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DETERMINING THE FUEL CONSUMPTION REQUIRED FOR AIR-CONDITIONING OF A PASSENGER CAR UNDER REAL-WORLD CONDITIONS

ABSTRACT: This paper presents an investigation of the impact of air-conditioning system operation on fuel consumption in real operating modes of a used passenger car. The motivation for the work is to determine additional amount of fuel needed for cabin air-conditioning in real driving conditions without the use of complex laboratory equipment. Official data on standardized fuel consumption are determined with the air-conditioner switched off and under strictly controlled conditions. Data available from the car's diagnostic data connector were acquired, processed and analysed. The results showed that an air-conditioner with a variable compressor increases fuel consumption by about 0.5-0.6 l/100km at speed 70 km/h. At the same car velocity, the fuel consumption depends on selected gear, i.e. on the engine speed and compressor speed. In this experiment, the better results were achieved in higher gear, i.e. at lower engine and compressor speed. Depending on the architecture of the OBD system in the car, the presented method could be used for more complex research into individual factors on the energy management of the car's HVAC system as well as other systems.

KEYWORDS: passenger car, air-conditioning system, fuel consumption, microclimate, diagnostic scanner

ODREĐIVANJE POTROŠNJE GORIVA POTREBNE ZA RAD KLIMA-UREĐAJA AUTOMOBILA U REALNIM USLOVIMA

REZIME: Rad predstavlja istraživanje uticaja rada klima-uređaja na potrošnju goriva automobila u stvarnim uslovima. Cilj rada je određivanje vrednosti dodatne količine goriva potrebne za klimatizaciju kabine u realnim uslovima vožnje, bez primene kompleksne laboratorijske opreme. Zvanični podaci o potrošnji goriva nekog automobila se određuju na standardizovani način, sa isključenim klima-uređajem i u strogo kontrolisanim uslovima. Raspoloživi podaci sa dijagnostičkog priključka automobila su sakupljeni, obrađeni i analizirani. Rezultati su pokazali da klima-uređaj sa varijabilnim kompresorom u datim uslovima povećava potrošnju goriva za oko 0,5 do 0.6 l/100 km pri brzini 70 km/h. Pri istoj brzini kretanja potrošnja zavisi od stepena prenosa menjača, odnosno od broja obrtaja motora, tj. broja obrtaja kompresora. U zavisnosti od arhitekture OBD sistema u automobilu, prikazani metod bi se mogao koristiti i za kompleksnija istraživanja pojedinih faktora na upravljanje energijom HVAC sistema ali i drugih sistema.

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KLJUČNE REČI: automobil, klima-uređaj, potrošnja goriva, mikroklima, dijagnostički uređaj

INTRODUCTION

Energy/fuel consumption is an area that has been continuously improved since the advent of vehicles, whether they are powered by internal combustion engines, hybrids, or electric drivetrains. A heating, ventilation and air-conditioning system (HVAC), as a standard equipment of nowadays cars, is the largest power consumer, excluding the propulsion system (Leighton and Ruth (2016), Grossmann (2010)). The thermal comfort requirements must be achieved in every vehicle as fast as possible, with fresh air supply of breathing zone, low air velocities, moderate surfaces' temperature and low noise of ventilation system. In contrast to vehicles powered by internal combustion engine (ICE), HVAC system in battery electric (BEV) or hybrid electric vehicle (HEV) significantly influences the available driving range, sometimes to factor of 2 (Cigarini et al. (2021), Mišanović et al. (2018)).

Official data about energy consumption and emission are provided under the conditions where only the equipment necessary for the operation of the vehicle during the test is in use (for example, UN ECE regulation No 101 says: The passenger compartment heating system shall be switched off, as shall any air conditioning system...). Standards for requirements of thermal comfort in vehicles (standards ISO 14505-2, DIN 1946-3 and ASABE 14269-2) does not consider the energy consumption of HVAC system.

