Simulation and Test on Braking Performance of Electric Vehicle with Retrofit Solution of the Mechanical Braking System

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Abstract

In this study, a systematic procedure for mechanical braking system design is developed for the prototype of the electric vehicle which is modified from commercial car by replacing internal combustion engine with electric motor. A retrofit solution of mechanical braking system is designed as prototype to modify the conventional mechanical brake equipped with brake booster by adding the vacuum-assisted system consisting of vacuum pump, reservoir, relay switch, pressure sensor, and check valve to substitute the vacuum source from the internal combustion engine. To predict the braking performance represented by braking distance as well as deceleration, a vehicle model is developed in MATLAB. By means of a novel simulation method, the braking procedure of an electric vehicle with a retrofit kit of mechanical braking system can be simulated. Consequently, the braking distance and the deceleration depending on design parameters of an electric vehicle which affects the braking performance such as the change in weight distribution, the effect of ABS and EBD or road conditions can be estimated. To validate the simulation model and to ensure the reliability of the retrofit solution, several field tests based on the ECE 13 regulation is performed. This paper can be used as a guideline for one to develop an electric vehicle when considering about the braking system design. The results show that by using employed simulation model, the prediction of braking performance can be achieved. Nevertheless, the accuracy is to be improved.

Keywords: Braking Performance Prediction; Braking System Simulation; Vacuum-assisted Braking System (VBS); stopping distance; deceleration; ECE 13; Pedal effort; Brake force; Weight distribution; ABS

1. Introduction

Currently, the trend of eco-friendly vehicle has become a major consideration in the society. Hybrid vehicle, electric vehicle, hydrogen and fuel cell vehicle is by far the most popular vehicle to catch the interest of the researcher in order to release in the future market. The major problem in the present is that the costs of these vehicles are still far expensive for one to afford compare to internal combustion engine vehicles. The retrofit kit solution that converts standard commercial vehicle into the electric vehicle is therefore an interesting objective to be considered. Some research institutions are interesting in conversion of used car into electrical version by replacing the internal combustion engine with the electrical motor. The important fact is to move the car is a common topic for design engineer, but to make it stop is something more to be considered.

Braking system is fundamental and indispensable for a driving safety. Main equipment of the brake system is brake pedal, master cylinder, brake booster, pressure relief valves, metal pipes and flexible pipes, wheel cylinders and disc brake or brake hub (drum brake) [1].

The main objective of this project is to design and verify the mechanical braking system prototype for cars driven by the motor before the actual installation.

The modification of braking systems for electric vehicles, adapted from automotive internal combustion machine is important to be studied. Because the brakes on internal combustion engine vehicle are not designed and developed for electrical one. Therefore, to convert the combustion engine into electrical driven, a variety of factors must be taken into account such as

• Change in weight balance due to additional and removal parts such as battery or internal combustion engine.

• The need to install extra equipment to replace the vacuum power from engine, such as brake vacuum pump to a source of vacuum suction in brake booster.

• Terms such as changes in the overall lifespan. The maximum speed you want that will affect the distance and time required to brakes the vehicle.

Because of these factors will affect the calculation and analysis of materials and equipment necessary to develop an effective braking system. Results from the analysis including all design parameters have been selected and used as references such as changing the type of vacuum pump, the length and diameter of master pump, the size of the brake booster, the type of brake or increase contact area of the brake and so on.

Since the brake system has been developed as well as devices that have been selected from preliminary calculations. It is very necessary to bring the safety of drivers during the cruise. Furthermore, it is to avoid additional maintenances that can occur after the installation of brake system that does not meet quality requirements. To achieve this purpose, there must be a development of brake validation method before the actual usage. Based on results of calculated distance and time, some numerical simulation of braking situation, it is able to be ensured that the brakes meet the international safety standards.

2. Vacuum-assisted Braking System

The traditional brake system is made up of the vacuum booster and the high pressure circuit. When the driver steps on the brake pedal, the pedal transmits force on the push rod of the brake fluid's piston inside the vacuum booster, and later presses the master cylinder's piston to force the brake fluid to the system, generating the brake action [2].

When focusing on the electric vehicle, vacuum pressure from the gasoline engine is removed. Therefore there will be no assist pedal force generating from the engine causing the driver to spend much more pedal force effort in a braking situation.

