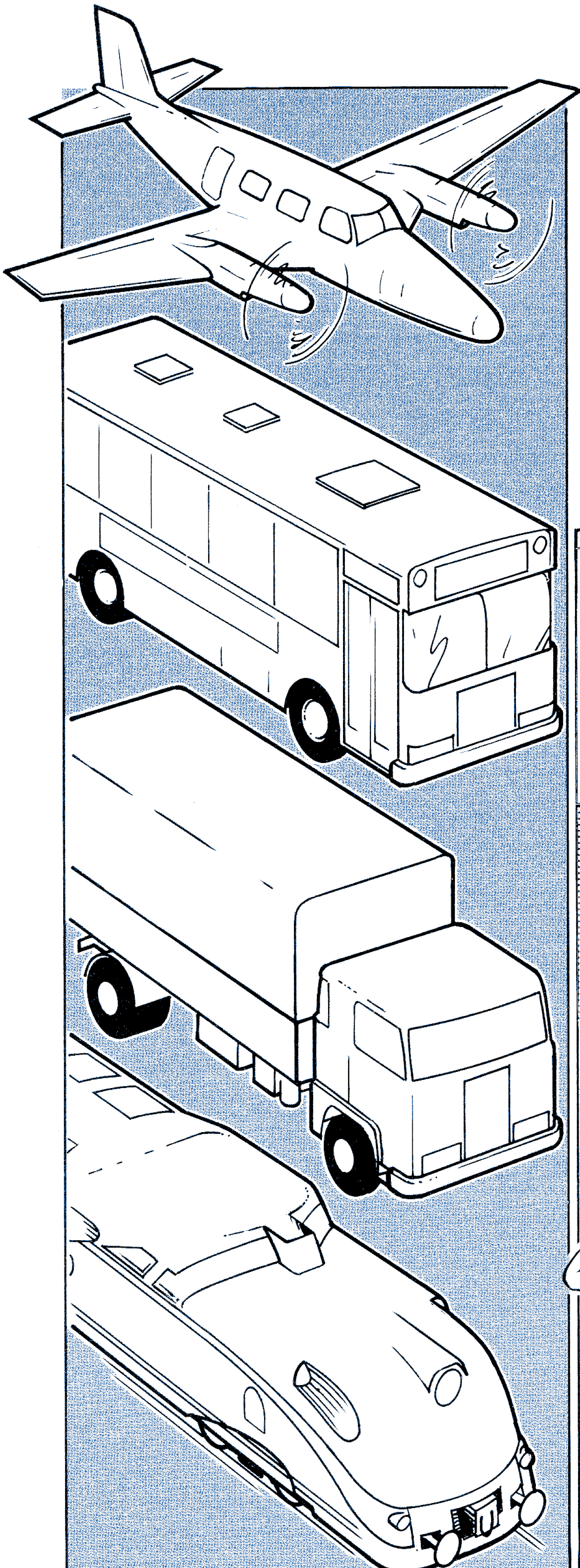
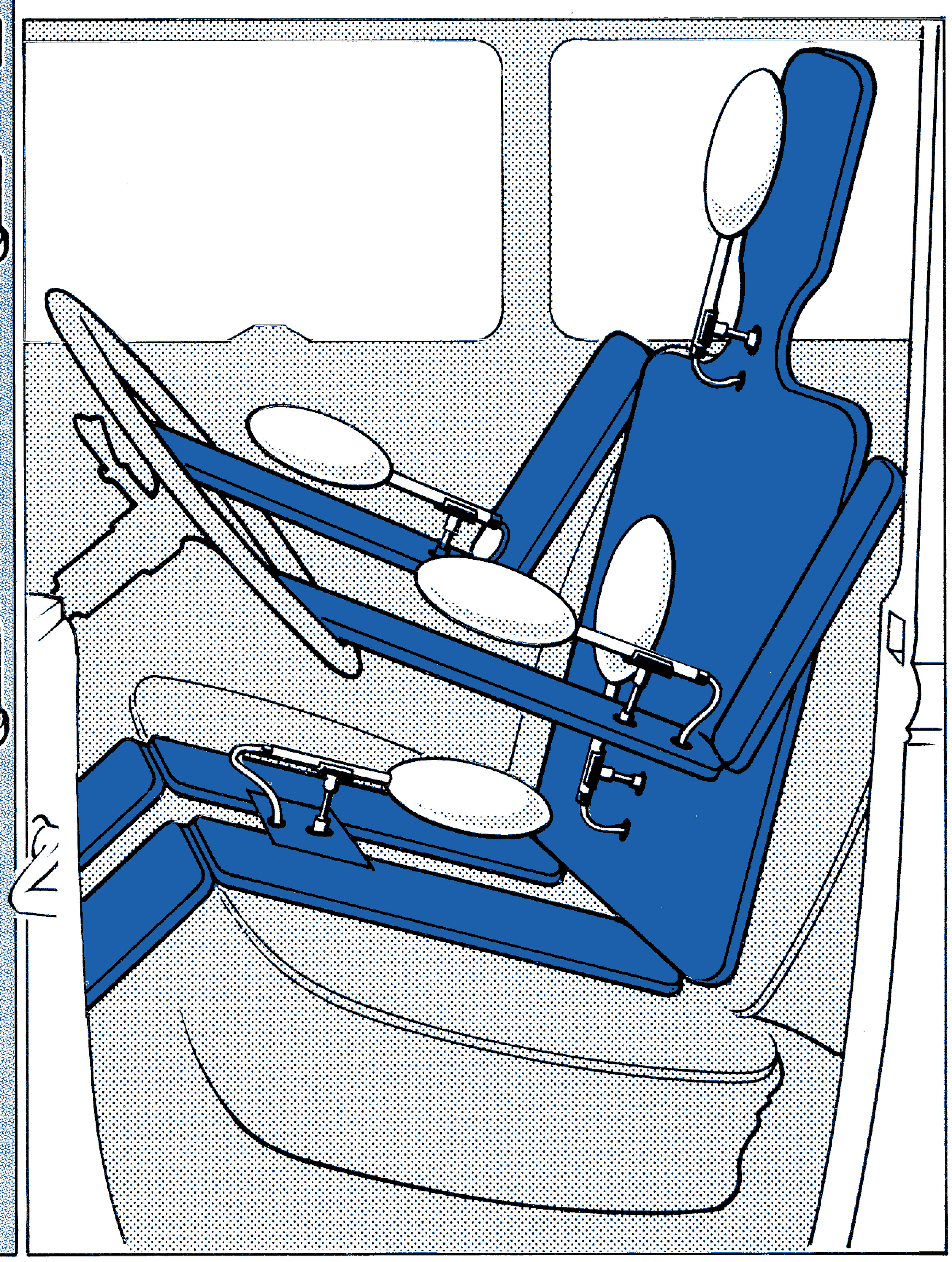
Brüel & Kjær application notes

Evaluation of the thermal environment in vehicles





BO 0281–11

Measurement of Thermal Comfort in Vehicles

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Introduction

Most people spend several hours a day in transportation means like cars, trains, planes, trucks or buses. This is either during transportation back and forth to work or as an occupation like taxi driver, truck driver, bus driver, plane captain etc. It is therefore very important to provide an acceptable thermal environment in vehicles, which will not disturb the passengers and give optimal comfort and performance for the driver.

Normally, a stable and acceptable indoor climate can be established and maintained in a building. The thermal environment in a car is more difficult to control and evaluate than in a building. These difficulties are due to external influences from the direct and varying solar radiation on some parts of the body, and the inhomogeneous air temperature and air velocity field created by the air-conditioning system. Last, but not least, neither driver nor passengers are able to change their positions much to make up for the asymmetric climate condition.

Thermal Comfort

Man's thermal comfort is a result of the combined effect of all six thermal climate parameters – activity level, clothing, air temperature, air velocity, air humidity and mean radiation temperature. According to ISO 7730 [1984], the degree of general thermal comfort can be given by the PMV-index (Fig. 1), which can be calculated when the six climate parameters are known. It is recommended that 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, draught and air temperature gradients. This standard may also be applied for vehicles. The activity in a vehicle will mainly be sedentary except for standing passengers in buses and trains and the service personnel working in planes and trains. This means the level will be between 1,2 met (seated-driving on highway) and 1,6 met (seated driving in traffic or standing). The clothing in a car can vary from 0,3 to 1,5 clo in relation to the time of the year. 0,3 clo represents a tropical clothing including short trousers and a short-sleeved shirt, 1,5 clo represents a normal business suit with a coat. The seat will also add to the thermal insulation, but as it only will be in touch with less than 15% of the body surface area, the addition will assumingly be around 0,2 clo. The thermal insulation for a clothing ensemble I_{cl} may be estimated from Table 1 as:

$$I_{cl} = \sum I_{clu}$$

Add then 0,2 clo for the seat.

