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EFFECT OF ENVIRONMENT ON VARIABILITY OF SKIN RESISTANCE IN VEHICLE INTERIOR

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This study explores the relationship between ambient temperature and skin resistance in a vehicle cabin during winter. Using 1 Hz sensor data collected from four participants in Škoda Kodiaq, key environmental factors, including temperature and comfort features, were analysed. Strong negative correlations (up to -0.88) were found between skin resistance and temperature, especially near the body or airflow sources. The physiological response was nonlinear, with faster reactions to cooling. Heated seats influenced skin resistance trends, while particulate matter had no effect. The results suggest skin resistance as a potential indicator for thermal comfort and adaptive climate control.

Keywords: electrodermal activity; temperature; thermal comfort; cabin; automotive

The human body is equipped with a complex thermoregulatory system that maintains internal temperature within a narrow range (approximately 36.5–37.5 °C), despite varying external conditions. This homeostatic mechanism is essential for the proper functioning of physiological processes and overall organism survival. In cold environments, mechanisms that reduce heat loss are activated, primarily the vasoconstriction of peripheral blood vessels, reduced skin perfusion, and in extreme cases, muscle shivering. These processes lead to an increase in skin resistance as the skin surface cools down, dries out, and becomes less conductive (Partin et al., 2006). Conversely, when exposed to heat, the body activates heat dissipation mechanisms through vasodilation, increased blood flow through the skin, and especially sweating, which results in decreased skin resistance due to the moistening of the skin surface and increased electrolyte concentration (Montagu, 1964).

However, the body's thermoregulatory responses are influenced not only by ambient temperature but also by a combination of environmental and internal factors. These include air humidity, airflow direction and speed, clothing insulation, individual thermal sensitivity, and psychological state (e.g., stress while driving), all of which can affect the measured physiological response (Paulov, 1995).

Skin resistance (electrodermal activity, EDA) has been increasingly used as a non-invasive physiological parameter reflecting changes in autonomic nervous system activity. It is particularly sensitive to emotional and thermal stimuli and has been proposed as a proxy for comfort, thermal perception, and even stress level in enclosed environments such as vehicle cabins.

Our previous studies (Kollárik and Vitázek, 2024; Kollárik et al., 2024) indicated a moderate correlation between skin resistance and ambient temperature. However, based on our latest measurements, we identified inconsistencies in this relationship, suggesting the influence of additional variables. These findings underscore the need for a more comprehensive investigation that accounts for factors such as airflow distribution, localised heating, cabin air quality, and precise temperature sensor placement.

Understanding the interaction between ambient conditions and physiological responses inside a vehicle has significant implications not only for optimising cabin climate control systems but also for future applications in driver monitoring, adaptive comfort algorithms, and autonomous vehicle development. This article presents the results of a pilot study focused on exploring the relationship between physiological responses and microclimatic conditions inside a vehicle. In this article, we demonstrate that seat heating shows a direct proportional relationship with skin resistance, in contrast to the effects of other comfort features and environmental factors.

Material and Methods

Based on a detailed analysis of the methodology and experimental conditions of both current and previous measurements (Kollárik et al., 2024), we formulated four key hypotheses presented in this study. Given the pilot nature of this study, the experimental conditions were designed to assess the feasibility of the measurements and to identify potential correlations.

The goal of these measurements is to evaluate the correlation between skin resistance and ambient temperature while eliminating or quantifying the influence of other environmental and systemic factors.

The main factors that may influence measurement results include:

- Particulate matter (PM) concentration in the air.
- Uneven temperature distribution within the vehicle interior.
- Impact of comfort features such as heated seats, heated steering wheel, and AirCare function.
- Placement of the temperature sensor inside the vehicle cabin.

Equipment used

Skin resistance was measured using the same system as in the study by Kollárik et al. (2024). Additional sensors included the following.

