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Research Article
Electro-hydro-mechanical Braking System for Passenger Vehicle

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Abstract

Background and Objective: Deceleration or stopping the vehicle without a diving and lateral acceleration is essential to develop an effective braking system. The antilock braking system (ABS) and electronic stability control (ESC) has been introduced to improve the braking performance of the vehicle. However, due to the insufficient human effort, the ABS and ESC to some extent, not function well. This study develops an electro-hydro-mechanical braking system by associating the wheel speed sensor and accelerator sensor. It had been developed the additional actuation force on the brake pad to decelerate the vehicle instantaneously in the desired braking distance corresponding to the speed with less lateral acceleration. **Materials and Methods:** This study investigates the DC motor amplified braking system theoretically by solid work simulation model and experimentally by developing an intelligent system for controlling the DC motor based on the Markov Decision Process model. **Results:** The simulation model has shown that a full load passenger car needs 15.7 Mpa of braking pressure to stop 50 km h^{-1} vehicle in 10 m. The experimental results of the model show that the pressure develops when the pedal fully applied without and with aids of the DC motor is 910 kPa and 1130, respectively, which contribute to increase pressure about 23.3%. **Conclusion:** The effectiveness of the DC motor amplified braking system would be able to break the vehicle to decelerate as soon as release the brake pedal even without the driver action which might prevent the fatal accident on the road.

Key words: Electro-mechanical braking system, digital decision process, safety, incident control

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Braking is an important safety feature of the vehicle. The National Transportation Safety Board-reported that the 90% of a vehicle rear-end accidents and 60% of frontal collision can be avoided effectively if the vehicle is braking ahead of time as soon as accelerator pedal is released[1]. The conventional hydraulic braking system has been used for a long time and it has been broadly utilized in a variety of vehicles including trucks and buses. The disc brake is a component, which slows down the rotation of the wheel by caused by friction. However, the performance of the braking system is not only depending on the friction of the brake disc, the material of friction used and the size of the brake pad, but it also depends on the force on the master cylinder and pressure available in brake fluid line. For a better performance, the brake system technologically keeps-on advancing it features in achieving a higher safety performance and avoid the fatal accident[2].

An accident still occurs either a minor or major accident even the vehicle is equipped with a good braking system like ABS. It is believed that the overall stopping distance is strongly affected by driver reaction time. This reaction time during emergency event generally includes the time period from the perception of the hazard until some or all brakes are locked or the ABS modulation begins[3]. Road safety plan of Malaysia reports that 477,204 road accident in 2013, the number of injuries 12,000 thousands of which more than 4000 were seriously injured, the number of fatalities from road accident was 6915, which is an average of 19 deaths on the country's road every day[4]. The fatality index was 2.9 per 10,000 registered vehicle in Malaysia while it is 2 in the developed countries. The implementation of UNECE Regulation through Vehicle Type Approval (VTA) will assist the Malaysian automobile industry to offer 'five star' vehicles to the road users include: (1) All new motor vehicles to be equipped with seat belts and anchorages that meet regulatory requirements of United Nations, (2) Deployment of crash avoidance technologies, which have been proven effective such as Electronic Stability Control and ABS in motorcycles, (3) Passive Safety Systems, (4) Active Safety Systems Management such as intelligent system with braking force amplified system, lighting and signalling[5] .

Electronic hydraulic brake system (EHBS) is one of the brake-by-wire systems. The EHBS has its own characteristic compatible with ABS and ESC system[5]. The EHBS is an improved system of a conventional hydraulic system that has complex hydraulic hoses. Thus, BOSCH, Delphi and Siemens have all developed their brake-by-wire (BBW) systems[6]. The BBW system is applied to different platforms of vehicles. However, this study has emphasized more to electro-hydraulic braking system (EHBS) with an additional force assisted by means of DC motor. The new system should have components: brake pedal mechanism, a push rod, a tandem master brake cylinder, an EHBS actuator, a valve control unit, DC motor amplified system with rack-pinion, fuzzy controller and wheel brakes[7]. A rack-pinion is a type of linear actuator that engages a pair of gears, which convert rotational motion into linear motion[8].

