AN ANALYSIS OF THE USE OF CRUISE CONTROL IN A PASSENGER CAR

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Abstract

Most vehicles are powered by internal combustion engines. Due to the nature of their operation they emit, among others, carbon dioxide which contributes to the greenhouse effect. CO_2 production is strictly correlated with fuel consumption. The article presents the results of road tests of a passenger car with a spark-ignition engine meeting the Euro 6 emission norm. The test vehicle was equipped with a classic exhaust gas aftertreatment system – a three-way catalytic converter. The aim of the study was to verify the impact of the cruise control use on the vehicle fuel consumption. The measurements were based on Portable Emission Measurement System type mobile equipment for exhaust emission tests. The tests were carried out in real driving conditions travelling on an express way. Test drives took place on a route with variable topographic profile. Three test drives with different speeds were carried out, but the aim was to obtain an average speed of 130 km/h.

Keywords: fuel consumption; cruise control; speed driving strategy

1. Introduction

Transport significantly affects the quality of life and economic growth of most countries in the world. Highly developed mobility also affects the environment. Most vehicles are powered by internal combustion engines which, due to the nature of their operation, emit harmful substances into the atmosphere, such as: carbon monoxide CO, nitrogen oxides NOx, particulates PM and hydrocarbons HC [17]. The combustion process also produces carbon dioxide CO_2, which largely contributes to the phenomenon known as global warming [29]. According to a 2018 report by the European Union, transport is responsible for about 27% of total carbon dioxide emissions in Europe [6]. Due to the fact that CO_2 production is closely correlated with fuel consumption, in order to meet restrictive emission norms, advanced technical solutions are introduced to the market to increase the efficiency of the engines as well as entire drive systems [11, 14].

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In addition to reducing fuel consumption, a significant problem is safety and improving the travel comfort. Passive safety systems protect the passengers of the means of transport, but their effectiveness is nevertheless limited for pedestrians and cyclists. This means that active systems are necessary to ensure the safety of all traffic users [4].

Driver Assistance Systems are a wide spectrum of solutions. The first systems aimed at dynamic vehicle stabilization include *Anti-lock Braking System*, commonly known as ABS, *Traction Control System* (TCS) and *Electronic Stability Control* (ESC) [4, 19]. Studies show that equipping a vehicle with ESC reduces the probability of a skid by 33%, a rollover by 59% and the participation in a fatal accident by 25% [1]. Giving direction to the development of driver assistance systems has allowed the development of more advanced technologies to provide information and warnings to the driver and to improve the travel comfort. Due to the fact that additional functions are intended to increase safety and facilitate driving, there are many solutions on the market, including *Park Assist, Autonomous Emergency Braking* (AEB), *Lane Departure Warning* (LDW), *Lane Keeping Assist System* (LKAS), *Road Sign Detection Systems, Pedestrian Detection System* [5, 27, 26]. The use of, for example, the emergency braking system reduces the incidence of vehicle collisions by over 40% [22]. Driver assistance systems are another group of solutions that enable the introduction of autonomous vehicles into serial production. Tesla has developed a technology that allows the vehicle to move independently while being supervised by the driver. All Tesla cars currently produced are equipped with devices enabling fully autonomous driving in the future [3].

Cruise control is one of the devices that can be found used increasingly more often in vehicles. It is defined as a device that maintains a constant vehicle speed. In modern vehicles, three types of cruise control systems are used [21]:

- CCS (*Cruising Control System*),
- ACC (*Adaptive Cruise Control*),
- PCC (*Predictive Cruise Control*).

The task of the traditional CCS cruise control is to maintain the set constant speed regardless of the terrain. In the case of an automatic gearbox, it is also possible to control the gear ratio. The device is automatically switched off by pressing the brake pedal. Currently, there are also solutions that allow the system to remember the last speed setting used [21].

Adaptive cruise control ACC, in addition to all the basic functions, i.e. maintaining vehicle speed, allows the vehicle to adjust its speed to match the speed of the vehicle in front by combining its function with systems responsible for vehicle acceleration and braking. According to the SAE classification, it is classed as the level 1 of driver assistance systems on a scale of 0-5, which determines the degree of vehicle automation [23]. The driver sets the desired speed and the distance from the vehicle in front. The element that determines the distance is the long-range or medium-range radar, which makes it possible to precisely determine the distance even in bad weather conditions. Detection of a vehicle ahead, moving at a lower speed, results in sending a signal to the engine control system that reduces the torque or activates the braking system [7, 9].

