Design of Condition Safety

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Contents

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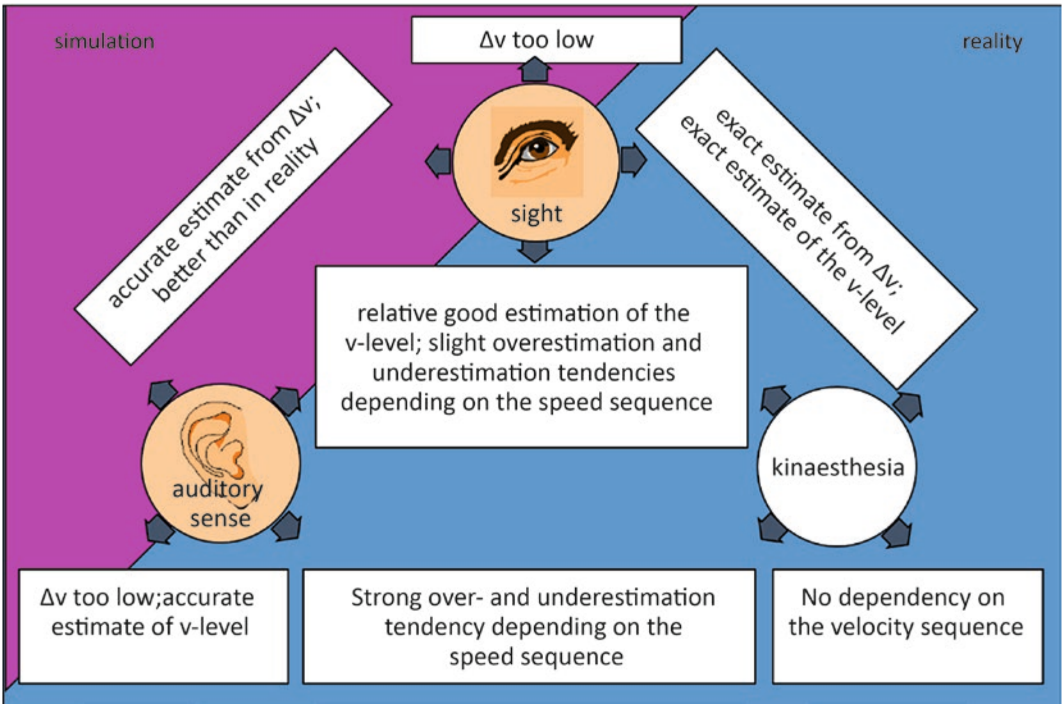

◘ **Fig. 8.1** Influences of the respective sensory impressions on the perception of speed. (Bubb 1977)

In all design measures, the dual character of these environmental factors must therefore be taken into account as feedback and impact factors.

8.1 Lighting

If 90% of the information is perceived via the optical sensory channel when driving a car, it is trivial to note that the lighting has a primary feedback character. On the other hand, the comfort pyramid shown in ◘ Fig. 3.72 shows that inadequate lighting, in addition to unpleasant odours, creates discomfort above all other environmental factors. The double character mentioned above therefore plays an important role in the design of the lighting.

8.1.1 Photometric Dimensions

Lighting dimensions play an important role in the assessment of lighting conditions. ◘ Fig. 8.2 shows a compilation. Although light is a form of energy and would therefore be the adequate unit of the power emitted by a light source Watt [W], the power emitted in the visible light range (wavelength between 390 and 770 nm) is evaluated by means of the so-called V(λ) curve, which takes into account that the eye is significantly less sensitive in the blue and red range than in the range of the centre of the sunlight at 555 nm (see also ► Sect. 3.2.1.1). The radiant power evaluated in this way is referred to as luminous flux and is quantified in the light unit lumen [lm]. The luminous flux emitted into the solid angle f/r^2 is referred to as luminous intensity (unit of measurement candela [cd]). The luminous flux emanating from the light source falls on the illuminated surface of interest. The luminous flux incident per unit surface is referred to as illuminance (unit lux [lx]). Depending on the optical properties (location- and space-dependent absorption and reflection coefficients) of the illuminated surface, the light is now reflected in the various spatial directions. The beam of light falling into the eye characterizes the location point seen in each case. The amount of light emitted from this point is called luminance. It is calculated from the illu-

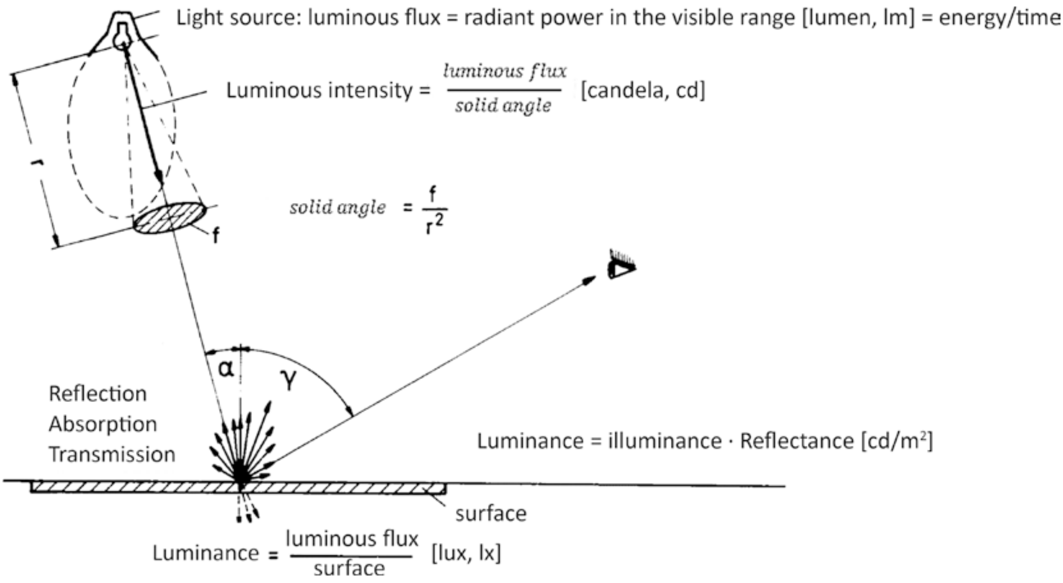

Fig. 8.2 Lighting dimensions

minance and the site-specific reflection coefficient. The unit of measurement the luminance is therefore cd/m^2.

