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Thermal comfort assessment in the modern passenger car under actual operational conditions

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Abstract
People's ever-increasing needs encourage designers of various vehicles to search for solutions that will provide the most comfortable internal environment conditions. Currently, partly due to the COVID-19 threat, many people use their individual cars to travel to work, college, shops, trips, and holidays. Proper internal air parameters that need to be maintained in vehicles are critical in the summer. The article discusses the thermal comfort of four passengers of a modern car produced in 2017 to verify if contemporary production technology can successfully meet the thermal needs of people under actual conditions in the Polish climate. For this purpose, five temperature values were tested: 20°C, 22°C, 24°C, 26°C, and 28°C for the car located in the shade and sun. In addition, the Testo 400 meter was used to control and measure the internal parameters, and questionnaires were used to find out about the thermal impressions of the respondents. The research was carried out in July when the air temperature in Poland was high.

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1. Introduction

Nowadays, passenger cars play a huge role in everyone's life. They allow you to cover long distances quickly, making people more mobile. Therefore, it would seem important that everyone feels satisfied with the internal environment when traveling. The internal conditions in the car affect the quality of the trip, well-being, nausea caused by excessive heat or chills due to excessive cooling of the air with air conditioning, and driving safety. The factors determining such an environment are air temperature, relative humidity, and air velocity (velocity caused by the cooling and heating system). In addition, essential elements of people's actual feelings are their clothes, body weight and age (Body Mass Index), and the speed of metabolism.

Many scientists are currently conducting research related to comfort in passenger cars and mass transport. One such example is the study (Danca et al., 2020), which used a dummy positioned in the center of a car parked in the shade and in the sun to analyze the effect of sunny weather on the exposed parts of the dummy's body. It turned out that in the places with no clothes, the temperature was around 36°C, and thus the temperature in the car increased by 10°C. The authors of the work (Zhou et al., 2020) examined the thermal comfort of 24 people in a car who experienced three different environmental conditions. The results confirmed that none of the studied models of thermal sensations could predict people's thermal sensations. Additionally, it should be mentioned that the same authors (Zhou et al., 2019) examined the feelings of a person driving a car. It turned out that the state of well-being of this person changed, for the worse, due to the influence of air conditioning. Thermal sensations were also examined by (Krawczyk et al., 2021; Danca et al., 2016; Ravindra et al., 2020; Khatoon and Kim, 2020) in passenger cars from the analysis of the Fanger model to the thermal comfort indices. Simon and his co-workers (Simion et al., 2016) also focused their attention on solar radiation, as did (Zhou et al., 2020; Danca et al., 2016). However, the main topic was the calculation and learning about Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). The research itself provided information that the main reason, according to the respondents, is too high air velocity, and any change in it, even a small one, may worsen the state of people's feelings.

Furthermore, authors (Rolle et al., 2021) conducted research on two types of cars, representing the middle class and the upper one. The test was performed outdoors in the temperature range from -20°C to +40°C. What is more interesting, it might seem that a higher-class car will prove to be a much better sphere to feel thermal comfort, but according to the respondents, this is not the case, and the middle class fares better with it. Moreover, the actual answers of the respondents did not correspond to the guidelines of the norm. Meanwhile, other authors (Feng et al., 2021) chose an air-conditioning blower in the car to assess passengers on a sunny day for various parameters, and it turned out that the driver felt the blowing best. Other studies related to in-car comfort were conducted by (Ravindra et al., 2020; Saleel et al., 2019) In both studies, hot, dry, and humid climate was used in order to solve the problem of rapid heating of the car body, which in both studies is a source of increasing discomfort.

Public transport is a no less important vehicle in which most people spend their time. Therefore, scientists invited 32 people to study three variants of temperature and 5 different levels of noise and accelerated vibrations. After the analysis, it turned out that it is noise and vibration that has a significant impact on the thermal sensation. More interestingly, these studies also provided additional information that changes in noise and vibration can cause an increase in heart rate and increase human metabolism (Zhou et al., 2021). A similar subject was chosen by (Cigaarini et al., 2021), examining not only thermal comfort but also energy consumption in an electric bus. Another study in which the main thought was the impact of the internal environment in the bus on passengers was proposed (Pala and Oz, 2015). Before the test, the bus stayed for 7 hours in a climatic chamber with a temperature lower than 20°C. On this basis, after that time, air temperature, speed, and relative humidity were measured, which enabled the creation of a model showing the thermal sensations of passengers. On the other hand, the plane became the next research point. According to the authors (Vink et al., 2012), the most important factor determining well-being is sitting and sufficient space for the legs. Another proposal for testing comfort in airplanes is presented (Giaconia et al., 2015), where 14 selected flights were tested in terms of air temperature, radiation, and relative humidity. From the obtained results, PMV and PPD were calculated, which differed from the real thermal impressions of passengers.

