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Wojciech CIEŚLIK*
Ireneusz PIELECHA*
Przemysław BOROWSKI*

EFFECTS OF START–STOP SYSTEM ON THE OPERATION OF DRIVE SYSTEM IN URBAN TRAFFIC CONDITIONS

The article discusses the impact of engine stopping and starting on conditions of operation of drive system in urban traffic. The motivation for the realization of the undertaken subject was assessment of the benefits of using a start–stop system in the aspect of increasing share of vehicles equipped with such a system. The article discusses the global sale of vehicles equipped with the start–stop system compared to the hybrid vehicles. There are presented general requirements for system activation and the methods of conducting tests. Analysis of the operational indexes of the combustion engine during idling were made on the basis of the tests of the passenger car of micro hybrid type equipped with the start–stop system. There were pointed out benefits ensuing from the reduction of the share of combustion engine operation during idling and also were estimated fuel savings due to the use of the start–stop system while driving in typical urban agglomeration.

Keywords: combustion engines, start–stop, transient conditions

1. INTRODUCTION

Serial production of start–stop systems by a Bosch started in 2007. It is estimated that over 50% of newly registered vehicles after 2014 will be with equipped with start–stop systems. Although this technology is commonly used in cars of the mid-size segment in Europe, it also has significant potential of utilization in compact and luxury cars. It can be expected that, in the years to come, there will be more significant increase in the meaning of the micro and medium hybrid propulsion systems [2].

The global sale of the start–stop systems increased mainly in the last decade – in 2011 there were 3 million systems sold, and up to 2020 the sale of about 37.3 million of systems is planned (Fig. 1). This means more than 1/3 of all sold vehicles of light-duty type. In 2011 for each sold vehicle with the hybrid drive system, 3.5 of a car was equipped with the start–stop system. Due to low price of such a system it is estimated that in 2017 there will be 16 start–stop systems per each hybrid vehicle [11].

In 2011 in Western Europe were sold 98% of all start–stop systems: 3 million units. In 2014, the sale in the United States amounted to only 1 million units. It is thought that use of the start–stop system reduced the fuel consumption and emission of carbon dioxide by 5–10%; taking into account the hybrid cars, this reduction might amount to 10–25% [11, 12].

The engine operation during stops is not advised because of the fuel consumption and emission of toxic compounds of exhaust gases. A system of periodic turning off the engine (start–stop system) during the stops forces the change in the design of some assemblies of the engine and vehicle.
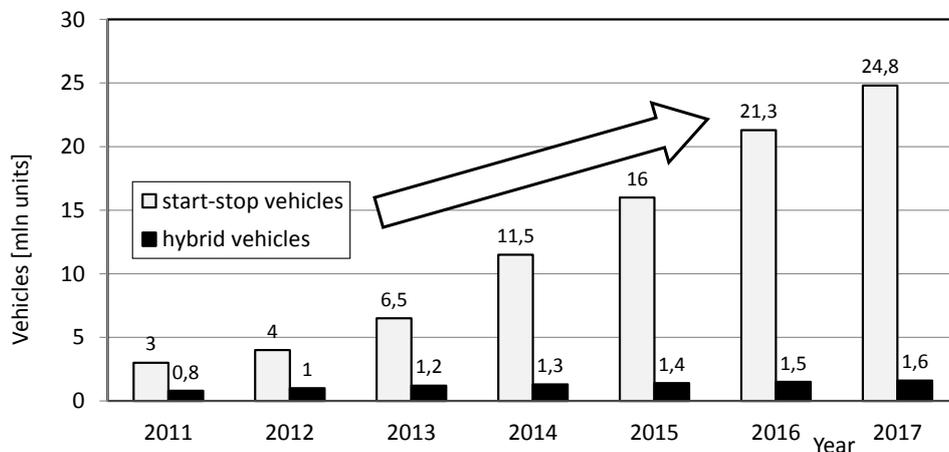

Fig. 1. Annual start–stop system sales: world markets [11]

