Applicability of Thermal Comfort Models to Car Cabin Environments

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Abstract: Car cabins are non-uniform and asymmetric environments in relation to both air velocity and temperature. Estimating and controlling vehicle occupant thermal comfort is therefore a challenging task. This paper focuses on evaluating the suitability of four existing thermal comfort models, namely the Predicted Mean Vote (PMV), Taniguchi's model, Zhang's model and Nilsson's model in a variety of car cabin conditions. A series of comfort trials were performed ranging from controlled indoor trials to on-road driving trials. The outputs of all four models were compared to the sensation index reported by the subjects situated in the driver seat. The results show that PMV and Nilsson's model are generally applicable for the car cabin environment, but that they are most accurate when there is a small air temperature rate of change (of under 1.5 °C per minute), giving correlation levels of 0.91 and 0.93 for the two models respectively. Taniguchi's and Zhang's models were found unsuitable for all conditions, with correlation levels ranging between 0.03 and 0.60. Nilsson's model is recommended by the authors based on the level of agreement with the subjective reports, its ability to estimate both local and overall thermal sensation and the smaller number of input parameters.

1 INTRODUCTION

Car cabins are environments with inherent non-uniformity and asymmetry in both air velocity and temperature fields. Steady-state trends can be encountered for journeys in excess of 15-20 minutes, however 85% of journeys are of shorter duration (Cisternino, 1999). Predicting passengers' thermal comfort for efficient Heating, Ventilation and Air Conditioning (HVAC) control is therefore a complex problem.

More than forty years after its development, Fanger's Predicted Mean Vote (PMV) (Fanger, 1973) remains the most used method for assessing occupant thermal comfort in a range of environments. Although designed specifically for use in buildings, PMV continues to drive research into vehicle HVAC control algorithms (Ueda and Taniguchi, 2000; Busl, 2011; Farzaneh and Tootoonchi, 2008). The main reasons are the simplicity of measuring the air temperature and humidity parameters, combined with the ability to estimate the remaining parameters within controlled tests. Nilsson (Nilsson, 2004) proposed thermal comfort zones for 18 different body parts and overall based on equivalent temperatures. Nilsson's model uses similar parameters with PMV (air temperature, air flow, mean radiant temperature and clothing index). However, the model has the advantage of estimating local thermal sensation, as well as overall.

Skin temperature is shown to be a good predictor of local and overall thermal sensation in the state of art (Bogdan, 2011; Wang et al., 2007). Taniguchi's model (Taniguchi et al., 1992) was designed for vehicular applications and is based on face skin temperature only. Zhang's thermal sensation and comfort model (Zhang, 2003), on the other hand, is a more recent model developed with transient, inhomogeneous environments in mind. The model, however, has been criticized in the literature for having too many coefficients, for the limitations of the experimentation and for the body part set-point temperature approach (Luo et al., 2007). Moreover, no validation of these two skin temperature based models within daily driving scenarios or other typical conditions encountered in vehicular environments exists in the literature.

Considering the above, this paper evaluates PMV, Taniguchi's model, Zhang's model and Nilsson's model on empirical data gathered in a variety of car cabin conditions, establishing whether they are suitable for comfort-oriented vehicular control.

The main contributions of this paper are: 1) illustrating the range of conditions in which these models could be applied to drive comfort-oriented HVAC control algorithms and 2) establishing which of the four thermal comfort models is a better match of cabin

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occupant thermal comfort in typical vehicular conditions based on gathered empirical data.

The paper is structured as follows: Section 2 presents an overview of the the four thermal comfort models. Section 3 describes the data gathering methodology, focusing on the instrumentation used, the participating subjects and the range of conditions encountered in the car cabin. Section 4 presents the results obtained when comparing the sensation index corresponding to the four models with the subjects' reported sensation. Finally, Section 5 concludes the paper.

2 BACKGROUND

Based on the review provided by Cheng *et al.* (Cheng et al., 2012), the following thermal comfort models were implemented and evaluated on the data gathered: PMV, Taniguchi's model, Nilsson's model and Zhang's model. These thermal comfort models are reviewed in (Alahmer et al., 2011; Cheng et al., 2012; Orosa, 2009) and discussed in the following subsections.