After analyzing the literature, it was noticed that despite the fact that research on thermal comfort in passenger and public vehicles is carried out, there are still problems to be solved. Many tests are performed in laboratory conditions (in climatic chambers) during the design of new cars, while the actual data during normal operational conditions, especially in Polish climatic conditions, are rare or missing. The aim of the present work is to analyze the thermal impressions of people for five selected temperatures and to compare TSV and PMV indexes as well as to select the appropriate temperature range for people staying in the car during its use. From the practical point of view, it should also provide information if modern cars actually meet the comfort condition requirements with regard to the thermal environment.

Similar thematic works were carried out in the field of subjective assessment of thermal comfort in the so-called intelligent buildings (Majewski et al., 2020; Petrash et al., 2021; Ujma and Jura, 2021). A similar approach to the subjective assessment of sensations can also be used in other environmental research (Bielski, 2021; Maltsevich, 2021; Wójcicka, 2021). The obtained results and observations should also inspire similar methods (Pietraszek et al., 2014; Pietraszek et al., 2017; Danielewski et al., 2021), including those using the non-parametric approach (Pietraszek, 2003; Regulski and Abramek, 2022; Djoković, et al. 2022). The subjective approach using mapping to the quantitative scale (in the Likert type) should be widely applicable in production engineering (Gazda et al., 2013; Wysoczański et al., 2021), including non-destructive testing (Siwiec et al., 2020) and logistics (Ulewicz et al., 2020). Similar imprecise but easy-to-obtain sensory assessments are valuable as a starting point in technological research, including laser processing of special coatings (Radek et al., 2018; Orman et al., 2020), testing of destructive paint coatings (Radek and Dwornicka, 2020), visual assessment of the state of explosives (Kubecki et al., 2021) and boiling states (Dabek et al., 2019). The promising results of the method used should also be inspiring for mechanical applications (Czyczuła and Rochel, 2021; Radzajewski, 2021; Kurp and Danielewski, 2022), as well as in material research (Szczotok and Chmiela, 2014; Miletic et al., 2020), especially in subjective assessments of visual images of microstructures (Szczotok et al., 2018; Szczotok et al., 2017).

2. Experimental

The measurements were carried out in a car manufactured in 2017. The car was black in color. Due to the occurrence of high temperatures in Poland (the central-eastern part of the country), July 2022 was the selected month for measuring the internal environment. The atmospheric conditions that prevailed during the tests were an outside air temperature of 28°C and an atmospheric pressure of 1020 hPa, and five variants of indoor air temperature for 20°C, 22°C, 24°C, 26°C, 28°C, changed every five minutes and set in the car's air conditioning control system. The temperature in the car was set manually by the driver. The first measurement was taken when the temperature was stable at 20 - this took about 5-7 minutes. The air direction was set to the windshield and the legs, because when the mode was selected to all sides, very large fluctuations in temperature and air speed were noticed. In addition, it was noted that there was excessive cooling of the test subjects, which suggested that the influence of air distribution may also have an impact on the perception of thermal comfort during car travel. The car was located in two places - in the sun and in the shade in the open space of the Kielce University of Technology (parking lot between the buildings belonging to the campus), similar to the research (Krawczyk, et al., 2021). In order to take measurements inside the car, the Testo 400 environmental meter was used, thus obtaining data such as air temperature, relative humidity or carbon dioxide value, etc. On the other hand, the task of selected people was to complete the questionnaires describing thermal sensations, temperature acceptance, temperature preferences and humidity, and a description of how you feel. Four people, aged 26 to 27, with clothing insulation of 0.38, participated in the study. Figure 1 shows the measuring station used in the study and its equipment with probes: 1 – air temperature, relative humidity; 2 – black ball; 3 – air speed; 4. carbon dioxide content and Table 1, which shows the measurement accuracy of the probes used in the study.