The eye has an enormous ability to adapt to different lighting conditions (approx. 1:10^{16}). As explained in ▶ Sect. 3.2.1.1, this adaptation is done through various mechanisms. A quick adjustment is done by narrowing and dilating the pupil, but this only allows an adjustment in the range of 1:4. The actual adaptation takes place on the one hand by changing the interconnection of the receptors to the retina of the eye (change in the receptive fields), which in principle takes time and is associated with a loss of local resolving power during dark adaptation. The adjustment effects described so far all occur in the so-called photopic region of the cone vision, which also allows a color resolution of the objects seen. In extreme darkness adaptation, light can only be perceived via the very light-sensitive rods. This area of vision is called scotopic. The transition area between rod vision and complete cone vision is called mesopic. ◘ Fig. 8.3 shows an assignment of these different visual ranges to the above-mentioned photometric units with some practical examples. In particular, it can be seen from the image that the brightness range of a car headlamp enables vision in the lower photoptical range.

8.1.2 Outdoor Lighting

It is not the framework here to deal with the various statutory approval regulations for vehicle lighting. ▶ Section 3.2.1.1 details the individual conditions that must be met in order for objects to be detected. The main problems of night driving are the luminance of the light reflected into the eye by the road and objects, possibly too high a luminance of the radiators themselves, which may also be sources of physiological and psychological glare. Since the eye has extreme adaptability to different lighting levels, the time required for adaptation plays a major role. Although in normal road traffic at night there is only mesopic adaptation (no complete dark adaptation, which still shows objectifiable improvements after half an hour, see above), it has to be considered that the adaptation process from light to dark is much slower (in the seconds to minutes range) than in the opposite direction (in the 100 ms to 1 s range). This plays a major role during the day, especially in the case of strongly changing lighting conditions (especially tunnel entrances and exits), but can practically not be absorbed by vehicle technology. Since, however, light adaptation is essentially controlled by the sensitivity of the rods in the fundus of the eye and these are

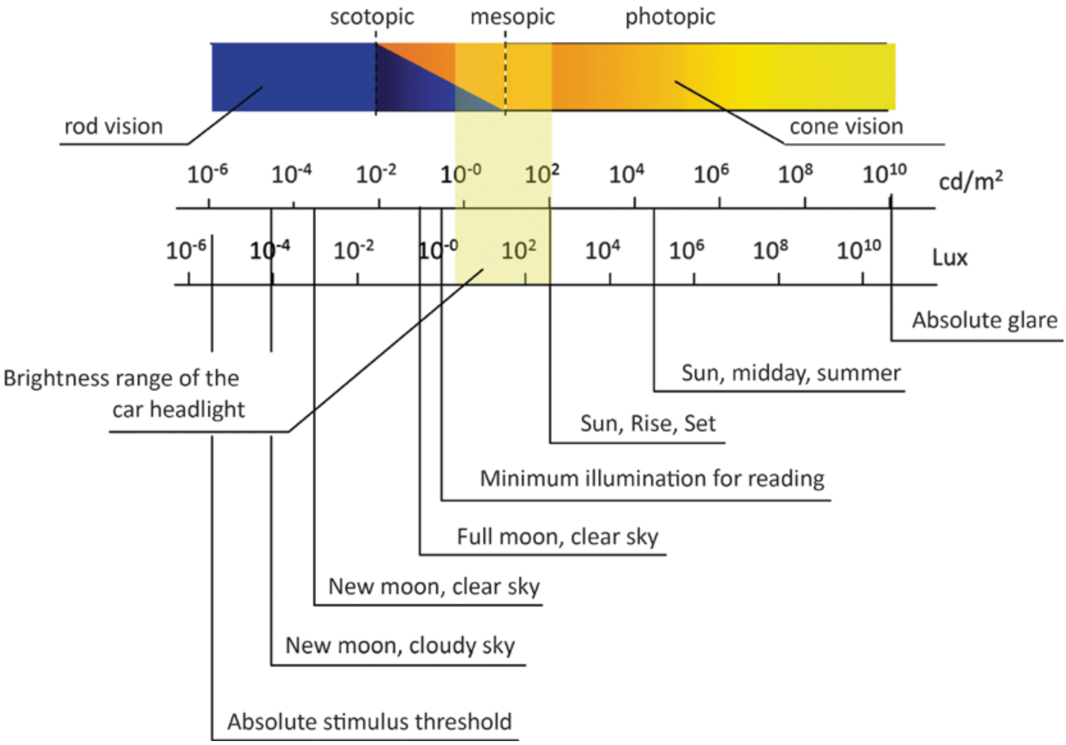

Fig. 8.3 Cone vision and rod vision as a function of luminance and illuminance

particularly sensitive to short-wave blue light, blue light sources, especially large-area light sources, should be avoided wherever possible in the vehicle interior in order to avoid undesired adaptation to apparently bright lighting conditions.[1] Otherwise, new developments in outdoor lighting, which can significantly improve night-time visual conditions, are dealt with in ► Sect. 9.2.1.3.

A special case of outdoor lighting is the automatic lighting of certain areas of the vehicle environment (e.g. lighting of door openers) when the driver approaches the vehicle in darkness. In order to prevent misuse by uninvolved pedestrians, these comfort functions can only be implemented in conjunction with the so-called keyless entry system, through which the vehicle recognizes the proximity of the authorized driver by means of a special transponder system.

8.1.3 Interior Lighting

8.1.3.1 Instrument Lighting

Since many drivers feel disturbed by excessively bright instrument lighting when driving at night, it is absolutely necessary to make it dimmable. The control unit provided for this purpose (usually in the form of a knob or knurled wheel) must be easily accessible. It is usually installed near the light switch. With conventional instrument lighting (incident light), *dimming* is no problem and is part of the standard equipment. However, dimmability must also refer to the LED displays that are increasingly being used today. In particular, this must be provided for the central display (CID) and for the instrument cluster, if this is implemented in LCD form. Particularly with LCDs, the option between a day and a