The aim of this study was to present an electro-hydro-mechanical braking system for the passenger car to reduce the road accident by developing the additional braking force with boosting the master cylinder hydraulic pressure. The mathematical model has been developed to estimate the braking pressure in associating the vehicle load distribution to the axles by modifying the equations[9-11]. Markov Decision Process (MDP) model in association with braking system control model and the model of DC motor amplified braking system.

MATERIALS AND METHODS

Performance characteristics of a road vehicle refer to its capability to decelerate and stops. However, the weight during deceleration event the maximum braking force that the maximum braking force needs to develop by the braking system can be estimated by modifying the mathematic models[9-11]:

$$F_{bf(d)}(t) = \mu_p \times W_{f(d)}(t) = \mu_p \left(W_{f(s)} + W_{T(d)}\right) \quad (1)$$

$$F_{br(d)}(t) = \mu_p \times W_{r(d)}(t) = \mu_p \left(W_{r(s)} - W_{T(d)}\right) \quad (2)$$

Where:

$$W_{T(d)} = \left(\frac{a_d}{g}\right)\left(\frac{h_{cg}}{L}\right) \times W$$

and:

$$L = \frac{W_r}{W} \times L + \frac{W_f}{W} \times L = CG_{f(x)} + CG_{f(r)},\ h_{cg}$$

is height, L the wheel base, a_d deceleration, $CG_{f(x)}$ location of centre of gravity from front axle while $CG_{r(x)}$ from the rear axle, m_p is the road adhesive coefficient, $F_{bf(d)}(t)$ and $F_{br(d)}(t)$ are the instantaneous dynamic braking force, $W_{f(d)}(t)$ and $W_{r(d)}(t)$ the instantaneous dynamic load distribution, $W_{f(s)}$ and $W_{r(s)}$ the static load distribution at the front and rear axle, respectively.

Instantaneous weight transfer which (%) determine the hydraulic pressure distribution from the master cylinder to the axles can be estimated:

$$\text{Front axle weight (\%)},\ x_f = \frac{W_{f(d)}(t)}{W} \times 100\% \tag{3}$$

$$\text{Rear axle weight (\%)},\ x_r = \frac{W_{r(d)}(t)}{W} \times 100\% \tag{4}$$

The force required to actuate the caliper against the rotation of the braking rotor can be estimated[9]:

$$F_{a(f)}(t) = x_f \times \frac{P_{mc}(t)\theta}{2}\left(r_o^2 - r_i^2\right) \tag{5}$$

$$F_{a(r)}(t) = x_r \times \frac{P_{mc}(t)\theta}{2}\left(r_o^2 - r_i^2\right) \tag{6}$$

where, $F_{a(f)}(t)$ is the actuation force at the front calipers and $F_{a(r)}(t)$ at the rear wheel's rotor calipers, r_o and r_i the outer and inner radius of the brake pad from the centre of the braking rotor, P_{mc} (t) instantaneous master cylinder pressure into the fluid pipe and $x_f+x_r = 100\%$. The braking torque required to decelerate or stop the vehicle can be estimated[9,10] :

$$T_{b(f)}(t) = \frac{\mu_m \times x_f \times P_{mc}(t) \times \theta}{3}\left(r_o^3 - r_i^3\right) \tag{7}$$

$$T_{b(r)}(t) = \frac{\mu_m \times x_r \times P_{mc}(t) \times \theta}{3}\left(r_o^3 - r_i^3\right) \tag{8}$$

Where:

$$P_{mc} = \frac{F_{p(a)d} + F_d}{A_{mc(p)}},\ \mu_m$$

is the friction coefficient of the braking pad, q is the angular position of the braking pad on the brake rotor, A_{mc} is the cross-sectional area of the master cylinder piston, F_d (t) instantaneous force applied by the driver to the brake pedal, $F_{p(a)d}(t)$ is the amplified force developed by the DC motor based on the policy making by the controller with the response of the WSS and accelerator sensor $T_{bf}(t)$ and $T_{br}(t)$ are the instantaneous braking torque of the front and rear rotor during the vehicle deceleration, respectively. It could be mention that if $T_{bf}(t)+T_{br}(t)<T_t$ the vehicle will be decelerate and if $T_{bf}(t)+T_{br}(t)\geq T_t$ the vehicle will be in full stop, T_t is the traction torque of the vehicle. The force required on the master cylinder to stop the vehicle in time T at distance S:

$$F_d \times \frac{l_2}{l_1} + F_{p(a)d} = \frac{mv^2}{2S \times T} \tag{9}$$

The power ($P_{p(a)d}$) required the DC motor to develop the amplified force:

$$P_{p(a)d} = \left[\frac{mv^2}{2s \times T} - F_d \times \frac{l_2}{l_1}\right]\left(\frac{S}{T}\right) \tag{10}$$