Temperature sensors:

- DHT11 sensor for measuring temperature and humidity, operating within 20–90% relative humidity (RH) and 0–50 °C, with ±5% RH humidity accuracy and ±2 °C temperature accuracy. It was placed approximately 5 cm from the solar plexus to monitor temperature conditions near the body.
- TMP36 temperature sensor (range from -40 to 125 °C, ±2 °C accuracy, and 0.5 °C accuracy at constant temperature). This sensor was mounted on the inner side of the sun visor to reflect the air temperature in the upper part of the cabin. An aluminium foil insulation layer was applied to the opposite side of the visor to mitigate the effects of solar radiation.

Particulate matter concentration sensor:

- Sharp GP2Y1010AU0F dust sensor (effective for detecting particles such as smoke, dust, and pollen, with a detection range of 0.5–10 μm). The sensor operates based on an infrared LED and phototransistor positioned diagonally to detect reflected light from airborne particles. It is sensitive to real-time changes in dust concentration and provides an analogue voltage output corresponding to particle density. In this study, the sensor was positioned near the vehicle's air vents to monitor PM levels entering the cabin. To reduce ambient light interference and airflow disturbances, the sensor housing was partially shielded using matte black tape and foam insulation.

All sensors were connected to an Arduino Mini microcontroller, which transmitted data to a portable computer for further processing (Kousis et al., 2022).

The test vehicle was 2019 Škoda Kodiaq, equipped with a heated steering wheel, heated seats, three-zone climate control, and AirCare function. Measurements took place on the premises of Mendel University in Brno, ensuring highly consistent conditions.

Experiment description

Each participant completed a 30-minute drive along the same route. Prior to each session, the vehicle was pre-heated to operating temperature. After every measurement, the vehicle interior was ventilated for 5 minutes at the same location in a garage to ensure consistent starting conditions for the next participant (Buchecker et al., 2022). The climate control system was left in automatic mode with target temperature settings listed in Table 1.

Four participants took part (age: 20–28 years; weight: 65–92 kg; height: 163–183 cm). All were healthy adults with no signs of acute illness. The gender ratio was balanced 1 : 1. All participants experienced a similar level of mental load, as the measurements took place within the premises of the university campus, ensuring consistent conditions for all drives. This controlled environment helped maintain uniform experimental parameters and minimised external influences that could affect skin resistance values.

Skin resistance signal analysis

To evaluate changes in skin resistance and its relationship to temperature, we used the same measurement device (Kollárik and Vitázek, 2024), with electrodes attached to participants' palms using adhesive conductive gel.

The sampling frequency for skin resistance was 1 Hz. The following analytical methods were applied:

- Outlier removal.
- Normality testing (Anderson-Darling, Shapiro-Wilk, Kolmogorov-Smirnov, D'Agostino & Pearson) to determine the appropriateness of parametric vs nonparametric tests.
- Spearman correlation analysis – used to confirm a monotonic relationship between skin resistance and temperature where linearity could not be assumed.
- Segmented signal analysis – signal divided into segments based on changing conditions (e.g., comfort feature activation, temperature change) to better identify local trends and physiological responses.
- Moving average method (window of 30 values, one-point step) to smooth the signal and identify long-term trends.
- Time-delay analysis to detect the lag between temperature changes and physiological response.

Table 1 Experimental measurement settings

Set temperature (°C)	Time interval (min)	Heated seat	Heated steering wheel	AirCare
18	5	off	off	off
18	5	off	off	on
22	5	off	on	off
22	5	off	on	on
24	5	on	off	off
24	5	on	on	on

– By comparing median skin resistance values under different thermal conditions, we could characterise bodily responses to heating and cooling. Data analysis was performed using GNU Octave.

Hypotheses

H1: The correlation between ambient temperature and skin resistance is affected by the placement of the temperature sensor. The closer the sensor is to the subject, the better it reflects thermal load and the stronger the observed correlation.

H2: The relationship between temperature and skin resistance is nonlinear and shows different dynamics during heating versus cooling. We expect that temperature effects on skin resistance will have varying delays and intensities depending on the direction of change.

H3: The use of comfort features (heated seats, heated steering wheel) has a measurable effect on skin resistance, even at identical cabin air temperatures.

