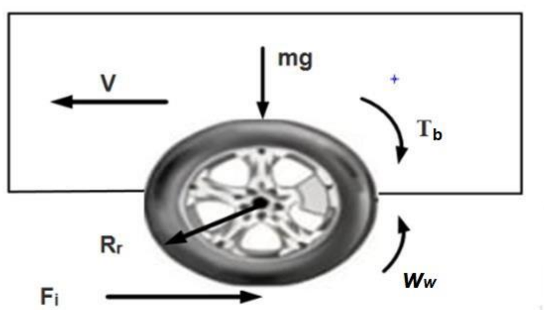
Where J_w, is the wheel moment of inertia, and dw is the angular speed of the wheel. From equation (24) the wheel acceleration can be also calculated as.

$$\frac{dw}{dt} = \frac{1}{J_w} \left(T_b - F_f \times r_w \right) \tag{25}$$

Automatic brake system controls the slip by controlling the wheel speed, so equation (26) is used to calculate the actual slip, then compared with the desired slip which equals 0.2, [16]. The wheel speed can be controlled to reach an appropriate value of desired slip by using an appropriate control strategy like the PID controller which is used in this paper to prevent locking up of the wheel.

$$Slip = 1 - \frac{Wheel\ speed}{Vehicle\ speed} \tag{26}$$





(b)

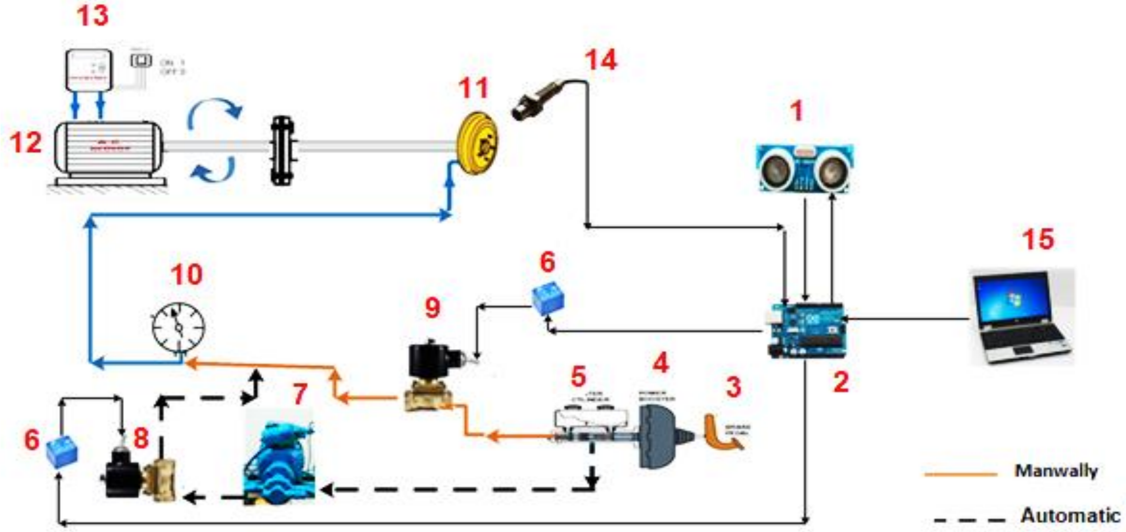
Fig 7 (a) Forces applied to vehicle model. (b) Forces applied to wheel model.

The proposed automatic braking system mainly consists of the mechanical components, the electronic components, and the control architecture.

Mechanical components of the proposed automatic braking system

The main mechanical components of the automatic brake system are the drum brake, brake pedal, master cylinder (single acting hydraulic cylinder), brake booster, solenoids valves, hydraulic pump, and the electric motor. The drum brake provides the required rotational speed and the applied pressure to the actual braking applications. The brake pedal transfers the braking power starting at the driver's foot towards the master cylinder, and then to the wheel's cylinders, it also enlarges the braking force by a suitable proportion. A brake booster gives additional braking power keeping a minimum pressure on the brake pedal. The brake booster is positioned between the master cylinder and the brake pedal. Two solenoid valves are used to control the brake fluid's direction and pressure, one is normally open, which is placed after brake pedal, the other one is normally closed, which is mounted after the pump. The pump is used to pump the brake fluid with a proper quantity and pressure to halt drum brake rotation; it operates over pressure value of 30 bars, and

maximum volume flow rate of 1/4 L/sec. The drum brake is connected to an electric motor by an appropriate rod, the drum brake can rotate by variable speeds, and the electric motor is 2 HP capacity, Figure 8 displays a schematic diagram of the test rig.



1. Ultrasonic sensor, 2. Arduino Uno, 3. Brake pedal, 4. Brake booster, 5. Master cylinder, 6. Relay, 7. Electric pump, 8. solenoid valve normal open, 9. Solenoid valve normal closed, 10. Pressure gauge, 11. Drum brake, 12. electric motor, 13. Inverter, 14. RPM sensor, 15. Computer.

Figure 8. Schematic diagram of the test rig.

Electronic components of the automatic brake system

An Arduino Uno board, ultrasonic sensor, and an electric relay are the main electronic components used in the brake system. The Arduino Uno board of a microcontroller, [10], is used to process signals received from ultrasonic sensor, then directs the signals to the electric relays. Ultrasonic sensor module is HC-SR04, it is equipped with an emitter and a detector with a timing unit used for pulse detection. It detects signals in proximity range from 2cm-400cm, and with an accuracy of 3mm. Input/output trigger is used by the sensor for 10 µs high-level signal, it automatically sends 40 kHz and detects for pulse signal, and record the time taken for waves to go back, ultrasonic sensor is selected because of being a cheap and less demanding of hardware than other types of sensors presently used, such as the sensors based on computer vision or radar. Test distance equals the production of travel time with the velocity of sound, velocity of sound equals 340 m/s. The sensor provides 2cm – 450 cm non-contact measurement function, the ranging accuracy can reach up to 3mm [11]. An electronic relay functions as a switch, which is turned off and on by a signal. It can be controlled through digital I/O ports, such as lamps, solenoid valves, motors, and other high voltage or high current devices. The electronic relay is used to control normally open or normally closed solenoid valves by signals received from the microcontroller board. A 12 volts power supply is used in the circuit. To achieve the measurements after 4 m distance, Senix ultrasonic (RS-232) sensors are used, a measurement rang of 4 – 1500 cm of non-contact measurement function is provided. Figure 9 shows a schematic diagram of Ultrasound working principles.