The energy ($e_{p(a)d}$) Wh required for the motor to develop the amplified force in time T:

$$e_{p(a)d} = V_b \times I_b \times \eta_m \times \frac{T}{3600} \tag{11}$$

where, S is the stopping distance in m and T is the stopping time in sec, V_b and I_b are the battery terminal voltage and current delivered to the DC motor, h_m efficiency of the motor.

Electro-hydro-mechanical braking system: The Electro-hydro-mechanical Braking System (EHMBS) (Fig. 1) is one of the electro-hydraulic brake systems (EHBS). The advantages of this EHMBS, the intelligent system can read the amplified force level from the level of master cylinder pressure by a feedback system. In this system, the brake pedal force is assisted by the DC motor based on the Markov Decision Process (MDP) model which is initiated with a response of the wheel speed sensor and accelerator sensor (Fig. 2). The controlled system has been developed based on the study of researchers[12,13]. Figure 3 shows the control system of the DC amplified braking system. The proportional valve is a variable valve can be self-adjusted based on the pressure requirement of the axles. The wheel speed sensor output has been integrated and calibrated based on the study of the researchers to maintain the required pressure of the braking system by using the developed circuit[14,15].

DC motor amplified technique: The continuously growing need for better comfort and safety of automotive, it is almost impossible to imagine without intelligent systems. The researchers from all around the world have been working hard to invent intelligent devices consisting of not only sensors, but also controller, among other devices, that incorporate a certain amount of intelligence to the sensors themselves, transforming their response to the controller to make the system intelligent and auto pitched system.

