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Development and analysis of a driving cycle to identify the effectiveness of the vacuum brake booster

D. Berjoza[1,*], V. Pirs[1], I. Dukulis[1] and I. Jurgena[2]

[1]Latvia University of Agriculture, Faculty of Engineering, Institute of Motor Vehicle, 5 J. Cakstes boulevard, LV-3001 Jelgava, Latvia
[2]Latvia University of Agriculture, Faculty of Economics and Social Development, Institute of Business and Management Science, 18 Svetes str., LV-3001 Jelgava, Latvia
[*]Correspondence: dainis.berjoza@llu.lv

Abstract. In electric vehicles electric vacuum pumps are used instead of traditional vacuum generation devices – the vacuum pump or the intake manifold that are specific to vehicles with internal combustion engines. A special driving cycle has to be designed to identify the effectiveness of electric vacuum pumps. The initial experiments were carried out on a real road, intensively applying the breaks and exploiting the vacuum generation devices as long and intensively as possible. Basing on these experiments brake test cycle was developed. It consists of three braking regimes that involve smooth and uninterrupted braking, interrupted and repeated braking and multiple activation of the brake pedal. Using this cycle, it is possible to conduct research on the performance of various automobile components during braking.

Key words: vacuum booster, brake system, brake regimes, test cycle, braking time.

INTRODUCTION

The key purpose of the main brake system is to ensure the automobile stops within the shortest possible distance after the driver has activated the brake system. The brake system is one of the structural elements of automobiles on which focus is placed both during annual roadworthiness tests and when undergoing a certification procedure for a new automobile.

A group of scientists of the Faculty of Engineering, Latvia University of Agriculture, developed an electric automobile within an EU project. The electric automobile was built up by converting an internal combustion engine automobile – its standard internal combustion engine was removed and replaced with an electric motor. One of the elements changed in conversion was the brake vacuum generation device. Modern cars mainly use two types of engines: petrol and diesel engines. For petrol engines, vacuum is created by connecting the brake booster's vacuum hose to the intake manifold, whereas for diesel engines vacuum is provided by a special vacuum pump. In electric automobiles vacuum is provided by a special electric vacuum pump.

When reviewing the conversion design for the automobile, inspectors of the Road Traffic Safety Directorate of the Republic of Latvia raised a question about the productivity of vacuum pump in various operation regimes for the electric automobile. For this reason, it was necessary to conduct tests on a roll test bench, simulating the driving conditions. Since no special driving cycle for testing the brake system on a roll test bench had been designed, such a cycle had to be developed. The purpose of a driving cycle is active and multiple use of the brake system under the most disadvantaged operation regimes for the brake vacuum pump.

There are two ways of developing a driving cycle. Modal or polygonal cycle is composed from various driving modes of constant acceleration, deceleration and speed, for example, New European Driving Cycle (NEDC). The other type is derived from actual driving data and is referred as 'real world' cycle. Such cycle example is the FTP-75 (Federal Test Procedure) cycle. The 'real world' cycles are more dynamic, reflecting the more rapid acceleration and deceleration patterns experienced during on road conditions (Tzirakis et al., 2006).

In this particular case the second method is most suitable. Cycle development methodology is already developed and approved at the Faculty of Engineering in previous studies investigating the use of biofuels (Dukulis & Pirs, 2009).

Brake booster vacuum systems

A brake booster is a device that reduces the force to be applied to the brake pedal during braking by means of vacuum generation devices. Operational parameters of vacuum pumps that are powered by internal combustion engine shafts depend on the engine crankshaft's rotation frequency, while in electric automobiles the operational parameters are not affected by the main electric motor.

In the European Union, the key document that stipulates brake testing procedures is Commission Directive 98/12/EC regarding brake systems for vehicles of certain categories and their trailers (Commission Directive…, 1998). The Directive prescribes a methodology for calculating braking distances if the speed, deceleration and other parameters of a vehicle are known. Braking tests have to be performed with the engine both engaged and disengaged. Also, brakes have to be tested if their temperature is below 100 °C or exceeds it. In a test, M_1 category vehicles with the engine engaged have to make a deceleration of not less than 5.8 m s^{-2}, while with the engine disengaged it has to be not less than 5.0 m s^{-2}. The force applied to the brake pedal does not have to exceed 500 N (Commission Directive…, 1998). The Directive provides a methodology for determining the load on the vehicle's axles. The Directive does not provide information on how to perform tests for brake boosters.

