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ANALYSIS OF THERMAL COMFORT MODELS OF USERS OF PUBLIC URBAN AND INTERCITY TRANSPORT

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Abstract. Regardless of the vehicle's application, the thermal comfort of the vehicle's occupants and driver is given increased attention. Maintaining a sense of thermal comfort, whether for safety, health or occupant thermal well-being reasons, is one of the most important goals of heating, ventilation and air conditioning (HVAC) systems. There are a significant number of physical variables that affect thermal comfort. Therefore, evaluating thermal comfort has always been a complex issue and has attracted the attention of researchers. The feeling of thermal comfort is provided by factors that depend on the heat exchange between the human body and the external environment. It is well known that one of the requirements to be fulfilled is to find a person in thermal neutrality in the environment according to the comfort equation.

The article describes and evaluates the following indicators: DTS (dynamic thermal sensitivity), TS (thermal sensitivity), PMV (predicted mean voice) and PPD (predicted percentage of dissatisfaction). The most common models for evaluating thermal comfort, namely the Predicted Mean Vote (PMV), Taniguchi’s model, Zhang’s model and Nilsson’s model in a variety of car cabin conditions, have been reviewed. The limitations of these models in terms of the objectivity of the results obtained are analysed.

Keywords: thermal comfort, vehicle, DTS, TS, PMV, PPD, thermal model, energy balance.

Introduction

The global automotive industry is now seeking and refining technologies to improve vehicle occupant satisfaction. Therefore, the public transportation development process now includes thermal comfort assessment methods that best represent the passenger experience.

The concept of comfort, particularly thermal comfort, is directly related to vehicle safety. Unfavourable environmental conditions with excessive noise, polluted air and uncomfortable temperatures, encourage people to be in comfort in their vehicles. A comfortable vehicle environment reduces driver and passenger fatigue while driving and contributes to safety.

Thermal comfort can be considered as a subjective concept; it is related to a person's judgement of the thermal environment, is based on environmental conditions as assessed by the senses and includes various phenomena that contribute to the energy balance between the human body and the environment [1, 2].

Problem Statement

The purpose of this work was to review existing models of temperature comfort and analyze the possibility of their application to assess the comfort of passenger transportation and driver's working conditions in urban and intercity public buses.

Review of Modern Information Sources on the Subject of the Paper

The study of the relationship between temperature and the perception of thermal comfort began relatively recently. Fanger, one of the first researchers in this field, linked people's subjective feelings with physical parameters [3]. In order to describe these feelings numerically, a thermal comfort scale was developed based on Fanger's research. First, a model was developed that was based on people's voting behaviour towards the thermal environment they were in.

The human thermal comfort prediction was done depending on the different indices.This indices are used for describing:

- DTS (Dynamic Thermal Sensation),
- TS (Thermal Sensation),
- PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied).

The first two indices depend of the hypothalamus temperature and the mean skin temperature and PMV – PPD indices take into consideration the following parameters: activity, clothing, air temperature, mean radiant temperature, air velocity and humidity (ISO 7730) [4].

The DTS index is a functions which use for calculation the hypothalamus temperature T_{hy},.

$$F = F\left(T_{hy}, T_{sk.m}, \frac{\partial T_{sk.m}}{\partial t}\right), \tag{1}$$

where $T_{sk,m}$ – skin temperature

The DTS index consists of 3 sub-functions:

$$DTS = 3\cdot\tanh(f_{sk} + \varphi + \psi), \tag{2}$$

where f_{sk} is a function that depends exclusively on the mean skin temperature derivation towards the set point:

$f_{sk}=1.026\Delta T_{sk.m}$ for $\Delta T_{sk.}>0$,

$f_{sk}=0.298\,\Delta T_{sk.m}$ for $\Delta T_{sk.m}<0$.