The most advanced device is the PCC predictive cruise control. In addition to the functions of the adaptive cruise control, this device uses GPS technology to determine the position and topography of the area. Based on the road elevation profile, the optimal speed and gear ratio are determined, which reduces the observed fuel consumption [28, 15]. In the paper [18] presented the algorithms and quantified the fuel saving benefits. Experimental data show that more than 20 percent of fuel consumption can be reduced using the algorithms compared with conventional constant-speed cruise control.

Driver assistance systems are also used in other types of vehicles. It is common to use a traffic control system in sea and air transport. In aircraft, it allows to automate the guidance and control of the plane by, among others, maintaining altitude, descending and ascending along a designated path to a certain height, or maintaining a given course [2]. Rail vehicles are also equipped with assistance systems that carry out various tasks. An example of this is the Bosch tram warning and emergency braking system, which warns of obstacles and possible collisions at an early stage. If there is no human reaction, it automatically stops the vehicle [10]. In rail vehicles intended for the transport of goods, the Trip Optimizer system by General Electric makes it possible to optimize fuel consumption (while maintaining a given travel time) by calculating the appropriate speed in real time (depending on, among others, location, weight and aerodynamic drag) [24].

In order to optimize fuel consumption in vehicles, the motion resistances are analyzed, including aerodynamic resistance, rolling resistance, climb resistance and inertia. The amount of aerodynamic drag depends on the front surface, drag coefficient, air density and the square of the driving speed according to the formula (1):

$$F_p = 0{,}5\, \rho\, A C_x V^2 \tag{1}$$

where:

F_p – air resistance force [N];

ρ – air density [kg/m^3];

A – vehicle frontal surface area [m^2];

Cx – aerodynamic drag coefficient[-];

V – vehicle speed [m/s].

This means that the aerodynamic resistance increases with the square of the vehicle travel speed, and at high speed values it exceeds the rolling resistance. In the case of rail vehicles, the value of the aerodynamic drag is higher than the rolling resistance in the speed range above 60 km/h [16]. In passenger cars, at 60 km/h, aerodynamic and rolling resistance are comparable to each other [25]. Therefore, it should be noted that air resistance when driving at a high speed is responsible for the major part of the overall energy expenditure of the vehicle. In order to reduce the values of the drag forces in vehicles, it is important to reduce the frontal surface area of the vehicle and to design the vehicle body shape with a low coefficient of aerodynamic drag.

2. Method

The test object was a road vehicle powered by an SI engine, a Skoda passenger car (PC - *Passenger Car*) (Figure 1). The basic technical data of the drive system of the tested vehicle was listed in Table 1. The drive system was a 6-gear manual gearbox. The test vehicle was equipped with a classic exhaust gas aftertreatment system - a three-way catalytic converter (TWC - Three Way Catalyst).

Fig. 1. Test object with the measuring equipment

Tab. 1. Basic technical parameters of the tested vehicle's engine

Skoda Octavia III TSI	
Parameter	**Value**
Ignition type	Spark ignition
Engine type	4 cylinder/in-line, 4 valves/cylinder
Stroke volume	1.8 dm^3
Max. power	132 kW/(5100-6200) rpm
Max torque	250 N·m/(1250-5000) rpm
Engine and exhaust systems	turbocharger, injection system - DI gasoline direct injection + MPI multi-point injection, TWC catalytic converter
Emission norm	Euro 6

The SEMTECH DS apparatus from Sensors Inc. was used to measure the concentration of gaseous substances in the flue gases. The exhaust gas sample was transported through heated lines at 191°C, to the FID (*Flame Ionization Detector*) analyzer responsible for the measurement of the THC. The exhaust gas is then cooled to 4°C and the NOx (NO + NO_2)

value was determined using the NDUV (*Non-Dispersive Ultra Violet*) method. The NDIR (*Non-Dispersive Infra Red*) analyzer was then used to measure the concentration of CO and CO_2. The exhaust gas flow meter recorded the exhaust gas mass flow rate in order to determine the pollutant emission rate [20, 8]. The accuracy of the analyzers is shown in the table 2.