H4: Changes in PM concentration in the vehicle cabin do not have a significant effect on skin resistance.

To test these hypotheses, we designed an experimental methodology that minimises undesirable factors and enables precise quantification of the studied relationships.

Results and Discussion

Unlike in previous measurements (Kollárik et al., 2024), where temperature was recorded at one-minute intervals, this study used a much denser sampling frequency for temperature sensors (Naeimi et al., 2024), matching that of skin resistance measurements (1 Hz) (Herceg and Herceg, 2020). This enabled more precise detection of rapid changes and time lags in physiological responses (Xie et al., 2020).

These experimental measurements build upon our previous studies conducted during summer but were performed in winter conditions at outside temperatures between -2 °C and 2 °C. Due to the cold climate, participants wore long-sleeved clothing and trousers, which may have affected the timing of their physiological responses to interior temperature changes (Xie et al., 2020).

As shown in Table 2, the correlation between skin resistance and temperature increased when the sensor was placed closer to the body (Fig. 1), especially within direct airflow from the A/C system (Kristanto and Leephakpreeda, 2018). While sensors at more distant locations (e.g., (580, 200, -560)) showed correlations around -0.4991, sensors placed directly on the subject (0,0,0) showed values as high as -0.8818. This supports Hypothesis 1 regarding sensor placement affecting correlation strength.

Normality tests (Anderson-Darling, Shapiro-Wilk, Kolmogorov-Smirnov, and D'Agostino & Pearson) consistently showed significant deviations from a normal distribution (Beloev et al., 2021). Thus, Spearman correlation was chosen as the primary method, confirming a strong negative monotonic relationship between temperature and skin resistance (Zhang and Ruan, 2025). Normality was also rejected in segmented data, categorised by comfort feature activation.

The inclusion of the PM sensor enabled testing Hypothesis 4. The results (Fig. 2) indicate that cabin particulate levels (Tolis et al., 2021) have minimal impact on skin resistance, supported by weak Spearman correlations (r = 0.2205) and the assumption that short-term exposure to low PM concentrations does not elicit immediate physiological responses (da Graça and Martins, 2021).

An interesting phenomenon was observed during heated seat activation (from 1200 s), where the polarity of the correlation changed from a negative to a positive relationship between temperature and resistance (Mercier et al., 2022). This effect was consistent across participants, with moderate to strong correlations (r ≈ 0.5–0.8), supporting Hypothesis 3 about the measurable impact of comfort features. In contrast, the heated steering wheel

