EXPERIMENTAL INVESTIGATION OF EFFECTIVENESS OF ELECTRIC VEHICLE VACUUM BRAKE BOOSTER ON POWER TEST BENCH

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Abstract. An experiment on a roller power test bench was performed using a self-designed brake test cycle. The experiment was conducted on three different vehicles: a converted electric car Renault Clio, a Renault Trafic with a diesel engine and a Renault Clio with a petrol engine. The tests showed that the electric vacuum pump used on the electric car in different regimes provided a smoother vacuum pressure level than the vacuum generation system used on an analogous petrol engine vehicle and was fully suitable for the converted electric car in terms of capacity and vacuum pressure level.

Keywords: power test bench, driving cycle, vacuum brake booster, vacuum pressure, braking regime, vacuum pump.

Introduction

Fossil energy resources are limited in the world. Therefore, technologies and constructions running on other, non-traditional energy sources are designed. An example of such non-traditional technologies are electric vehicles. There are two ways of becoming the user of an electric vehicle: purchase of an industrially manufactured vehicle or conversion of an internal combustion engine vehicle into an electric one. If converting, vehicles can be adapted to particular exploitation conditions and consumer needs. However, one has to consider learning new technologies as well as the need to deal with paperwork and the registration of the electric vehicle. The vacuum brake booster is one of the assemblies that are involved in the conversion.

In internal combustion engine vehicles, vacuum pressure is generated mainly in two ways:

- in diesel engines, vacuum pressure is generated by means of a specific vacuum pump powered by the engine. In this case, vacuum pressure is sometimes used to operate other systems, for example, the control valve of the turbocharger;
- in petrol engines, vacuum pressure for the vacuum brake booster is acquired by connecting the brake booster's vacuum hose to the intake manifold.

Vacuum pressure and its decrease depend on the regime of operation of the car engine – crankshaft frequency, while in petrol engines it also depends on the extent to which the throttle valve is opened. However, the above-mentioned regimes depend on the vehicle speed, brake application intensity and the frequency of application of the brake pedal.

The purpose of the vacuum brake booster is to decrease the brake pedal effort during the application of the brake pedal. Vacuum brake boosters are usually used on automobiles. Two parameter groups are considered when setting automobile braking parameters. The first group includes direct brake effectiveness characteristics: wheel brake torque or force, braking time and braking deceleration. The second group includes characteristics related to the activation of the brake system. They are: brake pedal displacement, the force needed to activate the pedal, vacuum pressure in the vacuum brake booster and brake fluid pressure in every contour. The key focus is particularly placed on testing the first group parameters when undergoing a certification procedure for a new automobile or during annual roadworthiness tests. In the second group, the key prescribed parameter is brake pedal activation force, which may not exceed 500 N for M1 category vehicles [1]. Other parameters with regard to brake booster devices are not prescribed.

Wide investigations relating the brake system components are conducted at the University of Bradford. They analysed the pedal activation force as well as the brake pedal "feeling" [2]. A mathematical model for the vacuum brake booster is developed. At various loads, both the pedal separately and the pedal in combination with the vacuum brake booster and the master cylinder are tested within a range of force prescribed by the EU standards: 0-600 N. The tests of the vacuum brake booster were performed at a pressure of 0.7 bar, which was generated by the electric vacuum pump. The mathematical model, developed in the present research, includes also a vacuum brake booster module, in which the variable parameter is vacuum pressure, while the output parameter is the vacuum assisted brake booster ratio.

Analysing other sources of information on the safety of the braking systems, it can be concluded that most of them are devoted to different brake system components, such as brake disc studies [3] as well as human psychological factors that affect the braking efficiency [4; 5]. Studies on changes in the brake booster's pressure depending on the braking regimes were not identified.

That is why a driving cycle for the vacuum brake booster and other assemblies was developed at the Latvia University of Agriculture taking into account the mentioned aspects. The cycle was based on real driving tests and consists of three braking regimes that involve smooth and uninterrupted braking, interrupted and repeated braking and multiple activation of the brake pedal [6].

Using a previously developed cycle for testing the brakes on a roller test bench this investigation deals with the results of experiments, in which three automobiles were tested: *Renault Trafic* with a 2.0 litre diesel engine, *Renault Clio* with a 1.2 litre petrol engine and a converted electric *Renault Clio*. The research aim was to identify the change in vacuum pressure of the vacuum brake booster depending on various brake system activation regimes.