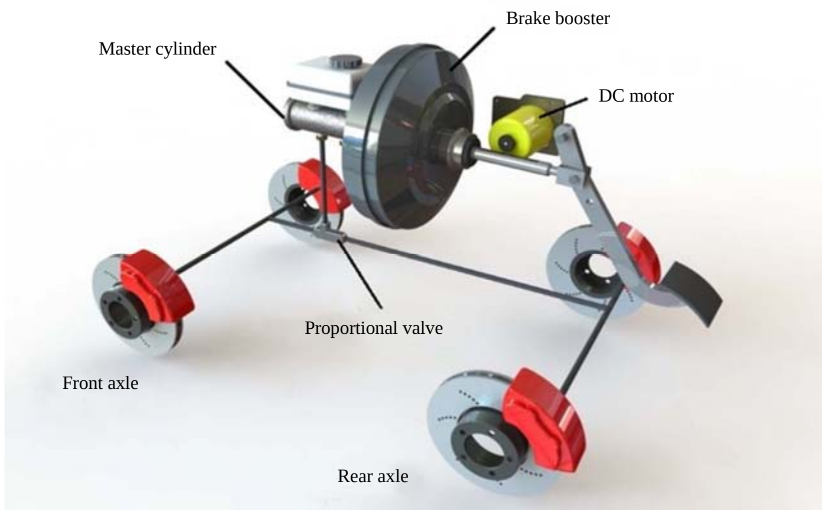

Fig. 1: DC motor amplified mechanical-hydraulic braking system

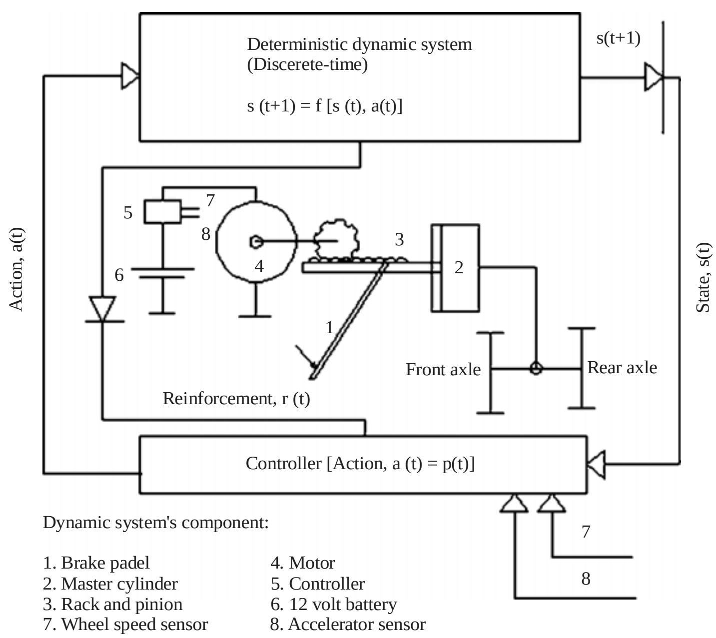

Fig. 2: Markov decision process model

The markov decision process (MDP) model has been considered in this study to develop the DC motor amplified intelligent system with integrating the WSS and accelerator sensors. It is assumed that the Markov property effects of an action based on a response (i.e., state) of sensors (wheel speed sensor, accelerator sensor and SOD sensor of the battery). The model contains:

- A set of possible states, 'S'. The state (S) of the MDP model in this study is referred as the force developed by the motor F_{pd} with the help of the rack-pinion to active the master cylinder for the additional pressure of the braking devices
- A set of possible action, 'a' based on the sensor response of the dynamic components not on any previous response. The controller action in this study has been referred as supply current (I_b) to the DC motor by the controller action to develop the necessary applied force tot he master cylinder through the rack and pinion
- A real valued reward function R(s,a)

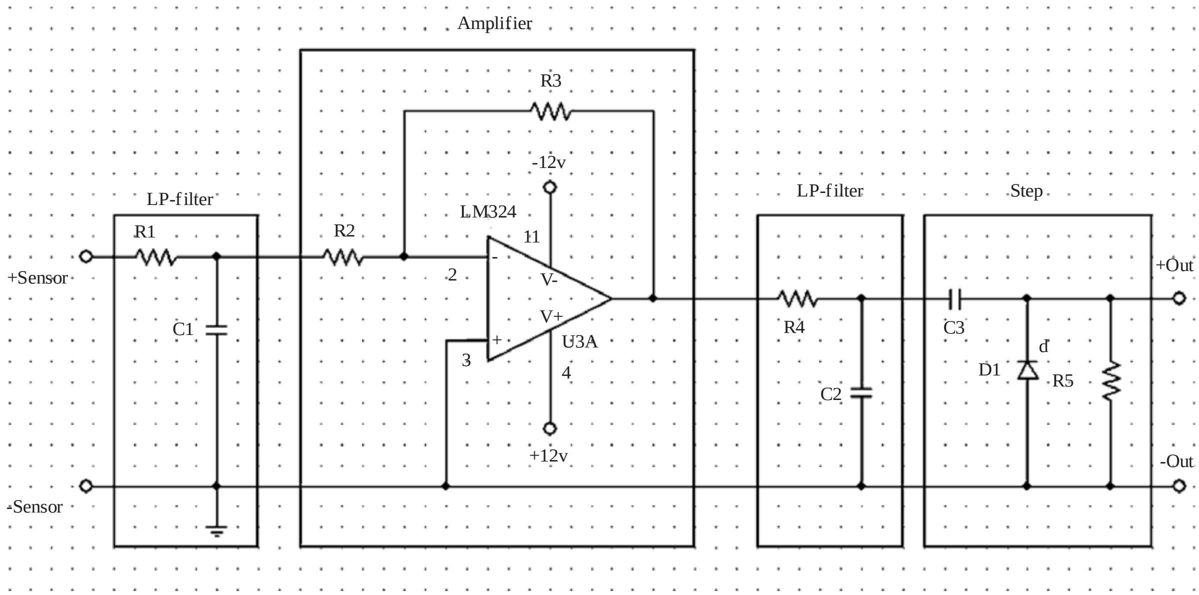

Fig. 3: Circuit solution of the WSS

- A description ,'t' of each action of controller in each state is called the instantaneous action of the controller based on the sensor response