Tab. 2. The accuracy of the analyzers

Exhaust component	Measuring method	Accuracy
CO	Non-Dispersive Infrared (0-10%)	± 3%
HC	Flame Ionisation Detector (0-10000 ppm)	± 3%
NOx	Non-Dispersive Ultraviolet (0-3000 ppm)	± 2.5%
CO_2	Non-Dispersive Infrared (0-20%)	±3%

Obtained results of road emission during tests allowed to determine the fuel consumption the carbon balance method, which uses formula [13]:

$$FC_w = \frac{1154}{\rho_{fuel}} \cdot [(0{,}866 \times HC) + (0{,}429 \times CO) + (0{,}273 \times CO_2)] \quad (2)$$

where:

FC – fuel consumption [$dm^3/100km$];

HC, CO, CO_2 – emission of ingredients harmful [g/km];

ρ_{fuel} – fuel density at temperature 15°C [g/cm^3].

The results of car driving energy consumption measurements in RDE (*Real Driving Emissions*) conditions presented in this article concern the analysis of using the cruise control system function. By definition, it is a device that maintains a constant travel speed of the vehicle regardless of whether the vehicle is travelling on a flat road or on a slope (inclines, declines). Thus, from the point of view of fuel consumption, the use of cruise control is not advantageous due to the necessity, for example, of continuously increasing the fuel dose supplied by the engine injection system in order to maintain the set vehicle speed while driving uphill. When going downhill, the vehicle brakes unnecessarily due to the commands of the cruise control system. However, as presented in the paper [12], driving with conventional control cruise is more efficient on downhill versus uphill sections. Therefore, the aim of the research was to verify the operation of the cruise control in terms of the assessment of energy consumption and cost of the vehicle movement.

The road test section was a 25 km fragment of the S11 expressway (Figure 2). The drives were made from the Poznań West junction to the Poznań North junction each time. This section was characterized by great variation in terms of the terrain profile – with a large number of hills. The maximum recorded difference in height above sea level was over 25 meters (Figure 3).

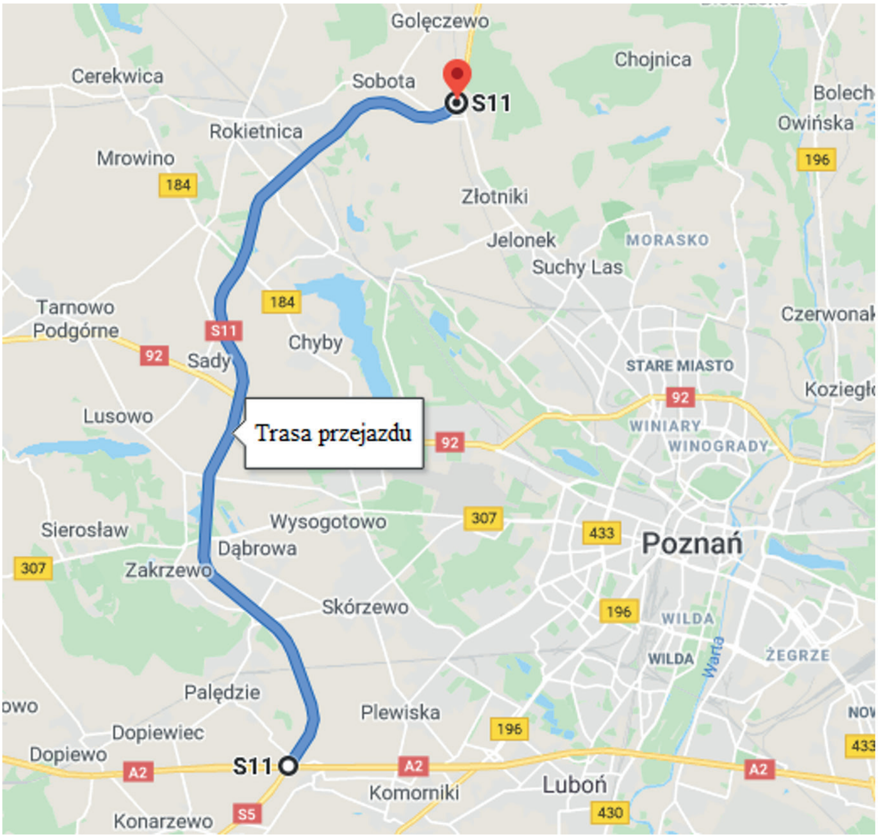

Fig. 2. Test route – the S11 expressway from the Poznań West junction to the Poznań North junction

The measurements were made as follows:

- reference drive at a constant speed of 130 km/h over the entire measuring distance,
- travel at a speed of 120 km/h while driving up hills andat a speed of 140 km/h while driving down hills,
- travel at a speed of 110 km/h while driving up hills andat a speed of 150 km/h while driving down hills.

