Climatic Wind Tunnel Vienna

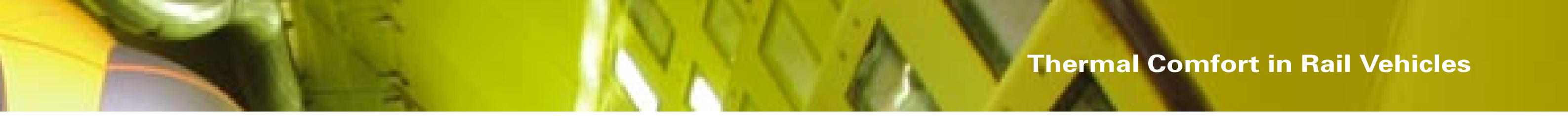
Thermal Comfort in Rail Vehicles

Dipl.-Ing. Gabriel Haller

Professional article September 2006

Quality in any weather

RAIL TEC ARSENAL



Thermal Comfort in Rail Vehicles

Improving the comfort conditions of rail vehicles is an important factor in increasing the attractiveness of public transport systems. In particular, providing air conditioning in the rolling stock can play a significant role in making public transport a viable alternative to the private car.

While air conditioning has already been installed in almost all main line rolling stock (with very few exceptions), it still cannot be taken for granted in urban and suburban transport systems in Central Europe. However, as a consequence of the global climate change and rising passenger expectations of comfort – partly due to the ease of comparison with the passengers' air-conditioned private cars – the demand for air-conditioned urban and suburban rolling stock can be expected to increase sharply in the future.

This article gives an overview of the current requirements for air conditioning systems in rail vehicles. In a detailed analysis of the comfort parameters, it presents all the possible ways of improving thermal comfort. It is designed as a guideline for railway operators, rail vehicle manufacturers, and manufacturers of air-conditioning systems.

What is thermal comfort?

Thermal comfort is achieved when passengers perceive the air temperature, humidity, air movement, and heat radiation of their surroundings as ideal and would not prefer warmer or colder air or a different humidity level.

Thermal comfort is influenced by:

- **Personal factors** (degree of activity, clothing, journey time)
- **Spatial factors** (radiant temperature, temperature of enclosing surfaces)
- **Ventilation factors** (air temperature, air speed, relative humidity).

These factors have complex effects on the heat balance of passengers. Thus all contributing factors must be considered in order to achieve conditions which will be perceived as comfortable by a majority of passengers.

Other factors influencing thermal comfort are air quality (dust content; microorganism content; gases and vapours; smells; ion content; electrical and electrostatic fields), noise, lighting, colour scheme, etc. While these factors do not have a direct effect on ambient temperature, they may influence the subjective perception of thermal comfort by passengers.

The standards

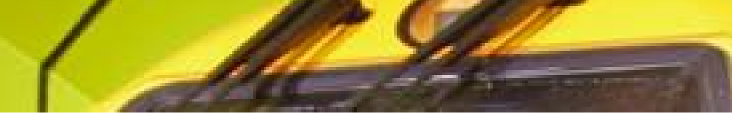
Over the past decades, many experiments and measurements have been carried out in the Vienna Climatic Wind Tunnel and its predecessor in the Vienna Arsenal to determine thermal comfort in rolling stock.

Based on the results of this work, UIC/ERRI defined comfort criteria for rail vehicles in the UIC 553 leaflet on "Ventilation, heating and air conditioning of passenger carriages" over thirty years ago. The related UIC 553-1 leaflet describes the tests that are necessary to prove compliance with these criteria.

Over the past few years, the following new European standards were developed for thermal comfort, taking into account the different operating requirements of rail vehicles (type of use, climatic zone, etc.):

- **EN 13129-1:2003:** Railway applications - Air conditioning for main line rolling stock - Part 1: Comfort parameters
- **EN 13129-2:2004:** Railway applications - Air conditioning for main line rolling stock - Part 2: Type tests
- **EN 14750-1:2006:** Railway applications - Air conditioning for urban and suburban rolling stock - Part 1: Comfort parameters
- **EN 14750-2:2006:** Railway applications - Air conditioning for urban and suburban rolling stock - Part 2: Type tests
- **EN 14813-1:2006:** Railway Applications - Air conditioning for driving cabs - Part 1: Comfort parameters
- **EN 14813-2:2006:** Railway Applications - Air conditioning for driving cabs - Part 2: Type tests

As the list shows, Part 1 of the standards specifies the comfort parameters and, by extension, the capacity of the air conditioning systems under defined conditions, while Part 2 describes the testing programme and the measurement procedures for evaluating the air conditioning systems.



Vehicle categories and climatic zones

The comfort criteria defined in the standard for **main line rolling stock** apply to all types of vehicles, i.e. both compartment and saloon coaches (single or double-deck).

In contrast, the standards for **urban and suburban rolling stock** and **driving cabs** each define two categories with different comfort requirements. The operator must specify the appropriate category in contractual agreements based on a classification matrix included in the standards (Table 1).

Table 1: Vehicle classification for urban and suburban rolling stock

Criterion	Category A	Category B
Standing passengers	< 4 passengers/m²	≥ 4 passengers/m²
Average passenger journey time	> 20 min	≤ 20 min
Average time between two station stops	> 3 min	≤ 3 min

In the case of urban and suburban rolling stock, coaches for suburban lines usually fall into category A, while all other vehicles, such as metros and trams, fall into category B.

In the case of driving cabs, the comfort criteria of category A are usually applicable both to main line and suburban trains, while driving cabs in urban trains fall into category B, especially when not separated from the passenger area by a partition.

Depending on where the vehicles are used, the climatological operating conditions for summer and winter are additionally divided into three climatic zones. For example, a vehicle destined for Southern Europe will not require elaborate heating, but must have a powerful air conditioning system which can guarantee a pleasant interior climate even in temperatures of 40°C, a relative humidity of 40 %, and a solar load of up to 800 W/m².

