

Issued 1993-01  
Reaffirmed 2007-06

Superseding J2234 OCT2001

**Equivalent Temperature—Truck and Bus**

- 1. Scope**—The scope of this SAE Information Report is to:
- Define the Equivalent temperature.
  - Describe how it can be used to evaluate the performance of a heating and/or air-conditioning system in a vehicle.
  - Describe how it can be measured.

**1.1 Rationale**—This document has been reaffirmed to comply with the SAE 5-Year Review policy.

**2. References**

**2.1 Applicable Publications**—The following publications form a part of this specification to the extent specified herein.

2.1.1 ANSI/ASHRAE PUBLICATIONS—Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, [www.ansi.org](http://www.ansi.org).

ANSI/ASHRAE-1992—Thermal environmental conditions for human occupancy

ANSI/ASHRAE 55-1992—Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

2.1.2 ISO PUBLICATIONS—Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, [www.ansi.org](http://www.ansi.org)

ISO 7726—"Thermal environments—Instruments and methods for measuring physical quantities," International Standards Organization, Geneva 1985

ISO 7730—"Moderate thermal environments—Determination of the PMV and PPD indices and specification of the conditions for thermal comfort," International Standards Organization, Geneva, 1984

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**2.2 Related Publications**—The following publications are provided for information purposes only and are not a required part of this document.

Fanger, P.O., 1982, "Thermal Comfort" Malabar, F1, Robert E. Krieger Publishing Company

Bedford, T., 1936, "The warmth factor in comfort at work," Rep. Industr. Hlth., Res. bd. No. 76, London

Dufton, A.F., 1932, "The equivalent temperature of a room and its measurement," Bldg. Res. Technical Paper No. 13, London

Gagge, A.P., et al., 1931, "Thermal interchanges between the human body and its atmospheric environment," Amer. J. of Hyg., 26:84-102

Gagge, A.P., 1940, "Standard operative temperature generalized temperature scale applicable to direct and partitional calorimetry," Amer. J. Physiol., 131:93

Hymore, R.R., R.F. Tweadey, and D.F. Wozniak, 1991, "Development of a Test Procedure for Quantifying Performance Benefits of Solar Control Glazings on Occupant Comfort," SAE International Congress and Exposition, Detroit, MI, Feb. 25-March 1

Madsen, T.L., Olesen, B.W., and Christensen, N.L., "Comparison between operative and equivalent temperature under typical indoor conditions," ASHRAE Trans., Vol. 90, Part 1, 1984

Madsen, T.L., Olesen, B.W., and Reid, K., 1986, "New methods for evaluation of the thermal environment in automotive vehicles," ASHRAE Transactions Vol. 92, Pt. 1

McIntyre, D.A., 1976, "Subjective temperature: A simple index of warmth," ECRC/M 916, The Electricity Council Research Center, Chester, UK

Olesen, Bjarne, 1988, "Evaluation of the thermal environment in vehicles," Bruel & Kjaer Application Notes

Olesen, B.W. and Jens Rosendahl, 1990, "Thermal Comfort in Trucks," FISITA '90, Torino, Italy, May 7–11

Wyon, D.P., Tennstedt, C., Lundgren, I., and Larsson, S.A., 1985, "A new method for the detailed assessment of human heat balance in vehicles—Volvo's thermal manikin," VOLTMAN, SAE, International Congress and Exposition, Detroit, MI

### 3. Definitions

**3.1 CLO**—A unit used to express the thermal insulation provided by garments and clothing ensembles, where:

$$1 \text{ c/o} = 0.155 \text{ m}^2 \cdot ^\circ\text{C}/\text{W} \quad (0.88 \text{ ft}^2 \cdot ^\circ\text{F}/\text{Btu}) \quad (\text{Eq. 1})$$

**3.2 Thermal, Comfort**—That condition of mind which expresses satisfaction with the thermal environment.

**3.3 Thermal, Comfort**—The characteristics of the environment which affect a person's heat loss.

**3.4 Relative Humidity (RH)**—The ratio of the mole fraction of water vapor present in the air to the mole fraction of water vapor present in saturated air at the same temperature and barometric pressure; alternatively, it equals the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature.

**3.5 MET**—A unit used to express the activity level (metabolic rate) of a person. 1 met = 58.2 W/m<sup>2</sup> (18.4 btu/h-ft<sup>2</sup>) which is equal to the energy produced per unit surface area of a seated person at rest.