With regard to other models, Matsunaga *et al.* (Matsunaga et al., 1993) adopted, for example, the concept of Average Equivalent Temperature (AET) in order to compute the PMV sensation index. The AET is a surface area-weighted value for three body parts: the head with a weight of 0.1, the abdomen with a weight of 0.7 and the feet with a weight of 0.2. Because the end product is the PMV index, this technique is not evaluated in this paper. Also, the Berkeley advanced human thermal comfort model (Arens et al., 2006) is used as a cabin occupant comfort estimator in multiple works. The virtual manikin in the software model estimates occupant skin temperatures and Zhang's model uses the latter to calculate thermal sensation and thermal comfort. As this paper is concerned with empirical results rather than simulation, only Zhang's model is evaluated.

2.1 Predicted Mean Vote (PMV)

Fanger (Fanger, 1970) developed the PMV model in 1967 based on thermo-regulation and heat balance theories. These theories are based on human bodies employing physiological processes in order to maintain a balance between the heat produced by metabolism and the heat lost from the body. The PMV index provides a score that corresponds to the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) thermal sensation scale shown in Table 1 and it is defined as the average thermal sensation felt by a large group of people in a space. The PMV model combines four physical variables (air temperature, air velocity, mean radiant temperature and relative humidity) and two personal variables (clothing insulation and activity level). The mathematical equations used to derive the PMV index are given in the ISO 7730 standard (ISO, 2005).

Table 1: PMV thermal sensation index.

3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Fanger validated and refined the comfort equation with data from other previous thermal comfort studies combined with his own, summing to approximately 1400 participants. Fanger stated that the PMV model should be used with care for indexes below -2 and above $+2$ and that significant errors can appear in hot environments. PMV's main advantages are the standardisation of the implementation and that if some of the constituent parameters cannot be measured, they can be approximated without introducing a significant error in the outputted PMV index.

However, PMV was never intended to be applied in transient, inhomogeneous conditions. Van Hoof (van Hoof, 2008) discussed PMV's applicability to transient conditions, concluding that there is a lack of PMV assessment in transient environments and that extensive research is still required. Also, body parts experience local discomfort and thermal sensation levels differ from each other and from the overall sensation (Arens et al., 2006; Nakamura et al., 2008). With the introduction of heated/cooled seats and steering wheels the impact on individual body part sensation is even higher. Therefore, a big disadvantage of the PMV model is that it is unable to differentiate between sensations at different body parts, which is an important capability in the case of vehicular HVAC control systems.

2.2 Taniguchi's Model

Skin temperature is shown to be a good predictor of local and overall thermal sensation in the state of art (Bogdan, 2011; Wang et al., 2007), especially in case of extremities such as face and hands. Taniguchi *et al.* (Taniguchi et al., 1992) developed a multiple linear regression model relating the average facial skin temperature and its rate of change to the Overall Thermal Sensation (OTS) in a vehicle environment. The model was proposed based on a series of human subject tests and OTS is calculated as:

$$OTS = 0.81\,(T_f - 33.9) + 39.1\frac{dT_f}{dt}$$

where T_f is the face skin temperature and $\frac{dT_f}{dt}$ is the face skin temperature rate of change.

A significant disadvantage of this model is not taking into account that the thermal sensation of body segments other than the face also impact the overall body thermal sensation. Moreover, it does not allow the computation of local thermal sensation.

2.3 Zhang's Model

Zhang (Zhang, 2003) developed local and overall thermal sensation and comfort models targeted at transient, non-uniform conditions. Unlike Taniguchi's model, Zhang's models are based on skin temperatures at multiple sites along with core temperature, if available. A nine point analogue scale (shown in Table 2) is used for expressing thermal sensation. Experimental tests were carried out at UC Berkeley, with subjects placed into chambers of uniform temperature and with heated or cooled air applied individually to 19 separate body areas. The tests were carried out in a climate-controlled chamber, consisting of both cold and hot test cases. Throughout these tests, subjects were allowed to adjust the HVAC settings to their preference. Skin temperature was measured at 19 locations using thermocouples, while core temperature was measured using an ingestible temperature device. Local and overall sensation equations were developed, using the measured skin temperature, mean skin temperature and core temperature along with subjective reports. Zhang validated the model against subjective reports and acceptable results were obtained. The coefficient of determination (R^2) for the overall sensation model was 0.95 and the standard deviation of residuals was 0.54.