Central European countries are assigned to Zone II. This means that heating systems must be designed for exterior temperatures of down to –20°C and air conditioning systems for exterior temperatures of up to 35°C, 50 % relative humidity, and a solar load of 700 W/m².

The required air temperature and relative humidity within the coach, and thus the design criteria for cooling and heating systems, are defined in accordance with the climatic conditions (temperature, relative humidity, and solar load) in each climatic zone, the operating requirements (main line or urban/suburban rolling stock, driving cab) and the expected passenger load in summer (Table 2).

Depending on the purpose of the vehicles, the requirements are designed to ensure the expected level of thermal comfort without oversizing the systems for extreme conditions. During high summer, for example, it is sufficient to lower the temperature in the passenger area of a tram or metro car (Category B) by only a few degrees while providing appropriate dehumidification.

Table 2: Comparison of design conditions for maximum mean interior temperature/relative humidity

Climatic zones		Main line rolling stock EN 13129-1	Urban and suburban rolling stock EN 14750-1		Driving cab EN 14813-1	
Zone	Temperature/relative humidity; equivalent solar load		Category A	Category B	Category A	Category B
I	+40°C / 40 %; 800 W/m²	+27°C / 51.6 %	+30°C / 50.0 %	+32°C / 57.4 %	+27°C / 50.0 %	+30°C / 60.0 %
Summer*) II	+35°C / 50 %; 700 W/m²	+27°C / 51.6 %	+30°C / 50.0 %	+33°C / 55.0 %	+26°C / 52.5 %	+28°C / 65.0 %
III	+28°C / 45 %; 600 W/m²	+25.25°C / 57.5 %	+26°C / 63.0 %	+29°C / 64.5 %	+22°C / 60.0 %	+24°C / 75.0 %
I	-10°C					
Winter**) II	-20°C	+22°C	+15°C	+10°C	+18°C	
III	-40°C					

*) Occupation: All seats for main line rolling stock and driving cab, all seats + 2 persons/m² standing area for urban and suburban rolling stock, vehicle at standstill

**) Without solar load and occupation, but with wind (regular operation)

Comfort parameters

The comfort parameters defined by the standards are: air temperature, surface temperature, air speed, and relative humidity.

The parameters for **air temperature** include the mean interior temperature and criteria for horizontal and vertical temperature distribution in order to reduce areas of local thermal discomfort to a minimum. Different requirements were also defined for **surface temperatures**. These requirements represent a compromise between subjective desires and what is possible in practice.

Table 3 provides a synopsis of the requirements for air and surface temperatures for main line and urban/suburban rolling stock as well as for driving cabs.

To minimise and analyse draughty areas, acceptable **air speeds** were defined in the standards by a limiting curve as a function of local air temperature.

Table 4 compares the maximum air speeds for two temperature values for passenger areas in main line and urban/suburban rolling stock as well as for driving cabs.

Table 3: Comparison of different requirements for air and surface temperatures

Standard requirements	Main line rolling stock EN 13129-1	Urban and suburban rolling stock EN 14750-1		Driving cab EN 14813-1	
		Category A	Category B	Category A	Category B
Range of mean interior temperature T_{im} in passenger areas with respect to temperature setting T_{ic}	+/-1 K	+/-2 K	+/-2 K	+/-1 K	+/-2 K
Horizontal temperature distribution measured 1.10 m from the floor	2 K 3 K for couchettes	4 K	8 K	-	-
Vertical temperature distribution	3 K	4 K	8 K	3 K	6 K
Mean interior temperature in corridors	$> T_{ic} - 6$ K in heating mode $< T_{ic} + 5$ K in cooling mode	-	-	-	-
Interior temperature T_i in vestibules	$+10°C < T_i < T_{ic}$ in heating mode $T_i < T_{ic} + 9$ K and $< +35°C$ in cooling mode	$+3°C < T_i < T_{im}$ in heating mode $T_i < T_{em}$ in cooling mode		-	-
Interior temperature in annexes	$> T_{ic} - 6$ K in heating mode $< T_{ic} + 6$ K in cooling mode	$> T_{im} - 6$ K and $> 3°C$ in heating mode $< T_{im} + 6$ K in cooling mode		-	-
Interior temperature T_i in nursery	$T_{im} < T_i < T_{ic} + 4$ K	-	-	-	-
Surface temperature of walls and ceilings in heating mode	$> T_{im} - 7$ K single deck vehicle $> T_{im} - 10$ K double deck vehicle	$> T_{im} - 10$ K	$> T_{im} - 13$ K	$> T_{im} - 7$ K	$> T_{im} - 12$ K
Surface temperature of windows / window frames in heating mode	$> T_{im} - 12$ K / $> T_{im} - 9$ K	$> T_{im} - 15$ K		$> T_{im} - 12$ K	$> T_{im} - 15$ K
Surface temperature of floors	> +8°C 1 h after start of preheating $> T_{im} - 10$ K 3 h after start of preheating < +27°C for underfloor heating	-	-	-	-
Specific surface temperature criteria	-	≥ +3°C lowest surface temperature, with the exception of windows		< +35°C for all heated areas	

Table 4: Comparison of maximum air speeds

Local interior air temperature T_i	Main line rolling stock EN 13129-1	Urban and suburban rolling stock EN 14750-1		Driving cab EN 14813-1
		Category A	Category B	
+22°C	0.25 m/s	0.25 m/s	0.35 m/s	0.25 m/s
+27°C	0.6 m/s	0.8 m/s	1.1 m/s	0.6 m/s 0.3 m/s (at driver's head)

The **relative humidity** requirements are defined in the form of diagrams and are to ensure adequate dehumidification in air-conditioned coaches.

Fresh air flow and heat transfer coefficient

The standards also define fresh air flow and the overall heat transfer coefficient (k), as these values have a significant effect on the comfort parameters.

High levels of CO_2 give rise to fatigue and impaired concentration and create an atmosphere that feels stuffy and stale. A defined **amount of fresh air** must therefore be supplied.

The values required in the standards (Table 5) represent a compromise between energy consumption and a sufficient reduction of CO_2 levels.