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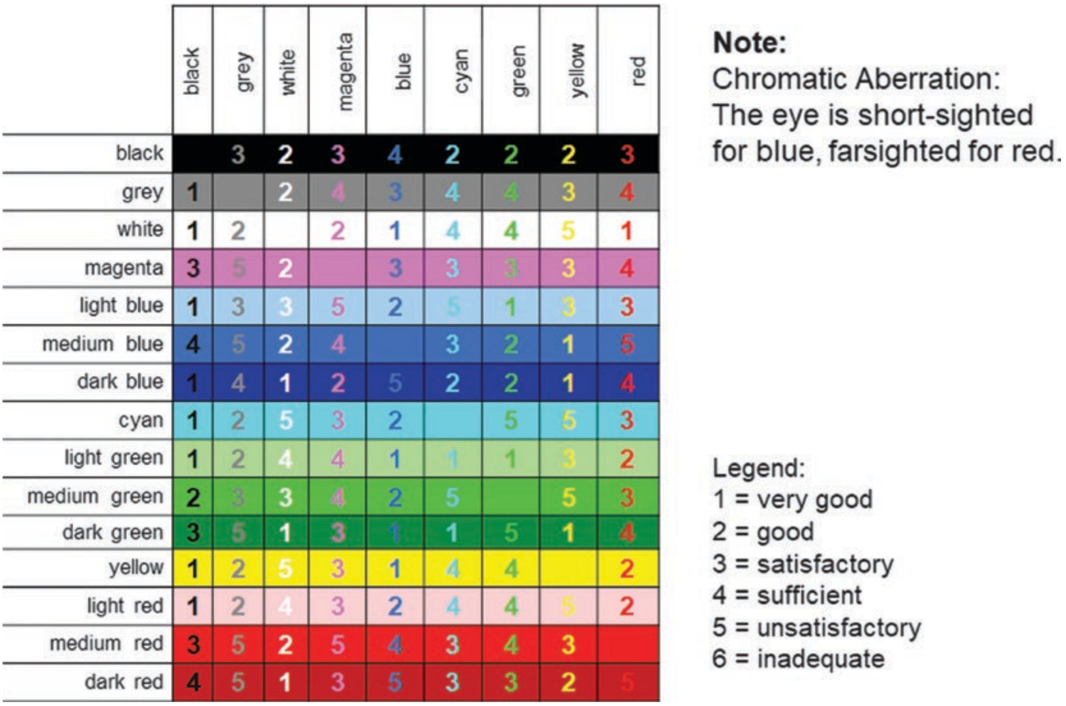
[1] In order to avoid undesired light adaptation, red light illumination was previously provided in the interior of submarines. Today it is known that so-called filtered white light (the extreme blue range is filtered out) has the best effect in terms of preventing light adaptation.



	black	grey	white	magenta	blue	cyan	green	yellow	red
black		3	2	3	4	2	2	2	3
grey	1		2	4	3	4	4	3	4
white	1	2		2	1	4	4	5	1
magenta	3	5	2		3	3	3	3	4
light blue	1	3	3	5	2	5	1	3	3
medium blue	4	5	2	4		3	2	1	5
dark blue	1	4	1	2	5	2	2	1	4
cyan	1	2	5	3	2		5	5	3
light green	1	2	4	4	1	1	1	3	2
medium green	2	3	3	4	2	5		5	3
dark green	3	5	1	3	1	1	5	1	4
yellow	1	2	5	3	1	4	4		2
light red	1	2	4	3	2	4	4	5	2
medium red	3	5	2	5	4	3	4	3	
dark red	4	5	1	3	5	3	3	2	5

Note:
Chromatic Aberration:
The eye is short-sighted
for blue, farsighted for red.

Legend:
1 = very good
2 = good
3 = satisfactory
4 = sufficient
5 = unsatisfactory
6 = inadequate

Fig. 8.4 Examples of good (2), medium (1) and bad (0) color contrast

night display version can be provided (day display: bright background – dark visual signs; night display: dark background – bright visual signs). However, automatic switching should be avoided, as irritating light stimuli may occur, especially in changing lighting conditions.

For good recognizability, visual signs must be marked with an *contrast* from 10: 1 (defined here as the ratio of the luminance of the visual sign to that of the background). In the case of external lamps, this is achieved by the graphic design – the contrast is maintained regardless of the intensity of the lighting (dark grey visual signs against a light grey background, for example, are unfavourable). However, the effective contrast of self emitting lamps depends on the ambient lighting. The light emission from LED displays, for example, would therefore have to be controlled depending on the outdoor illuminance.

In addition to brightness contrast, colour contrast is also very important for the recognition of visual signs. In principle, a high color contrast is achieved by a distance as large as possible between the color coordinates of the respective visual sign and the background in the color triangle of the Fig. 3.19. Fig. 8.4 gives examples. The correct choice of colour contrast is particularly important in conjunction with large LCD displays in the central instrument (CID) or, more recently, in the instrument cluster. It should also be noted in this context that due to the wavelength-dependent different refractive properties of the eye lens, the eye is short-sighted for blue light and farsighted for red light. This means that the direct contrast between red and blue visual signs should be avoided as far as possible (red visual signs against a blue illuminated background and vice versa are particularly unfavourable).

8.1.3.2 Interior Lighting

The interior lighting during a night-time drive is in principle even more disturbing than irritatingly bright instrument lighting. For various reasons, however, the desire for interior lighting occasionally arises (e.g. orientation on a map by the passenger, the desire of passengers to read while driving, etc.). Therefore, the design of the interior lighting requires spe-

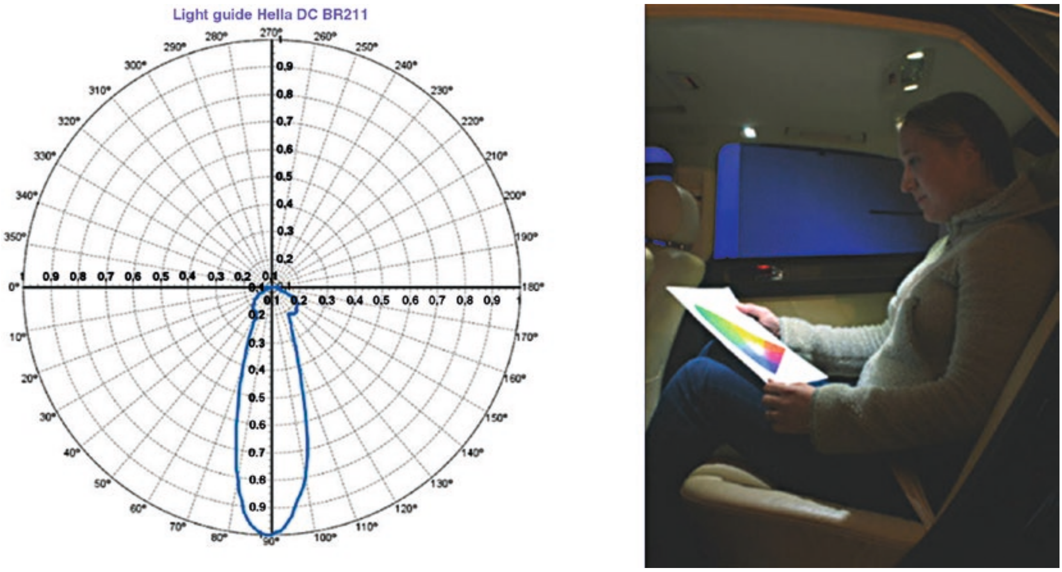


Fig. 8.5 Spatial emission spectrum of an interior light with prism optics. (Hella: Nachtigall 2007)