The most advanced and repetitive method for investigation of vehicle's and its systems' performances are experiments performed in laboratory conditions. However, in area of microclimate and thermal conditions those facilities have very high costs and complexity as well as energy consumption (Ružić and Poznanović (2021)). Field experiments with more or less simple mobile equipment can provide useful results for further investigation or simulation. Modern vehicles offer easy approach to data from onboard sensors and actuators thank to on board diagnostics system (OBD) and standardized protocols and connector. In the case study of Šarkan et al. (2025), various methods of measuring fuel consumption in laboratory conditions were analysed, including the use of a fuel flowmeter, OBD scanner and calculation based on emission tests. A relative difference between the fuel consumption measured by the OBD device and the volumetric flowmeters was around 5%. Abukhalil et al. (2020) used data from OBD to form a relationship between the monitored parameters and the fuel consumption. Their model showed good correlation with the data obtained by the conventional methods. Data from OBD port for energy consumption calculation were used in the study of Li, C. et al. (2018). The authors examined the effects of different cabin air ventilation settings on air-conditioner (AC) power consumption in plug-in HEV. They found out that AC compressor used about 12% and 30% of total power consumption, in air recirculation and fresh air mode, respectively. Thermal conditions inside the passenger compartment were not in the focus of this research.

Taking into account that AC system in passenger cars is standard equipment for almost 20 years, total energy required for air-conditioning of cars in operation can not be negligible. Furthermore, cars with conventional propulsion system (internal combustion engine), manual gearboxes and mechanically driven AC compressors are still produced and sold. The objective of this study is to experimentally investigate difference in fuel consumption of a used mid-sized passenger car with and without AC system turned on, in hot outside conditions. The car was driven at constant speed, in fourth and fifth gear, in order to have measurement with two compressor speeds. Additionally, the thermal conditions inside the passenger compartment were measured. The results should give an insight in factors that influence percentage of the power required for air-conditioning of the used common car's cabin in typical summer conditions in Central Europe region.

THEORETICAL BACKGROUND

A moving vehicle consumes energy on outer resistances (rolling resistance, air drag, road slope, acceleration) and inner consumers (electric and electronic systems, comfort systems, auxiliary systems...). The sum of the power requirements reflects in total energy consumption, and sometimes is not easy separate individual power consumers. Instead of direct measurement of the power used by AC system, comparison of instantaneous fuel consumption between drive with AC system switched off and with AC system switched on under the same other conditions was used in this study.

This measurement can be done by installation of suitable measuring equipment on the vehicle's engine. However, available data from the vehicle electronic control units (ECU) can be used to obtain comparable results. Data from the ECU are readable by commercial diagnostic tool (scanners) that is connected to the vehicle over existing and standardized data link connector (DLC). Diagnostic tool is connected to laptop with diagnostic software, enabling monitoring and recording of the data from the vehicle. The method for data acquisition is use of real-time values from ECU and sensors, and recording them over a chosen period of time. Once recorded on the computer, the data can be analysed using a commercial mathematic software (MS Excel, for example).

Fuel consumption calculation

The basic data available from the engine ECU needed to calculate fuel consumption are

- injection fuel quantity, m_f, mm^3
- engine speed, n, RPM
- vehicle speed, v, km/h

If the ECU sends data on fuel consumption in milligrams, conversion of mass values to volume values by specific gravity of fuel is necessary.

The range of data and units depend on type of vehicle and on type of diagnostic tool and software used.

Hourly fuel volume consumption of 4-stroke 4-cylinder engine:

$$g_h = \frac{n \cdot m_f \cdot 3600}{30 \cdot 10^6}, \left[\frac{\mathrm{l}}{\mathrm{h}}\right] \tag{1}$$

Instantaneous fuel consumption in litres per 100 km:

$$g_{100} = 100 \cdot \frac{g_h}{v}, \left[\frac{\mathrm{l}}{100\ \mathrm{km}}\right] \tag{2}$$

Additional real-time value for monitoring of the AC system wokring conditions is the AC system high-side pressure, as well as other related to AC system that are available in particular OBD system.

Thermal conditions inside a cabin

Thermal conditions inside the car's cabin are also important indicator of AC efficiency. The basic parameter to describe thermal conditions is an air temperature. However, the other influences on heat exchange between the human body and the vehicle cabin must be considered (Grossmann H. (2010), Parsons K. (2003), Ružić and Časnji, (2012), standards ISO 14505-2 and DIN 1943-2). In this research, air temperature, air velocity and radiant temperature were measured in the co-driver's head zone.