The humidity in a vehicle will depend on the outside climate, the air conditioning system and the number of persons in the vehicle. The dependent parameter for the sensation of warm and cool is the vapour pressure. Normally this may vary between 0,8 and 1,8 kPa except for aeroplanes where the vapour pressure may be much lower. The lowest values are obtained in winter and the range corre-

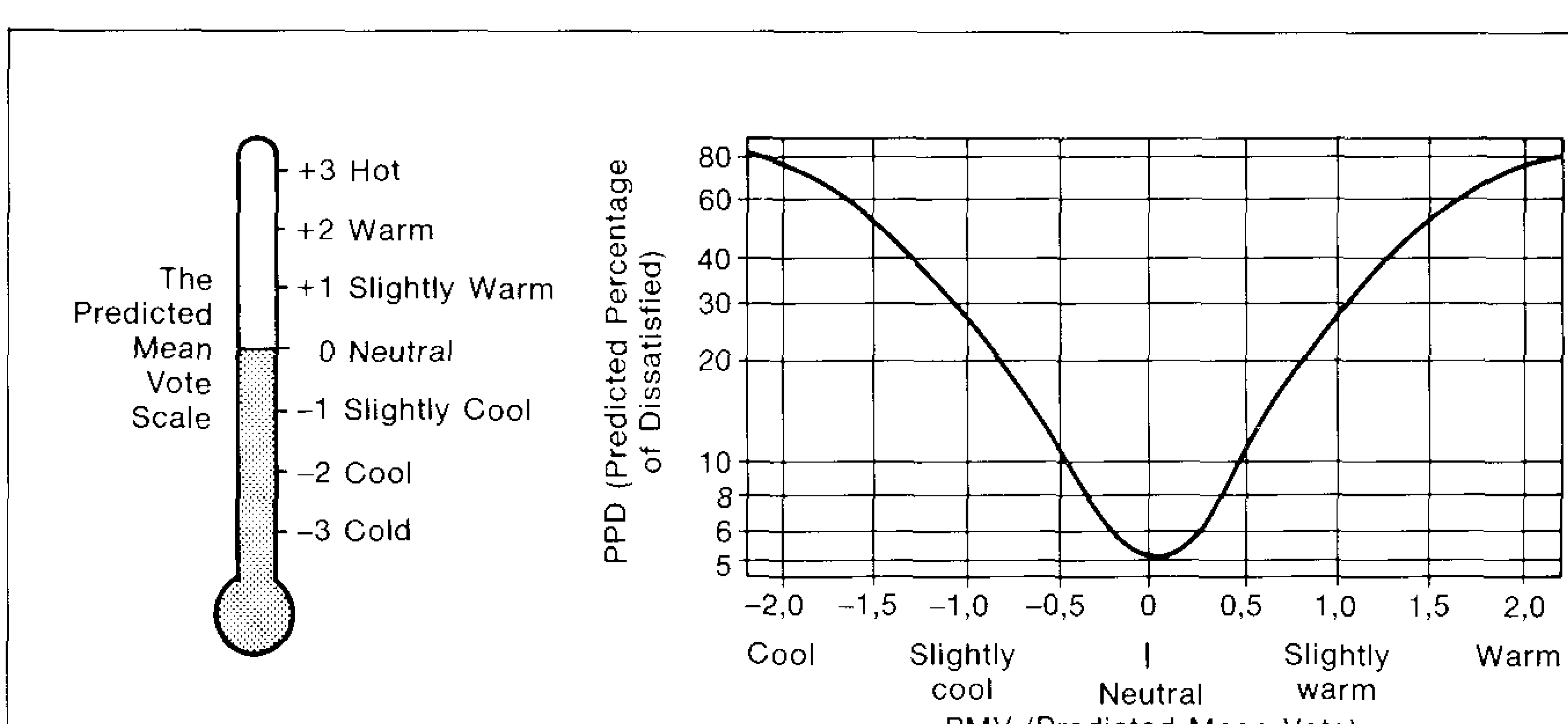

Fig. 1. The comfort scale used in ISO 7730 for moderate thermal environment. To the right is the correlation between the PMV-value and the percentage which is voting −3, −2, +2 or +3, which is the thermally dissatisfied (PPD)

Garment description	Thermal insulation, clo (I_{clu})
Underwear	
Briefs	0,03
Underpants with long legs	0,10
Singlet	0,04
T-Shirt	0,09
Shirt with long sleeves	0,12
Panties + Bra	0,03
Shirts — Blouses	
Short sleeves	0,15
Light weight, long sleeves	0,20
Normal, long sleeves	0,25
Flannel shirt, long sleeves	0,30
Light weight blouse, long sleeves	0,15
Trousers	
Shorts	0,06
Light weight	0,20
Normal	0,25
Flannel	0,28
Dresses — Skirts	
Light skirt (summer)	0,15
Heavy skirt (winter)	0,25
Light dress, short sleeves	0,20
Winter dress, long sleeves	0,40
Boiler suit	0,55
Sweaters	
Sleeveless vest	0,12

Garment description	Thermal insulation, clo (I_{clu})
Thin sweater	0,20
Sweater	0,28
Thick sweater	0,35
Jackets	
Light summer jacket	0,25
Jacket	0,35
Smock	0,30
High Insulative, Fiber-pelt	
Boiler suit	0,90
Trousers	0,35
Jacket	0,40
Vest	0,20
Outdoor clothing	
Coat	0,60
Down jacket	0,55
Parca	0,70
Fiber-pelt overalls	0,55
Sundries	
Socks	0,02
Thick ankle socks	0,05
Thick long socks	0,10
Nylon stockings	0,03
Shoes (thin soled)	0,02
Shoes, (thick soled)	0,04
Boots	0,10
Gloves	0,05

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Table 1. Clo-values for individual garments, I_{clu}. The insulation of a whole ensemble I_{cl} is estimated by $I_{cl} = \Sigma I_{clu}$

sponds to a relative humidity range of 30–70% at 22°C air temperature. For the conditions in a car a 10% increase of the relative humidity will have the same effect as approx. 0,3°C increase in the temperature level. So the influence of the humidity is not very significant.

To evaluate the thermal environment in a vehicle it is then basically a question of measuring the three remaining parameters air temperature, mean radiant temperature and air velocity

Measuring Methods

The usual method of evaluating the efficiency of the 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. Only one (air temperature) of the three main climatic parameters that concerns the thermal comfort sensations (air temperature, mean radiant temperature, air velocity) is measured. This fact is especially unfortunate in vehicles, as 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 non-uniform than in buildings. The combined effect of air temperature, mean radiant temperature and air velocity can be expressed by the equivalent temperature, which is 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 loss by radiation and convection as in the actual environment. The equivalent temperature is then related to the total dry heat loss from the body.

Measuring each parameter requires a lot of instrumentation and it is difficult to measure all parameters in the same position. Instead of measuring each parameter and then calculate the combined influence, it would be easier using a transducer that combines all the climate parameters into one temperature, the equivalent temperature.

The Brüel & Kjær Thermal Comfort Meter Type 1212 measures the equivalent temperature using one heated transducer (Fig. 2). The Thermal Comfort Meter gives the possibility of setting different clo-values, activity-levels and vapour pressures. The heated transducer, heated to the surface temperature of the actual clothing, is then influenced by the air temperature, mean radiant temperature and air velocity. Besides measuring the equivalent temperature the comfort meter can also measure operative temperature and the PMV-PPD index. Due to the very non-uniform conditions in vehicles it is often necessary to measure in more positions representing different body parts. The number of measuring points depends on the applications. If you want to test how fast the vehicle is heated up or cooled down it may be enough with three points (head, abdomen, feet, Fig. 3). When investigating the distribution over the body and the effect of different settings of the outlets from the air conditioner it will be necessary with more positions (head, left arm, right arm, left hand, right hand, abdomen, left leg, right leg, left foot, right foot, Fig. 4).

The position and direction of the sensor are set so it as best as possible simulates the shape and projected area of the body parts it represents, (Fig. 3).

