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ORIGINAL ARTICLE

The Use of Short-Term Compressed Air Supercharging in a Combustion Engine with Spark Ignition

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ABSTRACT – The powertrain is a very important subassembly in a car and is responsible not only for the automotive industry's impact on the environment but also for the safety of people travelling by car and performing overtaking manoeuvres and joining traffic. In general, the powertrain is a combination of the drive unit and drive transmission, wherein the drive unit is responsible for the available driving force in the car's wheels and for the car's ability to accelerate when the throttle pedal is rapidly pressed at a constant gearbox ratio. The availability of the driving force reserve in the powertrain is the most important issue for the reason of safety of the people travelling by car. In the case of drive unit what they are of the combustion engines, the rapid pressing of the throttle pedal in the car acceleration process leads to a temporary deficiency in the driving force and in the powertrain's output. The deficiency in the driving force has a negative impact on acceleration and driving comfort. In this paper, the authors assessed and analysed two different short-term compressed air supercharging systems for combustion engines with air supplied from a high-pressure tank. The analysis covered the response of the combustion engine with spark ignition to the gradual increase in pressure in the air-intake system. The assumption is that the applied short-term compressed air supercharging system could improve the driving force during the phase of the engine's increasing crankshaft rotational speed. This helps to achieve the improved passenger car acceleration dynamics, depending on the supercharging method and throttle pedal exertion. When analysing the car's acceleration dynamics, expressed by the shorter time of increasing the longitudinal speed from initial to final, it was possible to shorten the acceleration time. It is also possible to observe an improved driving force behaviour, especially during the first phase of acceleration.

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INTRODUCTION

In the current state of technology, much attention is devoted to the problem of ensuring good car acceleration dynamics, including the search for effective methods of improving the driving force in passenger cars in order to deprive them of any distractions during acceleration [2], [5], [8], [11], [13], [15]. The problem becomes especially important during rapid car acceleration when the throttle pedal is suddenly fully pressed (100%). In such a case, we are observing deficiencies in the driving force presented schematically in Figure 1 and deriving mainly from inertia accumulating in the car's powertrain. The combustion engine's torque was measured during the car's acceleration to identify the source of the deficiencies in the driving force (Figure 2).

Interference in the engine torque's behaviour is mainly observed during rapid car acceleration with the throttle pedal fully pressed. Areas I and II presented in Figure 1 are a derivative of the combustion engine torque's behaviour during the first phase of car acceleration. The problems occurring in area II can be limited by using an electronic throttle control (as shown in Figure 3) which is illustrated in the car's road testing [7], [20], [22]. In this case, the throttle speed in the engine's intake manifold was limited. This allowed for the throttle's operation independently of the throttle pedal. The limitation of the throttle speed improves the adverse torque waveform in area I and II and limits the engine torque's build-up rate and the driving force's build-up over time. This is especially important in the first phase of the driving force build-up because the acceleration process is delayed due to the car's inertia (the so-called jerking action). In his own research presented in Figure 3, Mamala [14-16] limited the throttle speed in the intake manifold to 75 degrees per second (°/s), which substantially limited the car acceleration delay. However, this limitation caused a reduction in the car's acceleration dynamics, and it was contrary to the new requirements for the throttle opening in the engine's intake manifold, which amounted to 200 °/s for the tested engine [8], [9], [33], [34].

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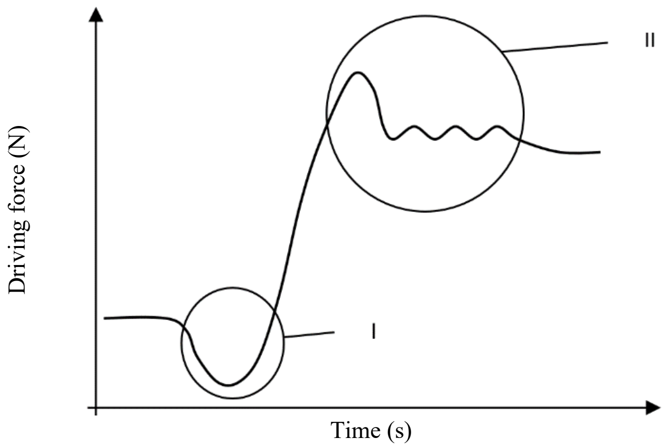


Figure 1. Deficiency in driving force during car acceleration (schematic behaviour).