The task of the controller is to make an action (or policy, P) to active the DC motor on creating an effort, P:S→A to amplify the mechanical-hydraulic braking system to provide the additional safety of the car during braking. For the instantaneous effort of the motor the controller take a policy, based on the signal of the WSS and accelerator sensors, $P(s_t) = a_t$. The deterministic dynamic system actions of the MDP is stated in this study as, t:s×a→s, for each action of controller based on the sensors response. The MDP policy mapping can be made based on s and a. Finite-horizon values at adjacent horizons are related by the system dynamic actions can be estimated by using the finite-horizon Bellman equation:

$$\begin{aligned} F_{b(a),0}(F_{p(a)d}) &= R\left(F_{p(a)d}, p\left(F_{p(a)d}\right)\right) \\ F_{b(a),n}(s) &= R\left(F_{p(a)d}, I_b\right) + \sum_{F'_{p(a)d}\in F_{p(a)d}} t\left(F_{p(a)d}, I_b, F'_{pd}\right).\gamma.F_{p(a),n-1}(s') \end{aligned} \quad (12)$$

The dynamic function $F_{b(p)}:F_{p(a)d}\rightarrow F\rightarrow\Re$ represents the expected objective valued obtained following policy (p) from each state in $F_{p(a)d}$.

The output current of the WSS can be estimated[15,16].

$$I_{o(wss)}(t) = \frac{2l_g}{\mu_0 N_s}\bar{B}_s \cos(2\pi ft) \quad (13)$$

where, l_g is the air gap between sensor and the sprocket wheel in mm.

RESULTS AND DISCUSSION

System performance

Theoretically: Braking performance had conducted theoretically by using Microsoft EXCEL to show the results of stopping distance, braking force and hydraulic pressure in graphical analysis. Some parameters were determined throughout the simulation process. The vehicle mass, m = 1793 kg, road adhesion, μ_p = 0.6, frictional coefficient of brake pad, μ_b = 0.46, lever ratio of 8:1 and master cylinder bore of 2.85 cm. Figure 4 showed the braking distance according to the vehicle sped. Result showed that the stopping distance had increased as it stops at higher speed. The braking force, F_b found after knowing the stopping distance of the vehicle. Furthermore, by having the braking force, the actuating braking force, F_a which was the clamping force on the brake pad shows in Fig. 5.

By having F_a and A_{mc} and F_a/A_{mc} gives the hydraulic pressure, P_h in the master cylinder. Figure 6 had shown the full illustration on pressure required, pressure developed by driver ad the pressure developed by DC motor. There is lack of pressure for braking needed by the car starting from 30 km h^{-1} and above. For example, the figure had showed the pressure difference between the required and delivered for the car to stop from 50 km h^{-1} is 17.17 Mpa. Therefore, the lack of pressure was assisted by DC motor that had developed the additional force on the master cylinder.