The concept of the start–stop system has to enable monitoring of numerous parameters for smooth operation of the system (Fig. 2). In order to avoid cold starts it is necessary to analyze the charge level of the battery (SOC – state of charge) and temperature of combustion engine operation. This provides, among the others, the optimum operation of the catalytic converter, which in turn reduces emission of exhaust gases. The requirements for integrated starter-generator are:
  − 12–24 V system voltage,
  − 3–10 kW of generator power,
  − efficiency > 80%,
  − 200–410 N·m start–up torque,
  − high current storage 200–1000 A,
  − lifetime up to 500.000 starts-ups,
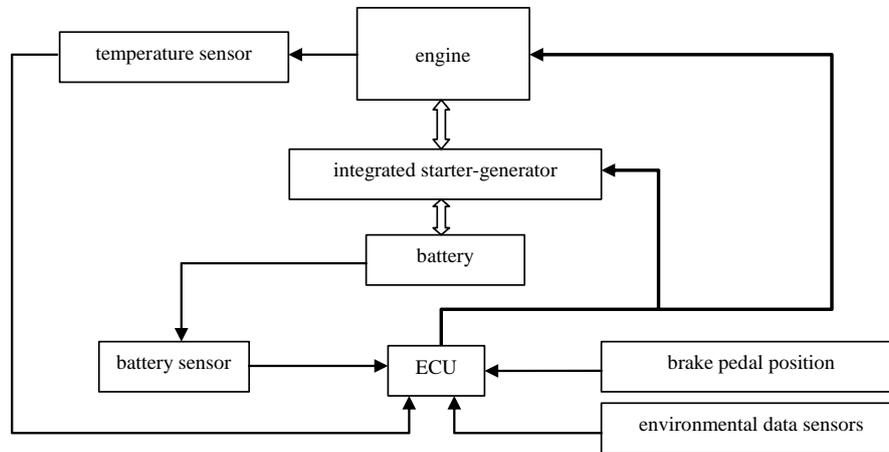 − cooling media up to 130°C.

Fig. 2. Model of electronic control system for start–stop system [14]

The start–stop system consists of four sub-assemblies, which are controlled by the central engine control unit (ECU):

– engine start–up – the subsystem consisting of the starter, crankshaft position sensor, engine injection system,

– energy management – including: appropriate battery, battery level sensor, DC/DC12V converter and alternator,

– safety – including: brake and clutch pedal sensor, sensor of opening engine bonnet, sensor of idle gear, pressure sensor in braking system and sensor of wheels speed,

– comfort – including: electrically propelled cooling liquid pump and air conditioning compressor, vehicle lighting system and system of vehicle ventilation.

The start–stop system can be activated by pressing a button on the dashboard. In order to operate, certain conditions have to be met, including: appropriate charge level of the battery, temperature of the cooling liquid between 40°C and 100°C, closed engine bonnet and pressing the clutch pedal at least once. The engine is automatically turned off when the vehicle is stopped (for longer than e.g. 3 seconds) with engine idling, without any gear put and without the clutch pedal pressed (currently this time is different for different manufacturers). With regard to vehicles from Mercedes, if a vehicle has a manual gearbox, the engine is automatically cut off while vehicle is stopped and the gear stick is in neutral position. When the driver will press the clutch pedal, the engine starts automatically. If the vehicle is equipped with automatic gearbox, the engine is turned off only after total stop (speed of 0 kph). Pressing the accelerator pedal restarts the engine.

The first mass-produced car equipped with the start–stop system was Toyota Crown manufactured in 1974. During the tests in urban traffic conditions in Tokyo, the fuel consumption of a car with this system amounted to 14,7 dm^3/100 km

which gave reduction of fuel consumption by 8% [3]. The Japanese manufacturer developed a system which cut off the engine after 1.5 seconds of engine stop.

The use of the start–stop system in vehicles is getting increasingly common [9, 10]. This system is a component of the vehicles of the micro-hybrid type [4, 7]. Taking into consideration various solutions of the system design, its operation has significant influence on the initial phase of combustion engine operation. The existing start–stop systems should be specified in terms of the time of reaction (stop and restart of the combustion engine), level of noise generated during engine start–up, level of complexity of the system and the costs of its installation. The type of the utilized solution will depend on the process of start–up of combustion engine, and particularly on the influence of the start–stop system on the changeable thermodynamic conditions of the combustion engine operation during the start–up. Utilization of this system is aimed at reduction of fuel consumption by turning off the combustion engine during vehicle stops. Main elements, which comprise the start–stop system are:

- sensor of charge level of battery (localized on the negative pole),
- sensor of power brake negative pressure,
- sensor of neutral position of the gear stick (version with manual gearbox),
- voltage regulator,
- button to turn off the system.