In the Republic of Latvia, the legal act that stipulates the technical condition of vehicles is Minister Cabinet Regulation No. 466 of 29 April 2004 'Regulations Regarding Roadworthiness Tests for Vehicles and Technical Roadside Inspections' (Regulations…, 2004). Clause 405.1 stipulates that for cars the force applied to the brake pedal does not have to exceed 500 N. Nothing is mentioned regarding brake booster tests, while for defects that are evaluated with code '2' – unacceptable – the Regulation states that the amount of force applied to the brake pedal may not exceed that set by law.

There have been research studies on the optimisation and modelling of regenerative braking for electric automobiles (Yeo et al., 2004). Extensive research studies have been conducted on the effects of brake system components on braking parameters (Maciuca & Hedrick, 1995). These studies analyse the effect of vacuum brake boosters of various structures on braking and develops an algorithm for a mathematical model for reading controller parameters, which includes vehicle speed control, brake torque control, wheel brake pressure control and actuator pressure control modules.

Specific research studies and research methodologies on brake boosters are available in a limited number. A research study conducted within a doctoral dissertation at the University of Bradford can be mentioned as one of the research studies on brake system vacuum boosters. The research focused on the influence of braking system component design parameters on pedal force and displacement characteristics (Ho, 2015). This research extensively analysed vacuum booster structures as well as the brake pedal 'feeling' for various brake systems depending on their structures. The research also analysed a mathematical model for the brake vacuum booster, pointing that modern automobiles usually used such boosters at a brake booster ratio ranging from 4:1 to 6:1. Characteristics were determined for every braking system component. In the research, the brake pedal was tested at a load within a range of 49.05–245.25 N. A test was performed also for the brake pedal together with the brake cylinder. The test showed a linear increase in braking fluid pressure in the master cylinder within a range of 0–13 bar at the force applied to the brake pedal within a range of 0–600 N. The research analysed an association between change in braking pressure and the brake pedal's displacement. A brake activation robot was used to activate the brake pedal. A 0.7 bar vacuum pressure generated by an electric vacuum pump was used to operate the vacuum booster in all tests on the whole braking system. The tests on the whole braking system produced data on the effect of the brake pedal's displacement on pressure in the braking system both with and without the vacuum booster. The maximum pressure in the brake pipe ranged from 50 to 59 bar. The tests were done also on a Honda automobile, recording braking parameters. The braking was done both by the brake activation robot and by a human. The data acquired were employed in the mathematical model. A mathematical model for the vacuum booster was developed too as one of the elements of the system researched. Characteristic curves both for boosters at various brake booster ratios and for the situation with no booster were acquired by means of this model.

An analysis of available information sources leads to a conclusion that no data on brake system vacuum boosters tested on a roll test bench at various braking regimes are available, and so far no custom-adjusted driving cycles have been designed to test vacuum boosters at various braking regimes. For these reasons, it is useful to design a driving cycle for testing brake system vacuum boosters. The cycle has to ensure that a brake can be tested under the most disadvantaged regimes for the vacuum booster.

MATERIALS AND METHODS

Choice of regimes to research brake vacuum booster pump parameters

One of the key tasks of researching a brake vacuum booster is the choice of regimes of braking. The key criteria for choosing a braking regime are as follows:

- multiple operations of smooth braking have to be performed, so that the brake vacuum booster is engaged a number of times;
- braking regimes have to be developed in a way to be precisely simulated on a roll test bench in the regime simulating real road conditions;
- braking regimes may be repeatedly employed for all vehicles researched;
- braking regimes have to be universal and appropriate for vehicles of any kind of engine and fuel.

To select test regimes when developing the initial test programme, an approximate driving cycle algorithm was chosen (Fig. 1).