Materials and methods

The tests were conducted on a chassis dynamometer *Mustang MD-1750* with a control platform *MDSP-7000*. The test bench was equipped with a roller loading device and data output to a computer. It was possible to simultaneously record 30 parameters and represent them graphically or export to data processing tools. The test bench was equipped with a system for removing exhaust gases if testing internal combustion engine vehicles.

Data storage device has a number of digital and analogue inputs. In these experiments channels for recording of travelled distance, vehicle speed, and brake booster vacuum pressure were used. The test bench control module recorded data 60 times per second.

A pressure sensor *Trafag 8472.77.8817* was used to measure the brake booster vacuum pressure. The sensor was connected to the test bench *Mustang MD-1750* data recording device through an additional adaptation unit. This unit served as a convertor of a signal into analogue format, so that the signal fits the test bench data input characteristics. The main technical characteristics of the measurement device and the data convertor are presented in Table 1.

Table 1

Technical characteristics of the devices used in the tests

No	Technical characteristics	Value
Pressure sensor *Trafag 8472.77.8817*		
1.	Measuring range, bar	0...6
2.	Voltage supply, V	10...30
3.	Output voltage, V	0...5
4.	Output amperage, mA	4...20
5.	Operating temperature, ºC	-25...125
Test bench *MD-1750*		
1.	Maximum measured power, kW	1287
2.	Maximal measured speed, $km \cdot h^{-1}$	362
3.	Rolls:	
	Diameter of roller, m	1.27
	Roller face length, m	0.71
	Inner track width, m	0.71
	Outer track width, m	2.13

Three different automobiles were tested. The *Renault Trafic* was equipped with a 2.0 l dCi engine, the *Renault Clio* had a 1.2 l petrol engine, while the converted *Renault Clio* electric had a 36 kW electric motor. The key technical characteristics of the automobiles and the brake vacuum pressure generation devices are summarised in Table 2.

Table 2

Technical characteristics of the automobiles used in the tests

No	Technical characteristics	*Renault Trafic* 2.0 dCi	*Renault Clio* 1.2	*Renault Clio* electric
1.	Engine capacity, cm^3	1995	1149	-
2.	Engine power, kW	66	43	36
3.	Gross weight, kg	2835	1425	1425
4.	Net weight, kg	2130	920	1010
5.	Maximum speed, $km \cdot h^{-1}$	150	160	100
6.	Brake type: front wheels rear wheels	Disc, ventilated Disc, ventilated	Disc, ventilated Shoes, drum	Disc, ventilated Shoes, drum
7.	Vacuum pressure generation device	Engine-powered vacuum pump	Connected to the intake manifold	Electric vacuum pump

Experiments were conducted under laboratory conditions. Before a test, an automobile was kept in the laboratory for at least 6 hours, so that the temperature of all its assemblies equalized with the ambient temperature inside the laboratory. Before carrying out a series of experiments pressure sensor calibration by means of a calibration pump and reference manometer was done. Readings on the data storage device and the calibration manometer might not differ by more than 1 %. A car was placed on a test bench and fastened by straps and anchors built in the floor. The vacuum sensor was connected to the car vacuum line, near the vacuum brake booster. A preliminary test was done to verify whether the car was fastened safely.

The tests were conducted at an ambient temperature of +15…+20 ºC with the engine being preheated to the working temperature. The internal combustion engine was preheated by running the car on the roller test bench at a variable speed within a range of 50...70 $km.h^{-1}$ for 5…6 minutes. The electric car was warmed up in an analogous regime, while the duration of running might be reduced by 50 to 60 %. The electric car batteries, motor and controller were warmed up, that resulted in their better performance. Since the purpose of the tests does not involve precise loading in the acceleration or braking regime, the test bench rollers were not loaded. A driving cycle was activated by means of the test bench control console and a driving regime was precisely performed by accelerating and braking the car. The test was repeated five times. Three measurements having the highest correlative coherence in terms of speed and vacuum brake booster pressure were selected out and their averages were calculated. Than a series of measurements were repeated for the next vehicle.

Results and discussion

The average vacuum pressure readings for the experimental automobiles are summarized in Figures 1, 2 and 3.