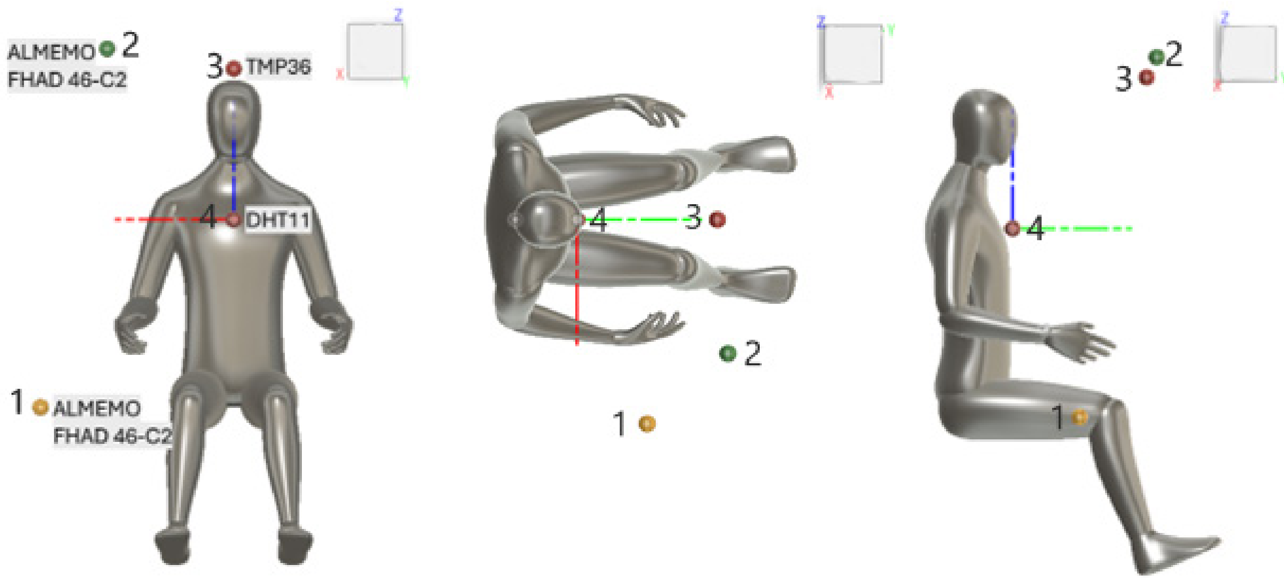

Fig. 1 Spatial location of sensors relative to the subject

Table 2 Spearman's coefficient from actual and our previous measurements with other parameters

Sensor no.	Sensor position from subject (*x*, *y*, *z*) (mm)	Temperature sampling frequency (*s*)	Duration (*s*)	Spearman´s coefficient
1	(580, 200, -560)	60	900	-0.4991 to -0.6706
2	(380,430, 510)	60	5400	-0.6256
3	(0,400, 450)	1	1800	-0.5606 to -0.7502
4	(0,0,0)	1	1800	-0.8020 to -0.8818

did not show the expected effect (from 600 s to 1200 s and from 1500 s to the end), despite its physical proximity to the measurement site. This is further analysed in Fig. 3 and Fig. 4. In the following figures, only the temperature from sensor no. 4 is presented, as it exhibited the highest correlation with skin resistance.

In the graphical representations of skin resistance and temperature over time (Fig. 3 for male participants and Fig. 4 for female participants), one of the first noticeable differences lies in the range of skin resistance values. Female subjects exhibited significantly higher resistance levels compared to their male counterparts (M from 35,000 to 80,000 Ω; F from 100,000 to 460,000 Ω). For both genders, a polarity shift in skin resistance is evident upon activation of heated seats.