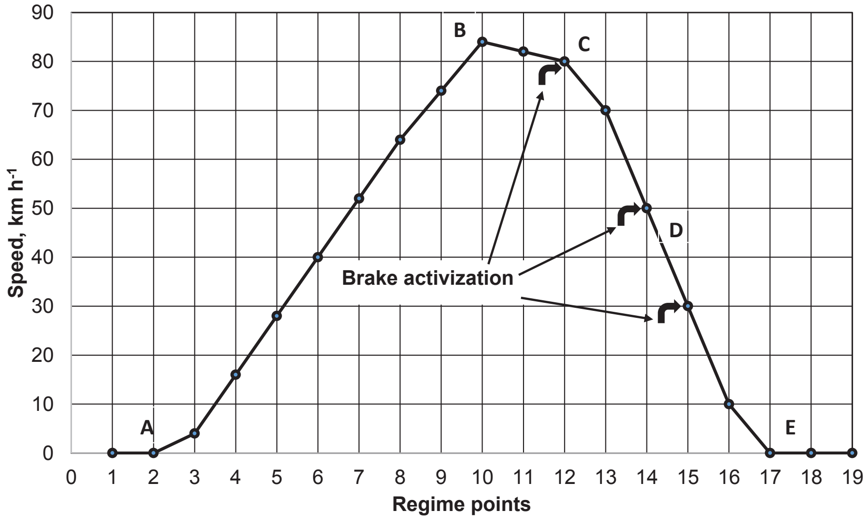

Figure 1. Algorithm for one regime of the driving cycle.

One stage of the driving cycle starts with an automobile being parked at point A. The automobile starts accelerating at Stage A–B. Stage B–C is characterised by depressing clutch movement at a speed of ≈ 80 km h^{-1}. It starts braking at point C. Stage A–C refers to preparing the test regime, while Stage C–E directly relates to braking. At Stage C–E, the brake is activated several times. At point E, the automobile is stopped and is at a standstill. The particular stage presented in Fig. 1 is used to read speed characteristics for the driving regimes in the road tests. By choosing various maximum speed and brake activation timing and frequency regimes, different characteristic curves are acquired. A driving cycle of braking regimes is acquired by placing these different stages one behind another, which corresponds to the brake booster pump's performance characteristics. A draft regime protocol is drawn for tests, which is used during the road tests for simulating a particular regime.

The following braking regimes are envisaged in the initial test programme:

- smooth braking starting at a speed of 80 km h^{-1} through to a complete stop;
- the braking regime in which the brake is activated multiple times at a specific speed of the automobile. The brake is activated to slow down from 80 to 60 km h^{-1}, then braking is interrupted and activated again to reach a speed of 40 km h^{-1}; the brake pedal is released and pushed down again to slow down to a speed of 20 km h^{-1}; the brake pedal is released and activated until the automobile comes to a complete stop;
- braking is started at a speed of 80 km h^{-1} and the brake pedal is activated 2–3 times; when a speed of 50 km h^{-1} is reached, the brake pedal is again pushed down 2–3 times.

All the mentioned driving regimes were used in the road tests.

Devices and vehicles used for the road tests

A compact passenger car *Renault Trafic* with a 2.0 l diesel engine was used in the road tests. The car was equipped with data reading and recording devices. The key parameters to be recorded in the road tests were speed, time, engine crankshaft frequency, brake pedal position and vacuum pressure in the brake booster pump's main pipe. The key characteristics of the devices used in experiments are given in Table 1.

Table 1. Technical characteristics of the devices used in experiments

No	Characteristics	Technical parameter
	Automobile *Renault Trafic*	
1.	Engine capacity, cm^3	1,995
2.	Engine power, kW	66
3.	Gross weight, kg	2,835
4.	Weight during road tests, kg	2,130
5.	Maximum speed, km h^{-1}	150
	Pressure sensor *Trafag 8472.77.8817*	
1.	Measuring range, bar (accuracy)	0...6 (± 0.05)
2.	Voltage supply, V	10...30
3.	Output voltage, V	0...5
4.	Output amperage, mA	4...20
5.	Operating temperature, °C	-25...125
	Data logger *DashDyno SPD*	
1.	Speed, km h^{-1} (accuracy)	0…250 (± 0.2)
2.	Simple recording time, s	0.2…1
3.	Engine RPM (accuracy)	0…10000 (± 5)
4.	Accuracy of distance measuring, m	±1
5.	Ambient operating temperature, °C	-10...55
	Additional adaptation unit	
1.	Unit model	CAN Interface Module 450FT0293-01
2.	Number of analog signals	2
3.	Number of binary signals	13
	Roll test bench MD-1750	
1.	Maximum measured power, kW (accuracy)	1,287 (± 1)
2.	Maximal measured speed, km h^{-1} (accuracy)	362 (± 0.2)
3.	Diameter of roller, m;	1.27
4.	Roller face length, m	0.71
5.	Inner track width, m	0.71
6.	Outer track width, m	2.13

