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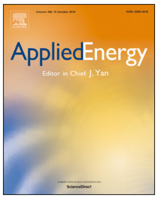

Computational performance analysis of overheating mitigation measures in parked vehicles

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HIGHLIGHTS

- EnergyPlus is capable of accurately estimating the heat transfer in parked vehicles.
- Spectrally selective glazing can cause an average temperature difference inside the cabin as high as 12.5 °C.
- Solar-reflective opaque coating in combination with ChLC glazing can reduce the cabin air temperature up to 23.8 °C.

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ABSTRACT

Parked vehicles have the tendency to overheat quickly. This can lead to a negative impact on the thermal comfort of the driver and its passengers, as well as intensive use of air conditioning systems, and thus fuel consumption of the vehicle or, in the case of electric mobility, a reduced cruising range. In the search for effective measures to mitigate this effect, important guidance can be provided by the field of sustainable building design. On the one hand, inspiration can come from design strategies in terms of shapes and advanced cover materials, but this paper advocates that this can also pertain to the simulation-based design support tools that are used by building engineers. This paper first presents the results of a thermal soak test, and then uses this data to demonstrate the suitability of the building performance simulation tool EnergyPlus for predicting the thermal behavior of parked vehicles. This fit-for-purpose validated model is used to evaluate the performance of three overheating mitigation measures for two car models in two climates. The results show that spectrally selective glazing can reduce the cabin air temperature by 12.5 °C and when combined with solar reflective opaque surfaces, the reduction of cabin air temperature can reach 23.8 °C. Increased use of building performance simulation in the automotive domain can help to further optimize the overheating reduction potential of cars.

1. Introduction

Management of thermal conditions inside vehicles is important to ensure the comfort of passengers [1,2]. It is of particular concern, due to the existing correlation between high cabin temperatures and reduced driver vigilance, and hence, higher accident rates [3,4]. Already after a short period of time, the cabins of vehicles parked in unshaded areas can reach temperatures that are 20–30 °C higher than the ambient [5,6]. Automobile air conditioning (AAC) systems used to be an exclusive add-on option. However, nowadays, nearly all new cars are sold with AAC systems, in both industrialized and developing countries [7,8]. AAC use is identified as the largest contributor to the auxiliary energy consumption of cars (i.e. the part that is not used for propelling the vehicle), and hence has a great influence on fuel economy and associated emissions [9]. As a consequence, there has been significant attention for enhancing the efficiency of AAC systems, as well as for improving their operation strategies [10,11].

With the rise of electric vehicles (EVs), car manufacturers for the first time also have an intrinsic motivation to promote reduced AAC use, because it has a direct influence on driving range; one of the most important factors in the purchasing decision of EVs [12–14]. Studies have shown that the seasonally-averaged loss in EV battery range due to AAC energy use can go above 23% [15,16]. Finding ways to reduce this impact can act as a main incentive towards widespread adoption of sustainable electric mobility. Preventing that cars already get too warm when they are not in use, is a good strategy to begin with.

The design of the body of a vehicle (i.e. shape, size and materials selection) has a considerable influence on its potential for overheating

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[17]. In this context, it is interesting to draw a parallel to the building industry. While passive overheating reduction measures are commonly applied and quite well understood for building envelopes [18–20], it is a relatively new field of investigation in the automotive sector. The physical principles that govern the thermal energy balance of the exterior shell are the same for parked vehicles as for buildings. Not only can car manufacturers and designers take inspiration from proven technologies in the construction sector [21], but they can potentially also take advantage of the performance analysis and design support approaches that have been developed in this field. The potential of using computational building performance simulation tools has previously been explored for long-haul truck cabins [22], but applications for passenger vehicles were not found in literature.

This paper has two main objectives. The first one is to validate the suitability of a building energy simulation program for the purpose of predicting the heat transfer and temperature profiles in parked vehicles. This is done using an experimental thermal soak test and the simulation program EnergyPlus, as described in Section 2. The second objective is to use the simulation tool for a comparative performance analysis of three overheating reduction measures for different climatic conditions and vehicle types. Three overheating reduction measures are investigated: spectrally selective glazing, solar reflective opaque surfaces, and windshield sunshades. The set-up of this case study is described in Section 3, and the results for four characteristic days, as well as the annual performance, is discussed in Section 4. The last Section of this article (Section 5) concludes by summarizing the main findings and providing directions for further research.