The **overall heat transfer coefficient** defined in the standards (Table 6) characterises the thermal quality of vehicles, i.e. the efficiency of their thermal insulation and the effect of leakages. Poor thermal insulation directly affects the surface temperatures within the coach. The resultant radiant temperature has a strong effect on the thermal comfort experienced by passengers.

Table 5: Overview of minimum fresh air rates

Exterior temperature T_{em}	Main line rolling stock EN 13129-1	Urban and suburban rolling stock EN 14750-1		Driving cab EN 14813-1
		Category A	Category B	
$T_{em} \le -20°C$	10 m^3/h/person	15 m^3/h/person (in extreme conditions air flow can be reduced to 10 m^3/h/person provided that the comfort criteria are met)	12 m^3/h/person (in extreme conditions air flow can be reduced to 8 m^3/h/person provided that the comfort criteria are met)	30 m^3/h/person
$-20°C < T_{em} \le -5°C$	15 m^3/h/person			
$-5°C < T_{em} \le +26°C$	20 m^3/h/person			
$T_{em} > +26°C$	15 m^3/h/person			

Table 6: Overall heat transfer coefficient required for different climatic zones and vehicle categories

Zone (winter)	Main line rolling stock EN 13129-1		Urban and suburban rolling stock EN 14750-1		Driving cab EN 14813-1	
	Single deck	Double deck	Category A	Category B	Category A	Category B
I	2.0 W/m^2K	2.5 W/m^2K	2.5 W/m^2K	3.5 W/m^2K	2.2 W/m^2K	4.0 W/m^2K
II	1.6 W/m^2K	2.5 W/m^2K	2.2 W/m^2K	3.0 W/m^2K	2.0 W/m^2K	3.5 W/m^2K
III	1.2 W/m^2K	-	2.0 W/m^2K	2.5 W/m^2K	2.0 W/m^2K	3.0 W/m^2K

Type tests

Part 2 of the standards defines the testing programme and measurement procedures for evaluating the comfort parameters and efficiency of the air conditioning system.

Type tests of main line rolling stock must be carried out in a suitable testing environment (e.g. a climatic wind tunnel) in order to ensure that environmental conditions can be reproduced with the required accuracy.

Two kinds of tests are permitted by the standards for urban/suburban rolling stock and driving cabs:

- **Test Level 1 (TL1)**) is a simplified test series, which provides basic information about the proper functioning of the system only. As the requirements for environmental conditions are greatly reduced, this test may be carried out in a (manufacturing) plant or workshop.

- **Test Level 2 (TL2)** is a complete test programme for evaluating comfort parameters and system capacity and thus requires high-quality testing facilities.

The operator may choose between the two test levels (TL1 or TL2). If no test level is specified, the tests must be carried out at TL2.

The number of measuring points and the test programmes for evaluating the comfort parameters reflect the operating requirements. The time required for comfort tests (without determining k) is as follows:

- **3 days** for Category B driving cabs and urban/suburban rolling stock
- **4 days** for Category A urban/suburban rolling stock
- **5 days** for Category A driving cabs
- **8 days** for main line rolling stock or UIC 553

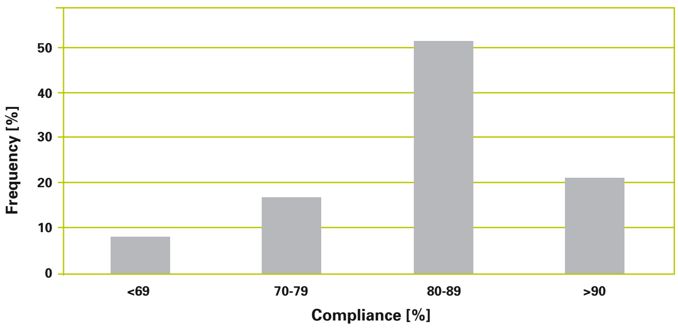
The comfort parameters are examined under different environmental conditions and summarised in an evaluation matrix. Table 7 shows an example of the evaluation of a Category A urban/suburban coach for Climatic Zone II

Use and misuse of standards

The standards described above define uniform comfort criteria for rail vehicles which are applicable throughout Europe. The requirements are technically feasible, even if statistical examinations of climatic tests in the Vienna Climatic Wind Tunnel suggest the contrary.

Figure 1 shows the frequency distribution of overall compliance for main line rolling stock in the years from 2003 to 2005. The diagram clearly shows that most vehicles lie in the 80% to 89% compliancy range. This diagram can serve as an indicator of general trends only, as direct comparisons between the results of climatic tests on rail vehicles are not always possible due to differences in the test programmes and specifications. However, the diagram clearly shows that not all the comfort criteria are fulfilled under all environmental conditions. The main reason for this is that climatic tests are naturally used for vehicle optimisation and improvement and the optimised state of the vehicles is generally not re-tested at the end of the process. In this regard it is important that the findings are implemented in the production run. That is not always the case. Therefore the operator is asked in his own interest to participate at the climatic tests to be able to review the measures on the test vehicle also on the production run vehicles.

Figure 1: Overall compliance for main line rolling stock in the years 2003 to 2005



In addition to the overall compliance rate, however, the fulfilment of individual requirements should always be given special attention, as a marked deviation in a single parameter may result in thermal conditions which passengers find unacceptable even though the deviation barely registers in the overall compliance rate. This does not present a problem as long as the results of the climatic tests and a potentially reduced air conditioning performance with regard to individual comfort criteria are objectively discussed and solved, as individual deviations can often be compensated by other comfort parameters. However, action must be taken if the operators state a vehicle's non-compliance with the full air conditioning standard as grounds for contractual consequences, ranging from a reduction in the price of the air conditioning system to non-acceptance of the entire vehicle. Doing so would represent a lack of foresight on the part of the operators, as the industry would respond either by increasing prices or by demanding that standards be lowered, which in turn would result in a reduction of thermal comfort in the vehicles.