The idea is then to measure the equivalent temperature at each positions and estimate an equivalent temperature (t_{eq}) for the whole body based on area weighted average. In Table 2 are shown the area of different body parts, examples of positions of sensors and the corresponding weighting factors for estimating the equivalent temperature for the body as a whole. In a test with three sensors (head, abdomen, feet) the calculations of the mean value will be:

$$t_{eq}\text{ (mean)} = 0{,}1 \cdot t_{eq}\text{ (head)} + 0{,}7 \cdot t_{eq}\text{ (abdomen)} + 0{,}2 \cdot t_{eq}\text{ (feet)}$$

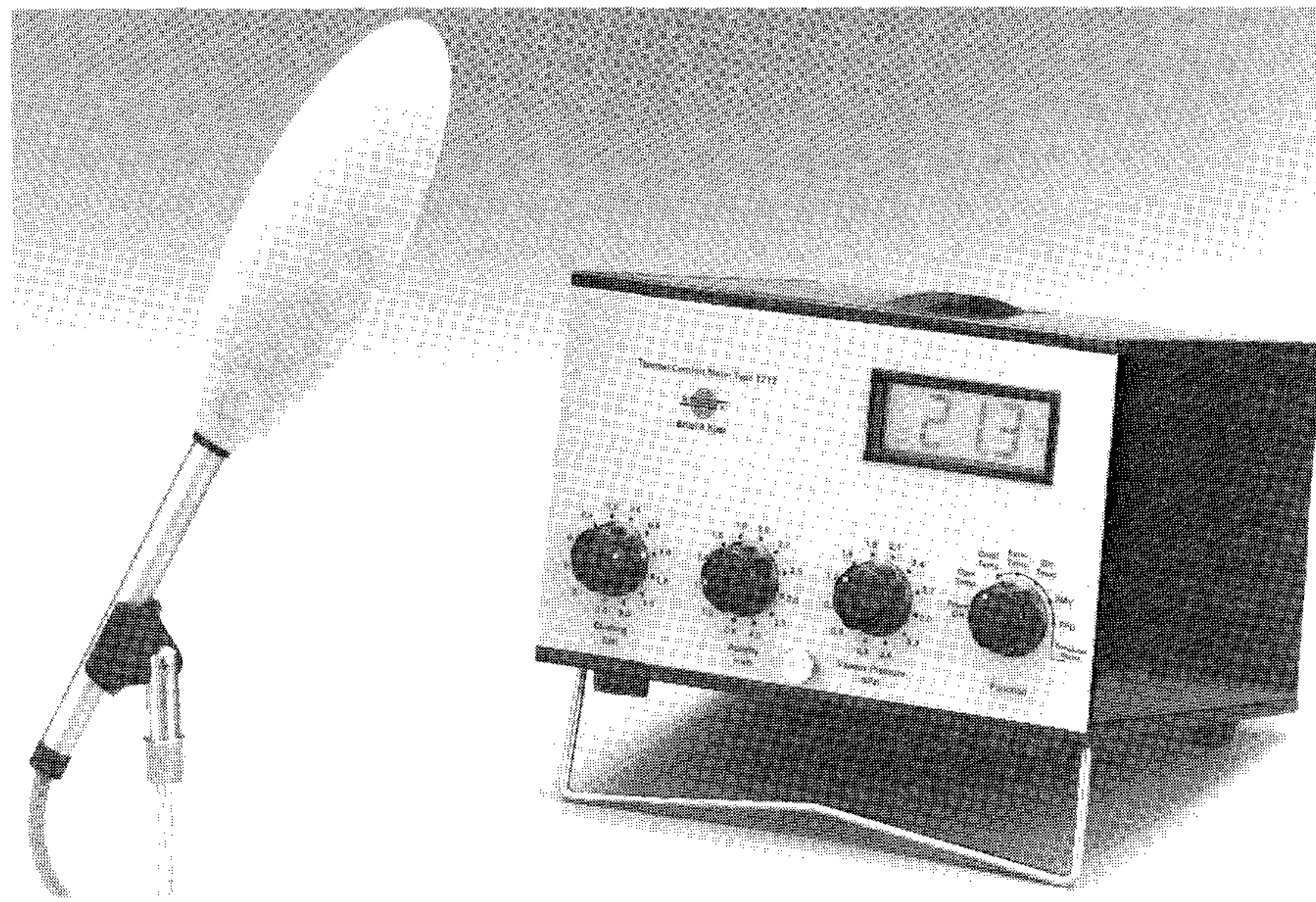

Fig. 2. The Thermal Comfort Meter

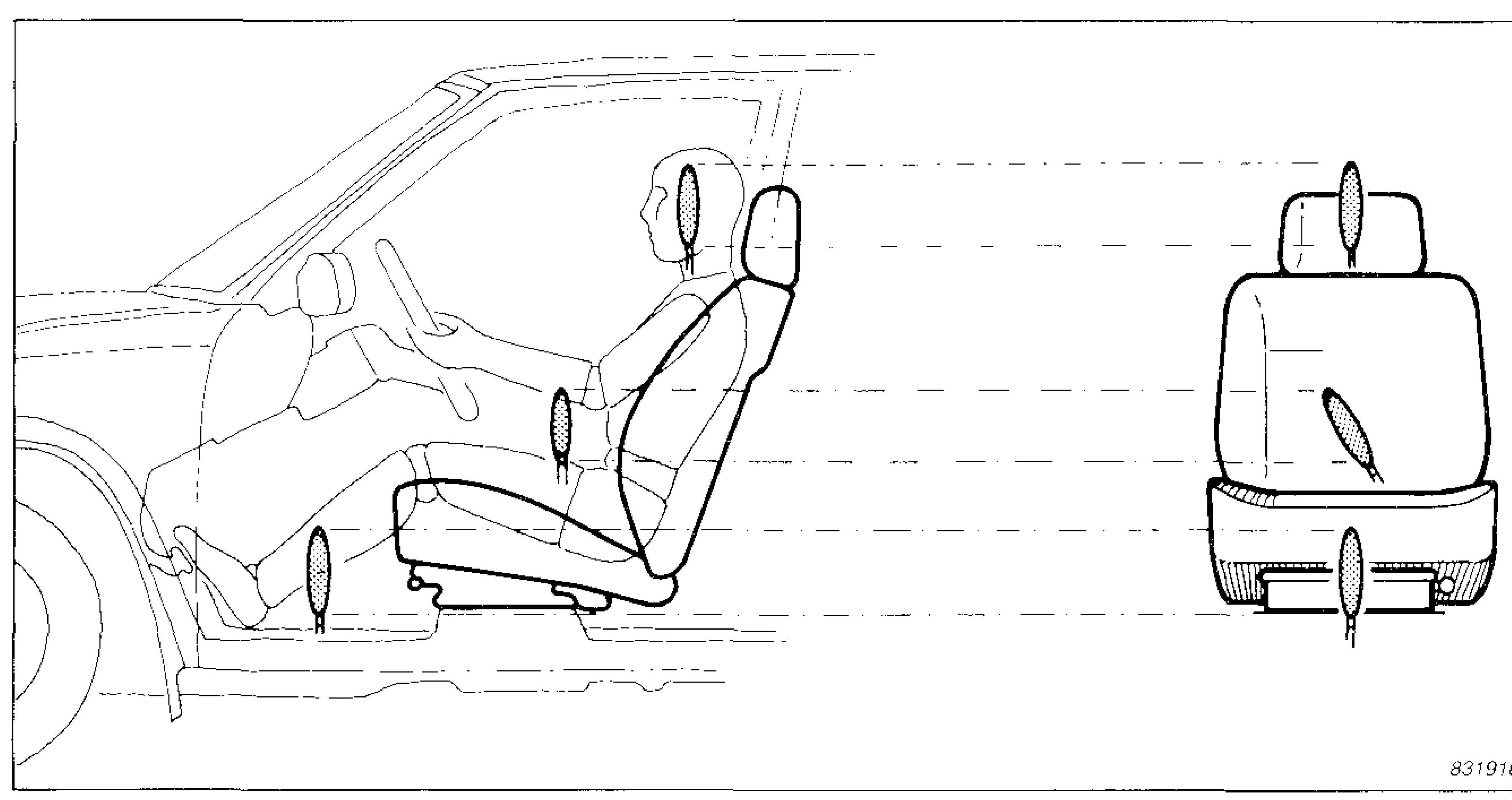

Fig. 3. Position of the three comfort transducers, when measuring in a car

Body Segment	Skin Area m^2	Relative Area %	3 Transducer	Area %	6 Transducers	Area %	10 Transducers	Area %
Head	0,180	10,3	1 : Head	10,3%	1 : Head	10,3	1 : Head	10,3
Left Upper Arm	0,077	4,0			2 : Abdomen	31,1	2 : Abdomen	23,1
Right Upper Arm	0,077	4,0			L. Upperarm		3 : R. Upperarm	4,0
Left Forearm	0,062	3,5			R. Upperarm		4 : L. Upperarm	4,8
Right Forearm	0,062	3,5			3 : L. Forearm	6,4	5 : R. Forearm	6,4
Left hand	0,050	2,9			L. Hand		R. Hand	
Right hand	0,050	2,9	2.: Abdomen	66,7	4 : R. Forearm	6,4	6 : L. Forearm	6,4
Chest	0,185	10,6			R. Hand		L. Hand	
Back	0,204	11,7			5 : L.Thigh		7 : R. Thigh	11,4
Pelvis	0,080	4,6			R. Thigh	22,8	½ Trunk	
Left thigh	0,160	9,1			Abdomen		8 : R. Thigh	11,4
Right thigh	0,160	9,1			6 : L. Foot		½Trunk	
Right fibula	0,140	8,0			R. Foot		9 : R. Fibula	11,5
Left fibula	0,140	8,0	3.. Legs	23,0	L. Fibula	23,0	R. Foot	
Left foot	0,062	3,5			R. Fibula		10 : L. Fibula	11,5