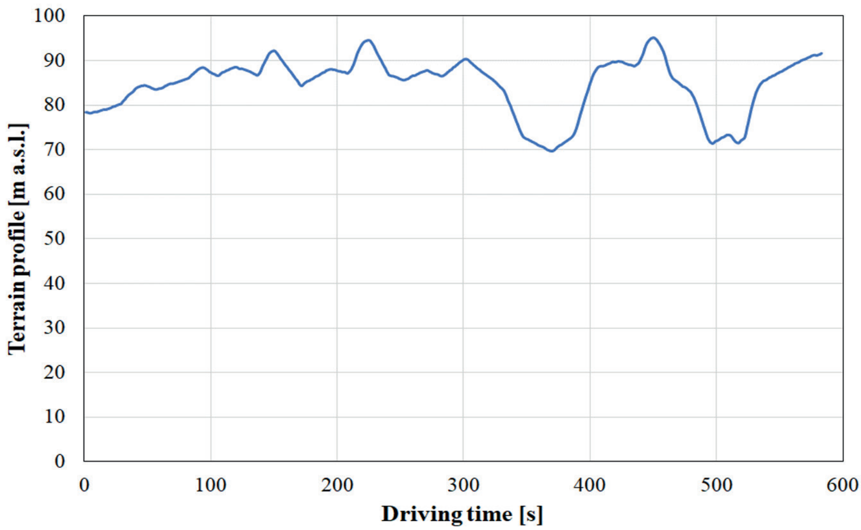

Fig. 3. Test route topology profile

3. Results

The research was conducted for three drives characterized by different travel speeds, but the main goal was to obtain a mean speed of 130 km/h for each one. The travel times are similar, with the reference run being the longest (Figure 4). The remaining travel time values differ by 5 seconds and 11 seconds for the drives with speeds in ranges between (120-140) km/h and (110-150) km/h respectively, compared to the drive with a constant speed. This means that the requirement to achieve a mean travel speed of 130 km/h has been fulfilled, which makes the test drive results comparable. It should be noted that the underestimated value of the speed in Figures 5, 6 and 7 results from the fact that the speed recorded by the GPS was used, which was slightly lower than the value on the pedometer.

The drives took place on a road characterized by heavy traffic. Despite this, it was possible to ensure minimal disruptions in each drive, i.e. changes in speed due to the inability to smoothly overtake slower cars and trucks. The highest number of disruptions to smooth travel was observed for the reference drive. Rapid changes in speed were shown in Figure 5. Five moments were recorded in which the speed decreased. In one case, it was reduced from 130 km/h to less than 100 km/h. During both drives, i.e. in the speed ranges of (120-140) km/h and (110-150) km/h, the speed was reduced seven times, and it increased eight times. The graph presented in Figures 6 and 7 presents a similar characteristic with the difference in speed amplitudes (in the range of (110-150) km/h the speed variations were greater). This indicates a low number of disruptions to travel speed during these test drives.

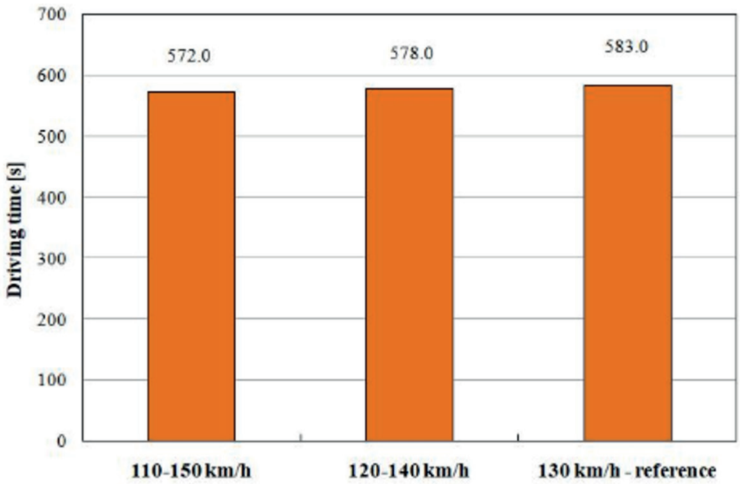

Fig. 4. Travel time through the test road section in relation to the different speed ranges used