Fig. 1. Location of the measuring station inside the car

Table 1. Measuring accuracy of the Testo 400

No	Measured parameter	Accuracy
1	Air temperature	± 0.3 °C
	Relative humidity	± 2 %
2	Black ball	-
3	Air speed	± 0.3 m/s
4	Carbon dioxide concentration	± 50 ppm

3. Results and discussion

First, the respondents' thermal sensations were analyzed according to the set temperature for a car located in the sun and in the shade. The respondents defined their feelings using a 7-point scale ranging from -3 to +3 by answering: too cold (-3), too cool (-2), pleasantly cool (-1), comfortable (0), pleasantly warm (+1), too warm (+2), too hot (+3). It should be noted that in the case of Thermal Sensation Vote, all responses of the test persons should be averaged. On this basis, 5 points were obtained for each of the tested sections (sun and shadow), which are presented in Figure 2.

Taken together, they obtained data showing that the higher the temperature, the worse the temperature sensation (e.g. less bearable to humans). As can be seen, the respondents felt better (e.g. cooler) in the car parked in the shade. In the case of the latter, all averages are higher than the former. Nevertheless, the comfort felt in the sun for the set air temperature, which was previously set on the air conditioning console for 20°C and 22°C, and in the shade only for the temperature of 22°C TSV was 0.

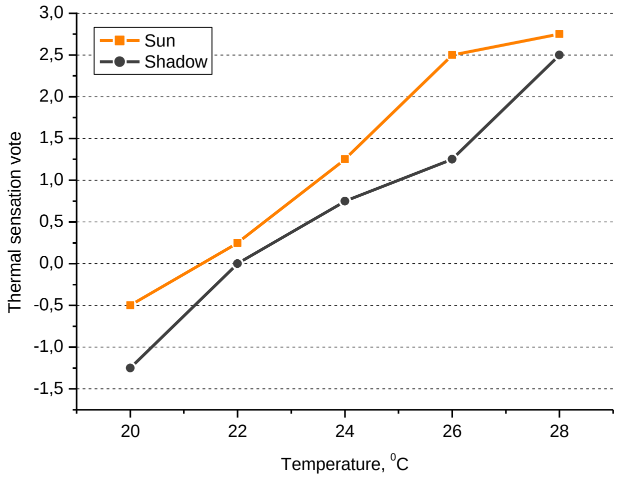

Fig. 2. Average thermal sensation of people depending on the temperature change for sun and shade.

However, attention should be paid to the set temperature of 26°C for both variants. Compared to the average TSV responses and the set temperatures, the biggest difference is visible at the temperature of 26°C, amounting to 1.25. On the other hand, the assessment of the set temperature of 28°C, the average TSV is above 2.5, so according to these people, it was already too hot in the car standing, in the sun, and in the shade. In addition, the thermal sensation in the study for temperatures 20°C, 22°C, 24°C, and 26°C is significantly better in the assessment of the respondents than in the study (Krawczyk, et al., 2021), where already at 23.5°C and 25°C the average thermal sensation was above +1.5, contrary to the latest studies. It should also be added that 19°C in the (Krawczyk, et al., 2021) tests for a car located in the sun was already assessed as too cool an environment, and in the newest tests for the set temperature of 20°C, it was already comfortable. Another important element in the assessment of thermal comfort will be the relative humidity in relation to the set temperature. The results are shown in Figure 3.

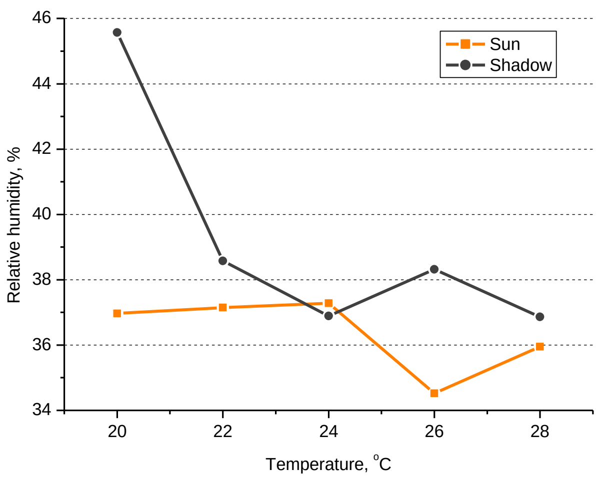

Fig. 3. Change of relative humidity in relation to the tested temperatures for sun and shade