While φ contains the hypothalamus temperature too:

$$\varphi = 6.662\cdot\exp\left(\frac{0.565}{\Delta T_{hy}}\right)\cdot\exp\left(\frac{-7.634}{5-\Delta T_{sk.m}}\right), \tag{3}$$

$$\Delta T_{hy} \le 0 \Rightarrow \varphi = 0, \quad \Delta T_{hy} \ge 5 \Rightarrow \varphi = 0$$

Dynamic components in the DTS index are collected in ψ:

$$\psi = \frac{0.114\frac{\partial T_{sk.m}}{\partial t}}{1+\varphi}. \tag{4}$$

The thermal sensation index, TS, not contain dynamic terms it can combines 2 sub-functions:

$$TS = 3\cdot\tanh(f_{sk} + \psi). \tag{5}$$

The degree of the thermal comfort for a person is influenced by six parameters: (Fig. 1)

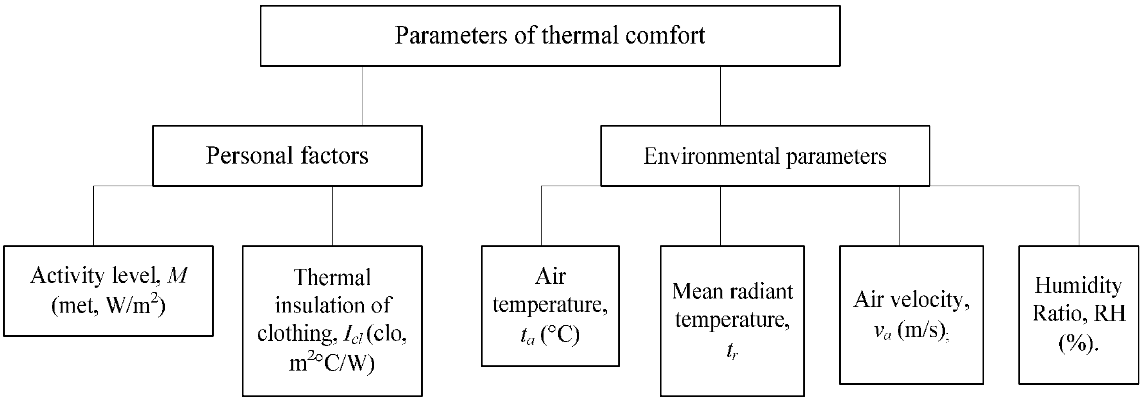

Fig. 1. Parameters of thermal comfort

ISO 7730 defines the degree of general comfort through a combination of these parameters as the PMV index. It is the result of a large group of people voting on a seven-point scale of thermal feelings [5].

The PMV index values for thermal comfort from -3 to +3 correlate with the ASHRAE 7-point scale (table 1) [2].

Table 1

ASHRAE Thermal comfort scale

	3	2	1	0	-1	-2	-3
PMV	Hot	Warm	Slightly warm	Comfortable	Slightly Cool	Cool	Cold
PPD	100 %	78 %	26 %	5 %	26 %	78 %	100 %

Negative values mean that the user feels cold, positive values suggest that the user feels warm, and a value of 0 shows that the user feels comfortable.

The recommended values for the PMV index are between -0.5 and +0.5, It means that less than 10 % of customers will find the thermal environment unacceptable.

The PMV index is used to graphically determine a person's percentage of discomfort using the PPD(Predicted Percentage of Dissatisfied) index. The minimum PPD index value is 5 % (Fig. 2).

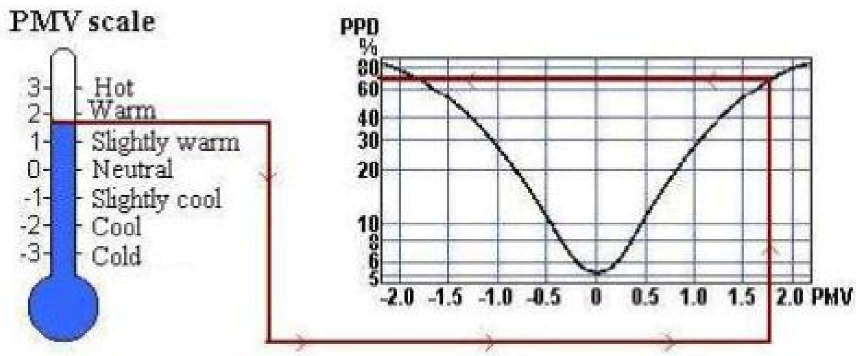

Fig. 2. Thermal sensation scale PMV and the variation of PPD index depending on PMV