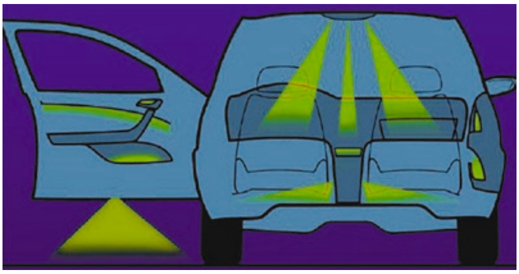


Fig. 8.6 Areas of interior lighting. (Hella: Nachtigall 2007)

cial care. In particular, it shall be avoided that the light source of the interior lighting may be in the driver's field of vision. In addition, directed light (in the sense of a spotlight) must be used (Fig. 8.5). Fig. 8.6 shows areas where interior lighting can be installed in the vehicle in a profitable way. Attention should also be paid to the light emitted by interior lighting and then reflected by objects. In this context, reference is made in particular to the comments in ► Sect. 7.3.4. The switch for activating the interior lighting should be easily accessible for the respective user. It should also be examined whether it makes sense for the driver to be able to switch off the interior lighting on his own initiative under certain circumstances.

In general, the night-time operation of controls in the vehicle cockpit may pose a problem that cannot always be solved satisfactorily by the backlighting of these controls that is common today. Hella has presented an innovative solution in the form of motion-guided light. The corresponding control element area for the driver is then illuminated glare-free (see above) when he approaches it with his hand (see Fig. 8.7). It is then even possible to illuminate the following control panels adaptively in advance for better orientation (e.g.: Air conditioning – ventilation nozzles; Pietzonka 2004).

8.1.3.3 Ambient Lighting

For many people, S in an absolutely darkened room is unpleasant. In this context, the outstanding importance of light for the reduction of discomfort sensitivity is again pointed out. This unpleasant feeling can be compensated for by discreet ambient lighting. Fig. 8.8 shows an example of such ambient lighting in the door leaf of the vehicle. In this context, particular care should be taken to ensure that this additional interior lighting neither impairs the view of the road nor creates any irritating reflections in the windscreen or side windows. Nachtigall (2007)

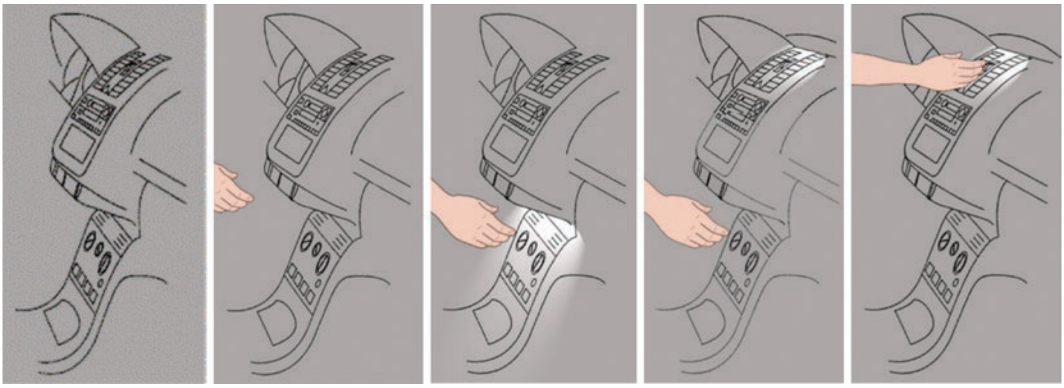


Fig. 8.7 "Motion-controlled light". (Hella: Pietzonka 2004)

Fig. 8.8 Ambient lighting in door leaf. For ambient lighting, blue light should be avoided, as light adaptation is mainly done by the blue light sensitive cones. (Source Hella)

reports that when asked what they saw as the main advantage of ambient lighting, about a quarter of respondents cited improved orientation and a pleasant atmosphere. 17% said they had a better sense of space and 12% even believed that this could help prevent fatigue.

8.2 Sound

8.2.1 Driving Noises

Irrespective of experience with technical systems, it is probably a fundamental object of human experience that increasing speed is always associated with increasing volume and increasing average frequency or individual frequency components of the associated noise (own movement, observation of animal movements and, of course, experience with technical noise development). In addition, sounds are perceived as pleasant (e.g. music) and annoying (the term is then "noise"). The sound generated by the vehicle thus cause a complex spectrum of sensations: they provide information about the driving condition (e.g. speed level, see above; feedback character), they can evoke joyful emotions ("great engine sound") and they can also be annoying (e.g. hissing joints, rattling noises). Vehicle acoustics is a complex and extensive field. Nor can it be dealt with in an almost exhaustive manner within the present framework. In this context, reference is made to e.g. the detailed work of Zeller (2011).

8.2.1.1 Noise Sources and Paths

Driving noise refers to all noises in the vehicle interior that are generated directly by the vehicle's movement. The noise sources are essentially the operating noise of the drive motor, wind noise at the body and rolling noises caused by the wheels and the chassis. Zeller (2011) states: "In the case of comfort-oriented mid-size sedans, rolling noise dominates the interior of the vehicle at low and medium driving speeds and low engine loads. This is perceived as airborne sound via the underbody and the side wall (panes) and as structure-borne sound via the chassis. As the load increases, the components of the engine noise become increasingly audible. In the low frequency range up to approx. 100 Hz, these are primarily airborne sound induced motor