Luo *et al.* (Luo et al., 2007) criticize the model, citing that "the mathematical model is not practicable as it is limited by having too many coefficients, and because of the experiment's limitation, the regression analysis result cannot be assured either". Furthermore, they criticize the body part set-point temperature approach of the model. Also, Cheng *et al.* (Cheng et al., 2012) points out that during the experiments, they focused more on cooling local body parts in warm environments than on warming local body parts in cool environments. In addition, the influence of local stimulation duration and intensity were not varied in the test. Moreover, no validation of the model within daily driving scenarios or other typical conditions encountered in vehicular environments exists in the literature. The main advantage of Zhang's model over PMV is its ability to determine local sensation indexes.

Table 2: Zhang's thermal sensation scale.

4	Very Hot
3	Hot
2	Warm
1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold
-4	Very Cold

2.4 Nilsson's Model

Nilsson (Nilsson, 2004) proposed clothing independent thermal comfort zones for 18 different body parts based on equivalent temperatures. Equivalent temperature is formally defined as the uniform temperature of an imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat by radiation and convection as in the actual non-uniform environment (Nilsson and Holmer, 2002). Equivalent temperature can be computed based on environmental parameters such as air temperature, mean radiant temperature, air flow and clothing index or it can be directly measured with appropriate instruments (Nilsson and Holmer, 2002). Once the equivalent temperature is calculated, the local or overall thermal sensation level can be estimated using the diagrams in Figure 1. Nilsson developed this model through experimentation with approximately 500 subjects.

A gap in the literature that this paper responds to is the lack of empirical evaluation of the thermal comfort models presented within vehicular environments in order to establish whether any of them is suitable for comfort-oriented HVAC control. According to the authors' knowledge, no empirical data based evaluation of these models in vehicular environments exists in the state of art.

3 METHODOLOGY

In order to address this lack of empirical evaluation, car cabin data and subjective comfort readings were gathered over a wide range of experimental conditions. This section provides a description of the par-

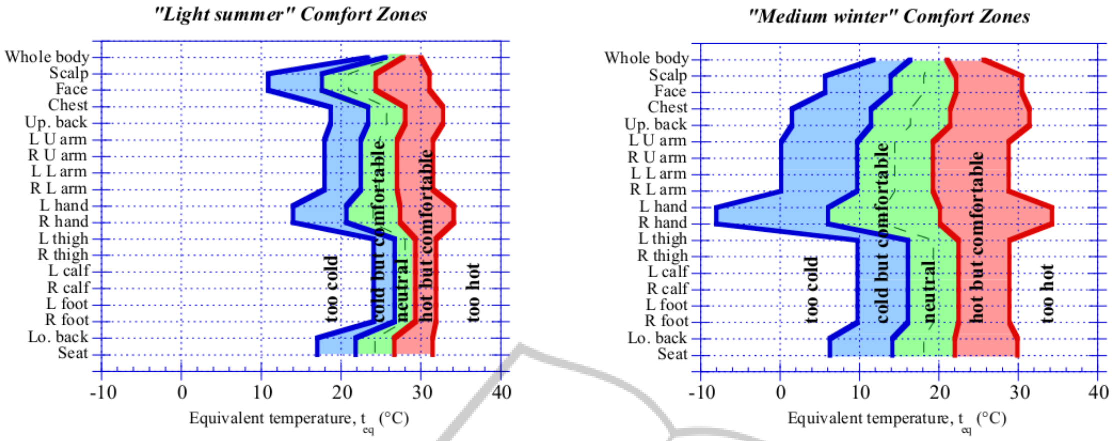

Figure 1: Nilsson's clothing independent thermal sensation diagrams (Nilsson, 2004).

Table 3: Subject details.

Subject	Gender	Age	Height (cm)	Weight (kg)
1	Male	46	173	78
2	Female	37	157	73
3	Male	56	166	70
4	Male	49	178	75
5	Female	24	162	48
6	Male	26	176	77
7	Female	34	160	55

ticipating subjects in the comfort trials, the instrumentation used and the variety of conditions encountered throughout the trials.

3.1 Participating Subjects

Seven adults (four males and three females) were selected as experimental subjects. Their ages were between 24 and 56 years old, with heights between 1.57 cm and 1.78 cm and weights between 48 kg and 78 kg, as presented in Table 3. The subjects occupied the driver seat and were asked by the observer in the right-hand rear passenger seat for their overall thermal sensation throughout the experimental trials (as detailed in Section 3.3). The thermal sensation scale used was the ASHRAE seven point scale (coincides with the PMV scale) shown in Table 1. Clothing was standardised across all trials and subjects, consisting of long trousers and a short-sleeved, light-coloured shirt or blouse, corresponding to a clothing index value of 0.7.