Negative values indicate that the customer feels cold, positive values indicate that the customer feels warm, and a value of 0 suggests that the customer feels comfortable. The PMV and PPD indices are determined by empirical formulas [1]:

$$PMV = \left[0.303\exp(-2.100\cdot M) + 0.028\right]\cdot\left[(M - W) - H - E_c - C_{res} - E_{res}\right], \qquad (6)$$

where M – the metabolic rate, in Watt per square meter (W/m^2); W – the effective mechanical power, in Watt per square meter (W/m^2); H – the sensitive heat losses; E_c – the heat exchange by evaporation on the skin; C_{res} – heat exchange by convection in breathing; E_{res} – the evaporative heat exchange in breathing.

Another representation of the formula:

$$PMV = \left[0.303\exp(-2.100\cdot M) + 0.028\right]\times$$
$$\times\begin{bmatrix} (M - V) - 3.05\cdot 10^{-3}\left[5733 - 6.99(M - V) - p_a\right] - 0{,}42\left[(M - V) - 58.15\right] - \\ - 1.7\cdot 10^{-5}\cdot M(5867 - p_a) - 0.0014M(34 - t_a) - \\ - 3.96\cdot 10^{-8} f_{cl}\left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] - f_{cl}h_c(t_{cl} - t_a) \end{bmatrix} \qquad (7)$$

where: p_a – the partial vapour pressure (Pa); t_a – the air temperature (°C); f_{cl} – the clothing area factor; t_{cl} – the external clothing mean temperature (°C); $\bar{t}_r$ – the mean radiant temperature (°C); h_c – the convective heat-transfer coefficient (W m^{-2} °C^{-1}); I_{cl} – the thermal resistance of clothing (m^2 C W^{-1}); V – the mean air velocity (m s^{-1}).

In some cases the PMV value calculated for the whole body is within the comfort range, but a person can express annoyance on account of local discomfort caused by unwanted cooling or heating of some parts of the body. The percentage of people dissatisfied (PPD) due to draught is predicted, as a function of air temperature, air velocity, and turbulence intensity, using the following expression:

$$PPD = (34 - t_0)(\bar{V}_a - 0.05)^{0,6223}(0.3696\bar{V}_a \times T_u + 3.1439)\,. \qquad (8)$$

Or it can be calculated from PMV:

$$PPD = (34 - t_0) - 95\exp(-0.00353 \times PMV^4 + 0.2179 \times PMV^2)\,. \qquad (9)$$

The effective temperature (ET) was originally introduced as an empirical index, derived from statistical studies in which a group of evaluators voted on different environments. Later, a new index was proposed, widely used today, which is defined as an ambient temperature with a relative humidity of 50 % that results in the same heat loss from the skin as the actual environment [6]:

$$ET = t_0 + w \cdot i_m \cdot LR(p_a - 0.5P_{et})\,, \qquad (10)$$

where t_0 – the operative temperature (defined below) (°C); w – the wet-skin fraction (dimensionless); i_m – the moisture permeability index (dimensionless); LR – the Lewis ratio (the relation between convective heat transfer and the mass-transfer coefficient, typically 16.5 °C kPa^{-1} in indoor conditions); p_a – the water vapour pressure in ambient air (kPa); P_{et} – the water vapour pressure at ET (kPa).

For a given environment the effects of air temperature, radiant temperature, air velocity, and relative humidity are included in the estimation of ET. The value of ET depends on the clothing and activity levels. To avoid this dependency, the standard effective temperature (SET) is defined as the equivalent air temperature of an isothermal environment at 50 % relative humidity [4]. A subject wearing clothing standardized for the activity concerned has the same heat stress and thermoregulatory strain as in the actual environment.