A data logger *DashDyno SPD* was used to record parameters, which received signals from the automobile's CAN pipe through a modifier and directly from the OBD diagnostic socket. A signal regarding change in vacuum system pressure was received from a pressure sensor *Trafag 8472.77.8817* (Fig. 2).

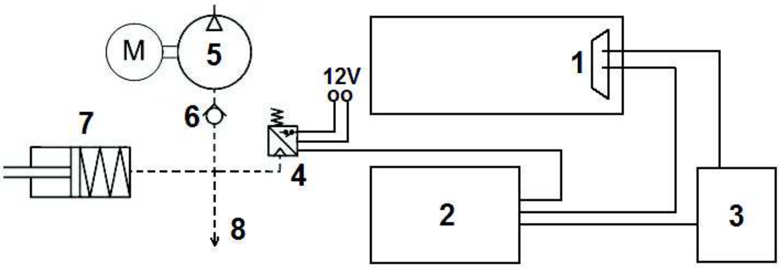

Figure 2. Scheme for connecting the devices to the automobile: 1 – car OBD connector; 2 – data logging system *DashDyno SPD*; 3 – CAN signal modifier for clutch and brake pedal position; 4 – pressure sensor; 5 – car vacuum pump; 6 – one way valve; 7 – vacuum booster; 8 – turbine pressure control valve line.

Methodology for the road tests

The tests were performed in December 2015 at an ambient temperature of +6 °C on a general purpose road between Tuski and Kalnciems. Before the tests, the devices were mounted on the automobile and checked for their functionality. Air pressure in tyres was also checked and adjusted to the nominal tire inflation pressure. Driving the automobile, its engine was warmed up to operating temperature. The data recording devices were turned on and test braking was done before starting the tests. After the data were saved, the data were checked for their consistency with the regime chosen.

The driving regimes were chosen according to the description given above. Measurements were done by two operators: a driving regime operator or the driver of the automobile and a data recording operator. The driver, taking into consideration the road conditions, gave a signal about his readiness, and the data recording operator activated the recording devices.

As an example Fig. 3 shows one of the acceleration and braking regimes. The automobile was accelerated from its initial speed to the speed of the chosen regime, which was 10 km h^{-1} greater than the initial braking speed (Fig. 3, a period from the 18^{th} to the 47^{th} second). Braking was done with the engine disengaged. The transmission was shifted to neutral or the clutch pedal was pushed down and braking was done according the regime chosen (a period from the 48^{th} to the 55^{th} second). The data recording device was stopped after the automobile came to a full stop.

Each test was repeated five times. When processing the data, three data series with the highest correlation were selected. The speed change in time and moments of the activation and deactivation of the brake pedal were selected as the key data.