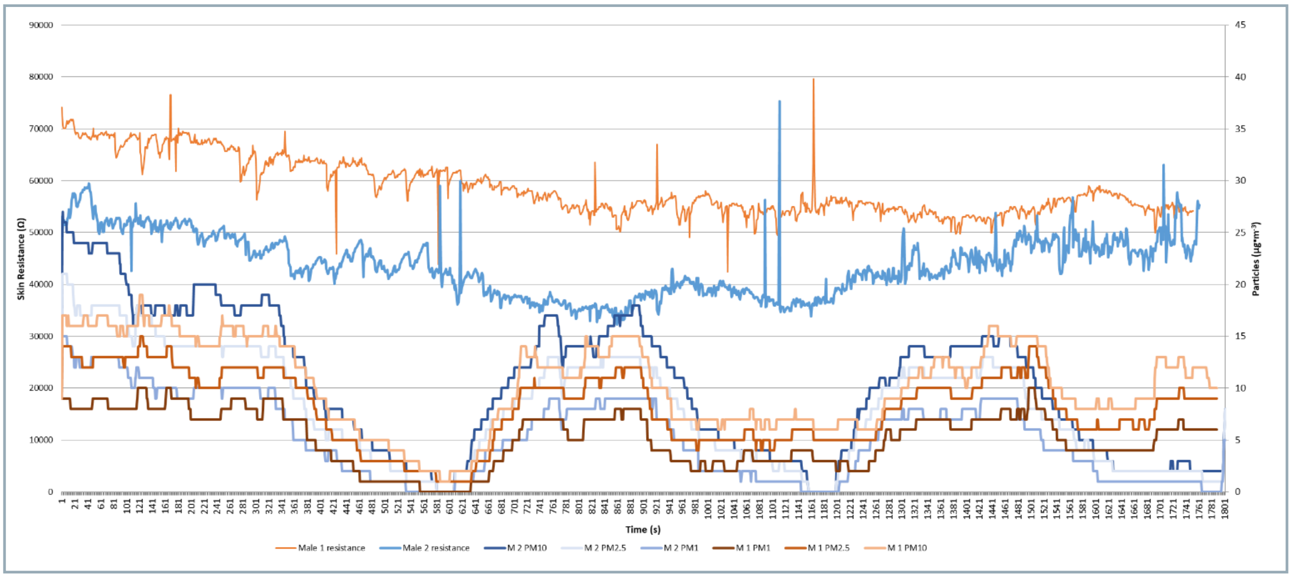

Fig. 2 Time-based graph of skin resistance and airborne particulate concentration

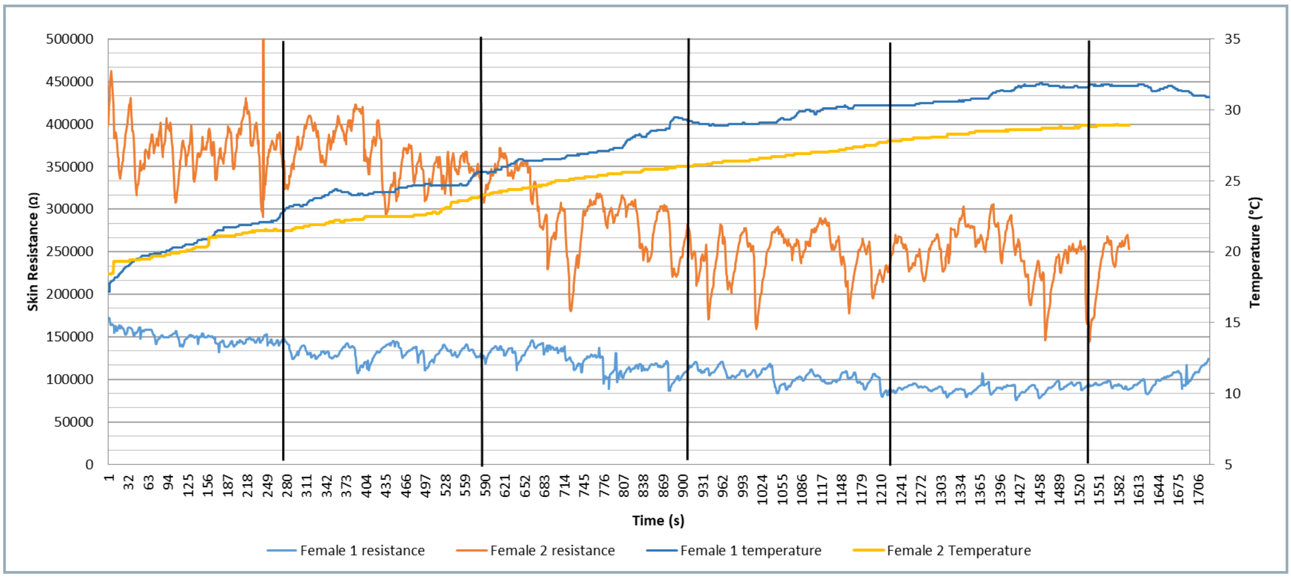

Fig. 3 Time-based graph of skin resistance and cabin temperature – male participants