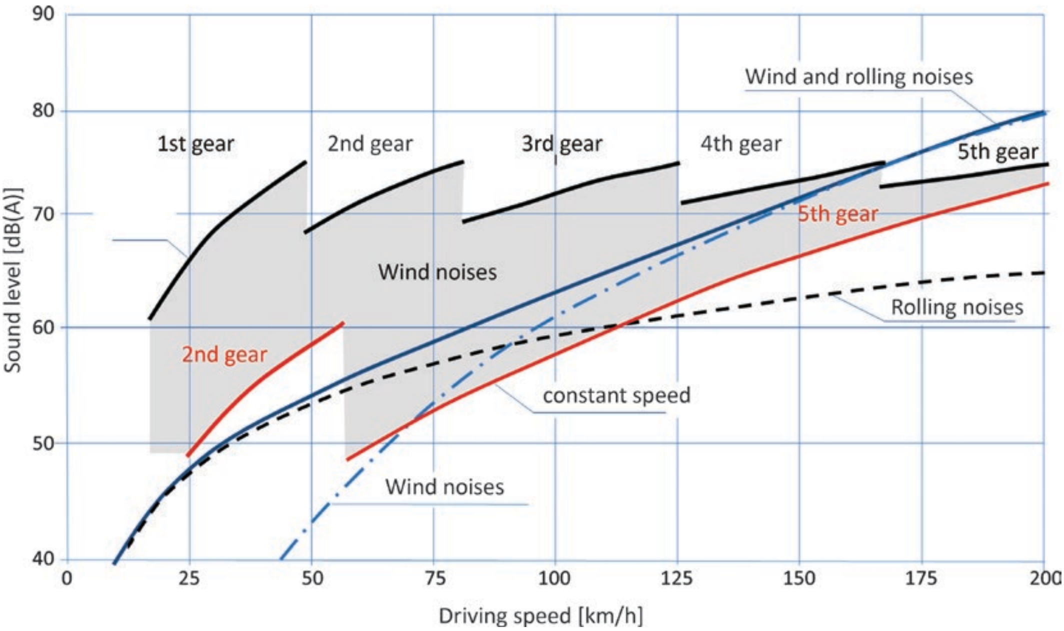


Fig. 8.9 Noise level in the vehicle interior as a function of driving speed and driving conditions. (Schematic, according to Zeller 2011)

orders.[2] The frequency range up to 400 Hz mainly includes structure-borne noise, which is excited by the gas and mass forces and introduced via the engine mount. At higher engine speeds, the mechanical engine noise becomes dominant in the area above 400 Hz, which is introduced as airborne noise via the front wall. Only at speeds above 80–100 km/h the rolling noise and later also the engine noise are increasingly "masked" by the wind noise. The noise generated by the motor depends considerably on its load condition. When the tyre rolls along the road, airborne and structure-borne noise is emitted due to the tread pattern of the tyre (rather singing, tonal noise) and due to unevenness of the road surface (rumbling noises). The wind noises are aerodynamically induced noises due to flow fluctuations on the outer skin of the vehicle. They cause a broadband noise that cannot be located directly. In order to produce as few discomforts as possible, this noise should contain as few tonal components as possible (e.g. high-frequency pipe tones). Fig. 8.9 shows a summary of the noise components described in the form of their contribution to the noise levels measured inside the vehicle.

8.2.1.2 Perception

The driver perceives not only the volume of the driving noise, but also its composition. This refers not only to the aspects of the audible individual noise sources, but also to the local assignment. All in all, the creation of the noise spectrum is an extremely complex matter. One reason for this is the narrow and complex structure of the vehicle interior. By reflecting the sound waves on the walls and on the various furnishings of this room, which can also be hard-acoustic and soft-acoustic, so-called standing waves are created if the corresponding distance happens to be a quarter of the wavelength of the respective sound component. Thus the vehicle interior is characterized by a confused mixture of such standing waves. One of the consequences of this is that very different spectra can be obtained depending on the position of the microphone of a sound analyzer in this room. Of course, this observation also applies to the

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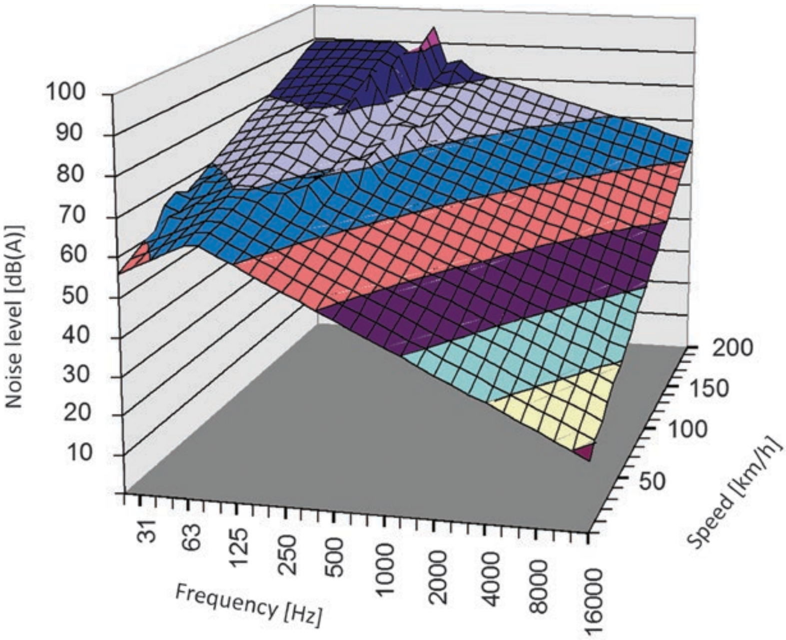
[2] Engine orders: Frequencies which are caused by the speed-dependent so-called ignition peaks and engine vibrations.

Fig. 8.10 Typical frequency composition of passenger car interior noise with 4-cylinder engine as a function of driving speed. (Bubb 1996)



human ear. If one now considers, however, that the hearing process consists in seeing the local temporal pattern of the travelling waves on the basilar membrane, as it were, whereby, among other things, similarities in noises are recognized (see ▶ Sect. 3.2.1.2), which are not easily explained by the frequency spectrum, it becomes understandable that for auditory perception – similar to other areas of perception – a constancy performance exists in the form that a sound can be recognized more or less independently of the properties of the sound chamber. At the same time, however, the type of sound chamber is also perceived. This means that a driver can easily recognize – even acoustically – whether he is in a larger or smaller vehicle. In particular, it is capable of detecting the engine noise of a convertible as such, regardless of whether the soft top is open or not. With some experience, he is still able to assign the individual noise components to different sources. For example, he detects the noise caused by the tyres independently of the aerodynamically induced noise due to flow fluctuations on the vehicle skin. These findings entitle us to interpret the frequency composition of a sound detected by a measuring microphone close to the ear. A prerequisite, however, is that the microphone is always positioned at the same point during repeated measurements. In detail, however, it is difficult to explain the performance of the human ear indicated above from the interpretation of this frequency spectrum alone.