A better solution would be for the operator and manufacturer to arrive at a joint definition of the requirements and determine permissible deviations in advance. Table 7 contains both comfort requirements according to EN 14750-1 and deviating criteria (range of mean interior air temperature with respect to temperature setting +/-3 K, vertical temperature distribution < 6 K) which are used for evaluation under certain extreme testing conditions (cells highlighted in blue). Additionally, certain degrees of compliance should be agreed in advance (e.g. 100% for air temperatures and air speeds in passenger areas). In this way, it is possible to define the requirements set down in the standards more exactly, taking into account the specific needs of the operator and giving the industry a higher degree of legal certainty.

Comfort parameters

The requirements for individual comfort parameters in rail vehicles were introduced in detail in the previous chapter. As these parameters have complex effects on the heat balance of passengers, the present section will present a method of describing thermal comfort in terms of "global" parameters.

Although these comfort parameters, standardised in ISO 7730 [1], were originally developed to describe thermal comfort in buildings, they are increasingly used for analysing comfort conditions in vehicles.

Predicted Mean Vote (PMV)

The Predicted Mean Vote (PMV), which predicts thermal sensation votes of a large group of people on a 7-point scale (Table 8), is used to describe thermal comfort.

Table 8: Comfort scale of predicted mean vote

PMV	Thermal sensation
+3	hot
+2	warm
+1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold

The relationship between the individual comfort parameters is defined by the following empirically derived comfort equation for PMV according to ISO 7730 [1]:

Table 7: Overview and evaluation matrix of climatic tests on an urban/suburban transport vehicle of Categor

Tests according to EN 14750-2													
Test	Test conditions				9.1.1		9.1.2		9.1.3			9.2.1	
	T_{em} / rF [°C] / [%]	Wind [km/h]	Solar load [W/m²]	Occupation [%]	Deviation interior temperature - temperature setting +/-2 K		Horizontal temperature distribution < 4 K		Vertical temperature distribution < 4 K			Temperature in vestibules Heating mode T_i in 1.7 m: +3°C < T_i < T_{im} T_i in 0.1 m: > +3°C Cooling mode T_i < T_{em}	
					+/-3 K				< 6 K				
TL211	-20 / -	Min.	0	0	x		x		x				x
TL212	-20 / -	Min.	0	0	x		x		x				x
TL213 heating capacity	-20 / -	Max.	0	0	x		x		x				x
TL215	0 / -	Min.	0	0	x		x		x			x	
TL216	0 / -	Max.	0	0	x		x		x			x	
TL217	0 / -	Min.	0	100	x		x		x			x	
TL218 Door open/closed	0 / -	Min.	0	0	x		x		x			x	
TL221	+35 / 50	Min.	700	0	x		x		x			x	
TL222	+35 / 50	Min.	700	100	x		x		x			x	
TL223 cooling capacity	+35 / 50	Min.	700	100	x		x		x			x	
TL224	+28 / 60	Min.	0	0	x		x		x			x	
TL225	+28 / 60	Min.	700	0	x		x		x			x	
TL226	+28 / 60	Min.	700	100	x		x		x			x	
TL227 Door open/closed	+28 / 60	Min.	700	100	x		x		x			x	
TL228	+28 / 60	Min.	700	100	x		x		x			x	
Performance in individual comfort criteria [%]					100	0	100	0	100	0	0	80	20

Tests according to EN 14750-2					Additional requirements according to EN 14750-1							
Test	Test conditions				10.1.2		10.1.3		7.2		7.4	
	T_{em} / rF [°C] / [%]	Wind [km/h]	Solar load [W/m²]	Occupation [%]	coefficient k total < 2.2 W/m²K		coefficient k vestibules < 3.2 W/m²K		Preheating		Precooling	
TL219	+5 / -	Min.	0	0	x		x					
TL210	-20 / -	Min.	0	0					x			
TL214	0 / -	Min.	0	0					x			
TL220	+35 / 50	Min.	700	0							x	

$$PMV = \left(0.303 \cdot e^{-0.036M} + 0.028\right) \cdot \left\{ \begin{aligned} &(M - W) - 3.05 \cdot 10^{-3} \cdot \left[5733 - 6.99 \cdot (M - W) - p_a\right] \\ &- 0.42 \cdot \left[(M - W) - 58.15\right] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) \\ &- 0.0014 \cdot M \cdot (34 - T_{im}) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(T_{cl} + 273)^4 - (T_r + 273)^4\right] \\ &- f_{cl} \cdot h_c \cdot (T_{cl} - T_{im}) \end{aligned} \right\}$$

with

$$T_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \left\{3.96 \cdot 10^{-8} \cdot f_{cl} \left[(T_{cl} + 273)^4 - (T_r + 273)^4\right] + f_{cl} \cdot h_c \cdot (T_{cl} - T_{im})\right\}$$

$$h_c = \begin{cases} 2.38 \cdot (T_{cl} - T_{im}) \text{ für } 2.38 \cdot (T_{cl} - T_{im})^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} \text{ für } 2.38 \cdot (T_{cl} - T_{im})^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases} \qquad f_{cl} = \begin{cases} 1.00 + 1.290 \cdot I_{cl} \text{ für } I_{cl} \le 0.078\, m^2 \cdot {}^\circ C/W \\ 1.00 + 1.290 \cdot I_{cl} \text{ für } I_{cl} \ge 0.078\, m^2 \cdot {}^\circ C/W \end{cases}$$

where:

PMV...... predicted mean vote

M.......... metabolism related to the surface of the human body [W/m²]
metabolic rate when seated: 1 met = 58 W/m²

W.......... external work [W/m²] (for most activities = 0 W/m²)

I_{cl}.......... insulation of clothing [m².°C/W]
measured in clothing units;
0.155 m².°C/W = 1 clo (clothing unit)

f_{cl}.......... ratio of clothed/nude surface area [-]

T_{im}........ mean interior temperature [°C]

T_r........... radiant temperature [°C]

v_{ar}.......... relative air speed [m/s]

p_a.......... partial pressure of water vapour [Pa] defined by relative humidity φ [%] and temperature [°C]

h_c.......... convective heat transfer coefficient [W/m²K]