MATERIAL AND METHOD

The experiment was performed on used passenger car, driving in different regimes on a selected public road. The same route was travelled with the AC system turned on and with the AC system turned off. Real driving conditions are consisted of nonstationary regimes of driving, but since acceleration, deceleration and braking can not be neither defined nor repeated precisely within the given conditions, the results from driving at steady speed controlled by cruise control were analysed in this paper. Since the test route was not without disturbances hence the driving resistances, the experiment conditions could be treated as quasi-steady driving conditions.

The vehicle specification

Experiments in this study were performed on the used passenger car Peugeot 307 (Figure 1). The vehicle specifications are given in the Table 1.



Figure 1 Passenger car used in the experiment: Peugeot 307, 2007

Table 1 The car specifications (https://www.ultimatespecs.com/car-specs/Peugeot/949/Peugeot-307-16-HDi-110.html, visited 06.03.2026.)

Make and model	Peugeot 307 1.6 HDI, 5-door hatchback
Model year/Year of manufacture	2005/2007
Test vehicle mass /Gross vehicle mass	1370 kg / 1810 kg
Tyres	195/65R15 M+S
Engine	PSA 9HZ DV6TED4: 4-cylinder turbodiesel, 80 kW at 4000 min^{-1}, 240 Nm at 1750 min^{-1}
Gearbox	manual, 5-speed, i_4 = 0.82, i_5 = 0.66, i_{fd} = 3.79
AC	variable compressor Sanden SD6C12, 120 cm^3, refrigerant r134a, pulley diameter 120 mm (1:0.76), automatic control
Body colour	black, metallic
Fuel Consumption (NEDC): City/Open road/Combined	6.1/4.3/4.9 l/100 km
CO_2 emission	129 g/km

Measuring equipment

Diagnostic scanner Bosch KTS 590 was connected with the car via standard DLC. The data were transferred to laptop with ESI[tronic] 2.0 software.

Recording the data from air temperature, air velocity and radiant temperature Brüel & Kjær sensors was carried out with Indoor climate analyser Brüel & Kjær 1213.

The pyranometer was used to record solar irradiation at the beginning and the end of the measurement.

The specification of the measuring equipment used in the experiment is presented in the Table 2.

Table 2 The specifications of the measuring equipment

Name	**Specifications**
Diagnostic scanner Bosch KTS 590 with Esi[tronic] 2.0 software	-
Brüel & Kjær 0034 air temperature sensor	Pt100, accuracy ±0.2°C from 5 to 40°C
Brüel & Kjær 0036 radiant temperature sensor	Pt100, range 50 K, accuracy 0.5 to 2.0 K
Brüel & Kjær 0038 air velocity sensor	constant temperature anemometer, range 0.05 to 1 m/s, accuracy ±0.05 m/s
Benning Sun 2 pyranometer, insolation measuring device	insolation range 100-1250 W/m^2

THE EXPERIMENTAL SETUP

The driving conditions:

- driving in both direction of chosen route on public road,
- steady speed of 70 km/h in cruise control mode,
- driving in 4th and in 5th gear.

Settings of HVAC system:

- AC in the lowest temperature settings,
- fan speed set to half,
- fresh air mode,
- the air vents on the instrument panel were set in horizontal middle position,
- all windows closed.

The vehicle condition:

- two persons inside the cabin,
- the engine on operating temperature (79-85°C),
- fuel tank half full,
- dipped beam switched on (daylight running lights),
- the AC was turned on before the measurements and the first set of measurements was performed with the air conditioner turned on, in order to stabilize the system operation.

Ambient conditions:

- date: 03.07.2025., start of the experiment at 10:40, end at 11:05,
- outside temperature 32 °C, (https://www.wunderground.com/weather/rs/novi-sad, visited 03.07.2025),
- relative humidity (RH) 20% (https://www.wunderground.com/weather/rs/novi-sad, visited 03.07.2025),
- insolation 916 W/m^2, clear sky,
- no wind.

Test road:

- Irmovo road, near Novi Sad, South Bačka District, Serbia,
- flat and paved,
- section of the road to which the displayed results refer: length 1.9 km, (Figure 2)



Figure 2 Road view and satellite view of measurement road section (https://www.google.com/maps/, visited 24.07.2026.)

The sensors for measuring thermal conditions inside the cabin, described in the Table 2, were placed in the co-driver's head zone on plastic dummy (Figure 3) and in one central air vent on the dashboard.