3.2 Measured Variables

Throughout all trials, equivalent temperature was monitored at eight locations (corresponding to head, chest, left lower arm, right lower arm, left upper arm, right upper arm, thigh and calf) using the INNOVA Flatman support manikin, shown in Figure 2 (right) and the associated INNOVA 1221 thermal comfort data-logger. Throughout the trials, the Flatman was positioned in the front passenger seat, continuously calculating equivalent temperature via the dry heat loss sensors and computing the PMV thermal sensation level. Cabin air and surface temperature data was gathered from 19 points using type K thermocouples and was recorded by a Grant Instruments DataTaker DT85 data logger. Near-body air temperature and relative humidity were measured at eight points (close to the neck, wrist, chest, thigh and calf locations) using type T thermocouples and Honeywell S&C HIH-5031 humidity sensors and also recorded by a SQ2040 data-logger. Solar loading at the driver sunroof location was measured using automotive solar sensors and recorded by a Grant Instruments Squirrel SQ2040 data-logger. The driver's center and outboard face vent air temperatures were monitored using type K thermocouples and recorded by the SQ2040 data-logger. Finally, subject skin temperature was also monitored at eight points (neck, left and right wrist, chest, left and right thigh and left and right calf) using Grant Instruments EUS-UU-VL2-0 thermistors and recorded by the SQ2040 data-logger.

3.3 Experimental Procedure

The trials were performed from the 8th to the 29th of August 2011. The test car used was a Jaguar XJ (2010 model year). Three types of trials were performed, with 78 trials in total, as described in the following sections.

Figure 2: Experimental data gathering. Left: Mean radiant temperature sensor. Right: Upper body of the Flatman thermal manikin.

3.3.1 Variable Cabin Temperatures Within Steady State External Conditions (T1)

These trials were performed within an enclosed space in order to eliminate wind and precipitation effects. Both the subjects and the test car were preconditioned for 20 minutes to 22 °C. At the outset of the experiment the subject, occupying the driver seat, remained in static conditions for 10 minutes. The temperature was then increased by 1 °C every 3 minutes until it reached 28 °C. The subject then left the car, which was again conditioned to 22 °C. After the subject returned, they again remained in static conditions for 10 minutes. Then the temperature was decreased by 1 °C every 3 minutes until it reached 16 °C. The air flow from the HVAC system was set to high or medium settings. During the static conditions, the subject reported thermal sensation and comfort at the 5, 7, and 9 minute marks and one minute before each temperature change when the HVAC set point was varied.

These trials are characterized by the following conditions: 1) absolute average car cabin temperature rates of change peaking at around 1.5 °C per minute, but usually under 1 °C per minute; 2) preconditioning of the cabin and subject at the same temperature; 3) no precipitation or wind effects; 4) steady ambient temperature (between 19 °C and 24 °C) varying by less than 1 °C within an individual trial.

3.3.2 User Control with Steady State External Conditions (T2)

These trials were performed within an enclosed space. The car and the subjects were preconditioned to a neutral (22 °C), hot (28 °C), or cold (16 °C) temperature. The subjects entered the car and remained inside for 15 minutes time, during which they were permitted to adjust the air conditioning at will in order to make themselves more comfortable. The control adjustments they made were logged in addition to the previously described parameters. Thermal comfort and sensation was reported every two minutes, with the first report being at the start of the test.

These trials are characterized by the following conditions: 1) absolute average car cabin temperature rates of change peaking at 8 °C per minute; 2) preconditioning of the cabin and subject at the same temperature; 3) no precipitation or wind effects; 4) steady outside temperature (between 17 °C and 25 °C) varying by less than 1 °C within an individual trial.

3.3.3 User Control in Driving Conditions (T3)

These trials are similar to the previous ones (*T2*), except that the subjects drove the car on private roads and there was no additional solar loading applied beyond that naturally falling on the car. Drivers were required to turn and change speed at frequent intervals in order to simulate to an extent the daily driving routine. This provided a comparison against the baseline established in the previous type of trials, as it was expected that the acceptable temperature range would widen as the driver was required to concentrate on driving. Thermal comfort and sensation was reported every two minutes, with the first report being at the start of the test.

These trials are characterized by the following conditions: 1) absolute average car cabin temperature rates of change peaking at 10 °C per minute; 2) preconditioning of the cabin and subject at the same temperature; 3) ambient solar load and wind; 4) ambient outside temperature (between 12 °C and 28 °C) varying by less than 2 °C within an individual trial.