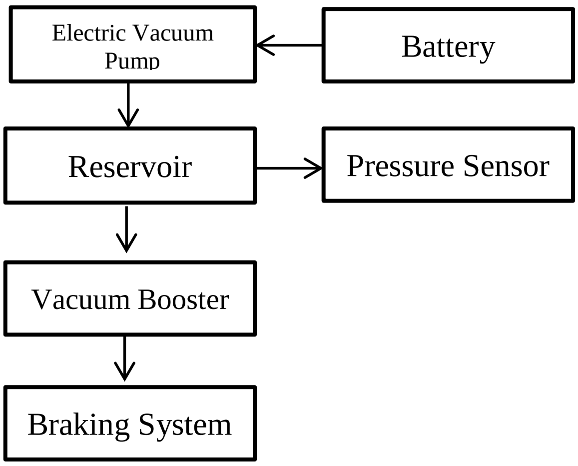


Fig. 1 VBS System Diagram

The main functions of Vacuum-assisted Braking System (VBS) as shown in Fig. 1 are

- To produce vacuum by means of an electric pump which should provide continuous and stable vacuum assistance to the brake booster. For an internal combustion engine with VBS installed, if the engine malfunctions, the vacuum brake system still keeps on working.
- In an electric vehicle, since no vacuum generates from the internal combustion engine. It gives the negative pressure to the vacuum booster which gives stable assistance to brake pedal and achieves the best brake effect.

3. Braking Distance of ABS equipped vehicle

The braking distance is the distance required for a vehicle moving at a specified velocity to come to a complete stop after its brakes have been activated.

To obtain the braking distance for the ABS equipped vehicle, there are two common methods in practice; one is by the measurement from field test, another is by the calculation method.

3.1 Braking distance measurement

The measurement of braking distance is carried out by the actual test drives and corresponded by data acquisition. The main parameters that are to be captured are the distance and period that the vehicle travels since the brake is activated. The test protocol can be varied based on to the regulation in the country and the situation in the design factor such as the vehicle initial speed, the road condition, the type of tire and etc.

3.2. Calculation of the braking distance

There are some researches on theoretical calculations on braking distance of automobile with ABS [3]. Since most of the vehicle nowadays is equipped with the ABS system which provides more stability when brakes. To calculate the braking distance of the automobile with ABS is quite different from the conventional braking scheme. Because when the driver gives pedal efforts until the wheel is locked, the ABS control system regulates the brake pressure and relief the locked situation to stable condition. The process keeps repeating until the vehicle is stopped.

Therefore the model of ABS brake in Force vs Time is explained;

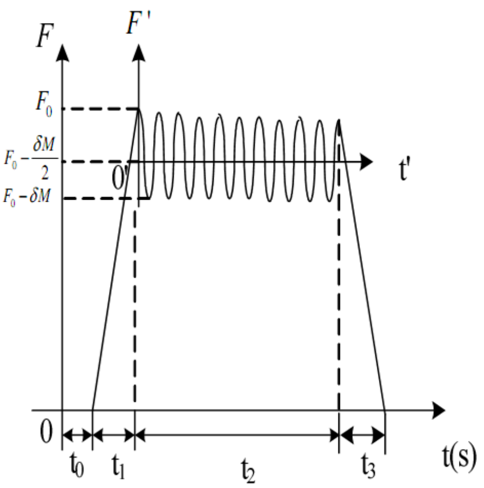


Fig. 2 ABS braking process [3]

The braking process of the ABS equipped vehicle is explained in Fig. 2 above. It is divided into 4 steps.

The first step, t_0 is the reaction time which depends mainly on the driver, and layout of the brake pedal and accelerator. Normally t_0 takes about 0.3 - 1.0 seconds which can be neglected in the calculation [3].

In the second step, the growing of the braking force as t_1, keeps increasing until reaches maximum point F_0.

Assumed that the maximum braking force reaches with maximum ground braking force, the maximum deceleration is,

$$F_0 = \varphi_p \cdot g \cdot m \tag{1}$$

Where F_0 is the maximum braking force exert on the road, φ_p is the peak adhesion coefficient, g is acceleration of gravity (9.8 m/s^2), and m is the total mass of the vehicle.