Fig. 8.10 shows the frequency composition of a passenger car interior noise as a function of the driving speed (Bubb 1996).[3] The picture shows the typical dependency: with increasing speed the volume level also increases, i.e. the whole noise mountain range is raised (see also Fig. 8.9). Overall, the spectrum shows a triangular shape with a peak at about 70 Hz, whose position on the frequency axis is independent of speed and motor speed. This is probably due to the resonance characteristics of the vehicle cab. Below 70 Hz, the noise level is raised mainly as a function of the speed, mainly due to rumbling noises from the chassis. The range above the top of 70 Hz increases with engine speed (which can be separated if measurements are made with different gears). In the upper frequency range (>4000 Hz) hiss-

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[3] The above-mentioned experiments were carried out in the mid-eighties; today's interior noise levels are about 10 dB lower than these measurements. This means a halving of the perceived volume.

ing noises are added at higher speeds. Individual frequency peaks, whose position depends on the motor speed, are superimposed on this noise mountain. With increasing engine speed they migrate to higher frequencies. The lowest frequency n is calculated from the motor speed N [1/min] as follows.

$$n = N/60[\mathrm{Hz}] \tag{8.1}$$

In a four-cylinder engine, the 2n peak shows the highest volume level according to the ignition sequence. For a six-cylinder engine, this applies to the 3n peak. In relation to this, there are increasingly weaker peaks at integer multiples of the base peak. Depending on the design of the exhaust system, half-numbered orders can also be observed. In particular, the integer engine orders from the third order onwards, which are characteristic of six-cylinder in-line engines in particular, are perceived as "silky smooth", while the second order in four-cylinder engines is responsible for a rather "grumpy" sound impression. The 1.5-fold engine order for eight-cylinder engines is responsible for their characteristic "babble" (Zeller 2011). All in all, these peaks of higher order and especially their loudness behaviour as a function of speed and load make up the acoustic characteristics of a motor.

8.2.1.3 Interpretation of Driving Noise

In the study mentioned above (Bubb 1996), the assessment of the acceleration of vehicles with different engine characteristics was compared with their noise characteristics. It was found out specifically:

- A vehicle whose noise spectrum increases only slightly with speed, engine speed and torque is considered to be comfortable but not particularly powerful. A more pronounced peak level emphasis improves this assessment more than a general increase in the overall noise mountain.
- Vehicles which are characterized by a noise spectrum during the acceleration process which increases with speed, especially in the higher frequency range, cause a similar acceleration assessment as vehicles with increasing peak levels.

On the basis of this experience, a noise simulator was developed that could generate different noise compositions in a real vehicle that was specially insulated for the tests. The recommendations quoted below were therefore based on the objective performance of the vehicle, which was always the same and only the acoustic impression was modified. For a good feeling of acceleration the following resulted:

- With increasing motor speed, the frequency edge > 70 Hz should increase,
- with increasing load (= demanded torque of the motor) the frequency slope should decrease > 70 Hz, that means the peaks should be audible more clearly,
- With increasing speed and load, the overall volume level should increase only slightly,
- the frequency edge <70 Hz should increase only slightly with speed and rpm.

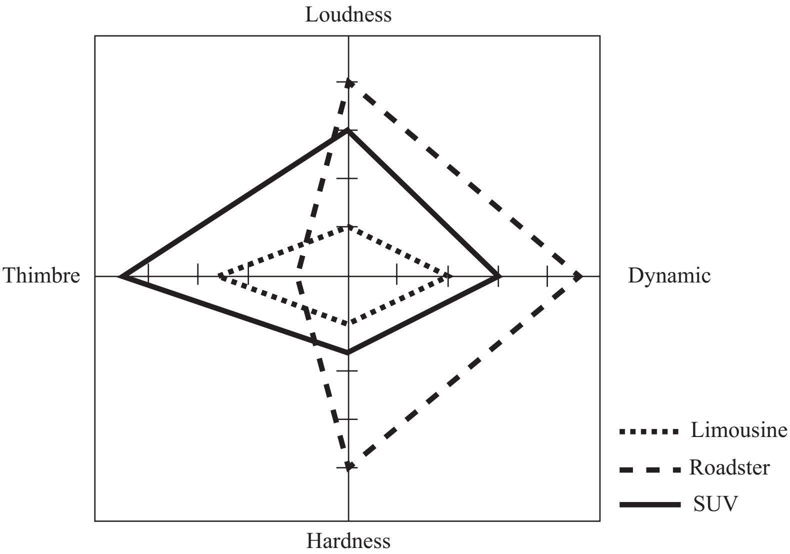
A negative effect was observed when individual peaks stand out clearly from the noise spectrum. This is described as uncomfortable, but can give a sporty impression. It turned out to be particularly favourable if the peaks only protrude from the noise mountain during the acceleration process. A noise level that was too low (< 65 dB (A)) proved to be unfavourable, indicating the feedback character of the noise for the driver..

8.2.1.4 Sound Design

The importance of noise for the subjective enjoyment of a vehicle has recently gained enormous importance. Sound design represents the creative creation of sounds in order to convey a specific hearing impression to the customer. On the basis of factor-analytical methods applied to semantic profiles with which test persons assessed the acoustic characteristics of engine noise, four largely independent descriptive factors were found. It's these:

- Loudness (e. g.: "loud – quiet", "booming – muffled"),
- Dynamics (e. g.: "sporty – unsporty", "weak – powerful"),
- Hardness (e. g.: "rough – smooth", "uniform – pulsed"),
- Timbre (e. g.: "low – high", "blunt – sharp").

Fig. 8.11 Noise character profile for different vehicle types. (From Zeller 2011)



Zeller (2011) explains that these orthogonal perception dimensions obtained by means of statistical analyses are a further step towards psychoacoustic modelling, whereby further research is necessary in order to identify those parameters on the physical or psychoacoustic level which form the basis of the respective hearing phenomenon. On the basis of these perception dimensions, target profiles can at least be defined for different vehicle types, represented in the form of the spider diagram technique (see Fig. 8.11).

The acoustic comfort impression in the vehicle interior is mainly determined by the noise at constant speed and thus by the wind roll noise (see also Fig. 8.9). However, the vehicle dynamic impression during longitudinal acceleration is significantly influenced by the prominent engine noise. One measure of this is the level jump from the noise level at constant speed to that during acceleration under full load. The level of wind roll noise and engine noise must therefore be adjusted so that only the former can be heard at constant speed and, at the same time, the level jump of the engine noise can sufficiently emerge when accelerating. The maximum acceptable overall level must not be exceeded (Zeller 2011).