The first set of trials were aimed at determining the extents of passenger thermal comfort with no extreme conditions, while the second set offered information on what control adjustments were required in order for the cabin occupants to feel comfortable and how quickly thermal neutrality was reached. The third set of trials aimed to capture the comfort ranges during daily driving and therefore with the subject less focused on their comfort. Altogether, the multitude of conditions (solar load, stationary or driving, different blower speeds, different initial temperatures) allowed a thorough evaluation of the validity of the selected thermal comfort models. Table 4 provides a summary of the trials performed.

Throughout the three sets of trials, the Flatman was positioned in the front passenger seat, with the subject occupying the driver seat. In order to ensure a valid comparison between the thermal sensation computed/reported by the two sides the following were ensured: 1) the front passenger vent and driver vent had the same orientation and delivered the same setpoint temperature; 2) both the test car (with the Flatman inside) and the driver were preconditioned to the same temperature prior to each trial.

Table 4: Summary of the experimental conditions in all trials.

Trial	Duration (mins)	Blower speed	Solar load	Driving	Pre-conditioning	Subjects
T1	56	High or Medium	Controlled	No	22 °C	7
T2	15	User	Controlled	No	16 °C, 22 °C or 28 °C	7
T3	15	User	Ambient	Yes	16 °C, 22 °C or 28 °C	6

4 RESULTS

This section provides an evaluation of the four thermal comfort models based on the gathered data described in Section 3. The purpose is to establish whether they can accurately predict car cabin occupant thermal sensation in any of the conditions in order to be used for comfort based HVAC control. For this purpose the overall thermal sensation reports of the drivers were compared to i) the PMV index as computed by the Flatman, ii) Zhang's index computed from the measured skin temperatures, iii) Taniguchi's index computed from the measured facial skin temperature and iv) Nilsson's index computed from the measured average body equivalent temperature.

PMV is widely used for car cabin comfort based HVAC controllers (Busl, 2011; Farzaneh and Tootoonchi, 2008). The reason is the simplicity of estimating the PMV index. However, does PMV actually reflect the reported sensation levels of the occupants? Table 5 presents the correlation coefficient and the determination coefficient R^2 between the subjective and experimental data for all models. The correlation coefficient quantifies the degree of correlation between two variables, while the R^2 coefficient indicates how well data points fit the linear regression. The p-value for a regression gives the probability that the result is not derived by chance. For all results presented, the p-value is smaller than the threshold (p ¡ 0.001) and the results are therefore significant.

In the case of PMV, the highest level of agreement corresponds to trials *T1,* with a correlation index of 0.91. The high correlation is somewhat expected due to the stable conditions encountered throughout trials *T1* (interior temperature rates of change less than 1.5 °C per minute, stable outside temperature and no wind or precipitation). The experimental data matches less accurately the subjective reports in trials *T2* and *T*3. The correlation index between the two is 0.76 for *T2* and 0.78 for *T3*. Overall Flatman's PMV tended towards colder reports than the subjective reports. For example, for *T1,* drivers reported thermal sensations of up to 4 (corresponding to "very hot"), whereas Flatman's PMV did not go beyond 3 (corresponding to "hot").

The results indicate that PMV can be applied in vehicle cabins to infer passenger comfort within a limited set of conditions, however the model brings forward another important issue in this type of environment, the inability to differentiate between different parts of the body. Due to the non-uniform nature of the environment, the difference in thermal sensation over small distances is considerable and so effective HVAC control should be able to warm up or cool down separately different body parts.

With PMV's accuracy limited to a narrow range of conditions, the authors further investigated two skin temperature based models: Taniguchi's model and Zhang's model. For Taniguchi's model, as Table 5 illustrates, the highest level of agreement corresponds to trials *T1,* with a correlation index of 0.56, while in trials *T2* and *T*3 the match is poor, with correlation indexes of 0.03 and 0.15, respectively. Face skin temperature seems to have a higher impact on overall thermal sensation when the rate of change of air temperature is low (less than 1.5 °C per minute), as suggested by the higher correlation for trials *T1*. As Taniguchi's model was developed only with respect to facial skin temperature, it is further interesting to see if Zhang's model improves on this by taking into consideration 8 different body parts.