Therefore the average braking force in 2nd step is;

$$\bar{F}_1 = \frac{\int_0^{T_1} \frac{mg\varphi_P}{T_1} dT}{T_1} = \frac{1}{2} mg\varphi_P \tag{2}$$

Applying Newton's 2nd law, average deceleration a_1 and terminal velocity v_1 is explained,

$$a_1 = \frac{\bar{F}_1}{m} = \frac{1}{2} g\varphi_P \tag{3}$$

$$v_1 = v_0 - \int_0^{t_1} \frac{g\varphi_P}{t_1} t\, dt = v_0 - \frac{1}{2} g\varphi_P t_1 \tag{4}$$

With the conservation of energy theory, work of braking force is equal to change in vehicle kinetic energy,

$$\bar{F}_1 \cdot S_1 = \frac{1}{2} mg\varphi_p^S F \frac{1}{2} m v_0^2 - \frac{1}{2} m v_1^2 \tag{5}$$

Therefore, the braking distance in 2nd step S_1 is,

$$S_1 = \frac{v_0^2 - v_1^2}{g\varphi_P} \tag{6}$$

The third step is braking duration. So pressure regulation frequency ω and amplitude δ are considered as design parameters, and pressure regulation process of ABS is simulated by cosine function, then coordinate is transformed (shown in Fig. 2). The equations can be written as below:

$$\left.\begin{aligned} F' &= \frac{\delta M}{2}\cos\omega t' \\ F' &= F - \left(F_0 - \frac{\delta M}{2}\right) \\ t' &= t - t_1 \end{aligned}\right\} \quad (7)$$

Then this equation is converted back to original coordinate system,

$$F = M\frac{d^2 s_2}{dt^2} = \left(F_0 - \frac{\delta}{2}\right) + \frac{\delta M}{2}\cos[\omega(t - t_1)] \quad (8)$$

Solve the equation we get S_2 equal to

$$\frac{\frac{1}{2}\varphi_p mgt^2 - \frac{1}{4}\delta t^2 - \frac{1}{2}\frac{\delta m\cos(\omega t - \omega t_1)}{\omega^2}}{m} \quad (9)$$

Therefore total braking distance (S) is summation of S_1, the distance in growing step of braking force, and S_2 the distance of the ABS working region.

$$s = s_1 + s_2 \quad (10)$$

4. Comparison of braking distance from measurement and calculation

It is an important indicator for braking performance evaluation, but the error is big for braking distance test of automobiles with ABS [4]. So its performance cannot be accurately shown from test results [5]. Therefore, the ABS braking distance is simulated through this theory method. Simulation results must be compared with the road test to verify the simulation accuracy [6].

4.1 Field Test

The field test on the braking distance has been done based on Requirement of StVZO (Germany), EU Directive 71/320 EEC and ECE 13 Regulation which requires the vehicle to stop under the specified distance, which is calculated from;

1.) Type O test (drive disengaged)

$$S \leq 0.1v + \frac{v^2}{150} \quad (11)$$

2.) Type O test (drive engaged)

$$S \leq 0.1v + \frac{v^2}{130} \quad (12)$$

Where S is the maximum braking distance which the vehicle should not exceed this value, V is the velocity of the vehicle when the brake pedal is pressed.

In testing protocol, some number of parameters has been varied such as the vehicle total mass, initial velocity, the drive engaging condition, and the vacuum source to compare the brake efficiency in different conditions.

There are eight different configurations shown in Table. 1 of the test trials simulating the vehicle when changing in total mass, drive engage conditions and vacuum source which may come from original ICE or vacuum booster system (VBS) equipped.

Table. 1 Stopping Distance of the vehicle at 80km/hr in different conditions.

Test No.	Battery	Drive	Vacuum Source	Stopping Distance (m)	Time (s)	Calculated Distance (m)
1	No	Engaged	Engine	20.20	2.48	22.55
2	No	Disengaged	Engine	19.87	2.50	23.19
3	Yes	Engaged	Engine	19.67	2.29	19.18
4	Yes	Disengaged	Engine	19.73	2.50	24.51
5	No	Engaged	VBS	20.70	2.31	18.89
6	No	Disengaged	VBS	19.27	2.41	20.98
7	Yes	Engaged	VBS	24.73	2.74	28.68
8	Yes	Disengaged	VBS	22.00	2.35	19.77

From the Table. 1. The battery indicates the condition when the vehicle is converted into electric version which results in additional weight of 250kg from 1060kg stock weight. The drive conditions show the engaging of the engine which results in engine brake that helps pulling down the speed of the vehicle besides the existed braking system. When drive disengaged, it shows that the brake system act as the only device to reduce the vehicle speed. Last condition is the vacuum sources which may come from the original ICE or VBS which we manually switch the system to compare the results.