2. Experimental validation of the simulation model

Most of the widely-used building performance simulation (BPS) software tools have undergone rigorous validation and quality assurance procedures [23]. The governing physical principles for heat and mass transfer in cars and buildings are similar. However, it is also known that there are certain “hidden” assumptions and semi-empirical formulations in BPS models that work well for buildings, but may impair the credibility of predictions when used outside the intended application domain [24]. Before BPS can confidently be applied to model the thermal performance of vehicle cabins, it is essential to ascertain the quality of the predictions. There are a few papers available in literature that present results of temperature measurements in parked cars [5,25,26]. However, these papers do not provide all information that would be needed to set up a comprehensive validation study, such as exact weather conditions of the day of the experiment and the material properties of vehicle body and windows.

In this study, a new experimental campaign was carried out, to overcome the data availability limitations in published literature.

2.1. Experimental procedures

A dark blue Citroën C3 (Fig. 1), is used for the thermal soak tests. The shape and dimensions of the body, including side, rear, and front windows are shown in Fig. 2.

The soak test was performed by parking the car with its front facing the south-east direction. The experiment was performed under clear sky conditions (30th March 2016), exposed to direct sunlight in a shading-free area, near the meteorological station of TITAN cement company S.A. at the site in Thessaloniki, Greece. The meteorological station is located at an elevation of 112 m, 40.7° latitude and 22.95° longitude. Three air temperature sensors were placed inside the vehicle’s cabin in order to investigate the interior temperature distribution. The first sensor was placed close to the dashboard, while the second sensor was placed behind the driver’s seat. Finally, a third sensor was placed between the front seats, at the passenger’s breathing level. The locations where the three sensors were placed are depicted in Fig. 3. All sensors were not in contact with any surface and were surrounded by an aluminum foil cylinder that functioned as a radiation shield, so that the sensors would not be affected by direct solar radiation.

Fig. 1. Vehicle used in experiments: Dark blue Citroën C3, Latitude: 40:7, Longitude: 22:95, Elevation: 112 m, time-zone: UTC/GMT +2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

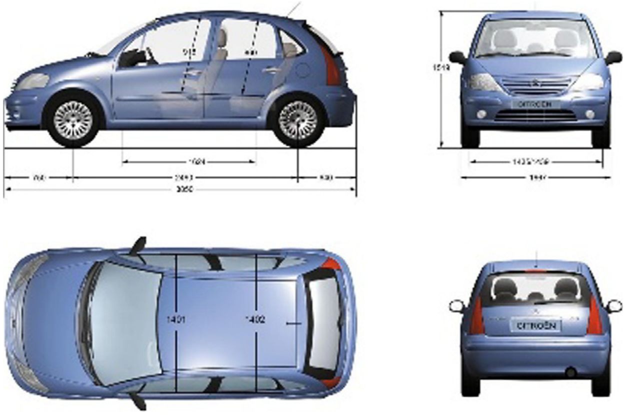

Fig. 2. Dimensions of the vehicle used in experiments (Citroen C3).

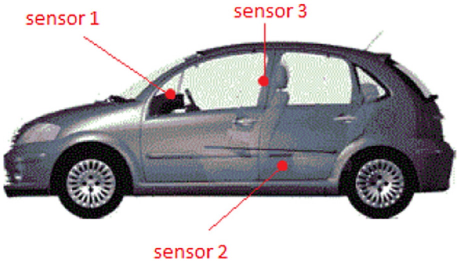

Fig. 3. Locations of the cabin temperature sensors.

The vehicle’s doors and windows remained sealed during the experiment and the measurements were obtained through the thermometers’ recorder, which was placed outside of the vehicle and was connected to the sensors through a cable.

Dry-bulb outside air temperature and global horizontal solar irradiance during the time of the experiment were taken from the neighboring weather station.