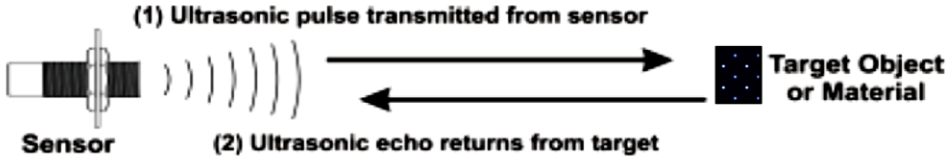


Fig. 9 An outline of the fundamental concepts of ultrasound operation, control architecture of automatic brake system,

The ultrasonic sensors function uninterruptedly with the start of vehicle driving, if an object is located at a distance, the ultrasound waves go back to the sensor receiver, then to the electronic control unit. The control unit processes these signals, and the distance between the vehicle and the obstacle is calculated. If the calculated distance is less than or equal to the safe stopping distance, the control unit sends proper signals to the two electric relays. The first relay is linked to the electric circuit related to the normally closed solenoid valve, which is linked to the hydraulic pump, whereas the other relay is linked to the electric circuit related to the normally open solenoid valve, which is mounted after the original master. This signal changes the state of the solenoid valve connected to oil pump from normally closed to open, and then the oil is transported from the oil pump to the hydraulic brake circuit. Simultaneously, the state of the solenoid valve normally opened linked to main brake master is changed from open to close to stop oil from returning. Thus, the pressure of the hydraulic circuit of the brake system rises, and the braking process is performed automatically without the driver intervention based on the distance measured between the vehicle and obstacle. Figure 10 shows a schematic diagram of the control architecture. After vehicle stopping, the solenoid valves that are active return to their original locations. The hydraulic oil goes back into the reservoir.

Simulink model development and dynamics simulation

Simulink® is a piece of software that Math works Inc. created for modeling, simulating, and analyzing dynamic systems, [19]. It supports sequential time, sampling time, or a combination of the two for modeling linear and nonlinear systems. Block diagrams are used to illustrate the system model and describe the system mode, [20]. The automatic hydraulic brake model was built in the SimMechanics library using the mathematical equations developed in section two. And simulation is performed to verify the design dynamics in the form of a Simulink model containing the blocks shown in Fig. 11. The blocks are arranged according to the engineering and physical laws, and the required assembly of system components. The Simulink model has three main block types: the input block, the system block, and the output block. The input block shows a simulation of the reference input signals (The desired wheel slip) designed to obtain the automatic brake system response (wheel speed, vehicle speed, stopping distance, and the actual wheel slip). The system blocks represent the automatic hydraulic brake system built based on the mathematical equations produced to vehicle, wheel, and wheel slip which have been used to construct this model in Matlab/Simulink software. The output block represents the actual slip value.

The vehicle model generated the vehicle speed, and the wheel model generated the wheel speed. From the slip ratio produced in equation (26) the slip value changes

according to the vehicle speed and the wheel speed. The antilock brake system controls the slip by controlling the brake pressure to reach the suitable slip value to decrease the stopping distance and get the stability of the vehicle during traction.

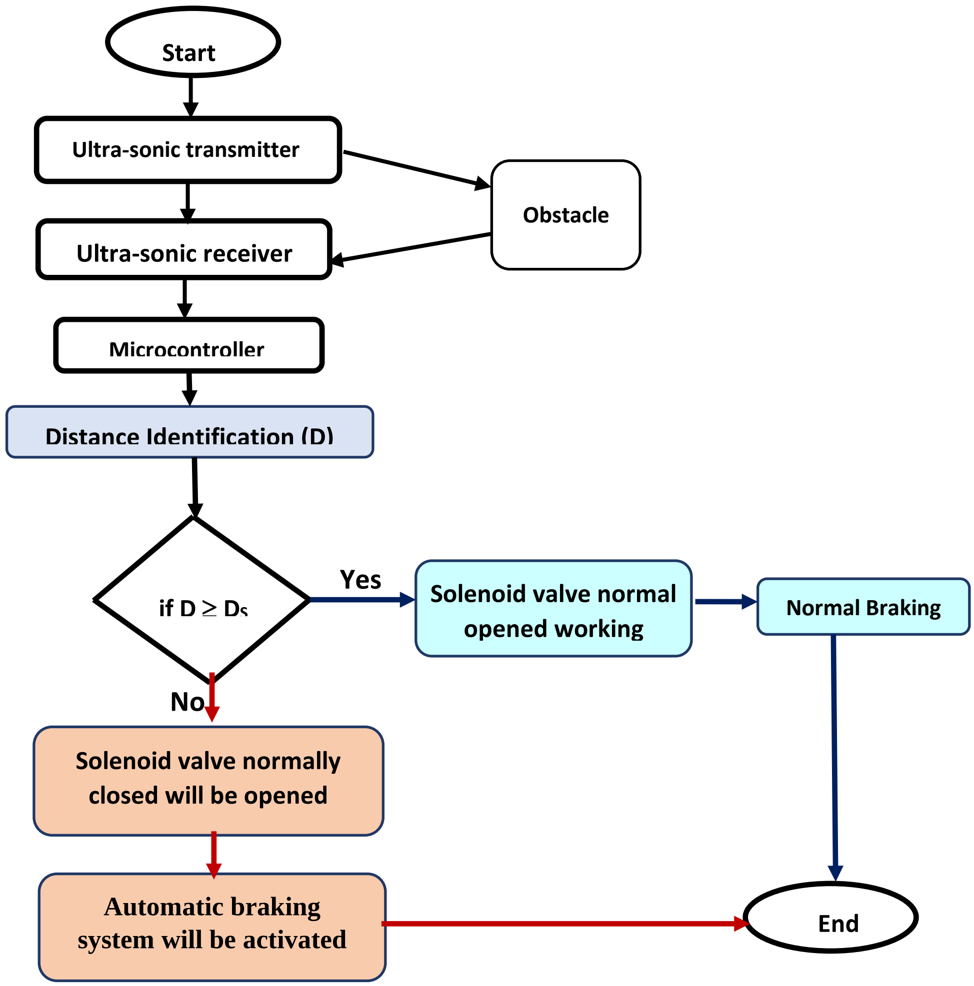


Fig. 10. A schematic diagram of automatic braking system working principle. Ds is the predefined stopping distance.