Right foot	0,062	3,5					L. Foot	

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Table 2. Area of different body parts, weighting coefficient

Based on this mean equivalent temperature, activity level, clothing insulation and the vapour pressure it will be possible to estimate the PMV-index either from Figs. 6 – 8 or by use of the PMV-equation, where the equivalent temperature is inserted for air and mean radiant temperature and the air velocity is equal to zero.

To take into account the obstruction that the human body will make to the air velocities it is recommended to mount the sensors on a skeleton which represents the contour of each body part (Figs. 4 and 5).

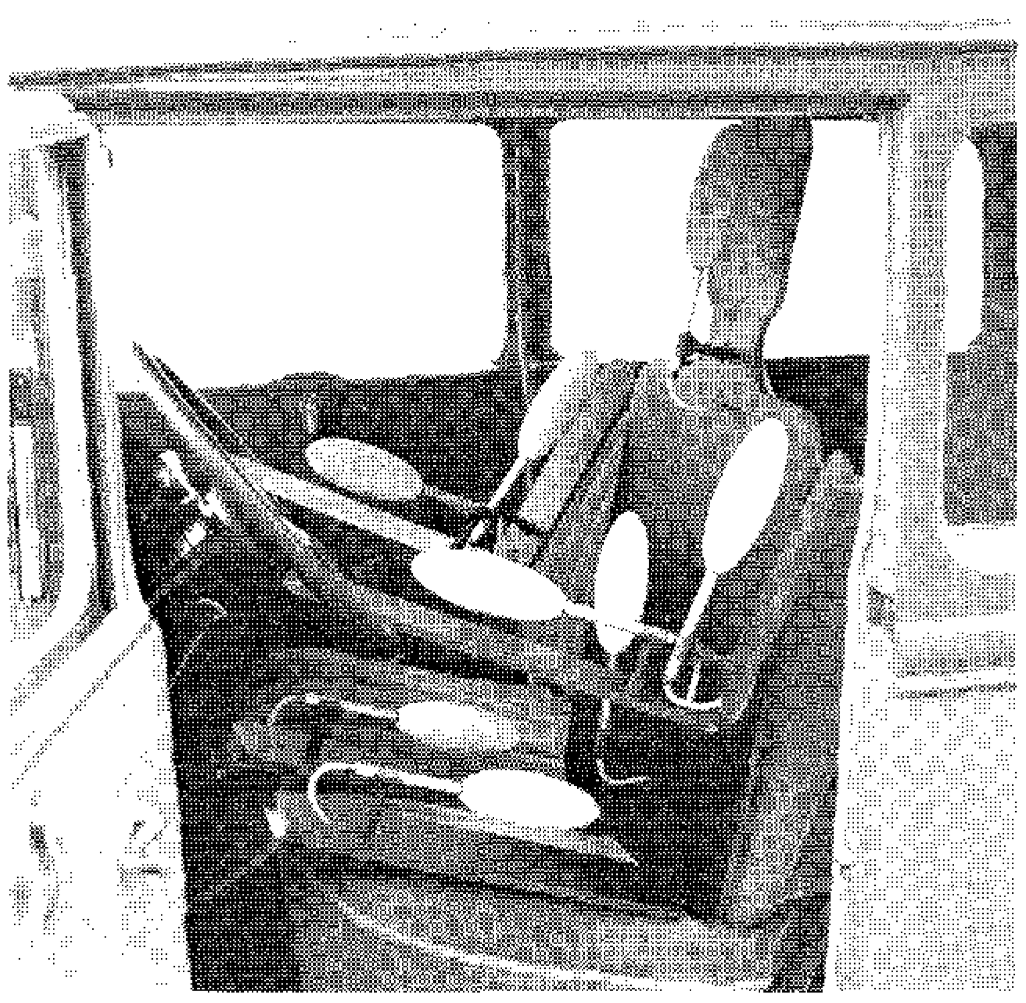

Fig. 5. Example of mounting skeleton in a car

Each of the comfort sensors have to be connected to its own control-box. The settings of humidity and activity level shall be the same for all sensors. These two parameters will not influence the measured equivalent temperature. The setting of the clo-value will influence the equivalent temperature. The cooling effect of air movements are much higher on nude parts of the body than on parts which are covered by clothing. This is taken into account by setting individual thermal insulation values (clo-values) for the sensors representing different body parts. An example of these settings are shown in Table 3.

Measuring Procedure

To evaluate the performance of the heating and air conditioning system in vehicles four types of tests are of interests.

Test A: Evaluation of the heating-cooling capacity of the air conditioning system, i.e. the ability to heat up or cool down the interior of a vehicle.