By means of active noise control (ANC), it is possible to at least partially compensate the interfering low frequencies by overlaying them with a corresponding counter spectrum by measuring the sound spectrum near the ear and applying various techniques (see Zeller 2011, page 209 ff.).[4] This method could be used, for example, to record the sound effects via the vehicle loudspeakers which have a positive influence on the perceived dynamics as described in ► Sect. 8.2.1.2. In this way, a comfortably quiet vehicle could be achieved at a constant speed, which is able to generate the emotionalising sound especially during acceleration processes. It would also be conceivable to meet different driver wishes with selectable sound programs. In particular, it is possible in this way, as is already happening in part today, to enhance the rather sober noise characteristics of a four-cylinder engine, which is preferable for consumption reasons, accordingly.

The future use of electric motors as a general drive source in vehicles places completely new demands on interior acoustics. As Fig. 8.12 shows, the engine noise of an electric vehicle is completely masked by wind and rolling noises from a speed of around 40 km/h and above. Many people who have had their first experience with electric vehicles have reported

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[4] In principle, this method only works for limited areas within the vehicle cabin. For reasons of energy conservation, the amplitude of the corresponding frequencies must be doubled at other points by the additional introduction of the compensation sound.

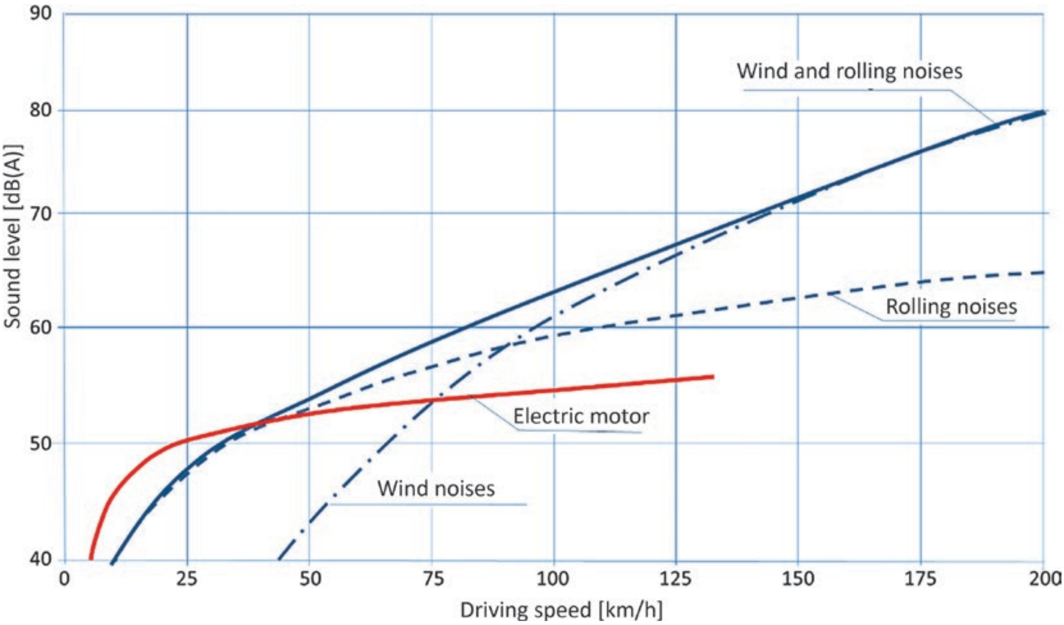

Fig. 8.12 Noise level in the vehicle interior as a function of driving speed and driving conditions with an electric drive. (According to Vogl 2010)

that they respond spontaneously to changes in the accelerator pedal position, but at the same time also complain about the "tram-like" driving noise. The even increase of volume level and frequency range with speed is at least compared to the usual sound of a vehicle with internal combustion engine needs getting used to. Obviously, the division of the entire speed spectrum into several upturns of the engine has a positive effect on the subjective feeling that "something is moving" (compare Fig. 8.9 with Fig. 8.12).[5] However, it is also questionable whether it can make sense to artificially introduce the noise of a combustion engine into the inherently quiet electric vehicle. All this shows that there is still a considerable need for research into the subjective experience of driving noise in electric vehicles.

With regard to the additional problems that arise in hybrid vehicles when the combustion engine is switched on or off during driving, reference is made to the treatise in Zeller (2011, p. 214).

8.2.2 Small Noises

With the reduction of noise levels in modern motor vehicles, the problem of annoying rattling, creaking or scraping noises has become more and more important, as these now stand out from the overall noise level and have thus become more and more dominant. In addition: if a disturbing noise is once consciously perceived, it remains in the foreground of attention and thus has an increasingly annoying effect.[6] Annoyance is a largely subjective phenomenon, which can vary greatly depending on the frequency of occurrence, intensity, localization, personal associations and noise character. In this context, it is also necessary to distinguish between disturbing noises which have nothing to do with the driving process or other functions of the vehicle and noises which are connected with certain functions and, if necessary, also give feedback on the use of the corresponding function as confirmation noise. Table 8.1 gives an exem-

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[5] The constant engine speed during the acceleration process in the initial designs of CVT transmissions was also judged negatively by most drivers.

[6] A well-known example of this is the ticking of the clock, which disturbs sleep once attention has been drawn to it.

Table 8.1 Classification mechatronics of operating noises (according to Zeller 2011). Grey background: most likely perceived as annoying

	Noise	Confirmation sound
Short operating time	Steering booster Level control Secondary air pump Braking noises (rubbing, squeaking and ä.)	Window lifter/sliding roof Seat adjustment Mirror adjustment Defrosting plant
Long operating time	Motor fan Fuel pump Roll stabilization	Air-conditioning fan Windscreen wiper Seat fan

plary compilation. All noises that appear to the driver as if by chance and not directly influenced by him are perceived as annoying disturbing noises. This applies all the more, the longer the corresponding noises are perceptible. For many self-initiated actions, however, the corresponding sounds can be understood as feedback for the action performed. However, this is only valid if the operating time is correspondingly short (e.g. only extends to the corresponding duration of the operating element operation). If the operating time is long, the perception of the corresponding noise quickly turns into annoyance.