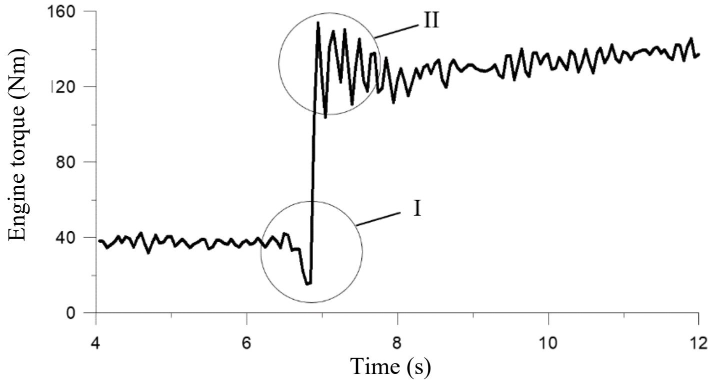


Figure 2. Behaviour of the powertrain's torque during rapid acceleration car.

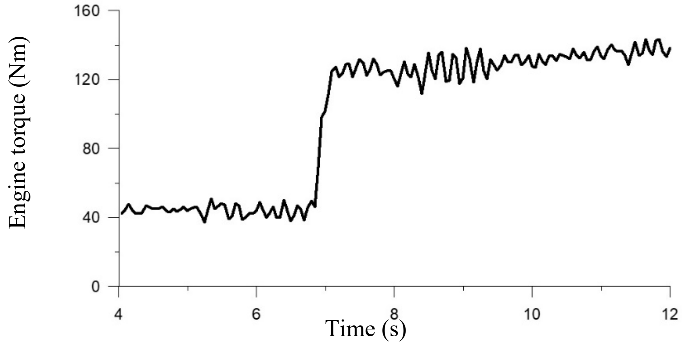


Figure 3. Behaviour of the powertrain's torque at a limited throttle opening during car acceleration.

The papers of [4], [4], [9], [15], [32], [27] feature an analysis on how to solve this difficult problem. An important obstacle for the full utilisation of the powertrain's potential in terms of using the available combustion engine's specification related to rapid acceleration is the issue of substantially increasing the crankshaft's angular velocity [14], [23]. Then, the driving force, F_d occurring in the powertrain and resulting from the combustion engine's available torque reduced by the inertia of rotating and progressive elements, according to Eq. (1).

$$F_d = \frac{(T_e - T_i) \times t_r \times \eta_t}{r_w} \leq (F_d)_l \tag{1}$$

where T_e is torque, t_r is total transmission ratio in the powertrain, η_t is powertrain efficiency and r_w is wheel dynamic rolling radius. The combustion engine's torque (T_e) is reduced by inertia (T_i). For the power transmission system, the moment of inertia is determined by the following dependency,

$$T_i = J_e \times \dot{\omega}_e + J_w \frac{\dot{\omega}_e \times t_r}{{t_{rg}}^3 {t_{rd}}^2}, \qquad (2)$$

where J_e is mass inertia in the engine's rotating motion, J_w is mass inertia in the wheels' rotating motion, t_{rg} is gearbox transmission ratio, and t_{rd} is differential transmission ratio. Equation (2) does not include mass inertia in the powertrain's rotating parts located between the engine and the wheels.

The occurrence of inertia, T_i in the powertrain is the main reason for driving force deficiencies during the first phase of acceleration (area I in Figure 1). It is a transitional and short-term process, but it affects the car acceleration process. Another problem is the engine's torque availability, which depends on the engine's specification. Figure 4 presents an example of torque behaviour in a combustion engine with spark-ignition based on the results of own station testing for an engine with the output of 1.242 dm^3 and an intermediate multi-point manner combustible mixture generation.

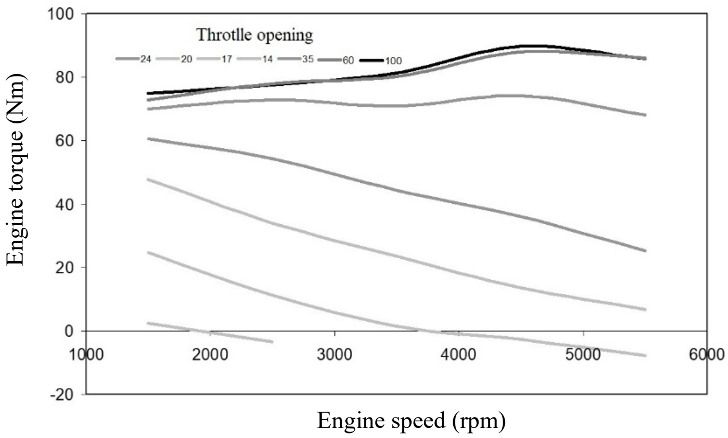


Figure 4. Specific torque of the test engine.