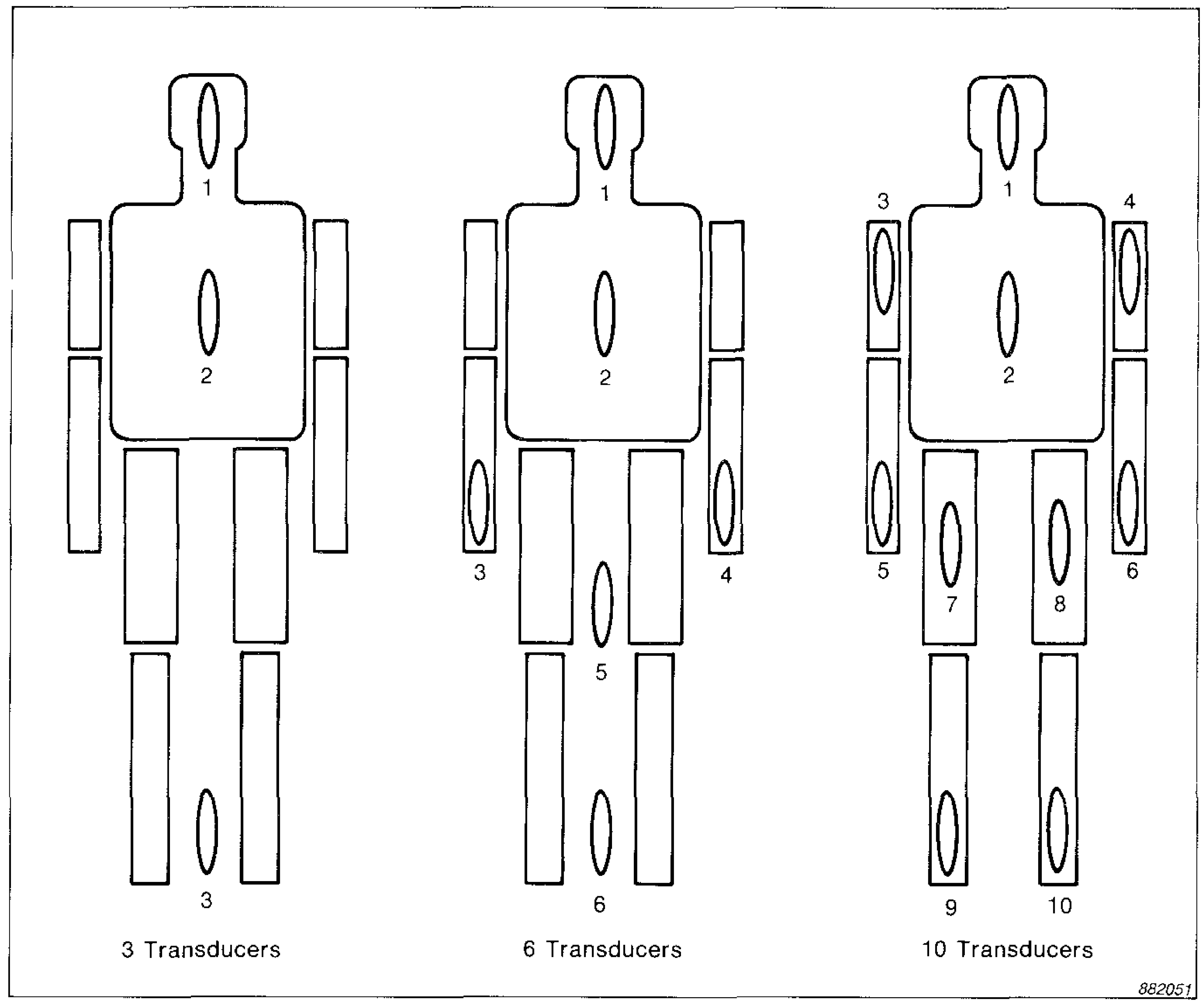

Fig. 4. Example of position of the sensors

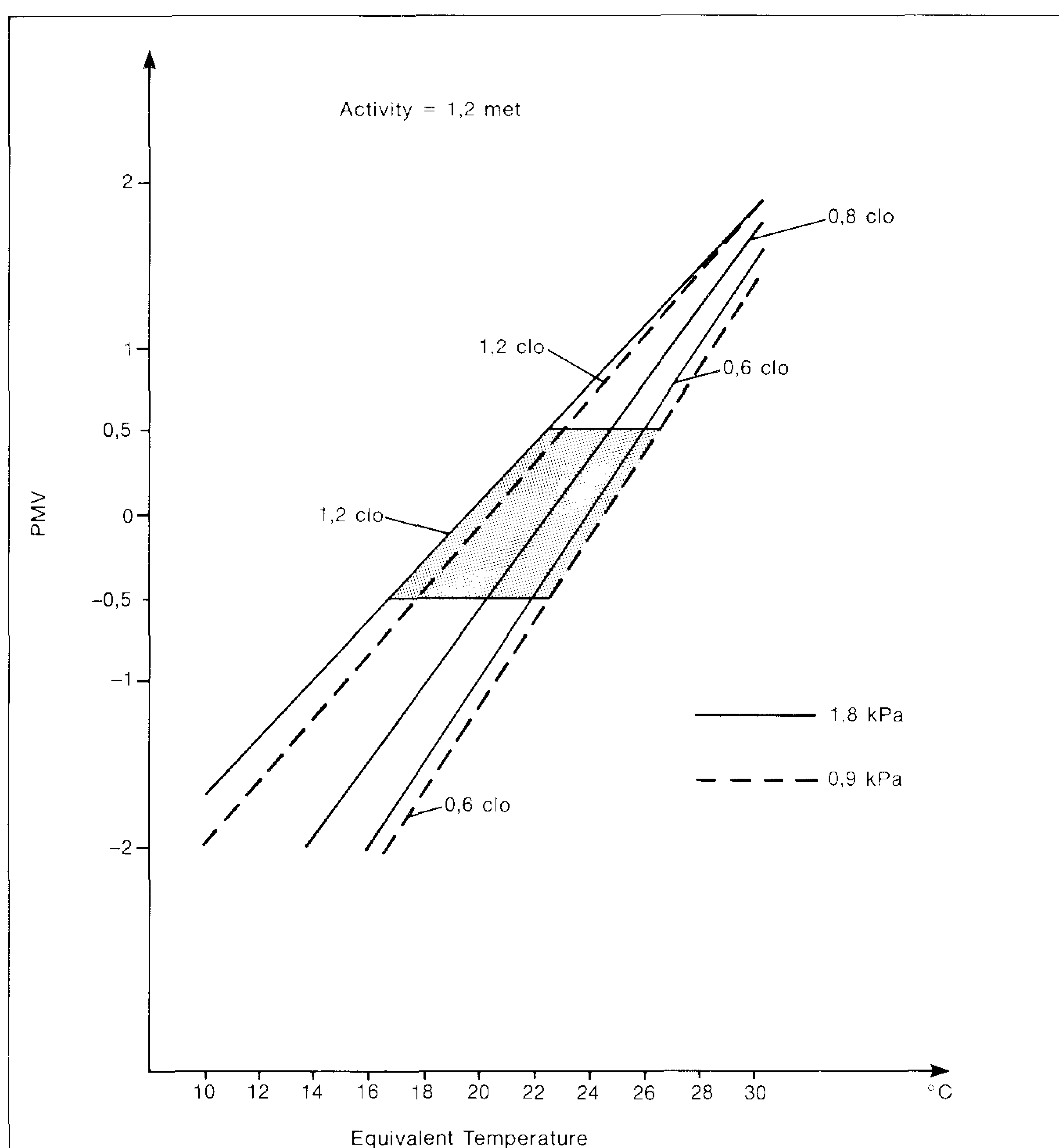

Fig. 6. Relation between equivalent temperature and PMV-index for activity level equal to 1,2 met

Test B: Evaluation of the non-uniformity of the thermal environment at the driver's seat (or one of the other seats), i.e. the influence of different positions of the outlets and the effect of direct sunshine through the windows.

Test C: Evaluation of the differences in the thermal environment from seat to seat.

Test D: Field trials under actual outside conditions.

Test A

This test is based on measurements of the mean equivalent temperature and the PMV-value at the driver's seat. For this test the transducers are fixed at the selected positions and all set to the equivalent temperature function. The setting of activity level (1,2 – 1,6 met) and humidity (0,8 – 1,8 kPa) shall be the same for all sensors. It is recommended to set the activity level at 1,4 met, which approximate a person seated after entering the vehicles. The setting of the clo-value is made individually according to Table 1 and Table 3.

Cool-down: To simulate summer conditions, the car is heated up in the wind tunnel with simulated sun load to an operative temperature around 60°C. After steady state conditions have been obtained for some time, the engine and air-conditioning system is started. The engine is running under a realistic load during the whole test. During the entire test the air temperature (+ 40°C) and sun load from above and/or from the side is kept constant. When the car is turned on, the wind speed in the tunnel is increased to a level that is equal to the relative air velocity when driving i.e. 80 km/h. Before the cool-down starts, the air-conditioning system and the fan speed has been set and the outlets set in a fixed position. Before the start all the comfort meters are turned on and the output from the equivalent temperature is recorded continuously. In the beginning of the test the transducer will not be heated internally because the ambient temperature is higher than the simulated skin temperature. During the cool down, when the sensors reach a temperature around 36°C the heating will automatically start and the surface temperature will be controlled at a comfortable level taking into account the level of clothing insulation.

		Warm-up winter	Cool down sunmmer
comfort meter	activity level	1,2 met	1,2 met
	vapour pressure	0,6 pa	0,9 pa
	clo-value feet	0,8 clo	0,8 clo
	clo-value abdomen	1,5 clo	0,8 clo
	clo-values head	0 clo	0 clo
Mean thermal insulation incl. seat (+ 0,2 clo)		1,4 clo	0,8 clo

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Table 3. Examples of Comfort Meter Settings during Test