Open loop dynamics

Experiment 1

The Simulink model of the automatic hydraulic brake is used to input the vehicle speed at different time values, and the measured output is the wheel speed, and the stopping distance. Figs. 12, 13 represent the input and output response of automatic hydraulic brake model in open loop dynamics; Fig. 12 presented the wheel speed versus stopping time values at different vehicle speed values; these are 50, 70, 90 Km/hr in open loop dynamics (without using a controller), the wheel speed is nearly the same as vehicle speed and tracks it along the time duration of the simulation. Stopping time decreases as vehicle speed decrease. Figure 13 illustrated the stopping distance versus stopping time at different vehicle speed values; these are 50, 70, 90 Km/hr (without using a controller), both the stopping distance and the stopping time

increase as vehicle speed increases. The desired and actual slip values were illustrated in Fig 14, that shows a great deviation between the desired and actual slip values.

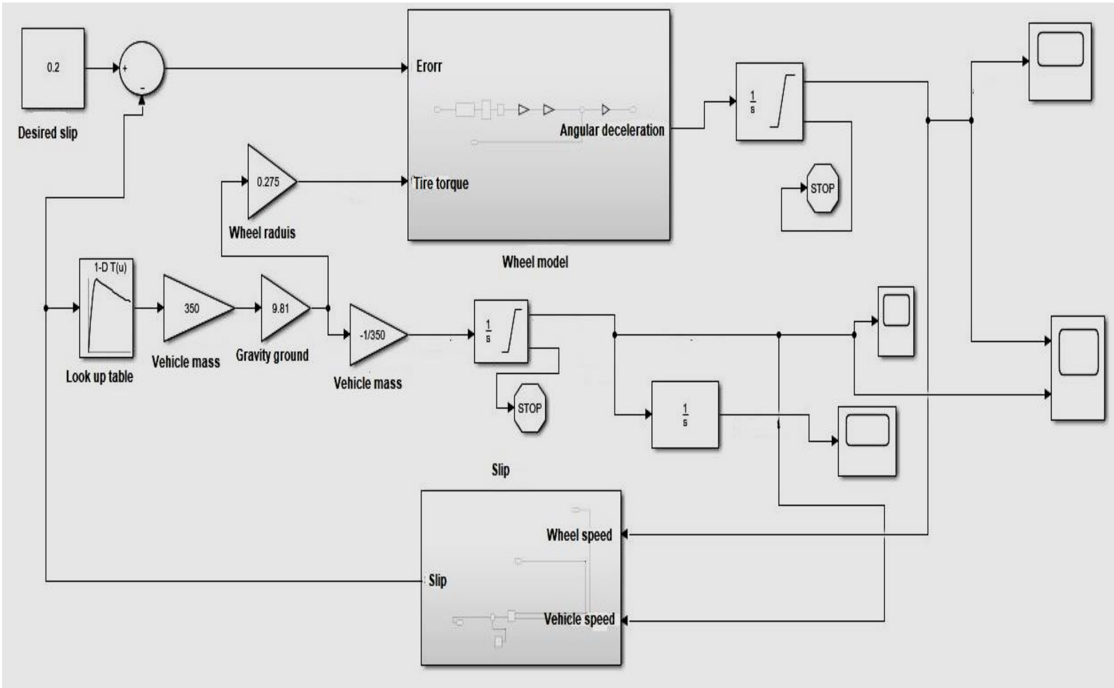


Fig. 11 Automatic hydraulic brake model in Simulink.

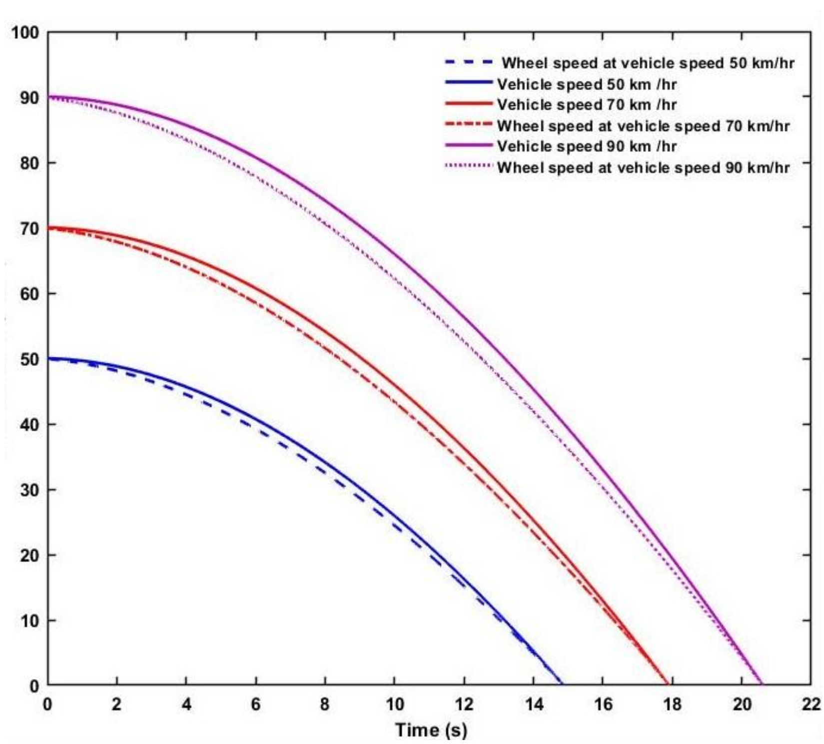


Fig. 12 Wheel speed and vehicle speed at different stopping time values in open loop dynamics (without controller).