T_{cl}......... surface temperature of clothing [°C]

y A and Climatic Zone II according to EN 14750

Tests according to EN 14750-1																			
9.2.3		9.3			9.4.1			9.4.2			9.4.3			9.5			9.6		
Temperature in annex areas Heating mode $T_i > T_{im}$ - 6 K respectivly $T_i > 3°C$ Cooling mode $T_i < T_{im}$ + 6 K		Relative humidity according to Annex C			Surface temperature walls and ceiling Heating > T_{im} - 10 K			Surface temperature windows Heating > T_{im} - 15 K			Surface temperature walls, ceiling and floor Heating > +3°C			Temperature at supply air outlets Heating < +65°C Cooling > +5°C			Air speeds according to Annex B		
x							x			x	x			x			x		
x							x			x	x			x			x		
	x						x			x	x			x			x		
x					x			x			x			x			x		
x					x			x			x			x			x		
x					x			x			x			x					
x					x			x			x			x			x		
x		x												x			x		
x		x												x					
x		x												x			x		
x		x												x			x		
x		x												x			x		
x		x												x					
x		x												x					
x		x												x					
93	7	100	0	0	57	0	43	57	0	43	100	0	0	100	0	0	100	0	0

Areas	Compliance [%]	Total performance [%]		
Passenger areas, air temperatures and air speeds	100	100	0	0
Total passenger areas	90	90	0	10
Annex areas	-	87		13
Total vehicle	90	90	0	10

TLxxx... Tests in heating mode
TLxxx... Tests in cooling mode
TLxxx...Other tests

x passed
x mainly passed
x failed

Blue cells: customer-specific requirements and evaluation
Lilac cells: not measured/calculated

The equation above allows PMV to be calculated iteratively for different combinations of clothing, air temperature, air speed, relative humidity and radiant temperature.

The parameters air temperature, air speed and relative humidity (defined by the corresponding partial pressure of water vapour) can be inserted into the equation directly as measurement values or as standard requirements. Additional considerations, however, must be addressed for local radiant temperature.

Local radiant temperature

The local radiant temperature is approximately equal to the enclosure temperature. However, specific surface temperatures in the passenger areas may vary markedly in individual locations.

A possible approach for determining radiant temperature is offered by the following equation:

$$T_r = \frac{A_1 \cdot T_1 + A_2 \cdot T_2 + \ldots + A_n \cdot T_n}{A_1 + A_2 + \ldots + A_n},$$

where radiant temperature can be taken as the temperature of the surroundings or as the uniform enveloping surface of the temperature. However, this equation does not take into account the proximity of individual passengers to the enclosure surface.

Alternatively, the radiant temperature can be determined using angle factors as described in [2]. This method of calculation is very time-consuming, however, as the passenger areas must be modelled from scratch for every analysis. For this reason, a simplified method of calculating the angle factors was chosen, which is based on the following principle:

In a first step, the angles between the location in question and the surfaces of uniform temperature (e.g. window) are determined in both plan and elevation views (so called „view factors"), thus obtaining a spherical section. The surface area of the spherical section is then determined with relation to the overall surface of the unit sphere. This ratio and the corresponding surface temperature are finally used to calculate the mean radiant temperature for the location in question. This method is sufficiently accurate for smaller angles, while angles greater than 50° must be subdivided into several parts.

The procedure outlined above was used to calculate the radiant temperature in two different vehicles with different surface temperatures of walls, floor and windows.

Table 9 shows the mean radiant temperatures for a main line vehicle (compartment car) at typical surface temperatures in winter and summer. For winter operations, the surface temperatures of walls, floor and windows begin with the minimum requirement of the main line standards at a mean interior temperature of 22°C (cf. Table 2) and then proceed in 2 K increments. At the minimum permissible surface temperature, the radiant temperature is 14.2°C. For summer operations, typical surface temperatures with and without solar load were used for the calculations.

Table 9: Radiant temperatures in a main line vehicle at different surface temperatures

Operating conditions	Surface temperature [°C]			Radiant temperature T_r [°C]
	Wall	Floor	Window	
Winter	13.0	10.0	8.0	12.6
Winter, minimal standard requirement	15.0	12.0	10.0	14.2
Winter	17.0	14.0	12.0	15.8
Winter	19.0	16.0	14.0	17.3
Winter	21.0	18.0	16.0	18.9
Summer, no solar load	26.0	26.0	26.0	26.0
Summer, no solar load	28.0	28.0	28.0	27.6
Summer, no solar load	30.0	30.0	30.0	29.1
Summer, solar load, measured values at exterior temperature 35°C and solar load 700 W/m²	31.0	30.0	39.0	29.7
Summer, solar load	33.0	32.0	41.0	31.2
Summer, solar load	35.0	34.0	43.0	32.8

Table 10 shows the mean radiant temperatures for an urban/suburban vehicle (double-deck) according to the same principles; however, the figures in this table represent the minimum requirements specified in the standards for urban/suburban rolling stock at a mean interior temperature of 21°C (temperature setting in winter). At the minimum permissible surface temperature, the radiant temperature is 10.6°C.

Since the maximum difference in local radiant temperatures between individual seats is no more than 1.4 K, no detailed breakdown of the individual values is given.

The calculations for the two vehicles with identical surface temperatures under identical environmental conditions yielded a maximum difference in radiant temperature of 1.9 K, which is attributable to the different geometries.

Predicted Percentage Dissatisfied (PPD)

The Predicted Percentage Dissatisfied (PPD) represents a qualitative prediction of the number of people who will not be satisfied with specific thermal conditions. The relationship between the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) is shown in the following equation according to ISO 7730 [1].

$$PPD = 100 - 95 \cdot e^{-\left(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2\right)}$$

This relationship is illustrated by the curve according to ISO 7730 [1] and Fanger [2] in Figure 2, where the minimum percentage of dissatisfied is 5 %.

While the PMV and PPD indices were developed in large-scale studies of thermal comfort in buildings, they can, in principle, also be used to evaluate thermal comfort in rolling stock.