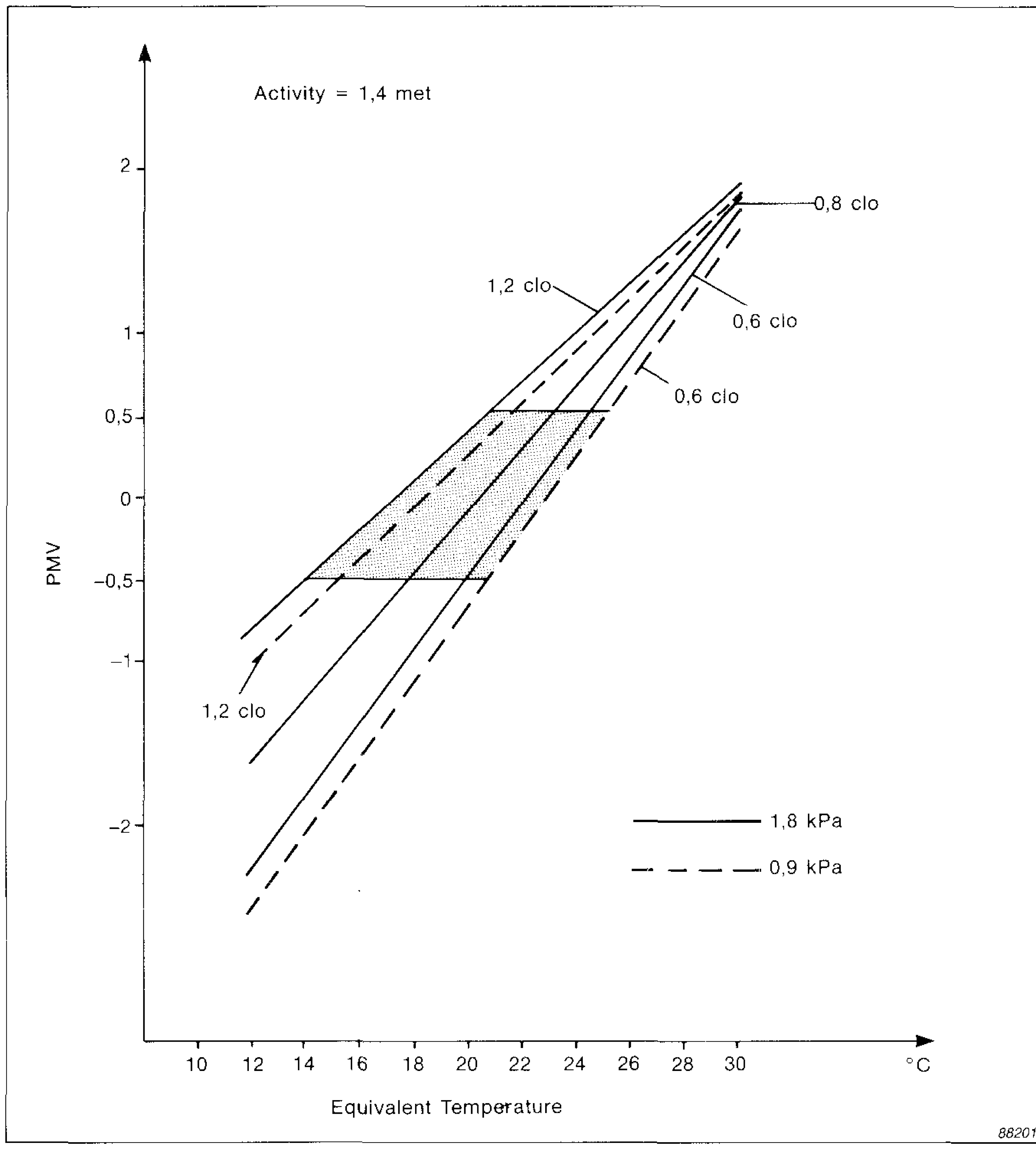

Fig. 7. Relation between equivalent temperature and PMV-index for activity level equal to 1,4 met

Based on the calculated mean equivalent temperature for the whole body (Table 2) and the corresponding PMV-value (Figs. 6–8) it is then estimated the time it takes before the temperature level has reached a comfortable level i.e. –05 < PMV < + 0,5. For the cool-down test (summer conditions) it is recommended to simulate a summer clothing i.e. ~ 0,6 clo.

Warm-up: To simulate winter conditions, the car is cooled down in a wind tunnel to an operative temperature of approx. – 18°C. After steady-state conditions have been reached for some time, the engine and the heating system is started. During the warm-up, similar measurements as for cool down are recorded. For the warm-up test (winter conditions) it is recommended to simulate a winter clothing i.e. ~ 1,0 clo.

Test B

This tests is normally made in a steady state conditions with the car running and a fixed outside climate. In comparison to test A it may here be necessary to measure at more positions either by using more sensors simultaneously or by changing the position of the sensors. This is possible because the tests are made in steady state conditions. When moving a sensor it takes about 5 mins. before it has stabilized at the new conditions. The best is if the change of position can be done without opening of the doors in the vehicle.

The non-uniformity of the thermal environment can then be expressed as the difference in equivalent temperature between different body parts i.e. head-feet or left-right side.

The setting of the instruments will be the same as in Test A.

More detailed information on the individual thermal parameters at the different body parts can be obtained by also measuring the operative temperature with the comfort meter and add a measurement of air temperature (Olesen et al. [1987].

The difference between operative- and equivalent temperature can be used to estimate the air velocity and the difference between operative- and air temperature can be used to estimate the radiant temperature.

When measuring the operative temperature the comfort meters has to be set a "operative temperature" functions and then it will take about 10–20 min. before the sensors have stabilized. If using this procedure it can be recommended to start by measuring the operative temperature and the change to equivalent temperature.

Test C
This test is in fact a comparison of the measurement according to test B at the different seat positions in the front and in the back of the car. To make the measuring time as short as possible you would need several instruments representing each passenger. However, because this test can be performed in a steady state condition you can measure one position at a time and then move the sensors.

Test D
In a field trial one will investigate how the thermal environment will change during a normal ride with changing car speed and sun position. For this test it is necessary with simultaneous measurements. Again the results are given as a mean equivalent temperature or PMV-value and then as the differences in equivalent temperature between different body parts. For this test it is convenient that the instruments may be operated on internal batteries or using the car batteries.

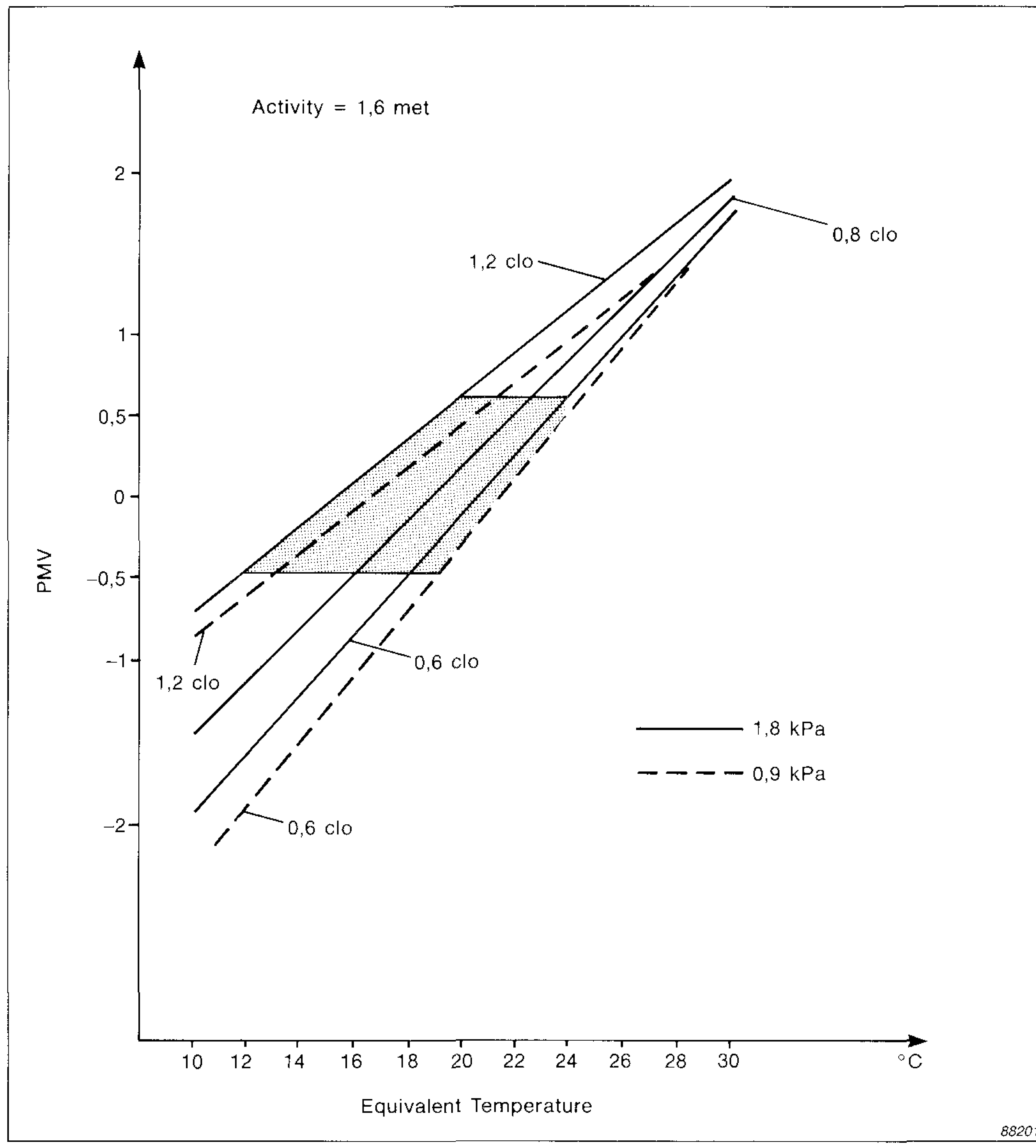

Fig. 8. Relation between equivalent temperature and PMV-index for activity level equal to 1,6 met

Evaluation of the results

The aim of the heating- or air-conditioning system is to obtain a comfortable temperature level i.e. PMV=0 as quickly as possible and an environment as uniform as possible i.e. the difference between the local equivalent temperatures as small as possible.