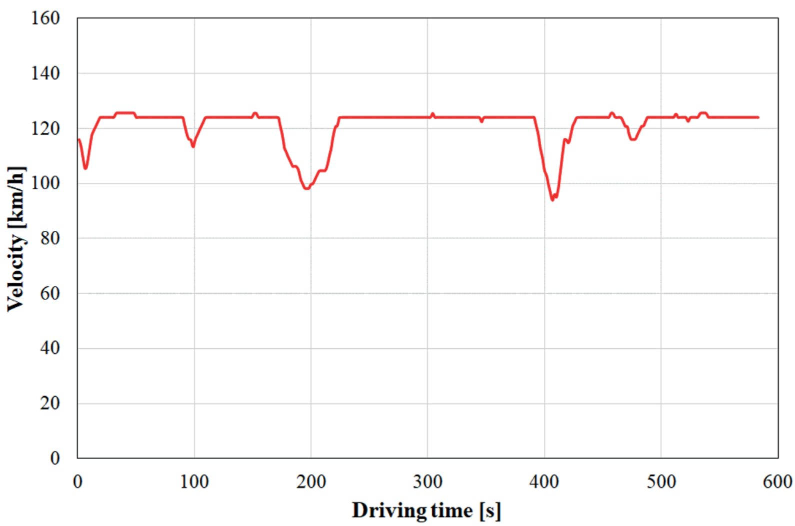

Fig. 5. Vehicle speed profile for V = 130 km/h

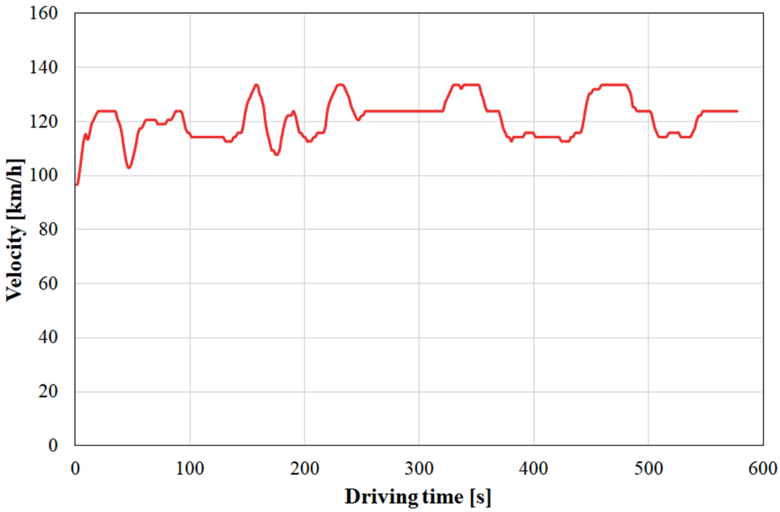

Fig. 6. Vehicle speed profile for V in the range (120-140) km/h

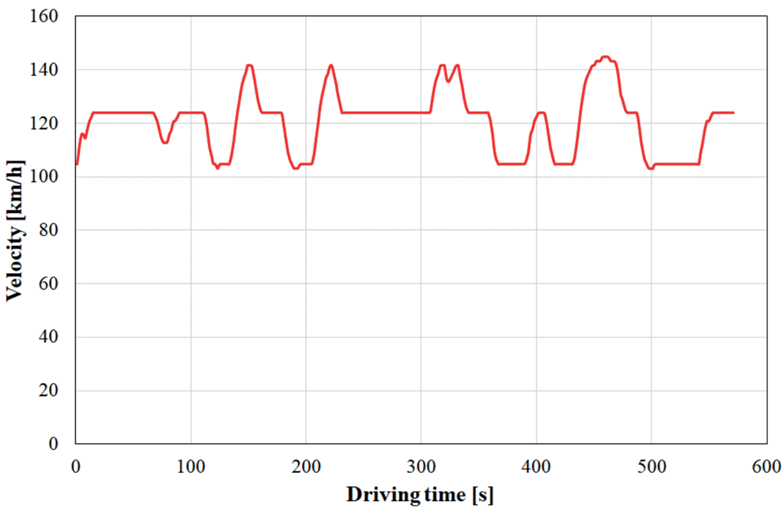

Fig. 7. Vehicle speed profile for V in the range (110-150) km/h

When analyzing fuel consumption for each of the test drives, observable differences were noted. The highest fuel consumption value was recorded for the drive in the speed range (110-150) km/h. It was 7.6 dm^3/100 km. During the test drive with speed in the range of (120-140) km/h the fuel consumption was 7.2 dm^3/100 km. The reference drive was characterized by the lowest fuel consumption value, 6.9 dm^3/100 km (Figure 8). Regarding driving at a steady speed, the vehicle fuel consumption during the test with speeds in the range of (120-140) km/h increased by 3.2% and by 9.1% for speed in the range of (110-150) km/h (Figure 9).