According to the results obtained from the Testo 400 meter, shown in Figure 3, the relative humidity was maintained for the tested temperatures in the range of about 37% to about 34% for a car standing in the sun. The only significant drop was recorded for the temperature of 26°C, but already at 28°C, the humidity started to increase to 36%. In fact, it should be said that the relative humidity was kept at a constant level. However, the same cannot be said for the shade location. For the temperature of 20°C, the relative humidity was about 46%. This may be because the car must have been very cold due to the air conditioning operation. In turn, already from 22°C, the relative humidity content ranged from about 36-39%. Comparing the above results with the data obtained by (Krawczyk, et al., 2021), in the earlier studies, the relative humidity for the car in the shade decreased systematically, while in the sun, the relative humidity was very high, over 43% (except for the decrease recorded for the temperature of 23.5°C). This assessment may be influenced by the air conditioning in both vehicles. Much better results were obtained for the vehicle from 2018 than for the vehicle from 2017.

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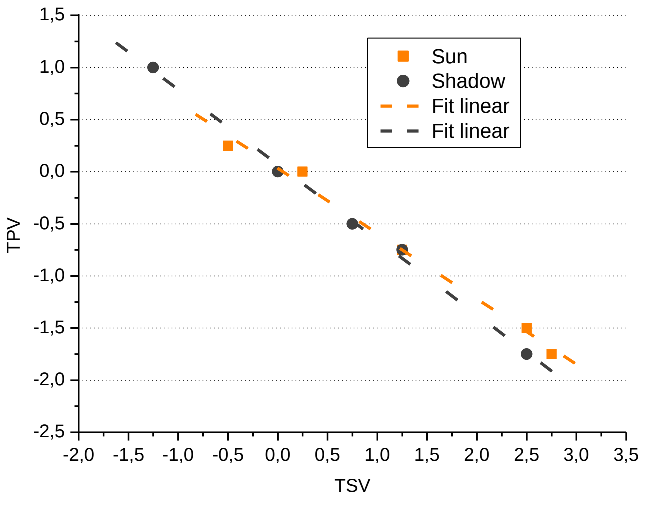

Fig. 4. Dependencies resulting from average answers to questions about Thermal Sensation Vote and Thermal Preference Vote for sun and shade

Much better results were obtained for the vehicle from 2018 than for the vehicle from 2017. From Figure 4 above, it should be noted that when the car was in the shade, respondents felt it was cooler and wanted to be warmer in the car. Similar results were obtained for the result of the sun. If respondents were too warm, they wanted the air temperature in the car to be lower. It is worth noting that the respondents felt most comfortable at the temperature of 22°C. in the sun and shade. At higher temperatures, they wanted it cooler, as can be seen in the graph. On the x-axis, above 2 means that respondents are too warm, and on the y-axis, values below 1 mean they want it to be cooler. Better results were found for the studies carried out in the shade. Even for 26°C in the shade, the respondents want it to be the same, while in the sun, it is definitely cooler. It is also worth paying attention to the values for the temperature equal to 20°C. They wanted it to be warmer in the shade and cooler in the sun.

Below in Figure 5, the relative humidity (Assessment humidity Vote – AHV) and its preferences (Humidity Preferences Vote – HPV) of the study participants were also analyzed. First, the respondents assessed the humidity in the tested space of the car, marking answers such as too humid (+2), quite humid (+1), pleasant (0), quite dry (-1), and too dry (-2). On this basis, in the next question regarding the preference to change this humidity, the respondents answered that the indoor environment could be more humid (+1), unchanged (0), or drier (-1). From all the responses obtained for the five tested temperatures and two positions of the car location for AHV and HPV, the average responses of the respondents were calculated.