In ISO 7730 the requirements for thermal comfort is:
$-0{,}5 < \text{PMV} < 0{,}5$, non-uniformity from radiant temperature asymmetry is less than 5°C for horizontal asymmetry (heated ceiling) and less than 10°C for vertical asymmetry (cold window), vertical air temperature difference between feet and head less than 3°C and mean air velocity less than $< 0{,}15$ m/s (air temperatures < 23°C) or less than 0,25 m/s (air temperatures > 23°C).

Regarding the non-uniformity it is really the combined effect of air velocity, air temperature differences and radiant asymmetry a person feels, which may be represented by a difference in equivalent temperature.

To evaluate if the temperature level is acceptable the mean equivalent temperature is measured and then PMV is estimated from Fig. 6–8 or by the PMV-equation. The PMV-index represents mainly steady state conditions. During a "warm-up" or "cool-down" test the driver will be in a transient conditions and his subjective reactions will be different from the steady-state conditions.

To evaluate if the non-uniformity is acceptable it is recommended that the variation in equivalent temperature between the different body parts may not vary more than 3°C.

An example of the measurement in a car

Using the method described above the thermal climate in a car was evaluated. Measurement was made according to test A, B and C. In addition to the measurement with three thermal comfort meters at feet, abdomen and head level also the air temperature was measured with thermocouples at feet and head level (Fig. 3). The setting of the comfort meter are shown in Table 3.

Test A: The ability to warm-up or cool down the car.
Warm-up: The car had been in a steady state at −18°C when the test started.

Fig. 9 shows the results from comfort meter and thermocouple measurements taken at the driver's seat during a warm-up test. The temperature measured by the thermocouples is several degrees higher than that measured by the comfort sensors. The reason is that the air temperature is increasing rapidly while the mean radiant temperature is increasing more slowly because of the thermal capacity in the car. In addition to that, the mean radiant temperature will remain lower than the air temperature because of the poor insulation of normal car walls and ceiling, and finally, the air velocity caused by the heating system will create an increase in the convective heat loss and thereby a decrease of the equivalent temperature.

During winter conditions, with an activity level of 1,2 met and a clo-value of 1,4, comfort (PMV = 0) is obtained at an equivalent temperature equal to 19°C. When using thermocouples, it seems like comfort is obtained after 15 minutes (Fig. 9). This is a false conclusion because the temperature experienced by the driver is about +5°C as measured by the comfort transducers. The comfort level is reached after 24 minutes based on the measured equivalent temperatures. It is, however, important to remember that during the warm-up period the driver will be in a transient state, he will actually feel the thermal environment warmer than indicated by the objective measurements; but the difference found between the thermocouples and the equivalent temperature indicates that the heating system is considerably less efficient than indicated by the simple measurement of air temperature.

Cool-down: The car had been in a steady state at 60°C when the test started. Fig. 10 shows the results. As the comfort meter is not able to perspire, it cannot exactly simulate the real heat loss from a person at high temperatures. The temperature given in Fig. 10 is the temperature of the sensor. But when the ambient temperature decreases below 36°C the heating of the transducer will start and the equivalent temperature is measured.

It is seen from Fig. 10 that in the cool-down test there is a better agreement between the two methods. This is, however, due to the fact that two

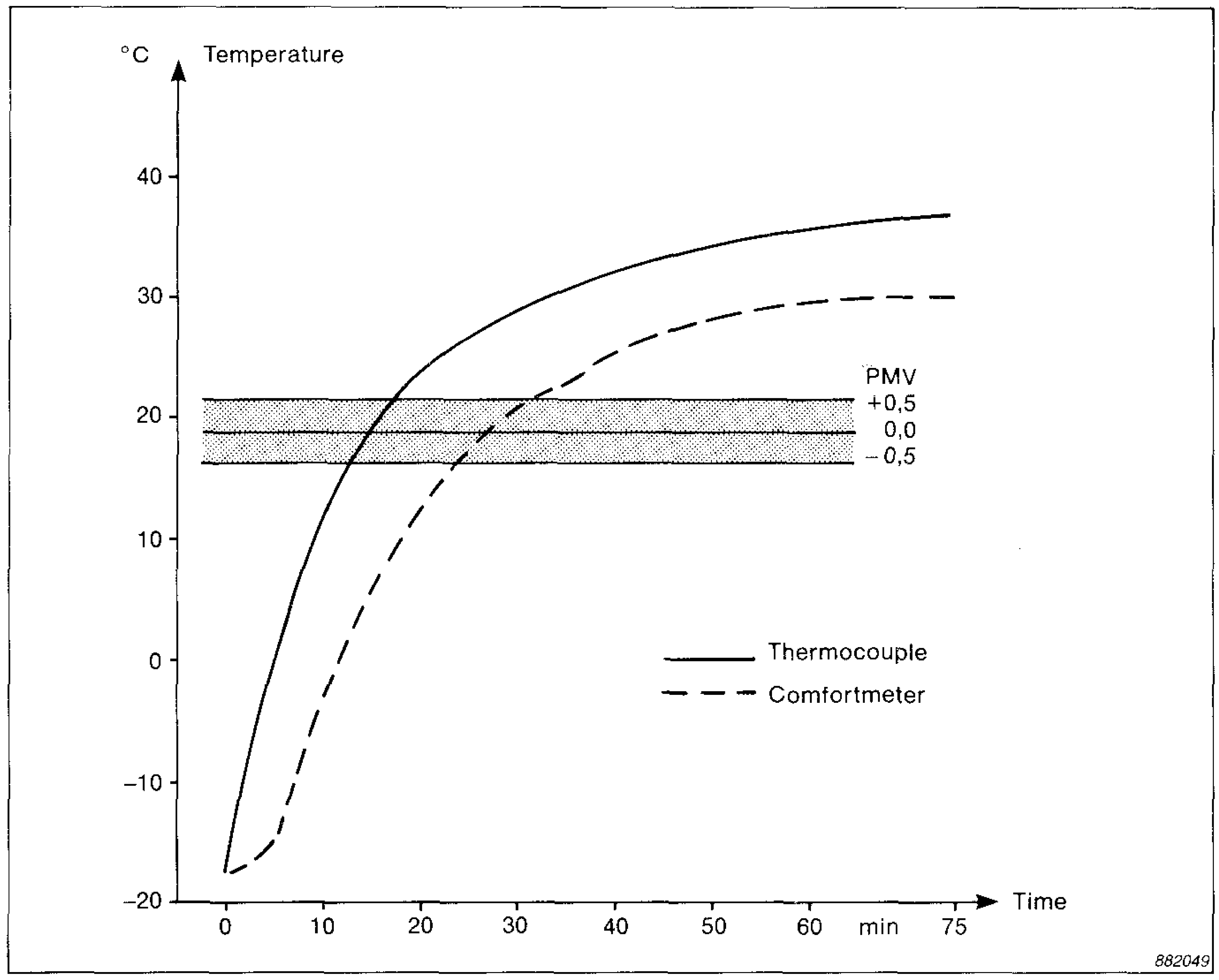

Fig. 9. Recording of temperature in drivers seat during warm-up text using two measuring methods. The horizontal lines indicate the comfort zone (−0,5 < PMV < 0,5) for 1,2 met and 1,4 clo