The specification features the curve of maximum torque for the 100% throttle opening in the intake manifold, marked with a straight dark line. The acceleration process requires a substantial increase in the engine's torque to overcome inertia and the moment of resistance of a moving car. However, the engine's torque increase is limited by the available external torque in the engine's specification (as in Figure 4). The differences in the engine's torque deriving from the throttle opening in the intake manifold of 60 to 100% are minor.

The conducted analysis demonstrated that due to the ability of increasing the torque, it is desired to achieve the highest possible cylinder supply with a fresh charge, causing an increase in average effective pressure during additional combustion and thereby increasing the torque. Therefore, in order to achieve additional torque, the paper features an analysis of experimental testing of a combustion engine's short-term supercharge in two variants affecting the car's driving force.

METHODOLOGY AND TEST ENGINE

Air charging is one of the methods that allows for obtaining greater torque from the powertrain during the car's rapid acceleration. In paper of Bozza [1], Hawary [4], Kusztelan [8], Meldolesi [12], Merkisz [18], Mysłowski [14], Sivaramen [19], Turner [21], Williams [24] and Wisłocki [25], feature many such air charging systems, starting with air supercharger systems (e.g. compression and turbocharge) or high-storage systems (e.g. nitrogen monoxide charging).

Despite their common use in combustion engine supply, the aforementioned systems are characterised by a series of limitations and flaws. One of the major flaws for turbochargers is the adaptation of the compression performance to the engine's rotational speed (excess air at high engine rotational speeds) and the so-called turbocharger lag effect. Therefore, research on new air supercharger structures can be divided into three categories with the following characteristics; variable supercharger specification, combined systems, combining superchargers into assemblies. As part of this study, an analysis of the intake method of topping up internal combustion engines with spark ignition with air was carried out in two variants: (I) short-term compressed air supercharging system downstream of the throttle, and (II) short-term compressed air supercharging system upstream of the turbocharger assembly.

Short-Term Compressed Air Supercharging System Downstream of the Throttle

An innovative approach to the supercharging problem is presented in Németh's paper [20], which utilises a combined system including a turbocharger and a compressed air tank for diesel engines. During acceleration, when there is a lack of air in the intake manifold, additional air is supplied from the tank (in this case, from the compressed air tank in the air brake system) through a special cylinder air infeed adjustment system. This way, the lack of air in the turbocharger of the intake manifold is compensated, thereby achieving a higher engine torque. In this case, the maximum turbocharger performance was achieved approximately 3.5 s earlier in comparison to a traditional turbocharger system. This system was used for locomotives diesel engine.

In spark-ignition engines, the supplied air quantity must be strictly controlled due to the possibility of incorrect combustion in the cylinder in the case of excessive supercharging. Excessive supercharging of cylinders with air can lead to knocking combustion. This type of combustion is adverse because it can result in mechanical damage done to the engine. One of the methods of avoiding this phenomenon is to lower the temperature of the supply air taken in by the engine.

Hence, in an earlier paper [15], the author used a new solution of the short-term compressed air supercharging system downstream of the intake manifold in a spark-ignition engine. In this system, the compressed air at 20 MPa pressure was fed from the tank via an assembly of reducers and air injector into the intake manifold downstream of the throttle. This allowed for the reduction in air temperature in the intake manifold as a result of reducing air pressure from the tank to approximately 0.35 MPa (pressure of the supply air for the manifold). Feeding an increased quantity of air into the intake manifold increased the degree of filling the cylinder with air. The increased degree of filling the cylinders with air can result in the occurrence of the knocking combustion. The verification of the supercharge system's operating conditions is presented below. It was assumed that in the case of the short-term compressed air supercharging, the quantity of additional air in the engine's cylinder, V_{SC1} is assumed as 50%. With the output of the test engine's single-cylinder, V amounting to 0.3×10^{-3} m^3, the universal gas constant, $R = 8314.7$ J/kmol·K, temperature $T_{EIN} = 300$ K and end pressure $p_{EIN} = 0.1$ MPa. We apply Eq. (3) to calculate the air quantity in the cylinder.

$$V_{c1} = \frac{p_{EIN} \times V}{(UG) \times T_{EIN}} = 9.02 \times 10^{-4}\, m^3 \tag{3}$$

where Vc_1 is the output of a single-cylinder, T_{EIN} is the intake temperature in the cylinder at 300 K, p_{EIN} is the intake pressure of the cylinder at 0.1 MPa.