Figure 3 Layout of the sensors for measuring microclimate parameters

The results and discussion

Fuel consumption

The results of fuel consumption in litres per 100 km with AC turned on and off are graphically presented in figures 4 and 5, for constant speed drive in 4th and 5th gear, on the part of the road section. As can be seen from the results, the instantaneous fuel consumption is very variable, although the vehicle speed was maintained constant, because of small but significant changes in driving resistances. Therefore, the results from acceleration phases and other transient regimes were not presented in this study.

The car speed recorded by diagnostic scanner was in range from 66 to 67 km/h, while engine speed data was 1767 min^{-1} and 1413 min^{-1} in 4th and 5th gear, respectively.

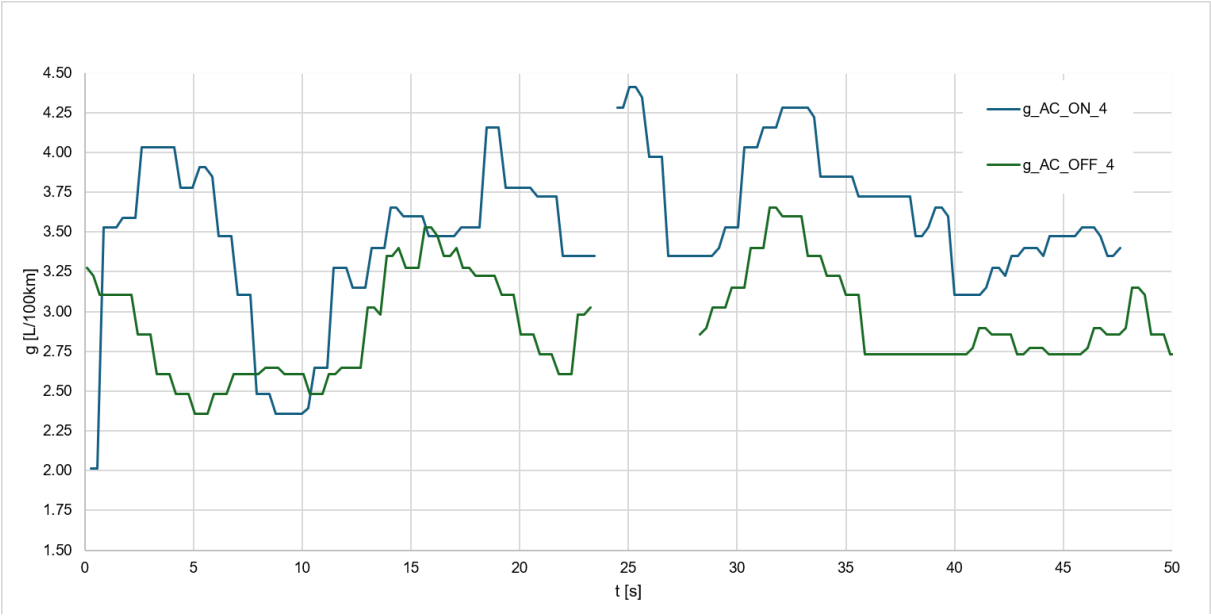


Figure 4 The results of instantaneous fuel consumption (*g*) for constant speed drive in 4th gear, in both direction