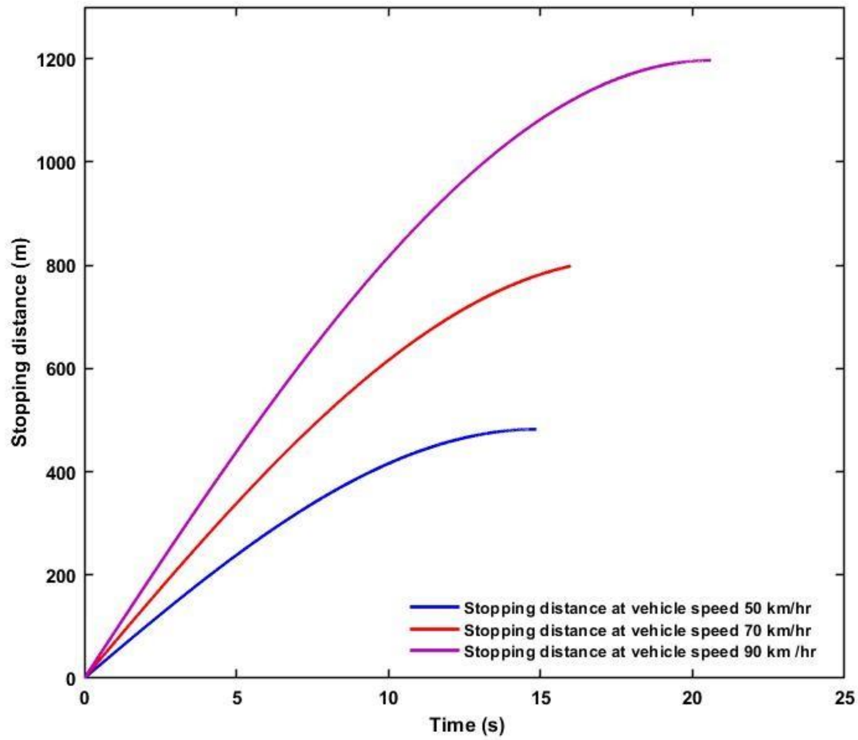


Fig. 13 Stopping distance at different vehicle speeds and different time values in open loop dynamics (without controller).

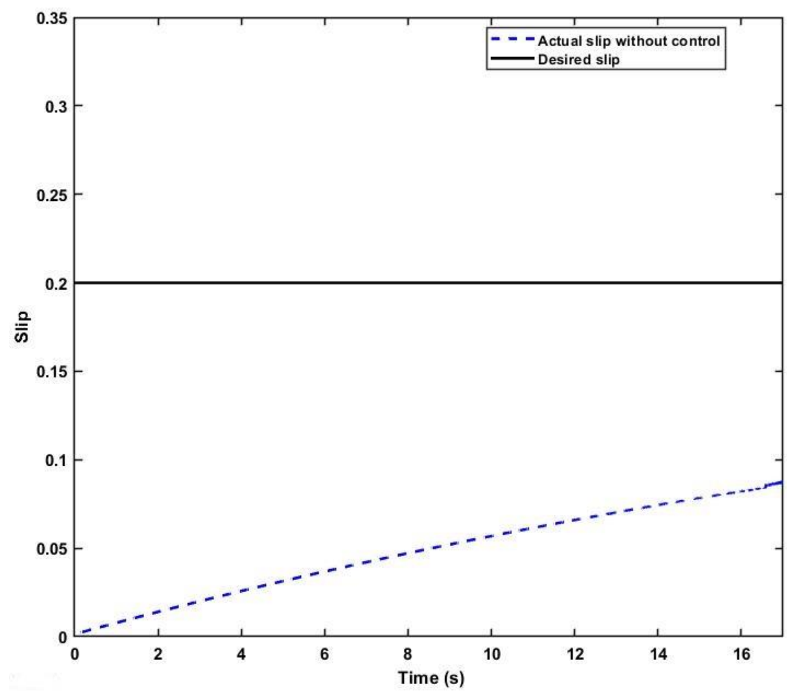


Fig. 14 Desired and actual slip ratio without controller.

PID controller design and simulation (closed loop dynamics).

The most popular feedback controller on the market is the one that uses the PID algorithm. It is a reliable and simple algorithm that, regardless of the dynamic behavior of a particular process plant, offers great control efficacy.

Gpid (s) = $k_p + k_i /s + k_d.s$ **(27)**

Equation (27) provides three distinct stationary coefficients for its computation algorithms: k_p, k_i and k_d. These coefficients can be expressed in terms of time, where k_i represents the accumulation of earlier errors, and k_p represents the current errors. Coefficient k_d means approaching error based on the uninterrupted pace of change [21].

PID controller block was added to the model. Parameters of the PID controller were tuned using Simulink. Figure 15 shows the block diagram of automatic hydraulic brake model and the PID controller. The step response and parameters and performance measures of the developed PID are shown in Figure 16(a) and (b).

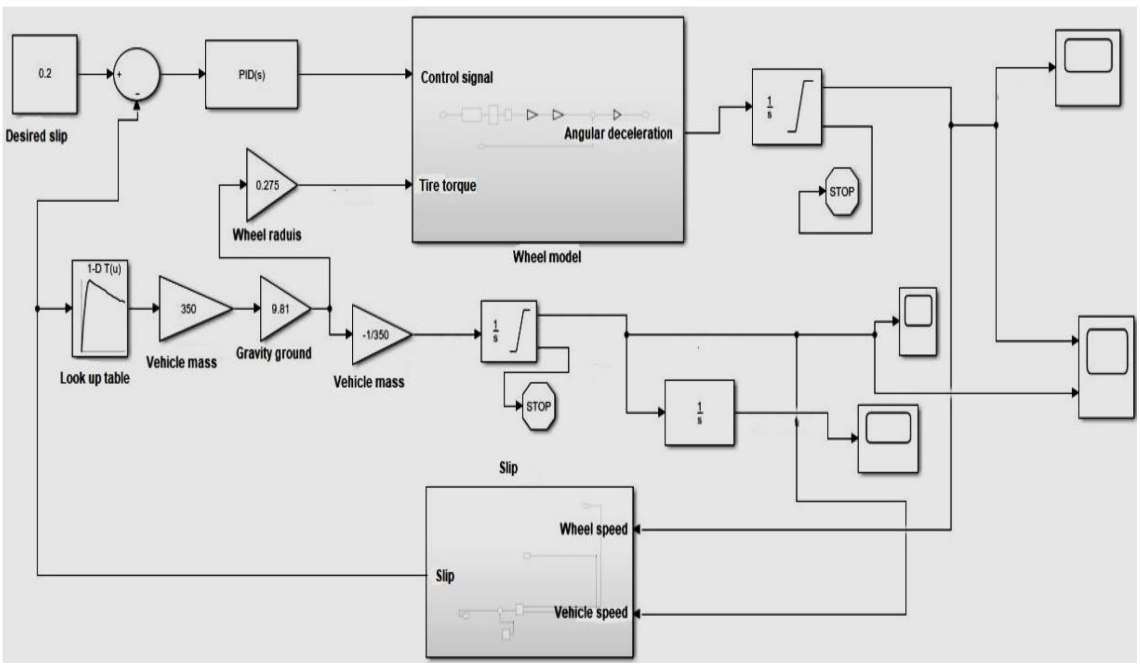
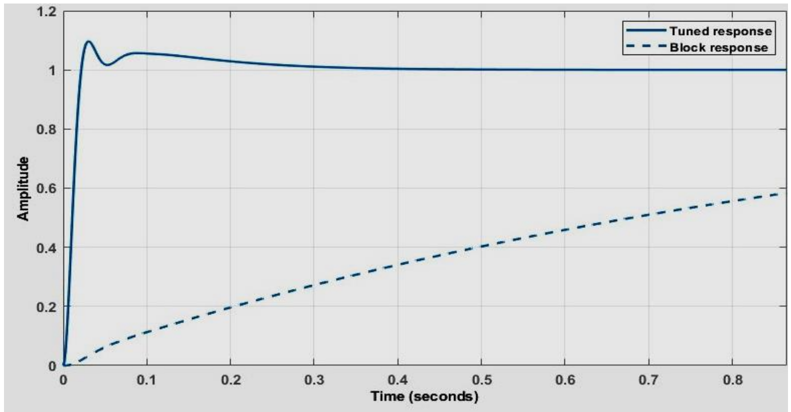