Equation (4) can be applied to calculate the temperature after high air short-term compressed air supercharging at the compression stroke's end

$$T_{E+S} = \frac{V_{SC1} \times \chi \times T_S - V_{C1} \times T_{EIN}}{V_{SC1} + V_{C1}} \tag{4}$$

where T_{E+S} is temperature after short-term compressed air supercharging at the compression stroke's end, V_{SC1} is the calculated volume of air supplied during supercharging, and χ, is the exponent of polytropic transformation during compression.

As specified in [17], the compressed temperature, T_S, can be calculated using the ideal gas formula, wherein the error does not exceed 1%. Assuming that the pressure in the air tank amount to $p_t = 10$ MPa and that the end pressure in the cylinder amounts to $p_{EC} = 1.5$ MPa, we can use Eq. (5).

$$\frac{T_t}{T_S} = \left(\frac{p_t}{p_{EIN}}\right)^{\frac{\chi-1}{\chi}} \tag{5}$$

where p_t is air tank pressure, p_{EC} is the end pressure in the cylinder, T_S is compressed temperature, and T_t is air tank temperature. After conversion, the supercharging temperature, T_S, is 176 K and the end temperature T of $_{EIN+S}$ is 449 K.

After replacing all dependencies in equation (6), it is possible to calculate the end pressure after short-term compressed air supercharging, p_{E+S}

$$p_{E+S} = \frac{(V_{SC1} + V_{C1}) \times T_{E+S}}{V} \tag{6}$$

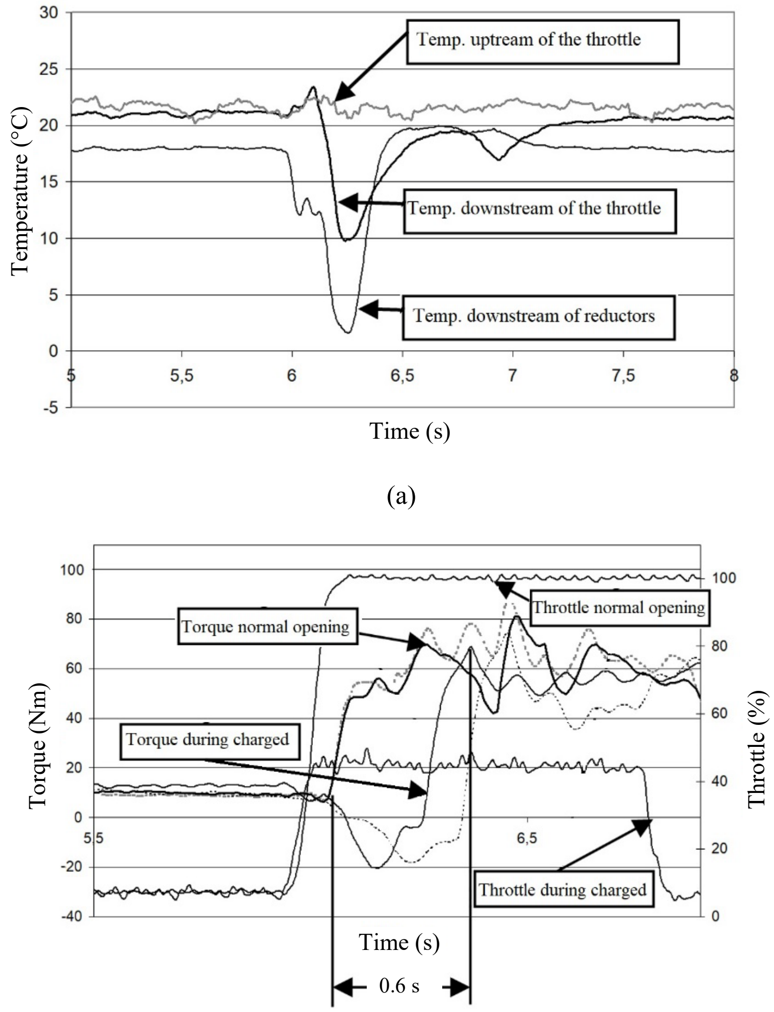
The above data enables calculating the structural dimensions of the air tank in the short-term supercharging system, in which the supercharging is performed only until the engine achieves its maximum torque. The research conducted in paper [15] demonstrates that the time of supercharging not exceeding 2 s.

As mentioned above, a huge threat for the described combustion engine is the possibility of knocking combustion. According to Livengood [26] and Sato [27], the knocking combustion phenomenon can occur in the combustion chamber when the mixture ignition time is shorter than the maximum pressure increase time adopted at the level of 10 ms. The estimation of the time of mixture ignition after supercharging utilised Eq. (7) developed by Livengood and Wu [30], applicable to the air-fuel mixture and the ON95 fuel at the compression ratio of 10:1, in which (τ) is the ignition delay in (ms).

$$\tau = 17.68\left(\frac{ON}{100}\right)^{3.402}\cdot p_{E+S}{}^{-1,7}\cdot e^{\left(\frac{3800}{T_{E+S}}\right)} \tag{7}$$

After adopting the above combustion parameters, the delay of the air-fuel mixture's ignition after supercharging can amount to approximately τ=166ms [31]. The above calculations show that the knocking combustion process does not occur.