2. METHODS

The tests of the start–stop system were conducted with the use of Mercedes-Benz C200 vehicles equipped with the combustion engine with direct fuel injection (marked CGI – *Charged Gasoline Injection*), cooperating with the automatic 7-speed gearbox 7G-TRONIC. Selected technical parameters of the combustion engine of the discussed vehicle are shown in Table 1.

Table 1

Technical characteristics of Mercedes-Benz C-class W204 [13]

Quantity	Value
Engine type	C200, gasoline, turbocharging
No. of cylinders	4, in-line
Compression ratio	9.3
Power [kW]/n [rpm]	135/5250
Torque [N·m]/n [rpm]	270/1800–4600
Engine displacement [cm^3]	1796
Fuel system	direct injection
IMEP [MPa]	1.8892

The tests were conducted in urban traffic conditions. In the study was used system for indicating and activating fast-varying processes (AVL IndiSmart) and pressure measurements were conducted for the fourth cylinder. In order to record the test route was used the GPS system and a tester monitoring the diagnostic parameters of the combustion engine (Fig. 3).

Fig. 3. Tested vehicle (Mercedes Benz C200) with the system
for measuring fast-varying processes

Tests of the start–stop system were conducted in urban traffic conditions (Fig. 4). The length of the reference route was 3 km. The measurements were conducted during several test runs with deactivated (one test run) and activated start–stop system (three test runs). The distance 3 km long was diversified in terms of traffic during consecutive test runs. Due to the different intensity of traffic, the time of the test run ranged from 425 s to 539 seconds (differences in the times of test runs amount to 25%).

Fig. 4. Reference map of the test route with total length of 3 km

3. ANALYSIS OF THE OPERATIONAL INDEXES
OF THE COMBUSTION ENGINE DURING IDLING

The tests of the combustion process for idling engine with the direct fuel injection have significant cognitive meaning in terms of specific preparation of mixture in such a combustion system. Significant non-repeatability of the engine operation creates unfavorable conditions in terms of fuel consumption and comfort of the driver. The results of the unevenness of the engine operation in subsequent 200 cycles of operation are presented in Fig. 5. Analysis of Fig. 5 shows that there are no fixed engine operation parameters such as maximum combustion pressure (PMAX), engine speed (SPEED), mean indicated pressure (IMEP4), which are the result of the combustion process. This characteristic was defined by the beginning (AI05_4) and end of heat release (AI90_40).
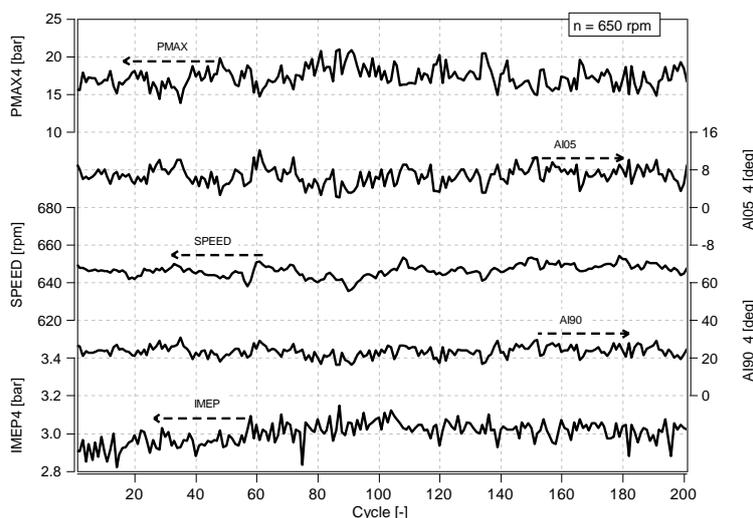
Fig. 5. Analysis of the operational indexes of the engine for speed during idling

The unevenness of the engine operation was characterized by significant changes of the maximum combustion pressure value (Fig. 6). The dispersion of the maximum combustion pressure (PMAX) from the mean value amounted to 20%, and the coefficient of variation CoV(PMAX) defined as the mean deviation from the mean value for 200 measuring cycles was 7.92%. The coefficient of variation of the mean indicated pressure was 1.94%, which is an acceptable value (maximum acceptable variation of this value is, according to different sources, 3.5–5%) [1, 8].