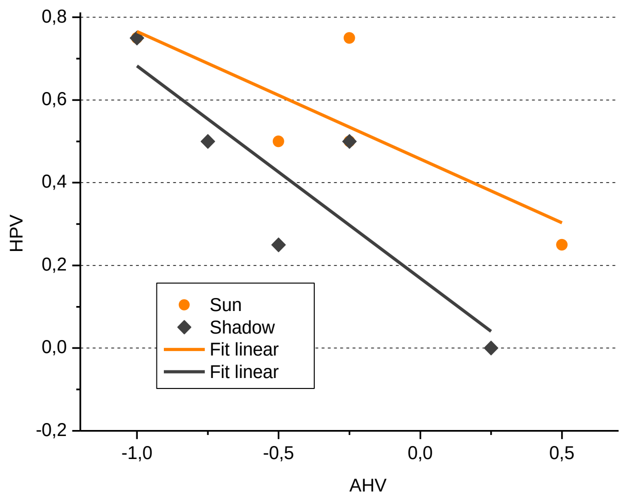

Fig. 5. Mean responses assessing relative humidity versus humidity preference by position in the sun and shade

The results obtained in Figure 5 show a relationship between the assessment of humidity and the preferences of the respondents. And in the case of a car parked in the sun and shade, it turns out that the drier the air, the more humid the respondents would like the air to be. On the other hand, if the humidity in this evaluation was "pleasant" or "quite humid", then their preferences were in the direction of 0. However, attention should be paid to the fitting lines, which show that the evaluation and humidity preferences are lower than in the case of the sun.

In order to find out if people could feel better in a car parked in the shade and in the sun, respondents answered the question about their overall feeling in the test vehicle. The respondents assessed their current well-being as very good (+2), good (+1), neutral (0), bad (-1), and very bad (-2). The results are shown in Figure 6.

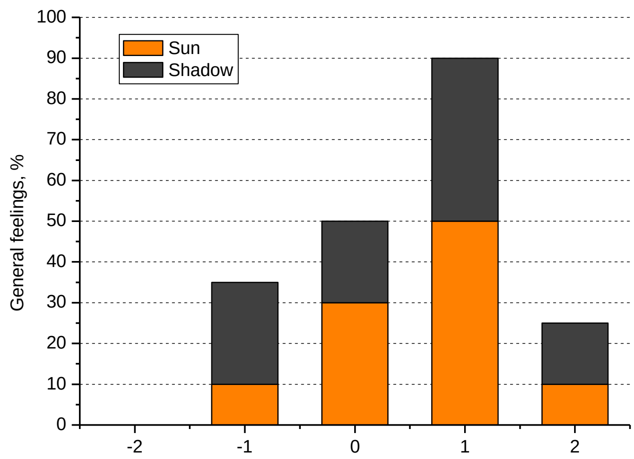

Fig. 6. General feelings according to passengers, broken down by position in the sun and shade: -2 - very bad, -1 - bad, 0 - neutral, +1 - good, +2 - very good

Only 10% of people rated their well-being in the sunny position as -1, and already 25% for the position in the shade. On the other hand, well-being was declared by 50% of respondents in the sun and 40% in the shade. On the other hand, 15% of people chose very well for a position in the shade, and 10% for a position in the sun. Assessment of how we feel may have been influenced by the installed air conditioning, everyone's clothing, tinted windows, and even the 2 with one's well-being was presented by people in a car located in the sun in the amount of 90%, while for the shadow only by 75%.

The first studies of thermal comfort were carried out in the 1970s. At that time, the model predicting the thermal sensations of people was created, and it is in this article that its accuracy will be verified. This is important because it is not known whether the model that was created in the 1970s will be able to accurately predict the thermal sensations of people traveling in modern cars. This is mainly due to the fact that modern people have high thermal requirements for confined spaces.

The Fanger model is focused on the concept that we feel the best if the amount of heat generated within the body is the same as the one which is released. It needs to be remembered that the release of heat can be done through conduction, convection, radiation, as well as phase – change, which is the most efficient (Orman, 2014a; Orman, 2014b). Thermal impressions are presented using Thermal Sensation Vote (TSV) and Predicted Mean Vote (PMV) obtained on the basis of the listed parameters from the environmental meter, such as air temperature, relative humidity, black sphere temperature, or air velocity (Figure 1). These parameters are necessary to substitute for the Fanger model (additionally, the insulation of the garment and the metabolism of the examined persons are taken into account). On the other hand, TSV is calculated as the average of all responses regarding the current temperature sensations (from too hot, too warm, pleasantly warm, comfortable to pleasantly cool, too cool to too cool) for 5 temperatures, for the position of the car in the sun and shade. Taking this into account, the mean TSV responses to the PMV values were compared to verify how much the actual feeling values would differ from the values obtained from the Fanger model. Figure 7 shows the obtained results.