The basic testing was conducted using a test engine with an output of 1.242 dm^3, installed on the engine test bench of the Opole University of Technology. The engine was modified in terms of the short-term compressed air supercharging system downstream of the intake manifold in a spark-ignition engine. The system utilised a special nozzle supplying compressed air from the tank via a set of reducers with an electromagnetic injector downstream of the throttle [16]. The algorithm for controlling the electronically controlled throttle was also modified so that the throttle could be controlled without limitation, and it was connected to the engine test bench and air injector control system. This throttle control system made it possible to limit the opening of the throttle during air charging.



(a)

(b)

Figure 5. Comparison of the torque for a normal engine and short-term compressed air supercharging system at an engine speed of 1500 rpm: (a) changes in temperature during supercharging of the intake manifold, (b) changes in torque during supercharging

This system achieved a higher torque than a conventional engine operating in the same conditions. The short-term compressed air supercharging with an initial throttle position of 7% and end position of 43% was compared to the results obtained after rapid throttle opening from 7% to the maximum of 100% in a conventional engine operating on the test bench. In this case, a decrease in the naturally aspirated engine's torque was observed in the first period, which does not occur in the supercharged engine, as shown in Figure 5(b). The modifications to the engine's supply system, comprising installing a short-term supercharger system, allowed for achieving full torque within a short time. The torque increase time was shortened by 0.6 s. Furthermore, the torque of the combustion engine with the supercharger system is comparable to the torque achieved for the normal operating opening. According to the conducted analysis, the short-term supercharging allowed for obtaining a substantially reduced temperature of the air in the intake manifold (Figure 5(a)) and no incorrect combustion in the form of knocking combustion was observed during the engine's operation. The additional torque achieved this way was used to overcome the resistance of the engine's inertia during acceleration. However, the short-term compressed air supercharger system downstream of the throttle is not without flaws. The largest of which proves to be a great demand for engine air and the need to replenish the air in the high-pressure tank continuously.

Short-Term Compressed Air Supercharging System Upstream of the Turbocharger Assembly

The use of a turbocharger, despite substantially improving the torque parameters, is not without flaws and does not solve the problem of lacking turbocharger. The lacking turbocharger is the reason for deficiencies in the driving force. When the torque demand rapidly increases at the crankshaft's low rotational speed, the insufficient turbine fuelling prevents the compressor from supplying sufficient air quantity to meet the condition related to the excess air ratio $\lambda=1$. The delay in the powertrain's reaction to the driving force demand and as well as the phenomenon of a gas connection in the intake manifold for the turbocharger system is the subject of research of many scientists like Bozzas [1], Hawary [6], Kusztelan [10], Mysłowski [19], Nithesh [21], Sivaraman [24], Szengel [20], Turner [25], Voser [26], and Williams [28]. Despite the flaw, this solution is most often used by engine manufacturers. However, new solutions feature a complex structure. The complex structure combining tank supercharging and a modified turbocharger was analysed as the second variant of the case study. The detailed schematics of the short-term compressed air supercharging system upstream of the turbocharger assembly is presented in Figure 6.