The operative temperature is defined as the uniform temperature of a black radiant enclosure [5], and is calculated from:

$$t_0 = \frac{h_r t_r + h_c t_a}{h_r + h_c}\,, \qquad (11)$$

where h_r – the radiant heat-transfer coefficient (W m^{-2} $°C^{-1}$)

Simplified equations for the estimation are given in the standards ISO 7730 [4] and ASHRAE 55 [7]. Mathematically, this corresponds to the average of the mean radiant and ambient air temperatures, weighted by their respective heat-transfer coefficients.

Main Material Presentation

Fanger carried out his own studies of the thermal comfort equation and combined the findings with those of other researchers. It was found that the PMV model has limitations when used for indices below -2 and above +2 and that significant inaccuracy can occur in hot environments [8]. The advantages of PMV are:

– the standardisation of implementation

– if some parameters cannot be measured, they can be approximated without introducing a significant error in the PMV index.

The main disadvantage of PMV is its limited applicability to transient, heterogeneous conditions. as evidenced by studies [9] . Another disadvantage of the PMV model is that it is unable to differentiate sensation on different body parts. It is sufficiently obvious that body parts can experience local discomfort and the levels of thermal sensation differ from each other and from the overall sensation [10–11]. With the implementation of temperature-controlled seats and steering wheels, which is an important possibility in the case of vehicle HVAC control systems, the impact on the feeling of the individual body parts is even greater.

Studies[12] have shown that skin temperature is a fairly universal indicator of local and general heat sensation. It can be used particularly effectively for extremities and the face. Taniguchi et al [13] developed a multiple linear regression model linking average facial skin temperature and its rate of change to overall thermal sensation (OTS) under vehicle conditions. The model was designed basing on the results of a series of tests on humans, and the OTS is calculated as:

$$OTS = 0.81\left(T_f - 33.9\right) + 39.1\frac{dTf}{dt}, \quad (12)$$

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

A significant disadvantage of this model is that it does not take into account the influence of body parts other than the face on the overall body heat sensation. It also does not allow for the calculation of the local thermal sensation.

Zhang considered the shortcomings of the Taniguchi model and introduced components to account for transient, non-uniform conditions [14]. He developed models of local and general thermal sensations, i.e. they are based on skin temperature in several places as well as body temperature if it is available. A nine-point analogue scale (shown in Table 2) was used to express thermal sensations. The model is based on experimental data. Subjects were placed in chambers with the same temperature, and heated or cooled air was administered individually to 19 selected body areas. Tests were conducted in a climate-controlled chamber consisting of cold and hot compartments. Throughout the trials, the subjects were able to adjust the HVAC parameters according to their preferences. Local and general sensation equations were developed using measured skin temperature, average skin temperature and body temperature along with subjective reports. Zhang compared the measured results with the subjects' reports and obtained acceptable results.

The authors [15] cite as disadvantages too many coefficients in the model, as well as limited experimentation. In addition, they criticise the model's approach to determining the body part temperature. Also, Cheng et al. [16] point out that their experiments focused more on cooling local body parts in a warm environment than on heating local body parts in a cool environment. In addition, the duration and intensity of local stimulation were not varied during the trials. The model was not tested in conditions typical of vehicle environments. The main benefit of Zhang's model compared to PMV is its ability to detect localised sensation indices.

Table 2

Zhang`s thermal sensation scale

Level	4	3	2	1	0	-1	-2	-3	-4
Sensation	Very hot	Hot	Warm	Slightly warm	Neutral	Slightly Cool	Cool	Cold	Very cold

Nilsson [17] proposed an estimate based on equivalent temperature. Equivalent temperature is formally defined as the uniform temperature of a notional envelope with zero air speed and humidity, in which a person will exchange the same heat by radiation and convection as in a real heterogeneous environment.

The equivalent temperature can be calculated on the basis of environmental parameters such as air temperature, average radiation temperature and clothing index. It can also be directly measured with appropriate instruments [18]. Once the equivalent temperature has been calculated, the local or general level of heat sensation is estimated using the diagrams shown in Fig.3. The model has been obtained experimentally with the results of approximately 500 experiments.

Nilsson [17] proposed clothing independent thermal comfort zones for 18 different body parts based on equivalent temperatures. Equivalent temper-ature 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. 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 [18]. Once the equivalent temperature is calculated, the local or overall thermal sensation level can be estimated using the diagrams in Fig.3. Nilsson developed this model through experimentation with approximately 500 subjects.