The presented unfavorable conditions of operation of engine with direct fuel injection with active start–stop system do not exist as the combustion engine is then turned off.
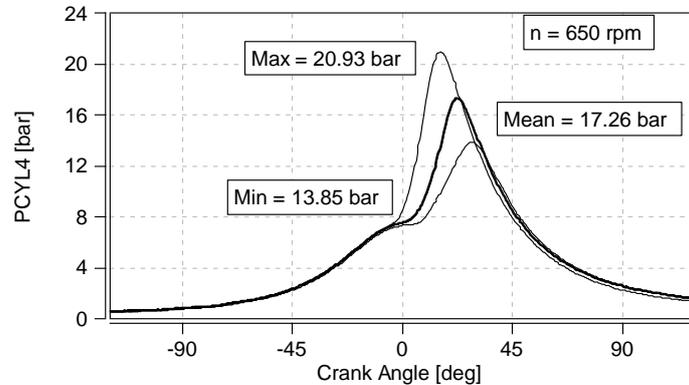
Fig. 6. Characteristics of the changes of pressure in cylinder during engine idling

4. EFFECTS OF START–STOP SYSTEM
ON THE CONDITIONS OF OPERATION OF DRIVE SYSTEM
IN REAL URBAN TRAFFIC CONDITIONS

Tests concerning the operational conditions of engine utilizing the start–stop system were conducted in relation to deactivated system. Figure 7 shows a comparison of two test routes with two options of utilization of the start–stop system. Driving conditions required change of the vehicle speed in range from 0 to 100 kph at the change of engine speed within the range from 0 to 6000 rpm. During the test run with the deactivated system there were periods, during which it would have been possible to turn off the combustion engine. For active start–stop system, the longest period of engine deactivation is marked in the figure, and the engine was stopped five times.
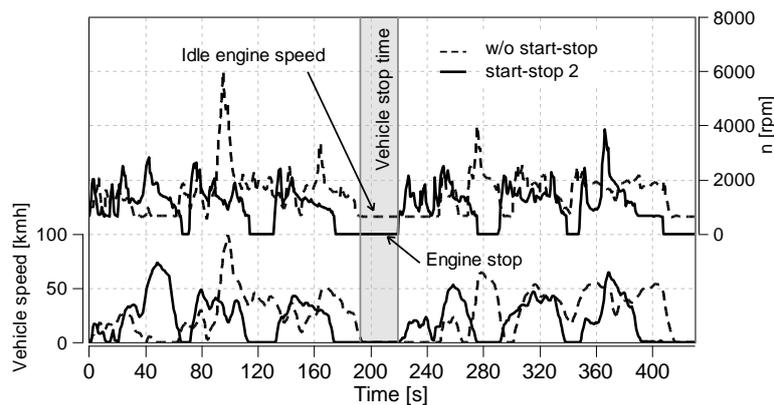

Fig. 7. Comparison of speeds of the vehicle and combustion engine for selected test runs