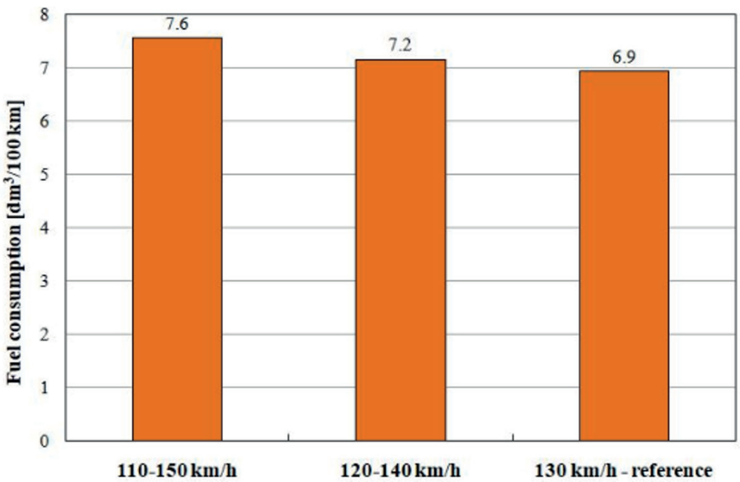

Fig. 8. The test vehicle fuel consumption values for each of the test drives

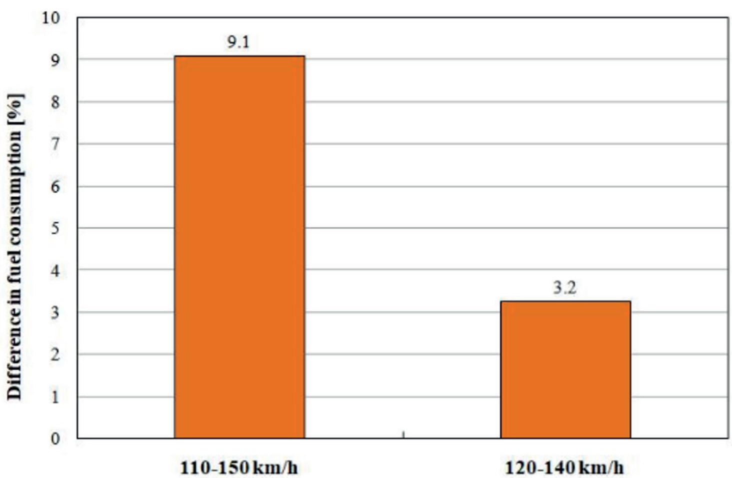

Fig. 9. Percentage change in vehicle fuel consumption in relation to the reference test drive at V = 130 km/h

4. Discussion and conclusions

The study revealed that the highest vehicle fuel consumption value could be found for a test drive at speed in the range of (110-150) km/h. The lowest fuel consumption was recorded for driving at a constant speed. In principle, the use of cruise control, whose task is to maintain a certain speed, is not favorable due to the elevations occurring on the route travelled. Nevertheless, fuel consumption for a single speed drive was still the lowest.