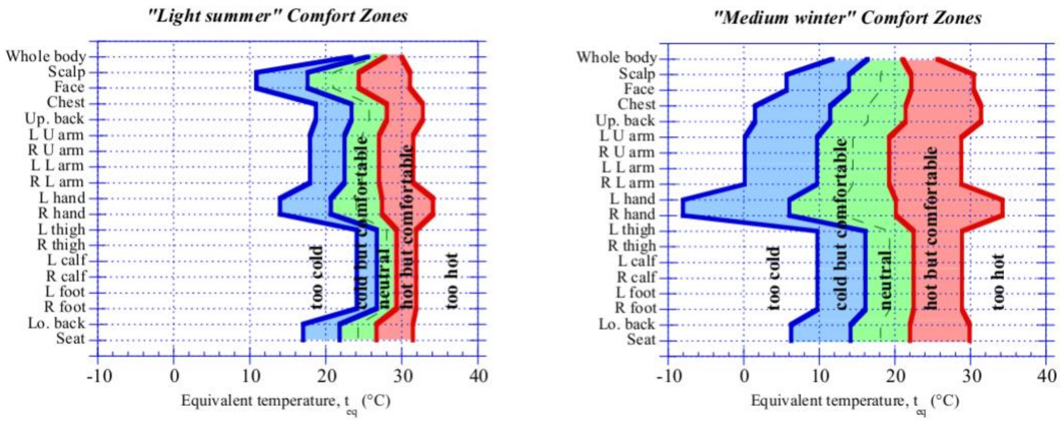

Fig. 3. Comfort zones

The summary of the analysis of the models, their limitations, evaluation of the results and features of the application are shown in the table 3.

Table 3

Psychological thermal comfort models

Data	Author	Description
1972	Fanger [1,2]	Concept of PDV.index.Whole body comfort.
1989	Wyon et al. [20]	Concept of the "Piste"; Steady-state; Non-uniform
1992	Taniguchi et al. [21]	Whole body thermal sensation
1992	Hagino and Junichiro [22]	Statistical model; Non-uniform
1993	Matsunaga et al. [23]	Adopt AETa value to calculate PMV. Non-uniform
1993	de Dear et al. [24]	Dynamic Thermal Stimulus Model; Whole body thermal state
1994	Wang X [25]	Whole body comfort; Transient thermal sensation
2002, 2003	Kohri I et al. [26_27]	Local SETb; Uniform; Non-uniform
2003	Guan. et al. [28,29]	Transient thermal sensation prediction model
2003, 2010	Fiala et al. [30,31]	Dynamic Thermal Sensation model; Transient thermal sensation mode
2003, 2007	Nilsson [17]	New thermal comfort zones based on teq c; Steady-state; non-uniform
2007	Arens et al. [10]	UC Berkeley Thermal Comfort. Model (UCB Model); Transient, Non-uniform or uniform
2003,2010	Zhang H. et al [14]	Model (UCB Model); Transient, Non-uniform or uniform

Conclusions

Fanger noted that the values of PMV are not sufficient to define the feeling of discomfort, as slightly warm or too cold, not express how dissatisfied the people are. Therefore, the idea of predicted Percentage of Dissatisfied (PPD) was associated to the PMV calculation. Even with the votes equal to zero (comfortable), 5 % of people are dissatisfied, and in extreme conditions there is 100 % of dissatisfaction by the people. In the next sessions it will be further detailed the equation of the PMV PPD.

Fanger model has limitations related to:

- thermal steady state or dynamic state,
- distinction between local and whole-body thermal comfort,
- environmental particularities of the vehicle.

The PMV model depends on the context and is more accurate in vehicles with air-conditioning systems than in the ones with natural ventilation, because of the influence of outside temperature. The inadequate measurements of the thermal insulation of clothing and the metabolic rate will reduce the accuracy of the PMV index.

Performed analysis 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.

The existing thermal comfort models that address the asymmetry environments need further development and improvement.

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