Fig. 15. Block diagram of automatic hydraulic brake system with PID controller.



(a)

Controller Parameters

	Tuned	Block
P	4202.7404	30.834
I	27168.9064	0.0012
D	93.9636	1.3
N	9398.4454	100

Performance and Robustness

	Tuned	Block
Rise time	0.0159 seconds	3.67 seconds
Settling time	0.249 seconds	6.52 seconds
Overshoot	10.6 %	0 %
Peak	1.11	1
Gain margin	39.4 dB @ 1.08e+03 ra...	46.3 dB @ 138 rad/s
Phase margin	60 deg @ 82.2 rad/s	90.6 deg @ 0.606 rad/s
Closed-loop stability	Stable	Stable

(b)

Fig. 16 PID controller: (a) The step response, and (b) controller parameters.

Experiment 2

The simulation was performed using the suggested PID controller. The system model in Figure 15 (Brake model with PID controller) was subjected to a reference step signal of the desired wheel slip at different vehicle speed and different stopping time. Simulations were performed for 10 sec. The feedback signal was then measured. All of wheel speed, stopping distance, slip ratio were also measured. Figure 17 shows the wheel speed and vehicle speed in closed loop dynamics, the wheel speed is slightly less than the vehicle speed and tracks it along the time duration of the simulation. Stopping time decreases as vehicle speed decreases. Further, the stopping time in closed loop dynamics decreases to halve values compared to the open loop dynamics. Figure 18 shows the stopping distance at different vehicle speeds and different time values, the stopping distance and time increase as vehicle speed increases also as in open loop dynamics but with much less in values of stopping distance and time related to each vehicle speed. The reference input signal and the measured signal of the slip ratio are shown in Fig. 19, the actual and desired slip ratio was illustrated in closed loop dynamics. Open loop dynamics gives a far slip ratio value from the required, in

the contrary; the closed loop slip ratio value followed the reference signal in an accepted manner.

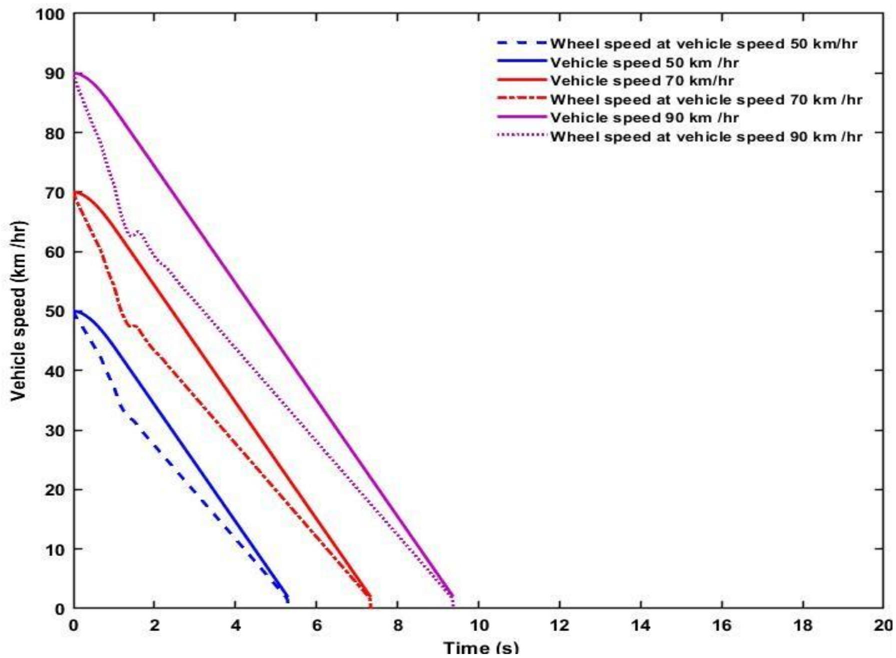


Fig. 17 Wheel speed and vehicle speed in closed loop dynamics (with PID controller).