The initial portion of the test route was characterized by a slow increase in altitude. According to the topographic profile, greater differences appeared in the later parts of the test drive. During the test, even with a slight change in elevation, as predicted, it was necessary to reduce or increase the speed of the vehicle. In the case of frequent changes in the elevation level, the car accelerated from the speed specified for driving uphill to the speed when driving downhill. This means that the vehicle speed increased from 120 km/h to 140 km/h (20 km/h difference) or 110 km/h to 150 km/h (40 km/h difference) and also from 120 km/h or 110 km/h to the speed of 130 km/h (difference of 10 km/h and 20 km/h). A greater difference in speeds on a comparable road section is synonymous with an increase in the acceleration value, which increases the fuel dose necessary to achieve the required vehicle speed. This is one of the reasons for higher fuel consumption observed for the drive in the (110-150) km/h speed range, as the speed differences were two time greater than compared to a (120-140) km/h drive. Aerodynamic resistance is also an important factor, which in motor vehicles during high speed driving exceeds the rolling resistance. According to the formula (1), the aerodynamic resistance increases in proportion to the square of the speed. This means a greater difference between the resistive forces at 140 km/h and 150 km/h than at 110 km/h and 120 km/h. At higher speeds, a greater aerodynamic force is created that has to be overcome, which naturally affects the energy expenditure.

Predictive cruise control determines what the vehicle speed should be using information such as the road topography. This means that it is also regulated according to the nature of the incline. During the tests on the Poznań West-Poznań North route in the range of (120-140) km/h and (110-150) km/h, the speed depended only on the occurrence of a change in elevation, i.e. its decrease or increase, and not on the exact value of these differences. Then, such action contributes to the increase in fuel consumption, which was found to be greater than when driving a vehicle operating using a basic cruise control system.

5. Nomenclature

ABS Anti-lock Braking System

ACC Adaptive Cruise Control

AEB Autonomous Emergency Braking

CCS Cruising Control System

CO carbon monoxide

CO_2 carbon dioxide

DI direct injection

ESC Electronic Stability Control

FID Flame Ionization Detector

GPS Global Positioning System

HC hydrocarbons

LDW Lane Departure Warning

LKAS Lane Keeping Assist System

MPI multi-point injection

NDIR Non-Dispersive Infra Red

NDUV Non-Dispersive Ultra Violet

NOx nitrogen oxides

PC Passenger Car

PCC Predictive Cruise Control

PM particulates

RDE Real Driving Emissions

SAE Society of Automotive Engineers

SI spark ignition

TCS Traction Control System

TWC Three Way Catalyst

6. References

[1] Advanced driver assistance systems. European Road Safety Observatory. 2016: https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/ersosynthesis2016-summary-adas5_en.pdf/ (accessed on 15.05.2020).

[2] Automated Flight Control: https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/advanced_avionics_handbook/media/aah_ch04.pdf (accessed on 15.05.2020).

[3] Autopilot: https://www.tesla.com/autopilot/ (accessed on 15.05.2020).

[4] Bengler K., Dietmayer K., Färber B., Maurer M., Stiller Ch., Winner H.: Three Decades of Driver Assistance Systems. Review and Future Perspectives. IEEE Intelligent Transportation Systems Magazine. 2014, 6(4), 6–22, DOI: 10.1109/MITS.2014.2336271.

[5] Bian Y., Ding J., Hu M., Xu Q., Wang J., Li K.: An Advanced Lane-Keeping Assistance System with Switchable Assistance Modes. IEEE Transactions on Intelligent Transportation Systems. 2020, 21(1), 385–396, DOI: 10.1109/TITS.2019.2892533.

[6] European Federation for Transport and Environment AISBL. CO2 Emission From Cars: The Facts. 2018.

[7] Filipiak M., Jajczyk J.: Diagnostyka radarowego systemu ACC. Poznań University of Technology Academic Journals. 2016, 88.

[8] Fuć P., Siedlecki M., Szymlet N., Sokolnicka B., Rymaniak Ł., Dobrzyński M.: Exhaust Emissions from a EURO 6c Compliant PC Vehicle in Real Operating Conditions. Journal of KONBiN. 2019, 49(4), 421–440, DOI: 10.2478/jok-2019-0094.

[9] He Y., Makridis M., Fontaras G., Mattas K., Xu H., Ciuffo B.: The energy impact of adaptive cruise control in real-world highway multiple-car-following scenarios. European Transport Research Review. 2020, 12(1), 17, DOI: 10.1186/s12544-020-00406-w.

[10] Kollisionswarnsystemfür Stadt- und Straßenbahnen: https://www.bosch-engineering.com/de/highlights/kollisionswarnsystem/ (accessed on 15.05.2020).