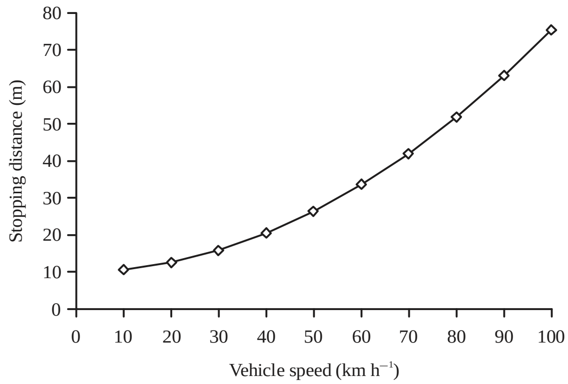

Fig. 4: Stopping distance of the vehicle

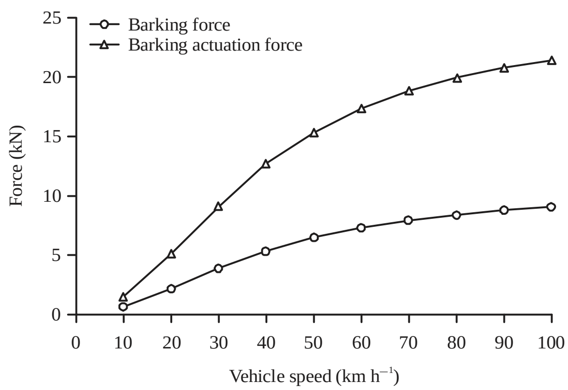

Fig. 5: Braking force and brake actuating force according to vehicle speed

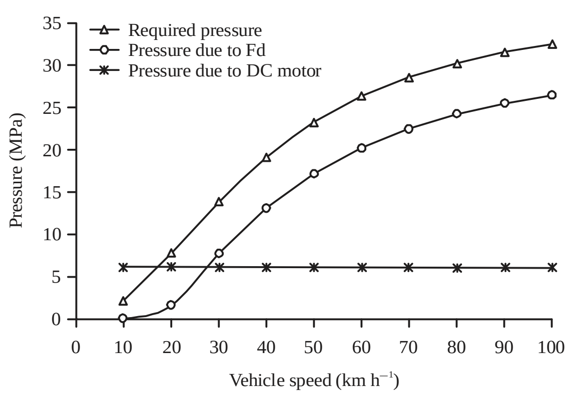

Fig. 6: Hydraulic pressure against vehicle speed

Figure 7 illustrated the hydraulic pressure based on load distribution on front axle. Note that the pressure required for braking on front axle is higher since the load was transferred to the front. Let's consider the speed of 50 km h^{-1}, the required pressure indicates that the car needs 15.7 Mpa while the effort by the driver only satisfy around half of it,

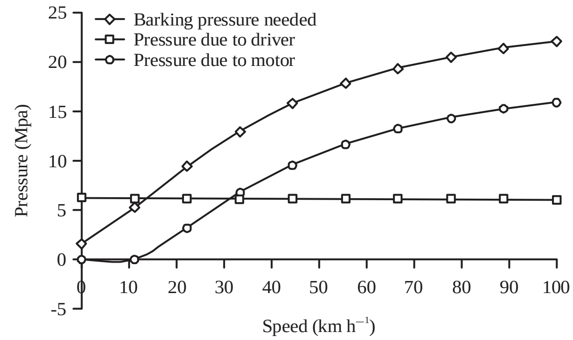

Fig. 7: Braking pressure based on front axle

which was 6.2 Mpa. Therefore, the force by the motor had supported the remaining required pressure by 9.6 Mpa.

System performance

Experimentally: In this study, a prototype of the electro-hydro-mechanical braking system had been developed (Fig. 8). The motor actuated the rack-pinion in order to develop the additional braking pressure of the master cylinder in-lined with the braking pad actuating force either in disc braking or drum braking system. In the DC motor braking amplified model had been developed with the wheel speed induction sensors-sprockets and the accelerator pedal sensor and the control model based on the Markov Decision Process (MDP) model.

The magnetic induction KMI 17/4 sensor used to measure the rotational speed or the wheel speed. It transmits the speed information's through a current signal at the supply pins[5,6]. The controller uses the output current to make a decision on the development of amplified force of the master cylinder. The total braking force of the master cylinder is the summation of the driver applied force plus the amplified force of the DC motor and its assembly.

The experiment had been conducted by installing the WSS and AC sensors, controller, 12 V battery and a pressure gauge at the end of the master cylinder. The wheel had been operated with pressing the accelerator pedal at maximum equivalent vehicle speed of 70 km h^{-1}. In each operation, the pressure had been recorded at the gauge of the master cylinder. The test results were recorder with DC motor and without DC motor. The test results had presented in Fig. 9.

Figure 10 shown the final test result of the system, the result showed that the hydraulic pressure developed when the DC motor was used to assist the braking system. Obviously, the hydraulic pressure produced is higher compared to the pressure developed with the assistance of