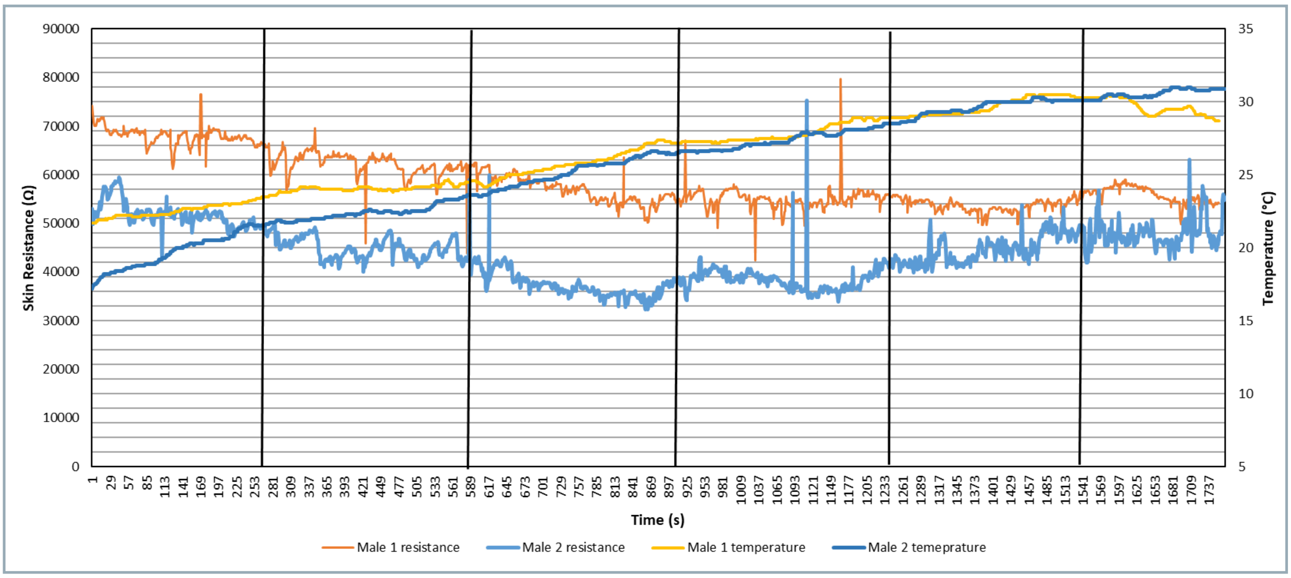

Fig. 4 Time-based graph of skin resistance and cabin temperature – female participants

As shown in Table 1, during the time interval from 900 s to 1,090 s, a slight increase in skin resistance was observed alongside rising temperature when both the heated steering wheel and AirCare function were activated. This is attributed partly to a decrease in relative humidity due to AirCare operation and partly to the effect of localised heating from the steering wheel. The resistance trend began to decline again approximately 200 s later.

It is important to note that, in the final five minutes of measurement for the female subjects, the intensity of heating functions was reduced in response to reported discomfort caused by excessive seat and steering wheel temperatures. Additionally, one participant from each group was selected for a temperature drop test: in the final three minutes, the cabin temperature was decreased to 19 °C to confirm the expected increase in skin resistance with decreasing ambient temperature.

The analysis of temporal responses revealed that the body reacted more quickly and strongly to temperature drops than to increases. This asymmetry in thermoregulatory response dynamics supports Hypothesis 2. Due to insulation, clothing, and the delayed heat distribution in the cabin (Plesner and Pomianowski, 2021), the skin may cool more effectively than it warms, explaining the varying response intensities. Same conclusions are also mentioned by D'Angelo and Lüth (2012) .

With sufficient calibration and known conditions (Mehel et al., 2023), it may be possible to estimate cabin temperature dynamics based on skin resistance data (He et al., 2024). This hypothesis will be the subject of future research.

Conclusion

In the present pilot study, we focused on identifying the relationship between skin resistance and ambient temperature in a vehicle cabin, while also considering the influence of additional environmental and comfort-related factors. The preliminary findings confirmed that the accuracy of assessing thermal load on the body is significantly affected by the placement of the temperature sensor: the closer the sensor was to the subject or to the air stream, the stronger the correlation with skin resistance.

In contrast, air quality measured via particulate matter concentration did not show a significant influence on skin resistance, thereby refuting the hypothesis of its impact.

The hypothesis of a nonlinear bodily response to temperature changes was only partially confirmed in the preliminary analysis and requires more detailed investigation of time delays and the dynamics of the response during heating and cooling. Individual psychological and physiological variability was not explored in this study.

The findings of this study open avenues for future research in which it may be possible to reconstruct cabin temperature changes retrospectively based on the analysed skin resistance trends. Such an approach could, in the future, serve as a supplementary tool for evaluating driver thermal comfort without the need for extensive environmental sensing.

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