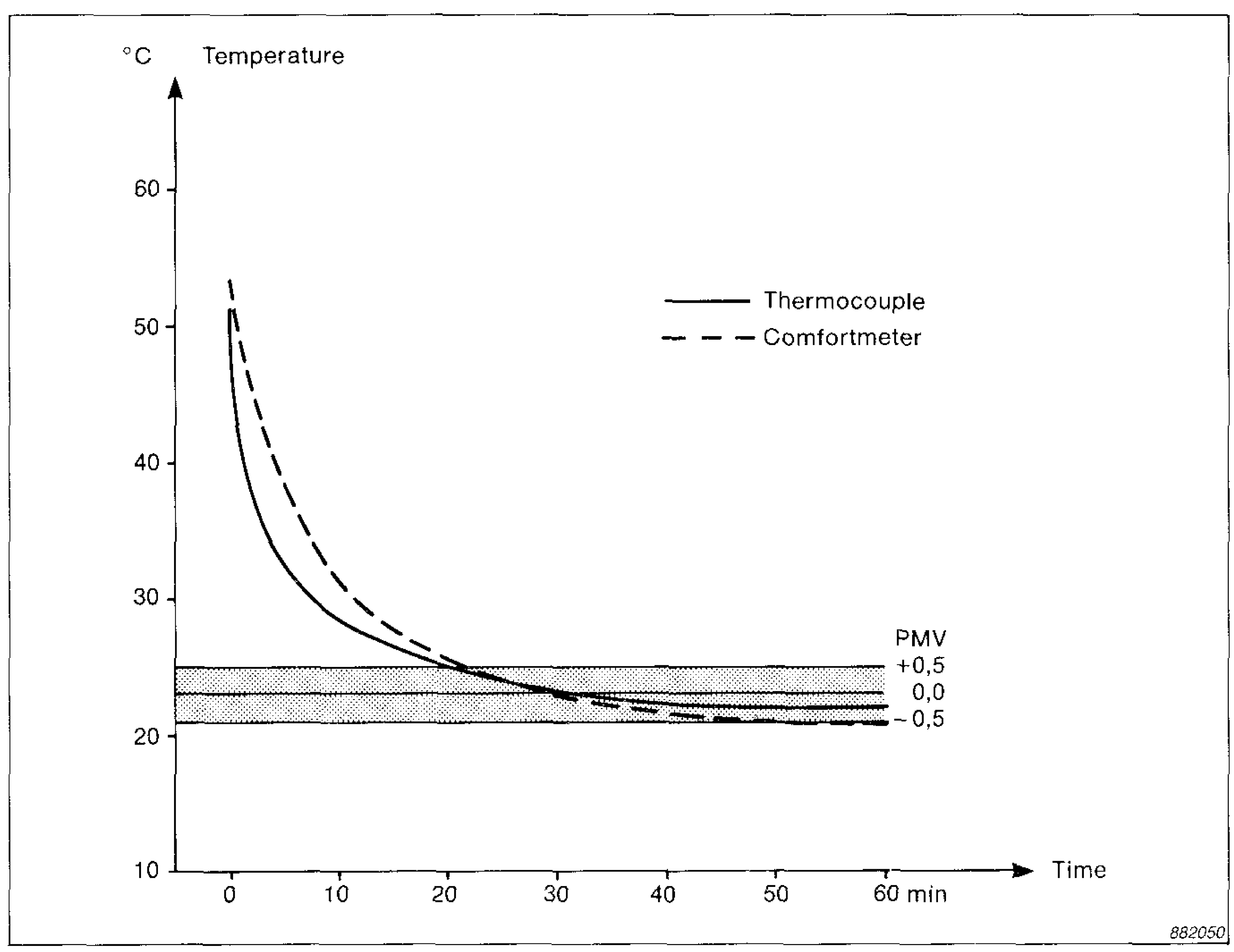

Fig. 10. Recording of temperature in driver's seat during cool-down test using the two different measuring methods. The horizontal lines indicate the comfort (−0,5 < PMV < 0,5) for 1,2 met and 0,8 clo

	Equivalent Temperature				Air Temperature			
	Mean °C	Feet °C	Head °C	Differences Head–Feet °C	Mean	Feet	Head	Difference Head–Feet
Cool environment max. outlet temp. high fan speed	31,9	39,5	30,0	−9,5	37,2	39,5	34,8	−4,7
max. outlet temp. low fan speed	24,7	32,0	22,8	−9,2	29,3	29,4	29,1	−0,3
Warm environment mean fan speed normal air conditioning no sun load	16,5	19,5	9,8	− 9,7	23,0	25,7	20,1	−5,6
mean fan speed normal air-conditioning sun load: side, front, roof	26,0	24,2	20,7	− 3,5	28,6	29,6	27,7	−1,9
low fan speed normal air-conditioning sun load: side, front, roof	30,3	27,8	41,0	+ 13,2	34,8	31,3	38,2	+ 6,9

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Table 4. Results from test B of measured equivalent and air temperatures. The results are given as mean values for driver and passenger seat

measuring inaccuracies for the thermocouples compensates for each other. In this test the outside temperature is much higher than the internal air temperature, which means that the mean radiant temperature in the car is higher than the air temperature. This should result in an equivalent temperature higher than the air temperature. But on the other hand the increased air velocity will increase the convective heat loss from the body and then decrease the equivalent temperature. In the present case this will result in an equivalent temperature almost equal to the air temperature, because the thermocouples do not respond to the air velocity and only a little to the mean radiant temperature. The optimum comfort temperature for 1,2 met and 0,8 clo is 23°C. This temperature is reached 30–35 minutes after start-up. From Figs. 8 and 9, it is seen that the "real" warm-up and cool-down times are approximately the same, around 30 minutes.

Test B: The non-uniformity was studied in steady state conditions, both in a cool (−18°C) and a warm (40°C + sunshine) outside climate. The results are given in Table 4. For the winter conditions (cool environment) the range of equivalent temperature which will result in $-0{,}5 < PMV < 0{,}5$ is 16,5°C – 21,5°. In both situations the temperature level in the actual case is too high. As mentioned above, is the temperatures measured by the thermocouples much higher than the equivalent temperature. The measured non-uniformity expressed by the temperature difference between head and feet is higher than the recommended 3°C. The thermocouples (air temperature sensors) are measuring two small differences between head and feet. This is because they are not influenced by the cold radiation from the ceiling and the windows on the upper part of the body (head).

For the summer conditions (warm environment) the range of equivalent temperatures which will result in $-0{,}5 < PMV < 0{,}5$ is 21°C – 25°C. In the case with no sun load the air temperature sensors are showing much too high values. The mean value for equivalent temperature is 16,5°C, while

Equivalent temperatures	Drivers Seat				Passenger Seat			
	Mean °C	Feet °C	Head °C	Differences Head–Feet °C	Mean	Feet	Head	Difference Head–Feet
Cool environment max. outlet temp. high fan speed	31,5	39,0	32,0	−7,0	32,1	40,0	28,0	−12,0
max. outlet temp. low fan speed	25,0	32,0	23,0	−9,0	24,3	32,0	22,0	−10,0
Warm environment mean fan speed normal air conditioning no sun load	18,5	20,4	14,3	−6,1	14,6	18,6	5,3	−13,3
mean fan speed normal air-conditioning sun load: side, front, roof	26,5	23,6	21,3	−2,3	25,6	24,8	20,1	− 4,7

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Table 5. Results from test C of measured equivalent temperatures

mean air temperature is 23°C. This is because the air temperature does not respond to the cooling effect of the air velocity. At head level this effect is very significant (t_{eq} = 9,8°C and t_a = 20,1°C). This was caused by the fact that the outlets from the cooling systems were directed towards the head level.

In the two last tests the sun load was on, which increases significantly the temperatures in the car (16,5°C → 26,0°C). By a low fan speed this increase is even greater. Especially at head level it is now felt very hot due to the sun radiation and the missing cooling effect from the cooled air, which with low fan speed does not seem to reach the head level. Both with mean fan speed, no sun and with low fan speed with sun the non-uniformity is very high.

Test C: Also a comparison between the conditions at the drivers and the passenger seat was done. These results are given in Table 5. In the cool environment the thermal climate at the passenger seat is very much the same as for the driver, except for the colder head (28°C) with the high fan speed.

A much more significant difference is found between head temperatures in the warm environment with no sun load. In the driver's seat the temperature at head level is 14,3°C while it is only 5,3°C at head level in the passenger seat. This may be due to the direction of the outlets which may not have been exactly the same for the driver and the passenger seat.

Conclusion

The present application note has shown that the evaluation of the thermal environment in a vehicle can be made more correctly using an integrating sensor like the thermal comfort meter than using simple measurement of air temperatures.

The sensor can be used to evaluate the performance of a heating/air-conditioning system when warming-up a cool car or cooling down a warm car.

Besides, when using several sensors representing different body parts, the non--uniformity of the thermal environment due to local air velocities and sunshine may also be evaluated.

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Printed in Denmark by Nærum Offset