A research project carried out by ÖFPZ Arsenal in 2000-2002 for the Austrian Ministry of Transport, Innovation and Technology (BMVIT) was aimed at examining the extent to which the results of studies in buildings can be applied to the non-stationary processes in rail vehicles. Using field studies carried out in cooperation with the three Austrian public transport companies ÖBB, Wiener Linien and Wiener Lokalbahnen, this research project was the first to determine actual thermal conditions in selected rail vehicles [4]. In the project, passengers were interviewed about their subjective perceptions, while the objective thermal conditions were determined by means of comfort measurements. A third basis for evaluation was provided by the results of the type tests in the climatic wind tunnel.

For the vehicles examined in the project (main line, urban/suburban, metro vehicles), the study arrived at a minimum percentage of dissatisfied of 18 % in winter and 20 % in summer (Figure 2), which corresponds roughly to the percentages obtained by Mayer [3]. However, the passengers' preferences were different for winter and summer conditions.

- In summer, the PPD curve shifts towards the top left. In other words, passengers would prefer a significantly lower interior temperature in summer. The minimum of the PPD curve lies at a PMV of -0.87.

- In winter, the PPD curve shifts to the top right. In other words, passengers would prefer a warmer interior temperature in winter. The minimum of the PPD curve lies at a PMV of +0.18.

Figure 2: Relationship between mean vote and percentage dissatisfied

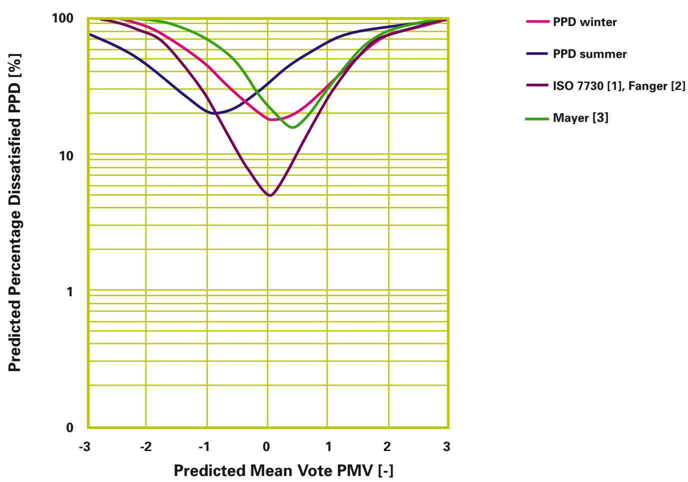


Table 10: Radiant temperatures in an urban/suburban transport vehicle at different surface temperatures

Operating conditions	Surface temperature [°C]			Radiant temperature T_r [°C]
	Wall	Floor	Window	
Winter	5.0	3.0	0.0	9.3
Winter, minimum standard requirements	7.0	5.0	2.0	10.6
Winter	9.0	7.0	4.0	11.9
Winter	11.0	9.0	6.0	13.2
Winter	13.0	11.0	8.0	14.5

Local thermal discomfort

It is not sufficient to satisfy the comfort equation of PMV = 0 in order to achieve optimum thermal conditions (PPD ≤ 5 %). Passengers may feel discomfort if only one body part is perceived to be too warm or cold, even though the overall thermal conditions are satisfactory. This kind of local thermal discomfort is usually experienced as a draught. However, it may also be caused by an asymmetry in radiant temperatures, by large differences between surface temperatures and air temperature, or by differences in vertical temperature layers. The exact relationship between global and local thermal comfort has not yet been adequately studied. Some results of studies of local thermal discomfort (radiation asymmetry, local draughts, vertical temperature differences, body contact with cold and warm surfaces) can be found in [5].

Relationship between comfort parameters and standard requirements

The following chapter investigates to what extent passengers experience a feeling of thermal comfort if the standard requirements are met, how the individual comfort parameters are related to each other and how they influence each other.

Winter conditions in main line transport

The following parameters were assumed for investigating a main line rail vehicle (compartment car) under winter conditions:

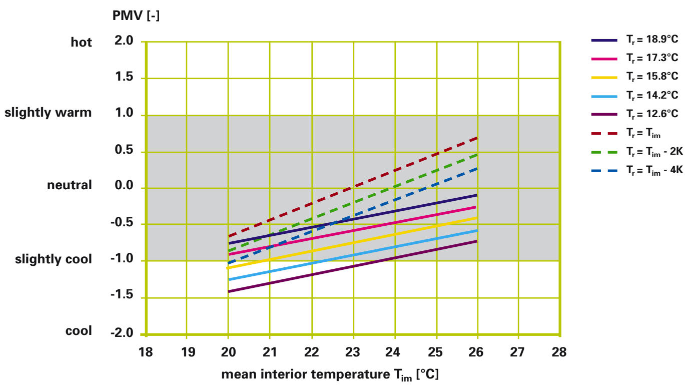
- Metabolic rate M = 1 met = 58 W/m²
- External work W = 0 W/m²
- Insulation of clothing I_{cl} = 1.3 clo
- Radiant temperature T_r = 14.2°C (at minimum surface temperature according to standard for main line rolling stock, cf. Table 9)
- Relative air speed v_{ar} = 0.1 m/s
- Relative humidity φ = 10%

For better comparison, the results of the variation of individual parameters are always correlated with the mean interior temperature. The grey shaded PMV area from -1 to +1 according to [1] corresponds to a PPD of about 25 %.

Figure 3 shows the influence of different radiant temperatures on PMV. The solid lines represent radiant temperatures taken from the surface temperature calculations (see Table 9), while the dashed lines show values with a constant difference relative to the mean interior temperature.

A radiant temperature of 14.2°C (minimum acceptable surface temperature) results in a PMV as low as –1 at a mean interior temperature of 22°C.

Figure 3: Variation of radiant temperature T_r and mean interior air temperature T_{im}



It has been shown that any variation in radiant temperature has a significant influence on PMV. Insufficient radiant temperatures can be compensated for by increasing the mean interior temperature.