- 3.6 Temperature, Equivalent  $T_{eq}$** —The uniform temperature of an imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat loss by radiation and convection as in the actual nonuniform environment.
- 3.7 Temperature, Air ( $t_a$ )**—The dry-bulb temperature of the air surrounding the occupant.
- 3.8 Humidity, Absolute**—Ambient water vapor pressure ( $P_a$ ), or dew point temperature ( $t_{dp}$ ), the temperature at which moist air becomes saturated (100% relative humidity) with water vapor ( $P_{sdp} = P_a$ ) when cooled at constant pressure.
- 3.9 Temperature, Mean Radiant ( $\bar{t}_r$ )**—The uniform surface temperature of an imaginary enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space.
- 3.10 Temperature, Operative ( $t_0$ )**—The uniform temperature of an imaginary enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment.
- 3.11 Temperature, Optimum Operative**—The operative temperature that satisfies the greatest possible number of people at a given clothing and activity level.
- 3.12 Thermal, Sensation**—A conscious feeling commonly graded into the categories, cold  $-3$ , cool  $-2$ , slightly cool  $-1$ , neutral  $0$ , slightly warm  $+1$ , warm  $+2$ , and hot  $+3$ ; it requires subjective evaluation.

#### 4. Symbols and Units

$h_c$ , convective heat transfer coefficient,  $W/m^2 \cdot ^\circ C$  (btu/h  $\cdot$  ft<sup>2</sup>  $\cdot$   $^\circ F$ )

$h_r$ , radiant heat transfer coefficient,  $W/m^2 \cdot ^\circ C$  (btu/h  $\cdot$  ft<sup>2</sup>  $\cdot$   $^\circ F$ )

$I_d$ , clothing insulation, clo

$P_a$ , water vapor pressure, kPa

rh, relative humidity, %

$t_a$ , air temperature,  $^\circ C$  ( $^\circ F$ )

$t_{dp}$ , dew point,  $^\circ C$  ( $^\circ F$ )

$t_{eq}$ , equivalent temperature,  $^\circ C$  ( $^\circ F$ )

$t_0$ , operative temperature,  $^\circ C$  ( $^\circ F$ )

$\bar{t}_r$ , mean radiant temperature,  $^\circ C$  ( $^\circ F$ )

$v_a$ , air velocity, m/s (ft/min)

- 5. Background**—Man's thermal comfort is a result of the combined effect of all six thermal climate parameters—activity level, clothing insulation, air temperature, mean radiant temperature, air velocity, and air humidity. According to ISO 7730, the degree of general thermal comfort can be given by the PMV-index, which can be calculated when the six climate parameters are known. It is recommended that the PMV-index is between  $-0.5$  and  $+0.5$ , which means that less than 10% will find that the thermal environment is unacceptable. In addition, the standard includes guidelines for local thermal discomfort like radiant asymmetry, draft, and air temperature gradients. This standard may also be applied for vehicles.

The activity level (met-value) and clothing (clo-value) is dependent on the person. In a vehicle the HVAC system mainly controls air temperature and air velocity, while the mean radiant temperature (surface temperature, sunshine) is significantly influenced by the outside climate and design of the body of the vehicle.

The usual method of evaluating the performance of the heating and air-conditioning system in vehicles is to apply sensors to measure the air temperature at feet and head level. The main purpose being to investigate how quickly the system will raise or lower the temperature in a cold or warm vehicle and to study the differences between temperature at head and feet. This means that only one of the three main climatic parameters that concern thermal comfort sensation (air temperature, mean radiant temperature, air velocity) is measured. This fact is especially unfortunate in vehicles, since the mean radiant temperature usually differs far more from the air temperature than is the case in buildings and the air velocity is also greater and more nonuniform than in buildings. The combined effect of air temperature, mean radiant temperature, and air velocity can be expressed by the equivalent temperature, which is related to the dry heat loss from the body.

In existing standards (ASHRAE, ISO) for the thermal environment the required temperature range is normally given as operative temperature. This is a combination of air and mean radiant temperature. This does not include the influence of air velocity, which on the other hand often is limited to very low values. In a vehicle the air velocity is, however, a major factor and must be taken into account when evaluating the performance of the HVAC system.