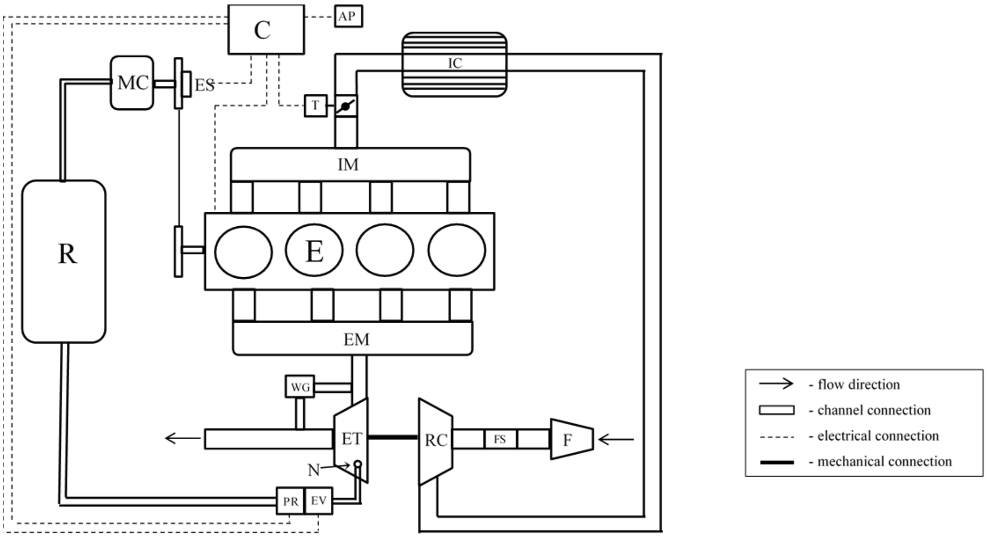


Figure 6. Short-term compressed air supercharging system downstream of the turbocharger assembly.
(E – engine, EM - exhaust manifold, WG – westgate, ET - exhaust turbine, PR - pressure regulator, T - throttle, EC - electromagnetic clutch, F - air filter, RC - radial compressor, IC-intercooler, IM - intake manifold, C – controller, AP – accelerator/throttle pedal, R – reservoir, FS - mass airflow sensor, EV – valve, MC - mechanical compressor, N – nozzle)

The application of the short-term supercharging directly into the turbocharger's assembly, instead of the intake manifold as in the case of variant I, in the quantity required to overcome the resistance of gas flow through the compressor will enable a vacuum-less engine supercharging with air required to accelerate it. This solution is based on a classic turbocharger assembly, in which the turbine was modified by placing an expansion nozzle supplying compressed air directly to the turbine's blades. This substantially improves the increase in the turbine's rotational speed in the conditions of its reduced performance. The adoption of these assumptions should have a positive impact on the car's acceleration dynamics.

The bench testing, conducted on the MAHA MSR 500 4x4 chassis dynamometer, utilised a passenger car equipped with a petrol engine with an intermediate multi-point fuel injection and a turbocharger system, with an output of 1781 cm^3, power of 150 KM (110 kW) at 5700 rpm and torque of 210 Nm at 1750 rpm, equipped with an electronically-controlled throttle. The power transmission system is equipped with a manual five-speed gearbox. The car's maximum speed amounted to 223 km/h as in Figure 7(a). The test car with elements of the modified turbocharging system is shown in Figure 7(b).

The bench testing was conducted to obtain a detailed image about the impact of the short-term compressed air supercharging directly onto the turbine's blades via an expansion nozzle, the end of which is connected to the intake channel of the engine's exhaust manifold. The air was fed from the storage tank at the pressure of 0.9 MPa directly onto the turbine blades during car acceleration on a chassis dynamometer. The air supercharging time amounted to 5s.

(a) (b)

Figure 7. Test car with a modified supercharging system: (a) car and (b) turbocharger assembly's

RESULTS AND DISCUSSION

The obtained results in Figure 8 demonstrate the charger's impact on the turbocharger assembly's rotational speed, which increased by approximately 30 thousand rotations. At the same time, the maximum speed in the given conditions was reduced by 1.2 s in relation to the classic solution. The increase in the turbocharger assembly's rotational speed also caused an increase in the turbocharger's rotations, thereby contributing to increased performance.

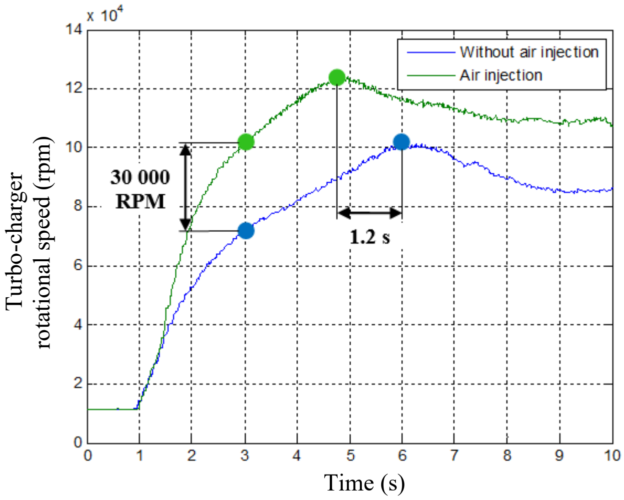


Figure 8. Comparison of the turbocharger assembly's acceleration with and without the supercharge.

The effect of the additional air charging of the turbocharger unit was measured on a chassis dynamometer in the form of an increase in the driving force during car acceleration from its initial speed, with a constant throttle position in the intake manifold (in Figure 9). According to literature [5], [14], [24], [29], a higher increase in driving force at partial throttle opening was achieved. The increase varies depending on the throttle opening in the intake manifold.