[11] Leach F., Kalghatgi G., Stone R., Miles P.: The scope for improving the efficiency and environmental impact of internal combustion engines. Transportation Engineering. 2020, 1, 100005, DOI: 10.1016/j.treng.2020.100005.

[12] Ma J., Hu J., Leslie E., Zhou F., Huang Z.: Eco-Drive Experiment on Rolling Terrain for Fuel Consumption Optimization – Summary Report. 2017.

[13] Merkisz J., Dobrzynski M., Kubiak K.: An impact assessment of functional systems in vehicles on CO2 emissions and fuel consumption. MATEC Web of Conferences. 2017, 118, 00030, DOI: 10/1051/matecconf/201711800030.

[14] Napolitano P., Fraioli V., Guido C., Beatrice C.: Assessment of optimized calibrations in minimizing GHG emissions from a Dual Fuel NG/Diesel automotive engine. Fuel. 2019, 258, 674705, DOI: 10.1016/j.fuel.2019.115997.

[15] Nie Z., Farzaneh H.: Adaptive cruise control for eco-driving based on model predictive control algorithm. Applied Sciences (Switzerland). 2020, 10(15), 5271, DOI: 10.3390/APP10155271.

[16] Orellano A.: Aerodynamic of High Speed Trains. Vehicle aero-dynamic lecture. 2010.

[17] Pant P., Harrison R. M.: Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review. Atmospheric Environment. 2013, 77, 78–97, DOI: 10.1016/j.atmosenv.2013.04.028.

[18] Park S., Rakha H. A., Ahn K., Moran K.: Fuel Economy Impacts of Manual, Conventional Cruise Control and Predictive Eco-Cruise Control Driving. International Journal of Transportation Science and Technology. 2013, 2(3), 227–242, DOI: 10.1260/2046-0430.2.3.227.

[19] Sasikala G., Ramesh Kumar V.: Development of Advanced Driver Assistance System Using Intelligent Surveillance. Lecture Notes on Data Engineering and Communications Technologies. 2019, 15, 991–1003, DOI: 10.1007/978-981-10-8681-6_91.

[20] Sensors Inc. Emissions Measurement Solutions. SEMTECH DS On Board In-Use Emissions Analyzer. Erkrath 2010.

[21] Sobczak P., Wąchała J.: Ocena wpływu systemów zwiększających komfort pracy kierowcy na poprawę bezpieczeństwa w transporcie drogowym w opinii kierowców. Autobusy. 2017, 9.

[22] Tan H., Zhao F., Hao H., Liu Z., Amer A.A., Babike H.: Automatic Emergency Braking (AEB) System Impact on Fatality and Injury Reduction in China. International Journal of Enviromental Research and Public Health. 2020, 17(3), DOI: 10.3390/ijerph17030917.

[23] Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-road Motor Vehicles. SAE International. 2018, DOI: 10.4271/j3016_201609.

[24] Trip Optimizer for Railroads: https://www.ge.com/research/project/trip-optimizer-railroads (accessed on 15.05.2020).

[25] Vdovin A.: Investigation of Aerodynamic Resistance of Rotating Wheels on Passenger Cars. Thesis for the degree of licentiate of engineering. 2013, Department of Applied Mechanics, Chalmars University of Technology.

[26] Yang W., Zhao H., Shu H.: Simulation and verification of the control strategies for aeb pedestrian collision avoidance system. Chongqing Daxue Xuebao/Journal of Chongqing University. 2019, 42(2), 1–10, DOI: 10.11835/j.issn.1000-582X.2019.02.001.

[27] Yue L., Abdel-Aty M.A., Wu Y., Farid, A.: The Practical Effectiveness of Advanced Driver Assistance Systems at Different Roadway Facilities: System Limitation, Adoption, and Usage. IEEE Transactions on Intelligent Transportation Systems. 2020, 21(9), 3859–3870, DOI: 10.1109/TITS.2019.2935195.

[28] Zautomatyzowane funkcje regulacji prędkości w pojazdach CF i XF: https://www.daftrucks.pl/pl-pl (accessed on 15.05.2020).

[29] Zimmerman N., Wang J. M., Jeong C., Wallace J. S., Evans G.J.: Assessing the Climate Trade-Offs of Gasoline Direct Injection Engines. Environmental Science&Technology. 2016, 50 (15), 8385–8392, DOI: 10.1021/acs.est.6b01800.