Different times of the test runs (ensuing form the real traffic conditions) were brought to relative values within which it was proved that the distance traveled during subsequent test runs does not differ significantly from the mean value (Fig. 8). Maximum difference relates to the middle period of each test route and was caused by large number of stops of vehicle caused by significant traffic.
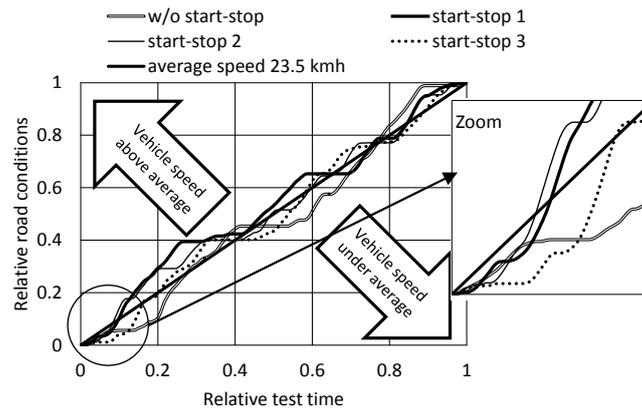
Fig. 8. Conditions of conducting tests in relation to the average speed

The analysis of the share of engine operation in particular ranges of engine speeds indicates reduced time of combustion engine operation for idling speed during activation of the start–stop system. For active start–stop system the share of deactivation time of combustion engine ranged from 15% to 26% (Fig. 9). Deactivation of the engine results in higher start–up speed which, in turn, causes higher share of engine speeds ranging from 650 to 1000 rpm.
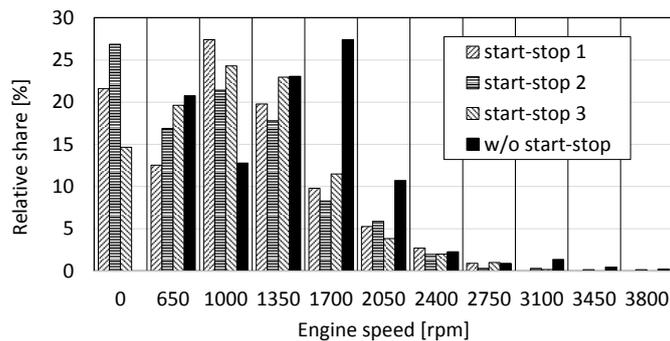
Fig. 9. Share (in percentages) of engine operation during the test run

Utilization of the start–stop system in real traffic conditions reduces the share of the combustion engine operation in the total time of the test run (Fig. 10). Accepting, as the reference, relative time of the test run as 100%, then the time of combustion engine operation with active start–stop system was reduced by maximum 25%. In each of the cases, active start–stop system reduces the time of engine operation by, respectively: 21%, 25% and 15%. This means the average reduction of operation time of the idling combustion engine by about 20%.
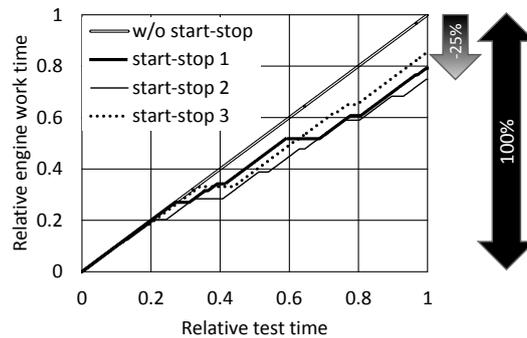

Fig. 10. Relative benefit of the engine operation time

Evaluation of possibilities of utilization of the start–stop system was conducted by defining typical parameters characterizing such a system. For each of the analyzed test runs was determined the time of combustion engine operation (Fig. 11a). Additionally, the total time of combustion engine deactivation was determined for each variant of the covered test route (Fig. 11b). Knowing the idling engine speed $n = 650$ rpm and the exact time of engine deactivation, the probable number of cycles conducted by the combustion engine was determined (Fig. 11c). Finally, also the mass (volume) of the fuel saved due to combustion engine deactivation during the vehicle stops was determined for each of the three vehicles (Fig. 11d).