The obtained higher driving force values improved acceleration over time, especially in the first acceleration phase. The engine test bench was used to conducts tests of car acceleration after rapid throttle opening from its initial position of 7% to the end position in the conditions of constant transmission in the powertrain. The initial throttle opening angle corresponded to the car's linear speed of 45 km/h, while the end throttle opening angle derived from the force balance or the measurement was interrupted after achieving the end speed of 125 km/h, which is presented in Figure 10.

Despite ensuring a greater driving force, the car's speed was increasing slightly faster. In the first area, the speed curves were concurrent, and however, due to the use of the short-term supercharging system, the linear speed increased faster. It was also observed that after stopping the supercharge process, the acceleration process intensity did not drop, as the driving force during acceleration.

The modifications to the turbocharger assembly's short-term supercharger system allowed achieving the linear speed within a shorter time. It was possible to observe the following dependency: the smaller the throttle opening angle during acceleration, the greater the importance of the short-term supercharger system. For the final throttle position of 20% in Figure 10(a), achieving the final linear speed of 65 km/h took 45 s in the case of the traditional engine with a supercharger system and 6 s less in the case of an engine utilising the supercharging. Similarly, for the throttle position of 35% of Figure 10(b), the time was shorter by 2.4 s and for the next throttle position of 70% in Figure 10(c) at 1.5 s.

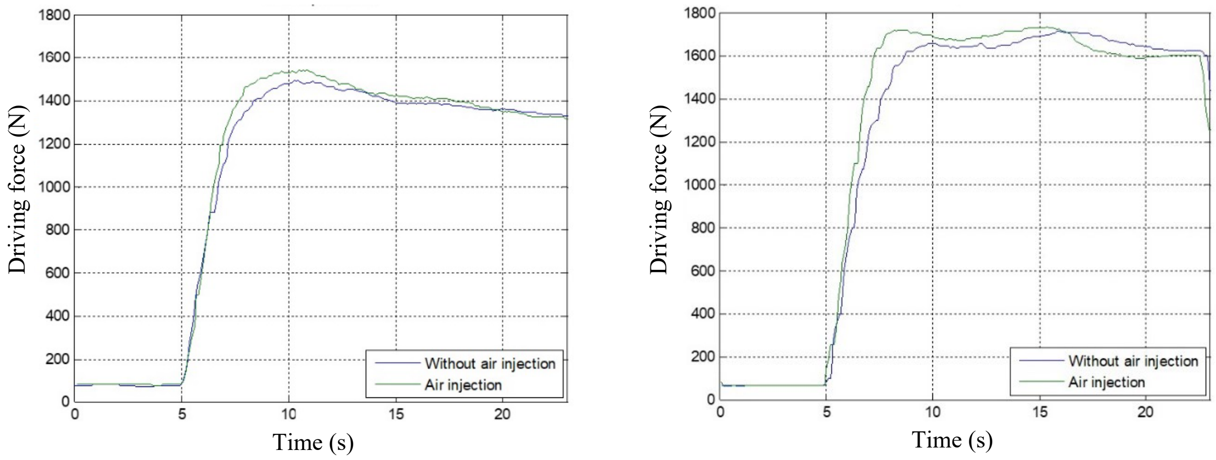
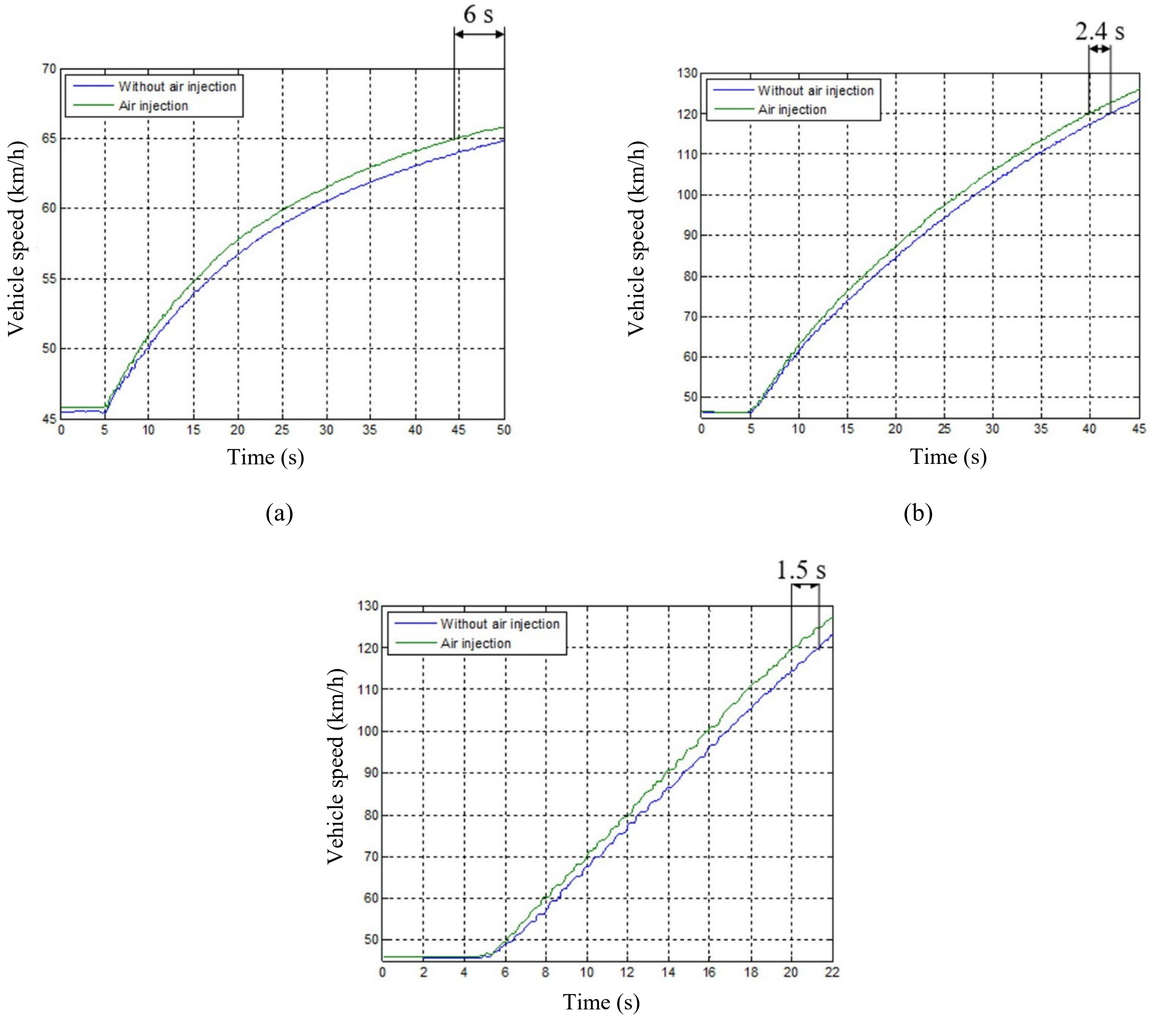