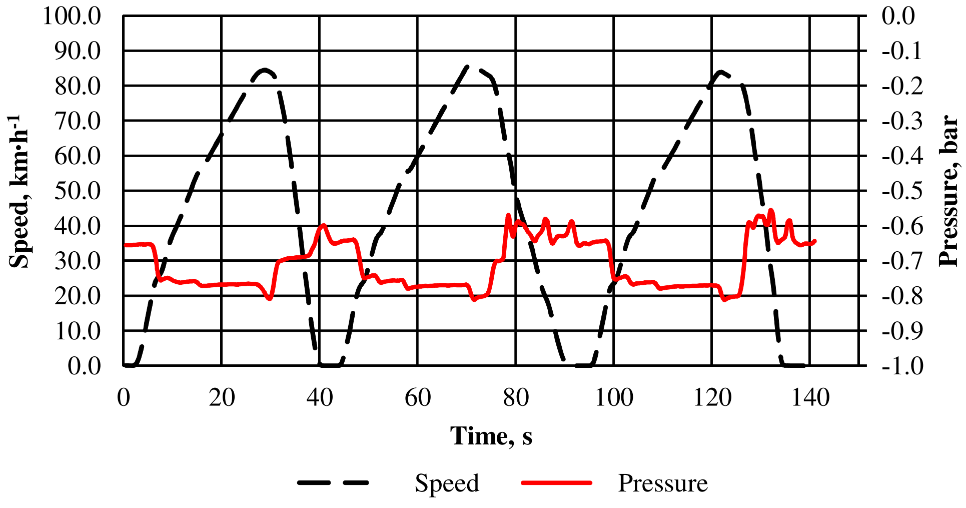

Fig. 1. ***Renault Clio* brake test**

The highest vacuum readings for the *Renault Clio 1.2* were recorded in the acceleration regime, reaching -0.82 bar (Fig. 1). However, when braking, the vacuum pressure sharply decreased to -0.60 bar if the brake was applied a single time. If activating the brake pedal several times, the vacuum pressure decreased even more, reaching a value of -0.53 bar. Such vacuum is sufficient to facilitate the brake pedal activation and ensure amplification effect.

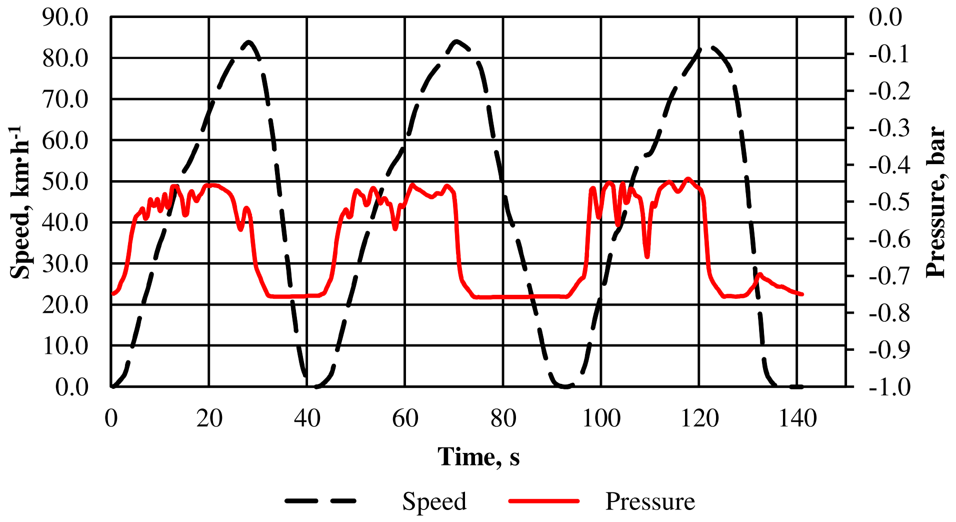

Fig. 2. ***Renault Trafic* brake test**

Figure 2 shows that the greatest decrease in the vacuum pressure for the *Renault Trafic* with a diesel engine was observed when accelerating rather than when braking. This can be explained by the fact that the servomechanism of the turbocharger's valve was connected to the vacuum line, which in the acceleration regime, when the turbocharger was engaged, consumed vacuum pressure to operate the turbocharger's valve. The lowest vacuum pressure readings in the acceleration regime for the diesel automobile reached -0.41 bar. At the moment when the engine ran almost at an idle frequency and braking was performed, the vacuum pressure increased, reaching -0.77 bar in the braking regime significantly reducing the brake pedal effort. Greater vacuum pressure ranges were observed particularly when braking.