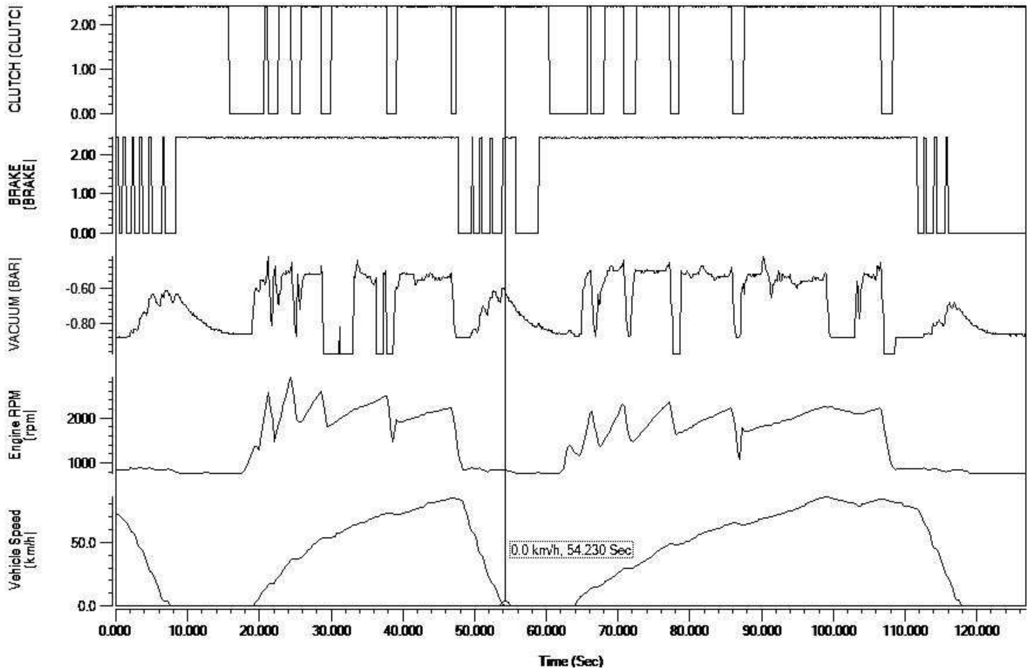

Figure 3. Screenshot of the test data from the logger.

RESULTS AND DISCUSSION

In developing the cycle, the following principles that could differ from the real driving conditions in road tests were taken into account:

- the roll test bench *Mustang* has not been designed for brake system tests in particular; therefore, no hard braking was allowed, which could cause poorer traction for the test automobile;
- no too fast acceleration was allowed for an automobile during the acceleration phase in order to test automobiles of all kinds.

As an example of the cycle development the second braking mode when the brake is activated multiple times at a specific speed is discussed. Fig. 4 shows the time-speed curve of three repetitions. Correlation between these data series of more than 99%.

For each second an average speed was calculated. Extreme phases were removed, and minor adjustments to speed curves' displacement were made. As the result a theoretical speed curve for a 140 second cycle was built (Fig. 5).

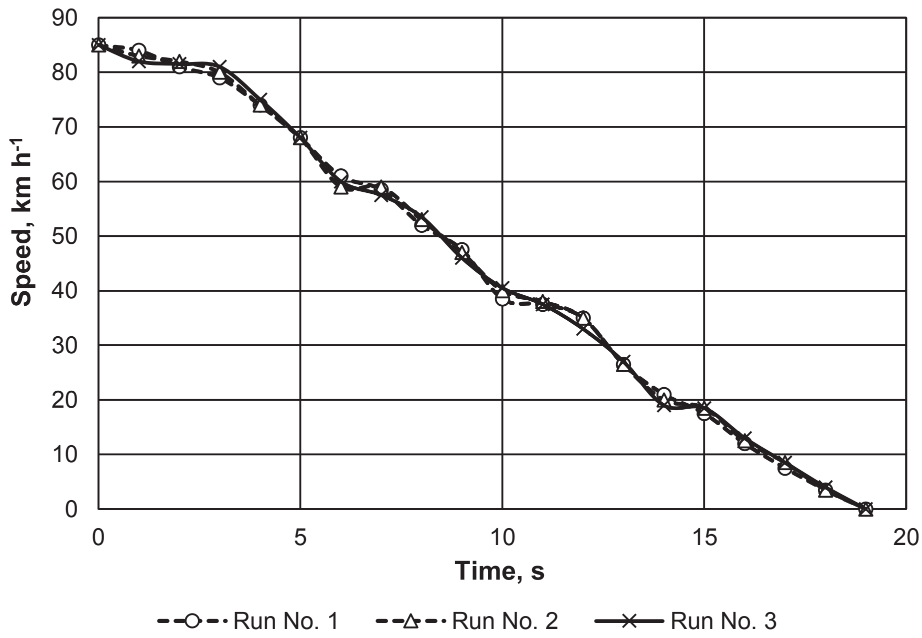

Figure 4. Experimental velocity curves of the second braking mode.