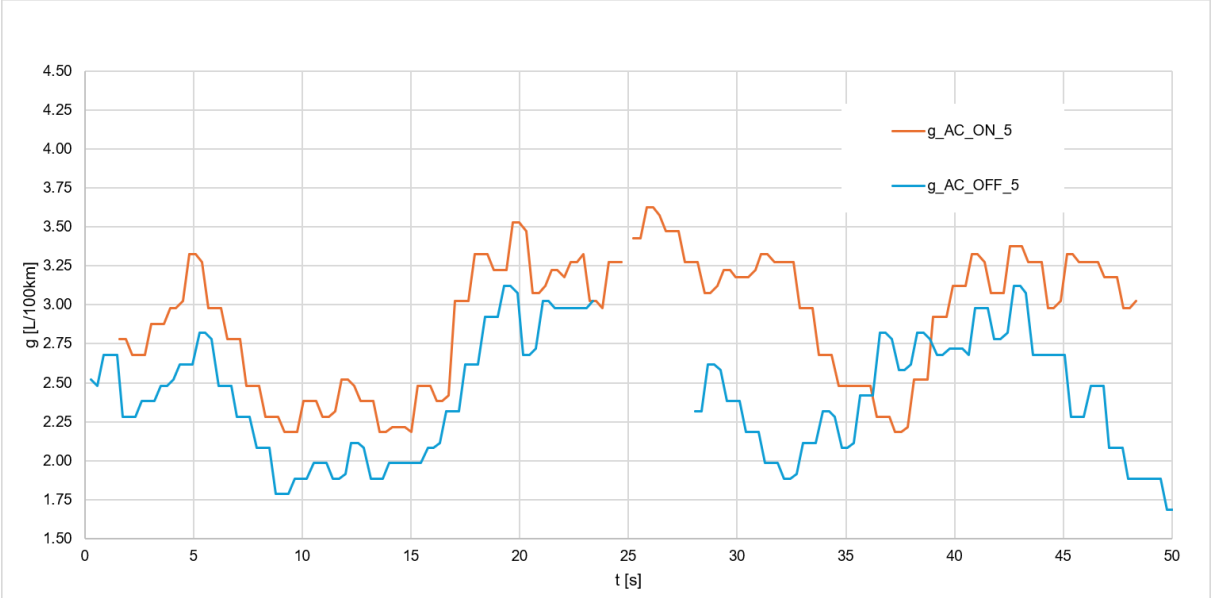


Figure 5 The results of instantaneous fuel consumption (*g*) for constant speed drive in 5th gear, in both direction

Table 3 gives insight in average values of fuel consumption, absolute and relative differences between the combination of driving regimes, during the steady car speed. The relative between consumption between 4th and 5th gear is showing percentage of the fuel consumption decrease.

Table 3. Average values of fuel consumption, absolute and relative differences between fuel consumption with and without air-conditioning, and between fuel consumption in 4th and 5th gear

	4th gear	5th gear	difference	reduction compared to 4th gear
AC on	3.52 l/100 km	2.91 l/100 km	0.61 l/100 km	17%
AC off	2.92 l/100 km	2.39 l/100 km	0.53 l/100 km	18%
difference	0.61 l/100 km	0.52 l/100 km	0.09 l/100 km	15%
relative increase compared to the AC off	21%	22%		
% of total energy	17%	18%		

A power required to move the car at 70 km/h is the same in the 4th and 5th gear. The absolute values in Table 3 shows that the efficiency of the IC engine is higher in the working point when the transmission is in 5th gear.

Almost the same values of the relative fuel consumption increase, and in turn the percentage of total energy required to drive the AC system, indicates that the AC system energy was approximately the same in both gears. Moreover, the percentage of total energy required to drive the AC system corresponds to the values given by Li, C. et al. (2018) for HEV.

The recirculation of the cabin air could reduce required power, but this is short-time solution (up to 15 minutes) because of influence on cabin air quality.

Air-conditioning system

The working points of AC system were

- 4th gear: high pressure 13,5 bar, compressor speed 2320 min^{-1}
- 5th gear: high pressure 12,3 bar, compressor speed 1860 min^{-1}

According to the compressor manufacturer's data, coefficient of performance (COP) decreases for around 5% with compressor speed, but available cooling power increases, depending on swept volume setting (Sanden, Figure 6). However, refrigerant flow rate as well as swept volume setting of the variable compressor could not be measured.

Comparing the thermal conditions in the cabin for the two modes, there was no significant difference in any of the monitored parameters.

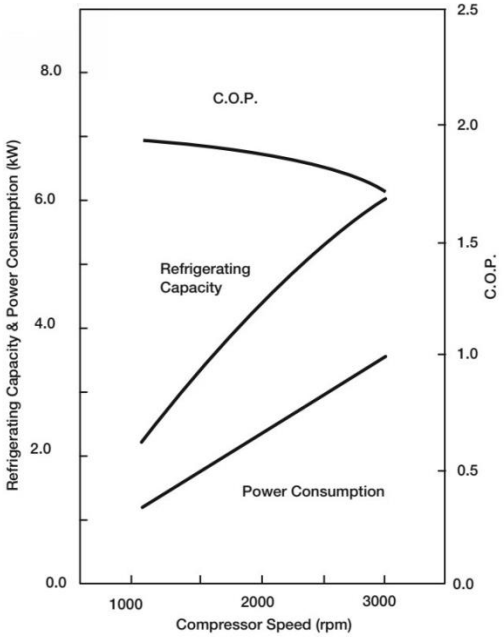


Figure 6. Performance curves of AC compressor Sanden SD6C12 (Sanden)

Cooling power was higher than initial cabin heat gain, since the air temperature and radiant temperature were decreasing when the AC was turned on. When the AC was turned on the air temperature in the air vents dropped from 30 °C to 8 °C in two minutes. The air temperature in the co-driver head zone has been changed from around 35 °C to 30 °C in 10 minutes.