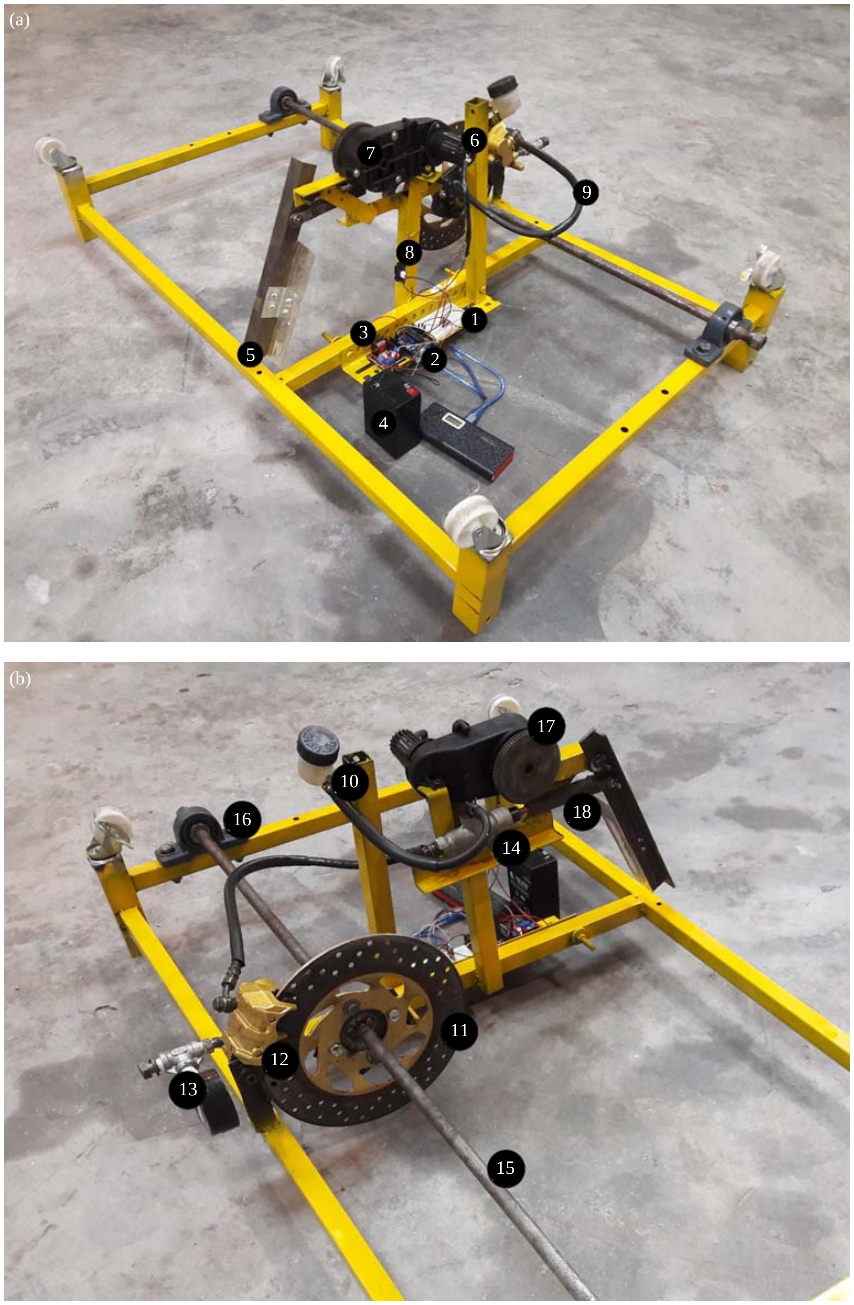

Fig. 8(a-b): Prototype electro-hydro-mechanical braking system for passenger car. Notification 2: Circuit bread board, 3: Arduino circuit controller, 4: L298N DC motor driver, 5: 6V battery, 6: Brake pedal, 7: DC motor 7, 8 : Gearbox, 9: Distance sensor, 10: Brake fluid hose and tank, 11: Brake pad, 11: Brake disc (Rotor), 12: Brake caliper, 13: Hydraulic valve, 14: Hydraulic pressure, 14: Master pump, 15: Rotating shaft, 16: Shaft bearing, 17: Bearing support, 18: Pinion, 19: Rack

DC motor. The result could be supported by the reported result available[10] . It was reported for the motorcycle that the maximum pressure imparted in the braking system should be in the range of 100-150 psi. From the average experimental result was presented in Fig. 8 when the brake pedal was fully pressed. By using the assistance of DC motor, the pressure increased is about 23.3%. So, this amount of additional pressure was useful to avoid road accident. This was because of a sufficient pressure might help the vehicle to stop within the desired distance.