Figure 9. Comparison of the driving forces during acceleration with and without the supercharger system for different throttle positions.



(a)

(b)

(c)

Figure 10. Comparison of the driving forces during acceleration with and without the supercharger system for different throttle positions of (a) 20%, (b) 35% and (c) 70%.

CONCLUSION

In summary, it should be emphasised that the main goal of this paper, i.e. an analysis of the operation of two different short-term compressed air supercharging systems, was achieved. The tests demonstrated, especially in variant II, that the short-term supercharging utilising compressed air directly on the turbine's blades via an expansion nozzle connected to the intake channel had a positive impact on the temporary driving force in the acceleration process. As a result of using the short-term supercharging, car's acceleration time reduced. At the same time, the proposed solution eliminated the disadvantage of variant I, related to the demand for large quantities of air being supplied to the engine's intake manifold. The conducted analysis of the state of knowledge and the analysis of own research on the development of short-term charging systems allowed for the development of the following conclusions:

i. the use of the short-term supercharger utilising compressed air downstream of the throttle in variant I has positive effects, but its application requires the modification of the ECU control system in an internal combustion engine,
ii. the use of the short-term supercharger utilising compressed air in the turbocharger's assembly in variant II allows for achieving greater turbocharger efficiency, including shortening the acceleration times of the turbocharger itself. This enabled solving the problem of its delay during acceleration by using the turbine's short-term impulse charger,
iii. the use of the short-term supercharger utilising compressed air provides much greater benefits in the case of partial throttle opening, resulting in the reduction of the acceleration time by 13.3%.

The short-term supercharger utilising compressed air proposed in the paper in variant II requires further detailed analysis, especially in terms of determining the system's operating conditions, the pressure of the air supporting the turbine as well as the tank's pressure. Full knowledge of the dependencies occurring in the various stages of the top-up requires a detailed diagnosis because the assumed top-up time of 5 s can be shortened as a result of the analysis and assessment of the recharging effects. Therefore, this paper specifies the directions for further extensive research, including adequate road research.

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