Figure 4: Variation of insulation of clothing I_{cl} and mean interior temperature T_{im}

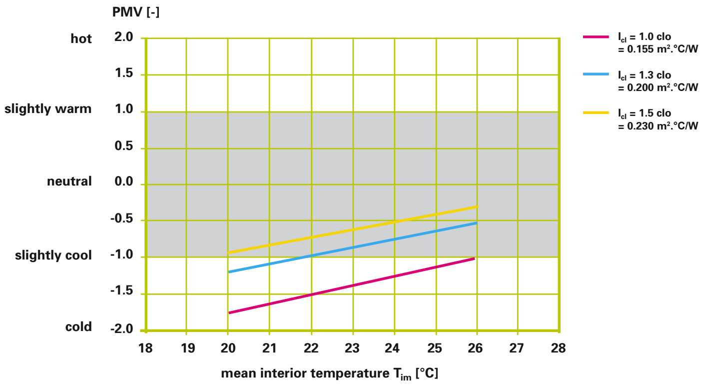


Figure 4 shows the influence of different insulation values on PMV. The insulation values used for the calculations and comparisons are listed in Table 11 (cf. [1]). Since the seat may provide additional insulation of 0 to 0.4 clo for seated persons, an insulation value of 1.3 was assumed for all calculations under winter conditions instead of 1.0.

Since clothing insulation also has a substantial effect on PMV, the insulation value must be defined in the comfort parameter requirements.

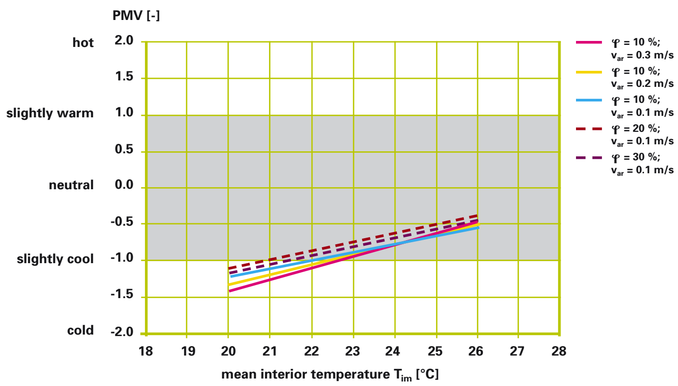
Table 11: Overview of clothing insulation values used

Type of clothing	Clothing insulation I_{cl}	
	[clo]	[m².°C/W]
Light summer clothing	0.5	0.080
Regular clothing	1.0	0.160
Warm clothing	1.3	0.200
Very warm clothing	1.5	0.230

Figure 5 shows the influence of air speed and relative humidity, which is usually not controlled and therefore very low under winter conditions.

As can be seen from the diagram, the influence of humidity on PMV is low. This also applies to "global" air speed, where local thermal phenomena, such as draughts at sensitive body areas (see also "Local thermal discomfort", page 10), must be considered separately.

Figure 5: Variation of relative humidity φ, air speed v_{ar} and mean interior temperature T_{im}



Winter conditions in urban/suburban transport

The same basic parameters, with the exception of radiant temperature and mean interior temperature, can also be applied in the comparative investigation of an urban/suburban rail vehicle. Since mean interior temperature is 21°C instead of 22°C for the temperature setting "Medium", the scale range must be adapted accordingly.

Figure 6: Variation of radiant temperature T_r and mean interior temperature T_{im}

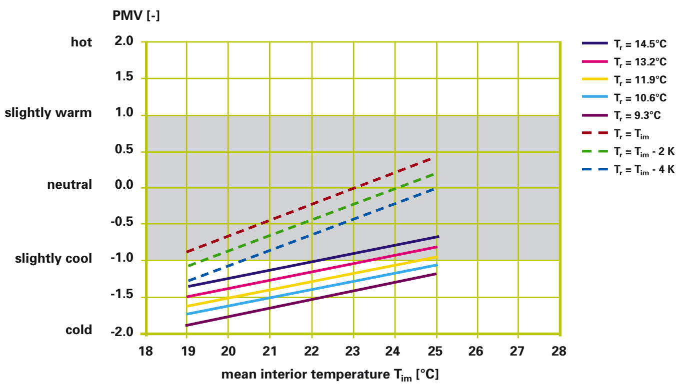


Figure 6 again shows the influence of radiant temperature on PMV. The solid lines represent radiant temperatures taken from the surface temperature calculations shown in Table 10. The PMV results for radiant temperatures with a constant difference relative to the mean interior temperature (dashed lines) are identical with those in Figure 3 and are shown for reference purposes.

A radiant temperature of 10.6°C (minimum acceptable surface temperature according to standard for urban/suburban rolling stock, see Table 10) results in a PMV of only –1.5 at a mean interior temperature of 21°C. PMV can of course be improved by increasing the mean interior temperature or radiant temperature (surface temperature) or by assuming a higher clothing insulation value.

Summer conditions in main line transport

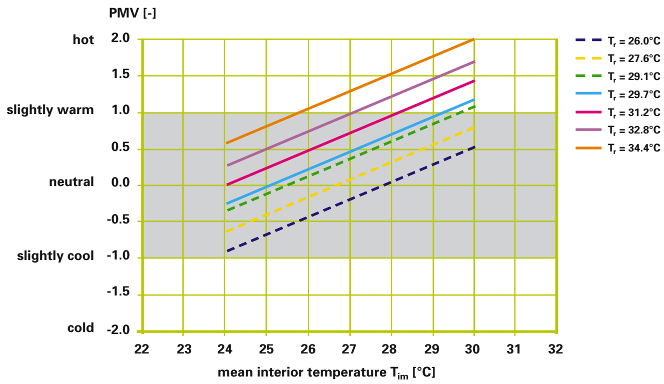
The following parameters were assumed for investigating a main line rail vehicle (compartment car) under summer conditions:

- Metabolic rate M = 1 met = 58 W/m²
- External work W = 0 W/m²
- Insulation of clothing I_{cl} = 0.5 clo
- Radiant temperature T_r = 29.7°C (cf. Table 9)
- Relative air speed v_{ar} = 0.2 m/s
- Relative humidity φ = 40%

For better comparison, the results of the variation of individual parameters are again correlated with mean interior temperature. The grey shaded PMV area from -1 to +1 according to [1] corresponds to a PPD of about 25 %.