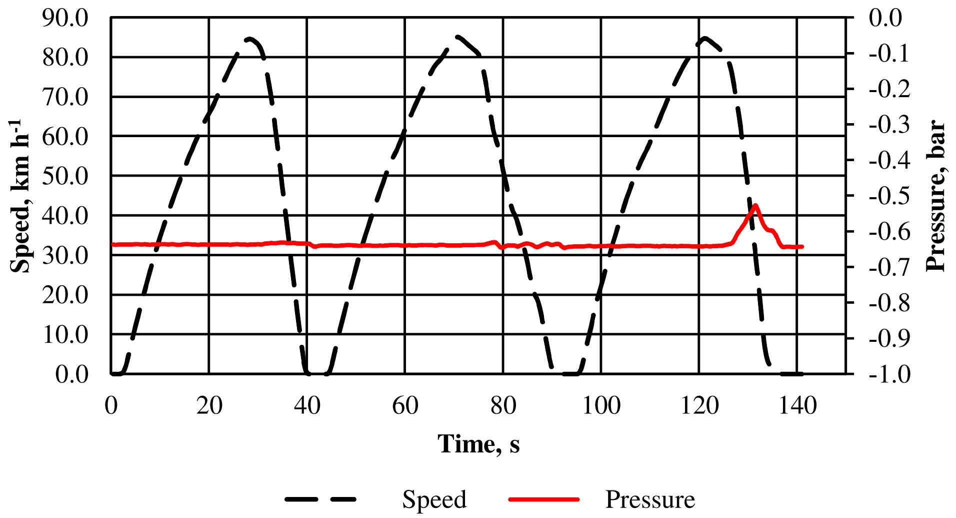

Fig. 3. ***Renault Clio* electric brake test**

The tests done on the car *Renault Clio* electric presented a very stable brake booster vacuum pressure of -0.63 bar (Fig. 3). The vacuum pressure readings changed very minimally during the first two braking cycle regimes. The greatest changes were observed when the brake pedal was activated multiple times in the third braking regime when the vacuum pressure decreased to -0.53 bar. The electric vacuum pump generated a very steady vacuum pressure level, and, compared with that presented by the characteristic curves for diesel and petrol engines, the vacuum pressure was much steadier and it was sufficient for normal force to be applied to the brake pedal.

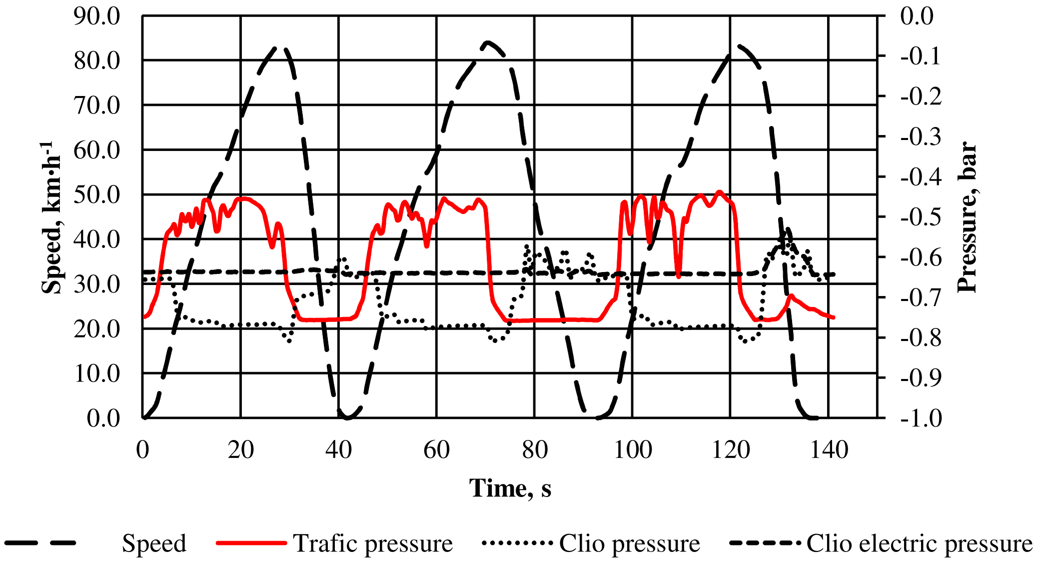

Fig. 4. **Changes in the brake booster vacuum pressure depending on the automobile speed and braking regime**

A comparison of all the characteristic curves (Fig. 4) for the brake booster vacuum pressure change revealed that the electric brake booster vacuum pump presented the steadiest performance. In the multiple brake application regime, the characteristic curve of the electric vacuum pump was very similar to that for the petrol engine car in terms of both the character and values.

To easier compare the performance of the vacuum brake booster, changes in the vacuum pressure range are summarized for all tested vehicles (Fig. 5).