The fuel mass was determined on the basis of measurements of carbon dioxide emissions from combustion engine operating at idling engine speed [5, 6]. Activation of the start–stop system is possible after fulfilling, among others, the requirements considering thermal condition of the engine, so the measurements were carried out after gaining the required parameters by the engine. Taking into consideration the fact that during complete combustion of 1 kg of gasoline is produced 3.1 kg of carbon dioxide (or, reversing the transformation, to produce 1 kg of CO_2 it is necessary to burn 0.322 kg of fuel), the fuel mass for idling engine operation was determined. The intensity of carbon dioxide emissions in these conditions amounts to 0.76 g/s. On this basis the specific fuel mass during engine operation was estimated:

$$0.76 \text{ g/s } CO_2 \cdot 0.332 \text{ g gasoline/g } CO_2 = 0.245 \text{ g/s gasoline}$$

Taking into account the gasoline density ($\rho = 0.745$ g/cm^3), the volumetric fuel consumption per second is determined:

0.76 g/s CO_2 · 0.332 g gasoline/g CO_2/0.745 g/cm^3 = 0.33 cm^3/s gasoline

Assuming the determined time of combustion engine deactivation for each of the three vehicles, the mass of the carbon dioxide emitted into the atmosphere was estimated. These values are, respectively: 66 g, 102 g and 51 g of carbon dioxide. The values of fuel savings for typical traffic conditions area presented in Fig. 11.
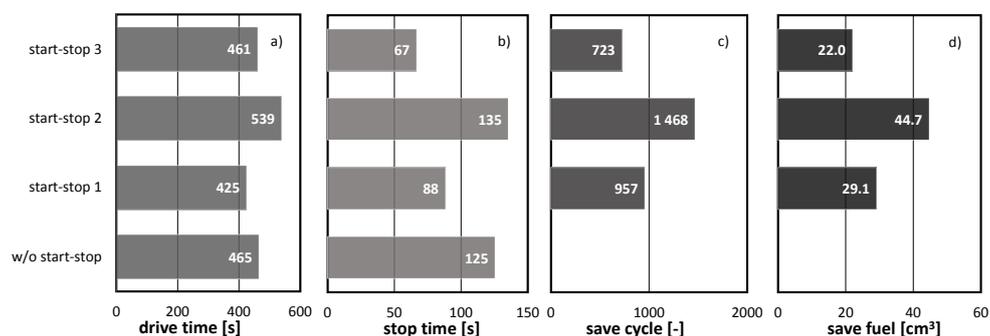

Fig. 11. Characteristic values obtained during the tests of the start–stop system

The above values refer to one vehicle during the test run lasting for about 5 minutes. If we accept that the number of vehicles in Poznan amounts to 554 per 1000 residents (data from Central Statistical Office – GUS), and only 20% out of 5% of all vehicles equipped with the start–stop system move around the city, then there are 3000 such vehicles in the city. Assuming that during 8 hours of driving in urban conditions the start–stop system will be active for about 30 minutes (6.5% of total driving time), then the savings in carbon dioxide emission will amount to 1.5 kg a day.

5. SUMMARY

Utilization of the start–stop system generates measurable environmental benefits especially in conditions of urban traffic. In the tests was obtained approximately 15% reduction in time of combustion engine operation, which means measurable benefits in reduction of fuel consumption.

Development of the start–stop systems is the reason for increasing number of newly registered vehicles with such a solution and this should result in the increase in the amount of not emitted carbon dioxide. This system can contribute to the reduction of emissions of CO_2 from the automotive vehicles, particularly in urban traffic conditions.

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**WPŁYW SYSTEMU START–STOP NA WARUNKI PRACY
SILNIKA SPALINOWEGO W RUCHU MIEJSKIM**

Streszczenie

W artykule omówiono wpływ systemu zatrzymywania i uruchamiania silnika na pracę napędu w warunkach ruchu miejskiego. Motywacją podjęcia tego tematu było oszacowanie korzyści zastosowania systemu start–stop w związku ze wzrostem liczby pojazdów wyposażonych w taki układ. W artykule porównano sprzedaż pojazdów wyposażonych w układ start–stop ze sprzedażą pojazdów hybrydowych. Przedstawiono ogólne wymagania aktywacji systemu. Wskaźniki pracy silnika spalinowego podczas biegu jałowego analizowano na przykładzie pojazdu osobowego typu micro hybrid wyposażonego w system start–stop. Wskazano korzyści wynikające z ograniczonej pracy silnika spalinowego w warunkach biegu jałowego oraz oszacowano oszczędność paliwa w warunkach jazdy miejskiej możliwą do uzyskania po zastosowaniu systemu start–stop.