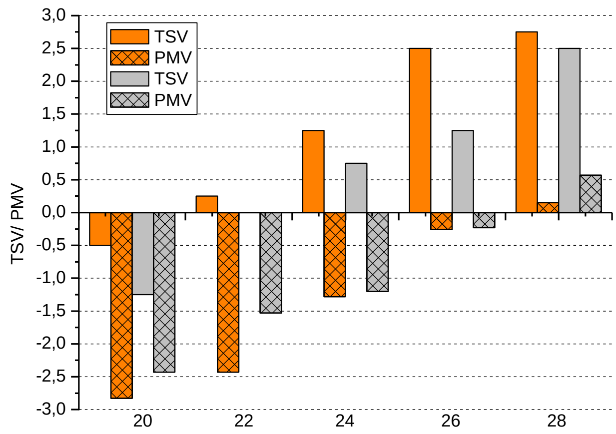

Fig. 7. General feelings according to passengers, broken down by position in the sun and shade: -2 - very bad, -1 - bad, 0 - neutral, +1 - good, +2 - very good

According to the above Figure 7 and Figure 2, it has already been mentioned that thermal comfort according to the respondents, i.e. TSV, was felt for the position in the sun for two temperatures, 20°C and 22°C, and for the position in the shade only temperature 22°C, for TSV equal to 0. However, according to the PMV value, comfort, which should be felt according to the ISO 7730 standard, refers to the temperatures of 26°C (for both variants) and only for the temperature in the sun, 28°C. Note the relationship that was obtained as a result of the TSV value - the higher the temperature, the higher its values. Similarly, it is also the case of PMV, where negative values, i.e. from the temperature of 20°C, gradually increase, reaching positive values at 28°C. The conclusion that comes to mind is that the mean TSV values for the sun are higher than the mean TSV values for the shade (except for the temperature of 20°C). The same is the case with PMV. Additionally, what can be noticed is the fact that PMV is very different from the actual thermal sensations of people. Where respondents described the environment as warm, PMV assumed it was too cool. It only proves that the standard does not take into account how people feel in the smoke, taking into account only the data obtained with the use of an environmental measure. What is certain is that the results obtained are satisfactory, in contrast to the results obtained in the study (Krawczyk, et al., 2021).

5. Summary and conclusion

Summarizing the collected data, it turns out that with the air conditioning working, the respondents felt better in the car parked in the sun (90%) than in the shade (75%). In addition, the relative humidity was better also for the tested position in the sun than in the shade. Nevertheless, for the given temperatures, the TSV was better for the shade than for the sun. However, it was for the sun that the respondents determined two temperatures in which thermal comfort was felt for 20°C and 22°C, and for the shade, only one equal to 22°C. The important elements that were discussed in the above article are the values of PMV and TSV. It turned out that according to the calculated PMV, the temperatures 26°C for both variants and 28°C only for the sun were a comfortable environment according to the standard, which is the opposite of the real thermal sensations of people obtained from the surveys. The colour of the car (black) was not observed to affect the perception of thermal comfort. The above-mentioned results could definitely be influenced by the air-conditioning and the clothing of the respondents (amounting to 0.38). Taking all this into account, the verification of the Fanger formula does not reflect the actual thermal sensations of people, as the results obtained differ significantly from each other. So the conclusion is that the model created in the 70s is not able to predict people's thermal sensations in modern cars, what's more, it could be modified to better match people's thermal expectations

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现代乘用车在实际运行条件下的热舒适性评估

關鍵詞
热舒适度
乘用车

摘要
人们不断增长的需求促使各种车辆的设计者寻找能够提供最舒适的内部环境条件的解决方案。目前，部分由于COVID19的威胁，许多人使用他们的个人汽车去工作、大学、商店、旅行和度假。在夏季，车辆中需要保持的适当的内部空气参数是至关重要的。文章讨论了2017年生产的现代汽车的四名乘客的热舒适度，以验证当代生产技术是否能成功满足波兰气候实际条件下人们的热需求。为此，测试了五个温度值：20℃、22℃、24℃、26℃ 和 28℃， 用于位于阴凉处和阳光下的汽车。 此外，Testo 400 仪表被用来控制和测量内部参数， 并使用问卷调查来了解受访者的热印象。 研究是在7月进行的，当时波兰的空气温度很高。