4.2 Calculated Distance

To predict the total braking distance (S) of the vehicle using Eqn.1 – 10 above, some initial conditions must be specified. On testing day, the road condition is dry concrete road. Total mass of the vehicle is set in 2 conditions, one with no load with 2 passengers; another is 250kg load with 2 passengers. Initial velocity of the vehicle when driver started to brake is 80km/hr. Pressure regulation frequency ω and amplitude δ of the ABS system is stated in Table. 2 below.

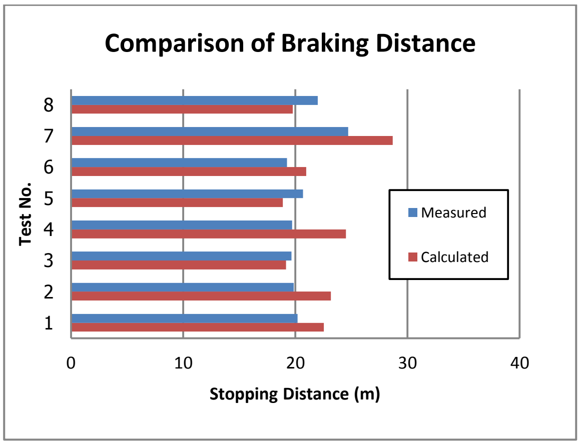
Table. 2 Design parameter values

Variable	Value
Vehicle Total Mass	1060kg / 1310kg
Velocity(80km/hr)	22 m/s
Dry Concrete road	
ω	50
δ	0.2647
φ_p	0.9

5. Results and Discussion

The required stopping distance based on ECE13 standard with drive disengaged is 50.67 m and 57.23 m when drive engaged according to the Eqn.11 – 12 above. The results of the field test, as shown in Table. 3, are far better than the required value which shows that the braking system design satisfied the safety conditions. When considering about the calculated distance compare to the actual distance, there are still some different in result which takes average error about 12%.

Table. 3 Comparison of braking distance



When comparing the result of the calculated distance and the actual testing, the possible error of braking distance calculation might come from the error in the time measurement. Because in the step of the distance calculation, the major parameters that can dramatically change the value of the stopping distance is the initial speed and the time consumption during the brake process. To be more accurate, some data collection method should be improved to achieve more precise result.

In addition, another source of error with distance calculation may come from the external factors such as the driver behavior, road conditions, aero dynamic drag, EBD system, and etc. Therefore the simulation model is to be improved in the future time with more consideration in these additional parameters.

6. Conclusion

- With the substitution in vacuum power source from ICE to VBS the results shows that VBS is effective enough to be used as the part of the braking system which can meets the safety standards of ECE13.
- The calculation of the braking distance comparing to the road test is effective enough for a preliminary calculation in the braking system design.
- The accuracy of the calculated braking distance can be further improved by considering more parameters which affects the braking distance such as the working of EBD system, drives behavior, road conditions or using different method to obtain the relationship between the input parameters and the output such as using neuron network.

7. Acknowledgement

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8. References

[1] Erjavec, J. (2005). Automotive technology: a systems approach, Cengage Learning.

[2] Mortimer, R.G. Segel, L. and Dugoff, H. (1970). Brake Force Requirement Study:Driver-Vehicle Braking Performance as a Function of Brake System Design Variables, Highway Safety Research Institute, University of Michigan.

[3] Dongsheng, W. Jun, L. Xiaoping, S. Xiaojing, Z. and Beili, X. (2011). Test Analysis and Theoretical Calculation on Braking Distance of Automobile with ABS, CCTA 2010, Part IV, IFIP AICT 347, pp. 521–527.

[4] Alvarez, L., Yi, J., Clarys, X., Horowitz, R. (2003). Emergency braking control with an observer-based dynamic tire/road friction model and wheel angular velocity measurement, Vehicle Syst. Dun 39(2), pp. 81–97.

[5] Schinkel, M., Hunt, K. (2002). Anti-lock braking control using a sliding mode like approach, In:Proc. American Conf., Anchorage, AK, USA, vol. 3, pp. 2386–2391.

[6] Chen, J. (1999). The Theory and Practice of ABS Automobile, Beijing Polytechnic University Press.