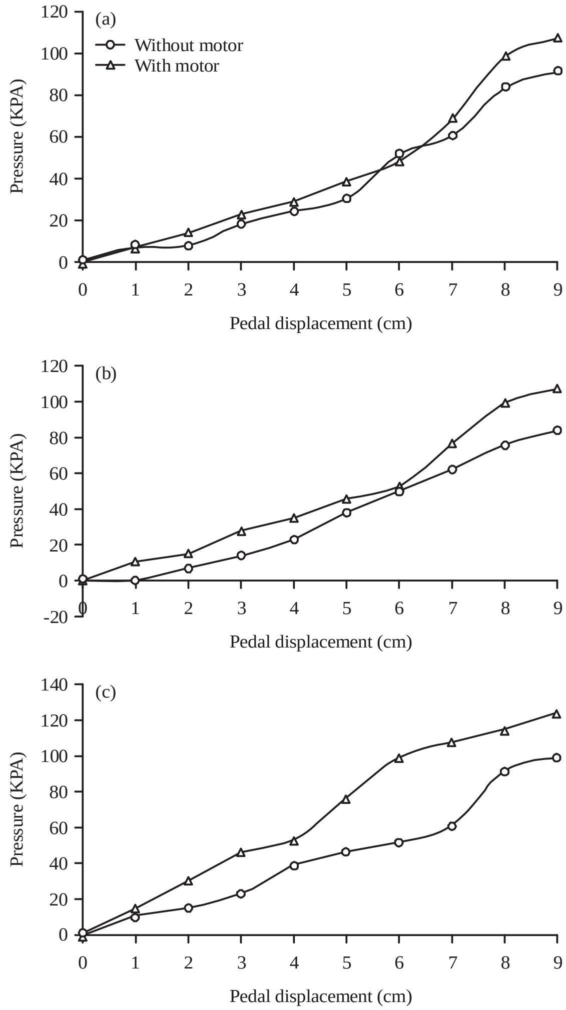

Fig. 9: DC amplified braking system performance

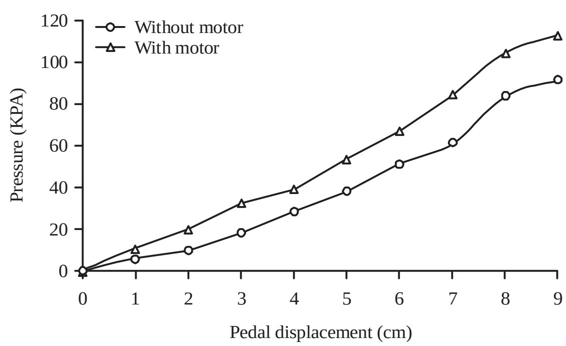

Fig. 10: Average pressure gauge reading vs. pedal displacement

CONCLUSION

The following conclusions have been made based on the contents of the manuscript:

- The conventional braking system is able to developed maximum ≤80% of the braking effort that required to stop the vehicle in desired distance. While, the braking system is designed to develop 100% braking effort to stop the car in desired distance corresponding to the speed. The lacking of the braking effort development due to the slow response of the driver
- The EHMBS could be able to compensate the additional about 23.3% of the braking effort and prevent the vehicle from road accident
- The pressure develops when the pedal fully applied without and with aids of the DC motor is 910 and 1130 kPa respectively based on the Markov decision process model, which contribute to increase pressure development about 23.3%

LIMITATION AND RECOMMENDATION

This laboratory scale is made for the motor bike braking mechanical force amplification. The additional maximum pressure developed in the braking system 150 psi which is very much suitable to stop the motor bike in 5 meters. The system effectiveness can be enhanced by using a sensor banks which can eliminate the uncertainty of the system effectiveness. Further study needs to initiate this study for the passenger cars.

SIGNIFICANCE STATEMENT

It is able to reduce the road accident by developing the additional braking force with boosting the braking system hydraulic pressure. The discussion has been made in presenting the paper on mathematical model to estimate the braking pressure in associating the vehicle load distribution to the axles and speed, Markov Decision Process (MDP) model in association with braking system control model and the model of DC motor amplified braking system make the full system automatization. It is able to initiate the system performance in desired range based on the wheel speed sensor and accelerator pedal sensor.

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