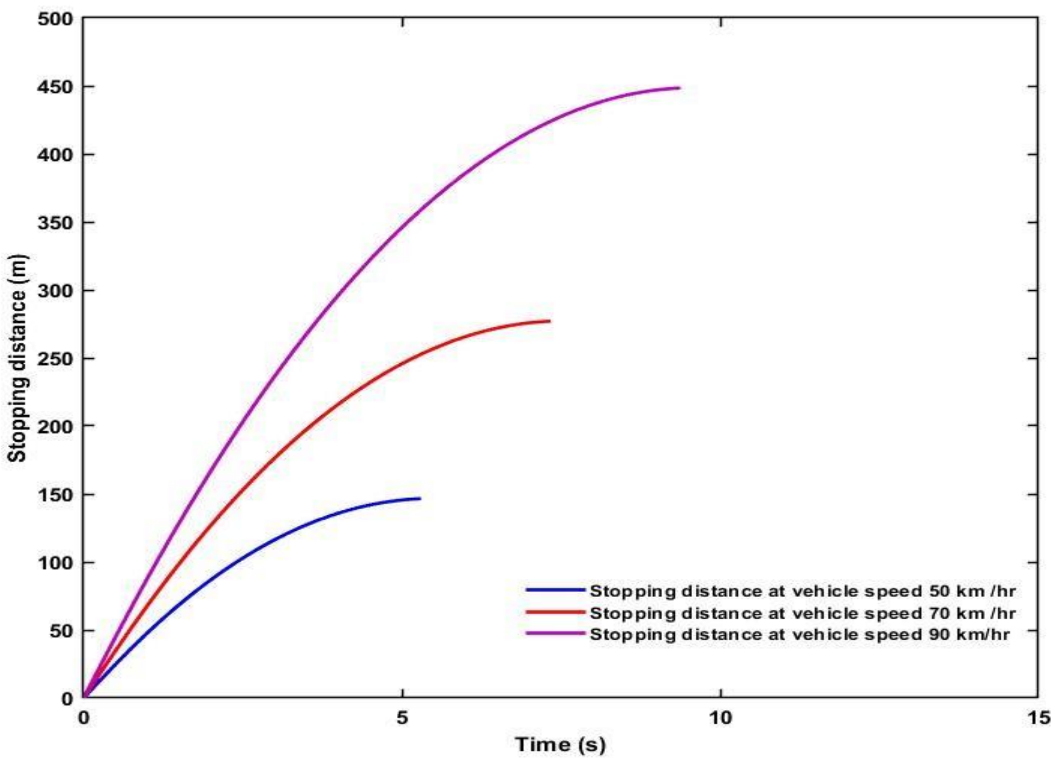


Fig. 18 Stopping distance at different vehicle speed closed loop (with controller).

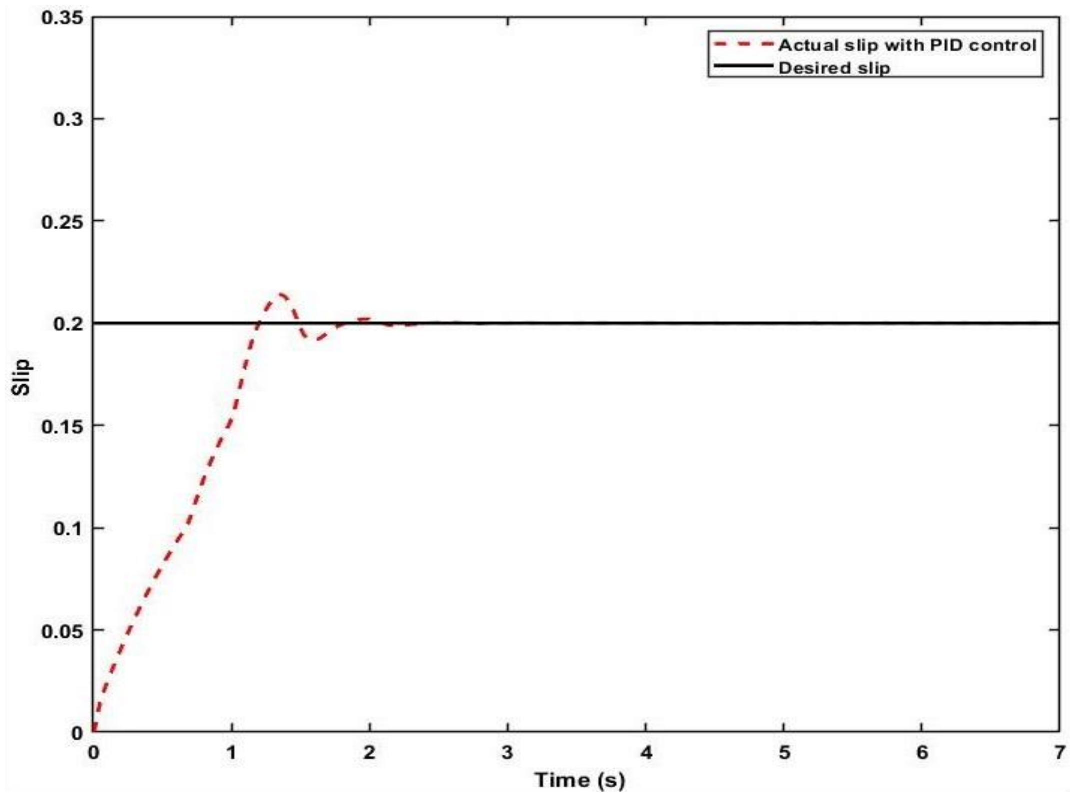
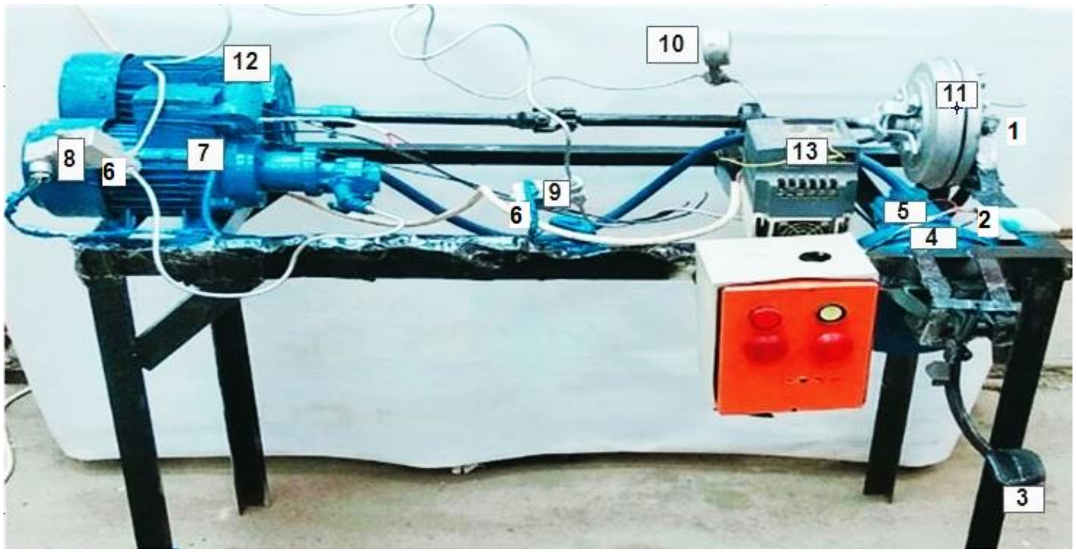


Fig. 19 Desired and actual slip ratio with PID controller.