## 6. Calculation of Equivalent Temperature

**6.1 Operative Temperature**—In all the previously mentioned standards, the operative temperature is defined as the uniform temperature of an imaginary inclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. The exact equation for the operative temperature is:

$$t_o = \frac{h_c \times t_a \times h_r \times \bar{t}_r}{h_c + h_r} \quad (\text{Eq. 2})$$

where:

$t_a$  = air temperature, °C  
 $\bar{t}_r$  = mean radiant temperature, °C  
 $h_c$  = heat-transfer coefficient by convection,  $\text{W/m}^2 \cdot \text{°C}$   
 $h_r$  = heat-transfer coefficient by radiation,  $\text{W/m}^2 \cdot \text{°C}$

A simplified equation for calculation of the operative temperature is given in ISO 7730 and ASHRAE 55–92:

$$t_o = A \times t_a + (1 - a) \times \bar{t}_r \quad (\text{Eq. 3})$$

where  $a$ , depends on the air velocity,  $v_a$ :

$v_a$ (m/s) < 0.2	0.2 – 0.6	0.6 – 1.0
$a$ 0.5	0.6	0.7

Both the definition of the operative temperature and Equations 2 and 3 can make people believe that the operative temperature takes into account the cooling effect that an air movement has on a heated body, like a man. The operative temperature does not do that. It only takes into account the relative influence of the parameters—air temperature,  $t_o$ , mean radiant temperature,  $\bar{t}_r$ , and velocity,  $v_a$ —on the temperature of an unheated body.

**6.2 Equivalent Temperature**—When the air velocity is low ( $v_a < 0.1$  m/s) the equivalent temperature is equal to the operative temperature:

$$t_{eq} = t_o = 0.5 \times (t_a + \dot{t}_r) \text{ for } v_a < 0.1 \text{ m/s} \quad (\text{Eq. 4})$$

For higher air velocities ( $v_a > 0.1$  m/s) the equivalent temperature can be calculated as:

$$t_{eq} = 0.55 \times t_a + 0.45 \times \dot{t}_r + \frac{0.24 - 0.75 \times \sqrt{v_a}}{1 + I_{cl}} (36.5 - t_a)^\circ\text{C} \quad (\text{Eq. 5})$$

where:

$I_{cl}$  = Thermal insulation of the clothing, clo

This equation, developed by Madsen (1984), agrees with the similar equations by Bedford (1936), Gagge (1940), and McIntyre (1976).

The equivalent temperature may also be calculated from the PMV-equation [Fanger (1982), ISO 7730] by setting air temperature equal to mean radiant temperature and air velocity to 0 m/s.

It is seen that the equivalent temperature is influenced by the thermal insulation of the clothing. A given air velocity ( $v_a$ ), has a higher cooling effect on nude skin ( $I_{cl} = 0$ ) than on skin covered with clothing ( $I_{cl} > 0$ ).

## 7. Measurement of Equivalent Temperature

**7.1 Individual Measurements**—Air temperature, mean radiant temperature, and air velocity may be measured with individual sensors and the equivalent temperature then calculated from Equation 5. The thermal insulation of the clothing must be evaluated before the calculation. (ASHRAE 55–92, ISO 7730)

The sensors must fulfill the requirements in ISO 7726.

**7.2 Integrating Sensor**—Measuring each parameter individually requires a lot of instrumentation and it is difficult to measure all parameters in the same position. Instead of measuring each parameter and then calculating the combined influence, it may be easier to use a transducer that integrates the three climate parameters into one temperature, the equivalent temperature.

The sensor requirements for direct measurements of equivalent temperature is that the size, color, and shape simulate the convective and radiant heat loss from a person shape and color of the human clothing/skin. The sensor must be heated to a surface temperature, which simulates the mean clothing surface temperature of a person. From the definition it is seen that the equivalent temperature depends on the clothing insulation, which means that the sensor should be able to simulate different clothing temperatures.

The mean clothing/skin surface temperature of a person for different combination of the thermal parameters may be calculated from the PMV-equation given in ISO 7730 [ISO 7730 (1984), Fanger (1982)].

These requirements are fulfilled with the sensor in Figure 1. The sensor has been carefully designed to simulate the dry heat loss from a person as precisely as possible. The size has been chosen so that the ratio between the heat loss by radiation and by convection is similar to that of a person.