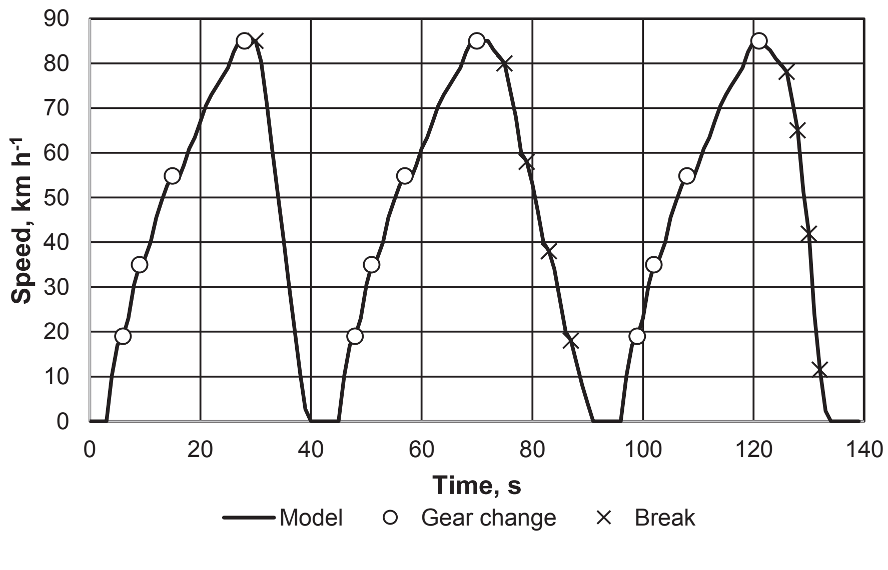

Figure 5. Cycle speed curves, gear changing and braking points.

Since the *Mustang* software interface and menu did not provide an option to add a new driving cycle, then the system software core was investigated, variables were identified and the current cycle parameter files were analysed, while the self-made cycle was programmed. Its fragments are given in Table 2.

Table 2. Program code fragments

Cycle general information	Speed points	Gear switching points
[General]	[SpeedPoints]	[ShiftPoint1]
Name=Break test	Point1 = 0	TimeIntoTest=7
RunningTime=140	Point2 = 0	FromGear=1
MaxSpeedToShow=60	Point3 = 0	ToGear=2
SpeedErrorLimit=2	Point4 = 0	[ShiftPoint2]
SpeedErrorTimeRange=1	Point5 = 6.27586464	TimeIntoTest=9
WarningToViolationTime=2	Point6 = 10.56333652	FromGear=2
MaxDistanceError=0.05	Point7 = 11.806082	ToGear=3
HPIntegrationWindow1Start=55	Point8 = 14.29157294	[ShiftPoint3]
HPIntegrationWindow1End=81	Point9 = 18.95186847	TimeIntoTest=15
HPIntegrationWindow1Tolerance=0.5	Point10 = 21.74804578	FromGear=3
HPIntegrationWindow2Start=189	Point11 = 22.68010489	ToGear=4
HPIntegrationWindow2End=201	…	…
HPIntegrationWindow2Tolerance=0.5	…	…
LR_MinSE=0	…	…
LR_MaxSE=2	Point131 = 26.03551767	…
LR_Minm=0.96	Point132 = 14.97508295	[ShiftPoint20]
LR_Maxm=1.01	Point133 = 7.145786471	TimeIntoTest=131
LR_MinR2=0.97	Point134 = 1.429157294	FromGear=0
LR_MaxR2=1	Point135 = 0	ToGear=0
LR_Minb=-2	Point136 = 0	[ShiftPoint21]
LR_Maxb=2	Point138 = 0	TimeIntoTest=133
MaxISEPercent=1	Point139 = 0	FromGear=0
MinPurgeFlow=1	Point140 = 0	ToGear=0

A screenshot of the developed cycle in the test mode is shown in Fig. 6. The figure shows the test bench's monitor screenshot for the cycle at the moment when the automobile accelerates. Lines around the central curve indicate considerable deviations in the speed and time curve. In case a significant deviation from the programmed curve was observed during the cycle, the cycle had to be repeated.