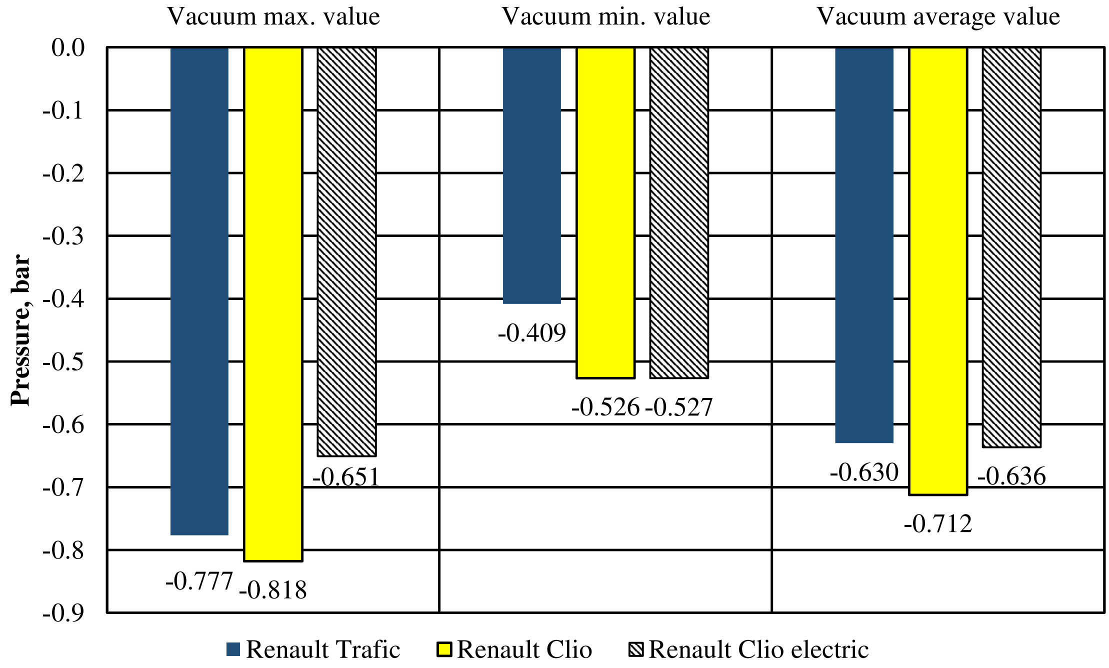

Fig. 5. **Changes in the vacuum pressure range for the experimental vehicles**

In all the experimental regimes, the maximum vacuum pressure was reached by the petrol engine. An analysis of the average vacuum pressure values revealed that the electric vacuum pump showed the steadiest performance; in the tests the average vacuum pressure was only 2.3 % lower than the maximum one. The greatest changes in the vacuum pressure were observed for the automobile with a diesel engine, but mainly in the acceleration regime when braking was not performed.

Conclusions

1. The tests performed to identify changes in the brake system vacuum pressure in different regimes allow judging whether the vacuum pressure generation device fits a particular vehicle and indirectly affects the traffic safety on roads.
2. The greatest vacuum pressure, -0.82 bar, was achieved by the *Renault Clio* with a 1.2 l petrol engine in the acceleration regime, while in the braking regime it decreased on average by 26.8 %. When performing multiple braking operations, the decrease in the vacuum pressure was even greater, reaching 36.4 %.
3. The automobile with a diesel engine presented the lowest vacuum pressure in the acceleration regime, reaching -0.41 bar when vacuum pressure was consumed to operate other control systems. When braking, a considerable increase in the vacuum pressure was observed, on average, by 87.8 %, which significantly reduced the brake pedal effort.
4. The tests on the *Renault Clio* electric presented a quite steady vacuum pressure in all the regimes. The average vacuum pressure stood at -0.63 bar, while the greatest decrease in the vacuum pressure was only 15.8 %. The greatest changes in the vacuum pressure were observed if activating the brake pedal multiple times.
5. An analysis of the overall results for changes in the vacuum pressure for all the automobiles showed that in different regimes the smallest changes were presented by the electric car vacuum pump. In the multiple brake application regime, the changes in the vacuum pressure for the electric vacuum pressure pump were very similar to those for the petrol engine car vacuum pressure generation system in terms of both the character and values.
6. The electric vacuum pressure pump for the converted electric car *Renault Clio* generated sufficient vacuum pressure and sufficiently reduced the brake pedal effort in all the experimental regimes and was fully suitable for the converted electric car in terms of capacity and vacuum pressure level.

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