The closed-loop system outperforms the open-loop system. The system response is stable, and system disturbances are small, leading to a perfectly controlled slip ratio and wheel speed. In addition, the presence of feedback contributed to the system's stability.

EXPERIMENTAL

The test rig of the automatic brake system was manufactured, and a real photo is shown in Fig. 20. A simple program to control the automatic braking system which is easy to be edited based on the braking distance tested was written and uploaded to the Arduino Uno board. Figure 21 presents a photo of the program code. Then the stopping or braking time is measured by a stop watch at five distances between the system and an obstacle, these distances are 2, 2.5, 3, 3.5, and 4 meters. Where at each distance, the stopping time is measured at five different speeds; these speeds are 70, 80, 90, 100, and 110 Km/hr, then a comparison between the measured stopping time and the theoretical time is done. Theoretical time is calculated as in equations (1), (2) and (3):



1. Ultrasonic sensor, 2. Arduino Uno, 3. Brake pedal, 4. Brake booster, 5. Master cylinder, 6. Relay, 7. Electric pump, 8. solenoid valve normal open, 9. Solenoid valve normal closed, 10. Pressure gauge, 11. Drum brake, 12. electric motor, 13. Inverter,

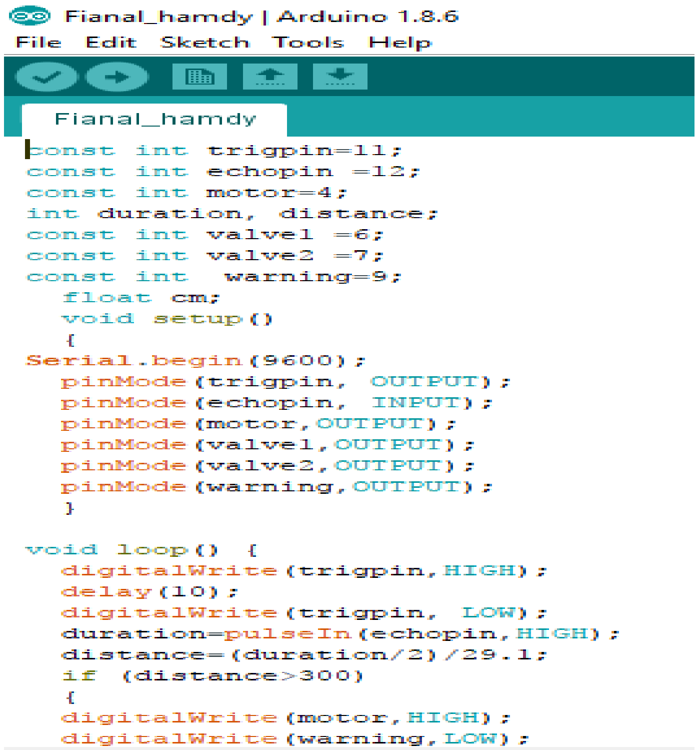
Figure 20. A photo of the real automatic brake system test rig.

$$V_f = V_i + at \tag{1}$$

$$D = V_i * t + 0.5 * a * t^2 \tag{2}$$

From equation (1) and (2);

t= d / 0.5 V_i is the initial speed, V_f is the final speed, a is the declaration of the vehicle, t is the braking or stopping time, and D is the distance.




```
const int trigpin=11;
const int echopin =12;
const int motor=4;
int duration, distance;
const int valve1 =6;
const int valve2 =7;
const int  warning=9;
  float cm;
  void setup()
  {
Serial.begin(9600);
  pinMode(trigpin, OUTPUT);
  pinMode(echopin, INPUT);
  pinMode(motor,OUTPUT);
  pinMode(valve1,OUTPUT);
  pinMode(valve2,OUTPUT);
  pinMode(warning,OUTPUT);
  }

void loop() {
  digitalWrite(trigpin,HIGH);
  delay(10);
  digitalWrite(trigpin, LOW);
  duration=pulseIn(echopin,HIGH);
  distance=(duration/2)/29.1;
  if (distance>300)
  {
  digitalWrite(motor,HIGH);
  digitalWrite(warning,LOW);
```

Fig. 21. Control program loaded to Arduino Uno board.

The values of the measured braking time are shown in Table 1.

Table 1: The values of the measured braking time at different distances and speeds

Vehicle speed (km/hr)	Braking time at distance 2 m (sec)	Braking time at distance 2.5 m (sec)	Braking time at distance 3 m (sec)	Braking time at distance 3.5 m (sec)	Braking time at distance 4 m (sec)
70	0.209721	0.262545	0.315341	0.366772	0.420588
80	0.182076	0.229501	0.276111	0.321696	0.366545
90	0.162285	0.202495	0.244989	0.284832	0.325753
100	0.145835	0.182921	0.218707	0.257596	0.293687
110	0.133837	0.166301	0.200526	0.231615	0.265654

Figure 22 shows the measured braking time and the theoretical braking time at different vehicle speeds when the distance between the system and the obstacle equals to 2 meters. And Fig. 23 shows the measured braking time and theoretical braking time at different vehicle speeds when the distance between the system and the obstacle equals to 2.5 meters. While Fig. 24 shows the measured braking time and theoretical braking time at different vehicle speeds when the distance between the system and the obstacle equals to 3 meters. Where Fig. 25 shows the measured braking time and theoretical braking time at different vehicle speeds when the distance between the system and the obstacle equals to 3.5 meter. And Fig. 26 shows the measured braking time and theoretical braking time at different vehicle speeds when the distance between the system and the obstacle equals to 4 meters.

The maximum measured braking time happened at speed equals to 70 km/hr, while the minimum measured braking time happened at speed value equals to 110 km /hr for the measured distances 2, 2.5, 3, 3.5, 4 meters. And braking time decreases with the increase of vehicle speed. Results showed that there is good agreement between measured braking time and theoretical or predicted braking time. Error analysis showed that errors have been found to be between 1.07 % at 70 km/hr and 2.17 % at 110 km/hr.

CONCLUSIONS

This paper presented a new hydraulic automatic braking system based on using an ultrasonic sensor in vehicles, that can solve the problem where drivers may not respond properly using a manual brake. An ultrasonic sensor was used in a system to measure the distance between a vehicle and the obstacle. This system operated manually and automatic in parallel, where the driver can use the brake pedal to stop the vehicle, if the driver doesn't stop a vehicle at right time this system can stop vehicle automatically without driver input. The components which are used in the system are available and low cost. The performance of system is easy to maintain and has an acceptable proper response. For further work in future a variable solenoid valve can be used to control the pressure of the brake fluid. And an electromagnetic actuator can be used to operate the brake pedal to control its angle.