Thermal conditions inside the cabin

An overview of the thermal conditions during the experiment is given in the Table 4.

Table 4. Thermal conditions in co-driver head zone

Parameter	Minimum	Maximum	Average	Comment
Air temperature	30.3 °C	36.5 °C	33.3 °C	corresponds to changes of the temperature in air vent
Air velocity	0.2 m/s	0.5 m/s	0.3 m/s	within comfort zone
Turbulence intensity	23%	59%	39%	within comfort zone
Radiant temperature	34.4 °C	41.6 °C	38.2 °C	the maximum value was from the direction of the windshield

Despite of activated AC system, the air and radiation temperatures in the cabin were very uncomfortable. The causes were high intensity of solar irradiation and relatively short time of the monitoring. The lowest values of air temperature and radiant temperature were recorded after the AC was turned on for a while. The temperatures will continue to drop until equalization of cooling power and cabin heat gain, if the same conditions were maintained longer.

The radiant temperature decreased more slowly than the air temperature, because it is related to the temperature of the cabin interior surfaces, which represents a thermal mass that must be cooled by convection. A higher level of thermal radiation was recorded from the direction of the windshield. Irradiation at horizontal surface under the windshield measured by the pyranometer was 404 W/m^2.

The air velocity and turbulence intensity were independent from air velocity and activation of AC system and they were within the comfort limits.

CONCLUSIONS

This paper presents the experimental investigation of fuel consumption required for air- conditioning in a used mid-sized passenger car under real-world conditions, in hot outside conditions. The fuel consumption was determined by difference in fuel consumption of a passenger car with and without air-conditioner turned on.

The data were collected under quasi-steady driving conditions, at a constant car speed using cruise control, in fourth and fifth gear. Thermal conditions inside the passenger compartment were measured as well.

This relatively simple experiment resulted in following concluding remarks:

- The instantaneous fuel consumption is very variable, even when the vehicle speed was maintained constant.
- The AC system required a power equivalent to increase of ICE fuel consumption from 0.5 to 0.6 l/100 km, depending on its working point.
- The percentage of total power required to drive the AC system was less than 20% when the car was driven at speed 70 km/h.
- In a car with manual transmission and ICE driven AC compressor, fuel consumption of both car and AC system relies on driver's decision about gear selection.
- Both AC system and ICE achieved a better efficiency in 5th gear, which means operation at lower engine and AC compressor speed.
- The air temperature and especially radiation temperature in the cabin were uncomfortable during the experiment and more time is needed to establish better thermal conditions, probably longer than 30 minutes under current conditions.

The boundary conditions in this experimental study were very unfavourable but also very common in a passenger car exploitation in typical summer conditions in Central Europe region. The power demand of the AC system is the highest at the beginning of cool-down regime, in order to as fast as possible obtain acceptable thermal conditions inside the cabin. The recirculation of the cabin air could reduce required power, but this is short-time solution (up to 15 minutes) because of influence on cabin air quality.

New BEVs and HEVs are already equipped with electricaly driven AC compressors and automatic control of thermal and energy management. However, conventionaly driven cars still have a large market share. Along with large number of conventional cars in operation equipped with AC, the use of AC in cars is longer and more frequent as a consequence of increasing global temperatures. One way to mitigate the problem with increased fuel consumption and in the same time emission due to air-conditioning of existing cars, would be an education of the car drivers about proper setting and control of the HVAC system as well as the car. The interface of the air conditioning system also plays an important role in the proper use of the system.

A direction of further investigations could be collecting a more data from real-word driving cases, depending on the architecture of the OBD system in different cars. Stable thermal conditions inside the cabin achieved after a sufficiently long drive should also be the subject of research, as the relationship between maximum cooling power during cabin cool-down regime and lower energy consumption during steady-state driving is important in terms of system dimensioning and selection of operating points with the highest efficiency. This would enable an expansion of the research into considering of more factors on the energy management of the car's HVAC system as well as other systems.

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