Figure 7 shows the influence of different radiant temperatures on PMV. The radiation temperatures were taken from the surface temperature calculations with and without solar load (see Table 9).

Figure 7: Variation of radiant temperature T_r and mean interior temperature T_{im}

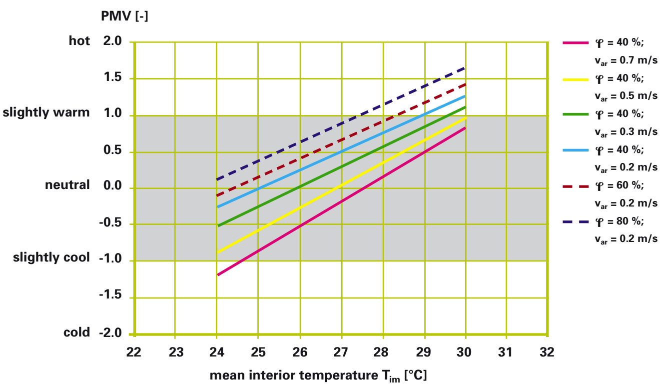


A radiant temperature of 29.7°C (corresponds to typical surface temperatures at 35°C and 700 W/m² solar load) results in a PMV of 0.5 at a mean interior temperature of 27°C.

The variation in radiant temperature again has a substantial influence on PMV. Excessive radiant temperatures can be compensated for by reducing the mean interior temperature.

Figure 8 shows the influence of air speed and relative humidity on PMV. As can be seen from the diagram, the influence of relative humidity on PMV is low. It must be kept in mind, however, that the standards define the comfort range for relative humidities of 25 % and 65 % so that the calculation based on a relative humidity of 80 % is for information only. This also applies to "global" air speed, which is defined only up to 0.5 m/s in the standards.

Figure 8: Variation of relative humidity φ, air speed v_{ar} and mean interior temperature T_{im}



Conclusions and outlook

The air conditioning standards for main line and urban/suburban rolling stock have defined uniform criteria for thermal comfort in passenger areas and driving cabs which are applicable throughout Europe. In addition to improving planning security and reducing risks for vehicle manufacturers, the standards also guarantee the availability of higher-quality rolling stock to rail operators and ultimately contribute to improved passenger comfort.

Because of the complex interrelationships between individual comfort parameters, it is advisable to determine precise requirements in advance in order to meet the specific expectations of rail operators and avoid disputes at a later stage.

An appropriate air conditioning concept is crucial for complying with the thermal comfort requirements (some air conditioning solutions for urban and suburban rolling stock are described in [6]). It is critically important to ensure adequate air distribution within the vehicle and to optimise the control system for all climate conditions. These optimisations can only be carried out on the vehicle as a whole within appropriate climatic testing facilities.

The analysis of the comfort parameters shows that it is feasible to achieve a maximum percentage of dissatisfied of 25 %, a figure demanded by some rail operators. To achieve this figure, the relevant framework conditions, such as the insulation value of clothing, must be agreed upon and taken into account.

Additionally, the issue of energy efficiency should be given greater attention in future when designing air conditioning systems (see [7]). Although the standards do provide some energy-saving measures, such as limiting the fresh air flow, there is still room for improvement in many areas. The most promising approaches include exhaust air heat recovery and fresh air control as a function of the CO_2 concentration.

All these efforts must be aimed at the goal of making rail traffic more reliable, more energy-efficient, and more attractive. Climatic testing can make an important contribution to this end.

Literature

[1] EN ISO 7730: *Gemäßigtes Umgebungsklima: Ermittlung des PMV und des PPD und Beschreibung der Bedingungen für thermische Behaglichkeit, 1995*

[2] Fanger, P. O.: *Thermal Comfort, Reprinted, R. Krieger Publishing Company, Malabar 1982*

[3] Mayer, E., Conrad, W.: *Untersuchung der thermischen Behaglichkeit bei Quelllüftung und Flächenkühlung, in: Mayer, E. (Hg.): Menschengerechte Raumklimatisierung durch Quelllüftung und Flächenkühlung, Bauforschung für die Praxis, Band 13, IRB Verlag, Stuttgart 1995*

[4] Bencsics D., Sorgalla U., Haller G.: *Subjective thermal comfort in railway vehicles, Proceedings of Workshop "Mobile Air Conditioning", Vienna, 2002*

[5] Fanger, P. O., Pedersen, C.J.K: *Discomfort due to air velocities in spaces. In Proc. of the Meeting of Commission B1, B2 and E1 of the IIF, Belgrade 1977/11*

[6] Haller G.: *Thermischer Komfort in Nahverkehrsfahrzeugen, ZEVrail Glasers Annalen, Juni 2004*

[7] Kreitmayer M., Haller G.: *Energy management in railway vehicles - analysis of energy consumption under testing conditions, Proceedings of Workshop "Mobile Air Conditioning", Vienna, 2002*

Imprint

RTA Rail Tec Arsenal Fahrzeugversuchsanlage GmbH
1210 Vienna
Paukerwerkstrasse 3
Austria
Tel: +43 1 256 80 81
Fax: +43 1 256 80 81-600
contact@rta.co.at
www.rta.co.at

Editor: Dipl.-Ing. Gabriel Haller
Layout: www.gruenberg4.at
Printed by: Druckerei Robitschek

Professional article September 2006

RTA Rail Tec Arsenal Fahrzeugversuchsanlage GmbH
1210 Vienna | Paukerwerkstrasse 3 | Austria
Tel: +43 1 256 80 81 | contact@rta.co.at | www.rta.co.at

RAIL TEC ARSENAL