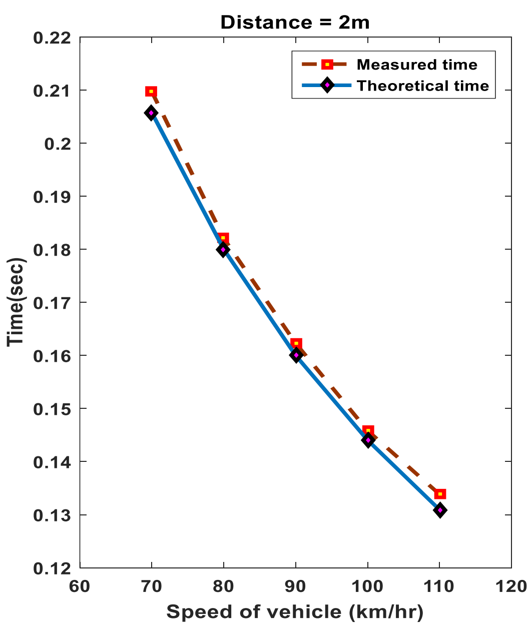


Fig. 22. Measured and theoretical time at distance 2 m.

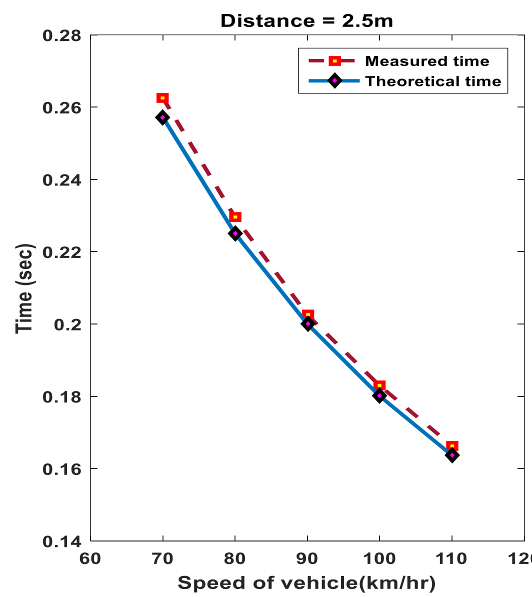


Fig. 23. Measured and theoretical time at distance 2.5 m.

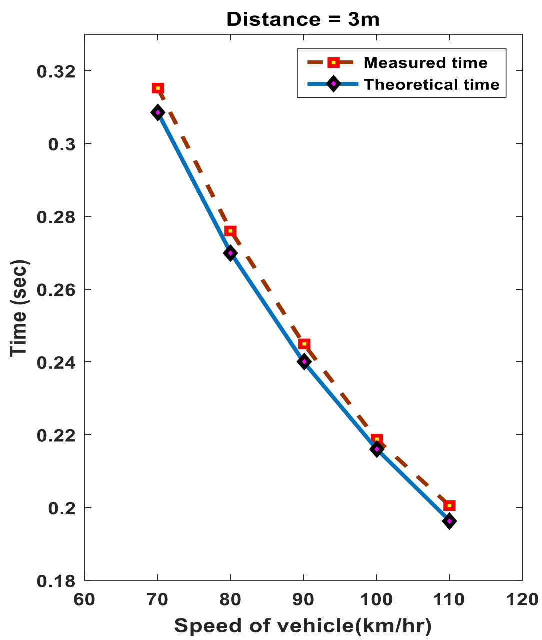


Fig. 24 Measured and theoretical time at distance 3 m.

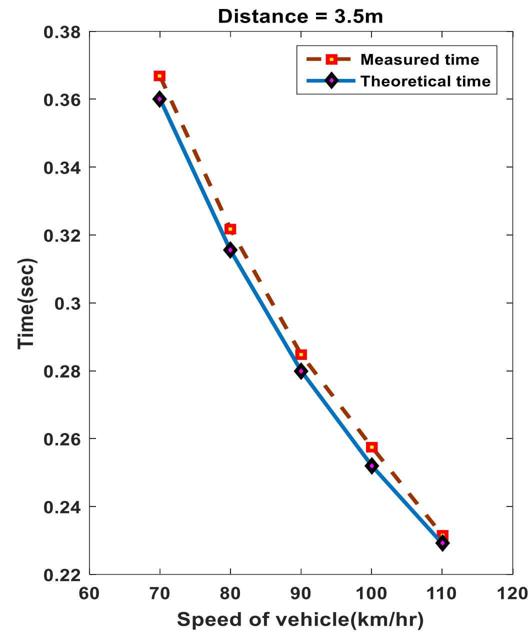


Fig. 25 Measured and theoretical time at distance 3.5 m.

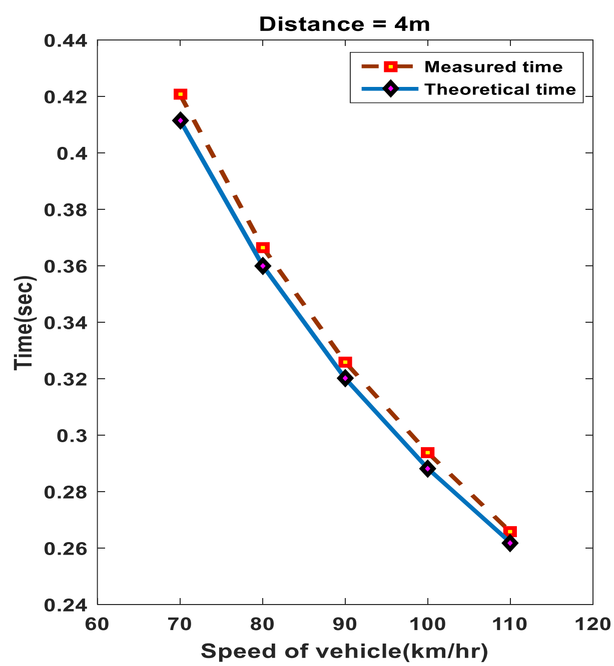


Fig. 26 Measured and theoretical time at distance 4 m.

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