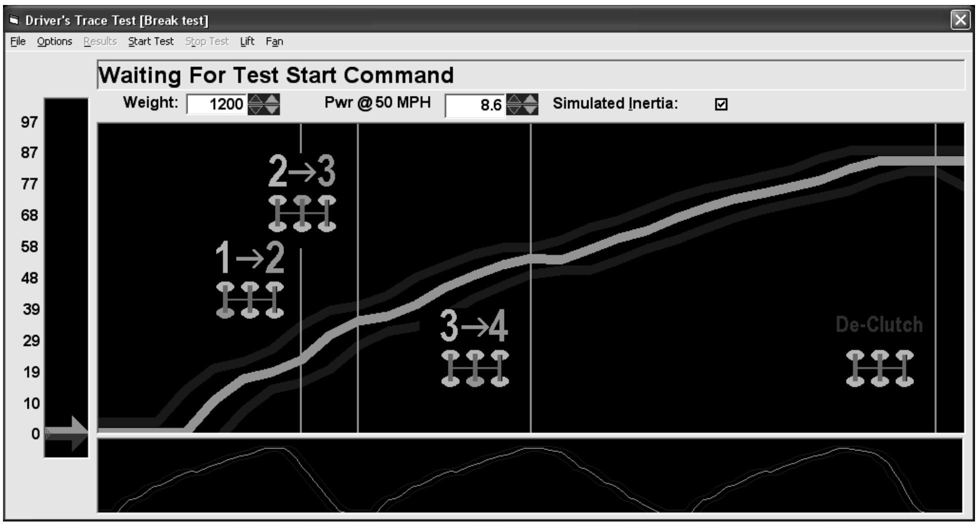

Figure 6. Screenshot of the developed cycle in the test mode.

The key characteristics of any driving cycle are maximum speed, average speed and cycle duration. The mentioned characteristics for the developed cycle are summarised in Table 3.

Table 3. Key characteristics of the brake vacuum booster for the test cycle

No	Parameter	Measurement unit	Value
1.	Distance covered	km	1.727
2.	Total duration of the cycle	s	140
3.	Maximum speed	km h^{-1}	85
4.	Average speed	km h^{-1}	44.41
5.	Movement duration in the cycle	s	118
6.	Stopping duration in the cycle	s	22

After the experimental cycle was developed, its quality was tested on a chassis dynamometer – roll test bench *Mustang MD1750*. Initially insignificant corrections were made in gear-shifting duration.

To determine whether a model (developed cycle) corresponds to the real driving, three test repetitions were made on the chassis dynamometer. Typically in such evaluation a comparison of the total cycle distance and average speed is performed. On the chassis dynamometer these parameters can be determined directly from the bench software. Real driving data were obtained by cutting out the corresponding data (acceleration and all braking modes) from the logger raw data. The results are summarized in the Table 4.

Table 4. Model quality verification results

No	Parameter	Road tests	Laboratory tests	Difference, %
1.	Distance covered, km	1.75	1.73	1.14
2.	Average speed, km h^{-1}	44.10	44.40	0.68

These results qualify as a high rating and developed cycle can be used in future experimental studies.

CONCLUSIONS

Brake tests in road tests on general purpose roads are dangerous, as the hard braking regime can negatively influence the smooth flow of other vehicles on the road. For this reason, it is useful to perform such experiments on a test bench or special testing grounds.

With regard to the effectiveness of brake system vacuum boosters, the EU legislation stipulates standards only for the force to be applied to the brake pedal at 500 N. No other parameters of this system are set.

The purpose of the road tests was to examine change in brake system vacuum pressure depending on the driving regime chosen and to identify an appropriate speed and time regime for the movement of an automobile. During the experiment, the vacuum pressure of the brake pump changed from 0.24 to 0.87 bar depending on the engine's operation regime.

An original driving cycle to test brake system components was developed based on the data for various braking regimes that were obtained in the experiment.

The developed brake test cycle consists of three braking regimes that involve smooth and uninterrupted braking, interrupted and repeated braking and multiple activation of the brake pedal. The regimes developed include the majority of potential brake exploitation regimes.

Using the developed driving cycle, it is possible to conduct research on the performance of various automobile components during braking. The following parameters of brake system components may be identified on a power test bench in experimental research: change in the vacuum pressure of a vacuum generation device, change in brake system pressure and change in the force applied to activate the brake pedal.

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