Zhang's model was developed, like Taniguchi's, for transient environments such as car cabins. During experimentation, skin temperature was sampled at only 8 sites, compared to the 19 sites specified by Zhang. This is justified by the fact that within real-time vehicular comfort control, it would be infeasible to monitor skin temperature at all locations specified by Zhang. However, in order to ensure that the sum of skin temperature segment weights is 1, the weights for the contribution of local thermal sensations to the overall sensation were normalised. Mean skin temperature was calculated as a proxy for core temperature (this approach being suggested by Zhang). The body part skin temperatures recorded at the beginning of each trial were used as the set point temperatures of the body segments in the model. As table 5 shows, the correlation levels are poor: 0.10 for *T1*, 0.50 for *T2* and 0.60 for *T3*. As it stands, for trials *T1,* facial skin temperature alone proved to be a better estimator than the combination of 8 different body parts. The performance of the two skin temperature based models does not appear to be sufficient to support vehicular HVAC comfort control.

Table 5: Statistic metrics between the models' thermal sensation index and the reported sensation.

	PMV		Taniguchi		Zhang		Nilsson	
Type	Correlation	R^2	Correlation	R^2	Correlation	R^2	Correlation	R^2
T1	0.91	0.85	0.56	0.32	0.10	0.0001	0.93	0.86
T2	0.76	0.57	0.03	0.001	0.50	0.25	0.77	0.59
T3	0.78	0.61	0.15	0.02	0.60	0.35	0.79	0.62

In order to compute the overall thermal sensation index of Nilsson's model, the equivalent temperature at 8 different body parts was averaged based on body area weights. Once the average equivalent temperature is computed, the overall thermal sensation index can be found from Figure 1, using the diagram corresponding to light clothing (the participants wore light clothing throughout the experiments). Nilsson's model had a similar performance to the PMV model. The highest level of agreement with the subjective reports corresponds to trials *T1,* with a correlation index of 0.93. For trials *T2* and *T3*, the correlation index is lower, of 0.77 and 0.79, respectively. The similar performance is somewhat expected, because Flatman's PMV index is also based on the measured average equivalent temperature. The advantage Nilsson's model has over PMV is that local thermal sensation can also be computed and used for control.

5 CONCLUSIONS AND DISCUSSION

In this paper we evaluated the applicability of four thermal comfort models, namely PMV, Taniguchi's model, Zhang's model and Nilsson's model in a range of conditions specific to cars. A first step towards this aim was to design experimental trials covering a wide range of conditions: with preconditioning of the occupants and cabin at different temperatures, with or without ambient solar load, wind and precipitations, with steady or varying outside ambient temperature and with different temperature rates of change within the cabin.

Based on the experimentally gathered data, the PMV index and Nilsson's index accurately matched (with correlations of 0.91 and 0.93, respectively) the occupant reported thermal sensation within a limited set of conditions: preconditioning of the passenger and the cabin at the same temperature, a steady outside temperature and low rates of change of the interior temperature (lower than 1.5 °C per minute). Higher interior temperature rates of change (up to 9 °C per minute), ambient solar load and wind leads to lower correlation factors, between 0.76 and 0.79.

The overall sensation computed using the two skin temperature based thermal comfort models (Taniguchi's model and Zhang's model) poorly matched the subjective reports throughout all trial types (correlations between 0.10 and 0.60). Overall, the two skin temperature based models appear to have little success and their accuracy is not sufficient to support vehicular HVAC comfort control.

Capitalizing on our findings, Nilsson's model is recommended by the authors in preference to the other three models for vehicular comfort oriented control. The model provided similar results to PMV. However, an important advantage Nilsson's model has over PMV is its ability to estimate local thermal sensation, which the authors see as an important capability for the new generation of vehicular HVAC control systems. Moreover, Nilsson's model only requires two input parameters—equivalent temperature and clothing index—rather than six parameters in PMV's case, some of which could not feasibly be determined by an automated system.

The deviation between the Flatman's PMV output and the subjective responses may be because the subjects were in contact with the seat and the steering wheel whereas the Flatman's dry heat loss sensors were not. This could be confirmed via further experimentation. Another related avenue for future work is in regard to heated/cooled seats and steering wheels. These are becoming more widespread and will clearly have an impact on thermal sensation and comfort, which should be evaluated through empirical work.

It is known that no thermal comfort model can provide a perfect match for what people feel. The description of PMV, for example, acknowledges that any given environment will leave at least 5% of people dissatisfied. One reason is the subjective nature of thermal sensation and comfort in terms of how they are felt and, also, how they are reported. However, adopting Nilsson's model as a basis for estimating occupant comfort control and further integrating online learning within the car for tuning individual preferences would lead to a more thermally comfortable vehicular environment.

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