In contrast to these noises which can be assigned to a function, contact point noises in particular, which are caused by relative movements of components to each other, are perceived as extremely unpleasant. Technically, these noises can be divided into impact noises (rattling, buzzing), stick-slip noises (creaking, cracking, squeaking) and other noises (e.g.: loosening of adhesive joints, smacking). They are stimulated by vibrations in the drive train, unevenness of the road surface and by specific acoustic frequencies in the Hi-Fi system. Regarding the evaluation of these annoying noises, the simple requirement is: “Disturbing noises must not be evaluated, but turned off!”. (Moosmayr 2011). However, it is necessary to prioritise the measures according to probability of occurrence and annoyance within the framework of a cost-benefit analysis. However, hearing impressions from different customer groups are only assessed to a limited extent in a uniform manner (Moosmayr 2008). While some test persons classify a certain noise as “very annoying“, other test persons do not perceive the same noise at all. When made aware of this, they also classify it as “very annoying“(see also footnote 7). In addition, the assessment as background noise depends very much on the situation-related expectations. From the corresponding investigations by Moosmayr (2008) it can be summarised that the acceptance of background noise is significantly lower with low vehicle excitation (e.g. city driving at constant speed on asphalt) than with strong excitation (e.g. cobblestones or potholes). This again points to the fact that masking effects of driving noise can conceal useful and background noise (Grimm et al. 2007). The Zwicker method (Zwicker and Fastl 1990) for determining loudness makes it possible to objectify this effect. Moosmayr (2008) presents a new method for finding sources of background noise which, in combination with a hydropulse/shaker system, evaluates the background noises that occur, combines identical noises into clusters and automatically creates a uniform problem documentation.

The acoustic experience associated with opening and closing the vehicle door is a special feature with regard to noise evaluation. Consciously or unconsciously, it already conveys an impression of solidity, which is often used to draw conclusions about the quality of the entire vehicle. According to Liebing (2009), test persons prefer significantly higher sound levels for closing noises (preferred 58 to 62 dB (A)) than for opening noises (preferred 50 to 54 dB (A)). Levels above or below this level are increasingly rejected, regardless of the vehicle type. A rather dark sound image (emphasis on the bass range < 100 Hz) without audible clicks (noise shortly after the main sound with frequencies >3 kHz) with at most slight pops (similar to champagne corks) is desirable. Any kind of post-oscillation is rejected (appears to be "tinny") and reduces the quality impression of the door slamming noise (see Zeller 2011 for details).

8.2.3 Useful Signals

In contrast to the small noises described above, which should "hide" behind the noise mountain of the driving noise if possible, useful signals must protrude clearly from this noise mountain so that they can be perceived safely. Useful signals in this sense are all acoustic feedback signals (see also ▶ Sect. 6.2.1.1), signals from the infotainment systems installed on the vehicle (hi-fi system, voice instructions of the navigation system, telephone system, reading of e-mails and internet messages etc.), understanding of mobile infotainment systems (smartphones) and last but not least the possibility of talking to passengers of the vehicle.

In order to objectify the protrusion of useful signals against the noise mountain of driving noise, the methods developed for measuring speech intelligibility can be used. All common methods are based on the assumption that the entire auditory frequency range is divided into different frequency bands. Usually, the third-octave bands are used for this purpose, since they largely correspond to the 24 frequency groups found by Zwicker (bark), in which the loudness impression in the inner ear is formed (see Zwickler and Fastl 1990). Each of these frequency bands k carries a weighting factor g_k for comprehensibility or audibility. g_k is maximum if only the undisturbed useful signal is present in the respective frequency band and zero if it is completely covered by the driving noise. In each frequency band, the signal-to-noise ratio $(S/N)_k$ is calculated from the measured signal level S[dB(A)] and the noise level N[dB(A)]. Values > 15 dB or < 15 dB are limited to these numbers, as signal-to-noise ratios from 15 dB are already full speech intelligibility and – 15 dB represent absolute incomprehensibility. For simple signal tones, which are only presented in a narrow frequency band, the same limit values naturally apply. It is generally assumed that the signal tone must be at least +6 dB higher than the weighted volume level in the corresponding frequency band. The articulation index AI or the speech transmission index STI[7] is determined as a weighted sum over all frequency bands:

$$\text{AI or STI} = \sum_k g_k (S - N)k \tag{8.2}$$

The weighting factors g_k represent a frequency weighting dependent on the language material. For example, with whole sentences and multi-syllable words, the low frequencies are relatively more important than with monosyllable speech material, which is characterized by less redundancy. The resulting index is a quantity normalized to the range from 0 to +1, which represents a measure of intelligibility and is strictly monotonously related to speech intelligibility for the speech material used.

From the dependence of speech intelligibility as well as the recognition of signal tones it is already clear that the volume level of the useful signal must be raised or lowered as a function of the volume level of the driving noise, taking into account the above premises. In principle, this also applies to hi-fi systems installed in the vehicle.

Especially in premium automobiles with high-quality hi-fi systems, the reproduction of audio signals represents a particularly outstanding point of complaint in customer surveys. As Zeller explains, this is usually not caused by disturbances in the electrical part of the audio system, but in many cases by mechanical interfering noises, which are reso-

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[7] AI and STI differ only in the determination of the S/N ratio (for details see Zeller, 2011, chapter 8.4)

natorily excited by the powerful audio system. The acoustic coupling of the loudspeakers to the body structure is the main cause of errors.[8] Otherwise, it is up to specialists to design the right choice of loudspeakers and their localisation in the vehicle interior. The individual taste with regard to the resulting spatial sound plays an outstanding role.

8.3 Vibrations

Both in the technical area and in the area of ergonomics, movement phenomena are treated under the generic term "vibrations". Just like the acoustic effects, the vehicle vibrations also have a dual character: on the one hand, they contribute considerably to discomfort when the driver or passengers feel "shaken" by the vehicle. On the other hand, the driver needs a sufficiently precise perception of the vehicle movement to ensure safe vehicle guidance (see ◘ Fig. 8.1). Acoustic and vibration discomfort are thus closely related disciplines in several respects, since in both cases the adequate stimuli are induced by structure-borne sound, but in different frequency ranges. While the vibration sensitivity of humans ranges from 0 Hz to a maximum of approx. 500 Hz (vibration sensitivity, see ► Sect. 3.2.1.3), an acoustic sensation only begins clearly via 20 Hz and reaches at least 10 kHz for older persons and 20 kHz for young persons.

8.3.1 Vibration Phenomena

The passengers in a vehicle are exposed to vehicle movements or vibrations in different ways. Due to road unevenness, the entire vehicle is set in motion, which is essentially represented as a lifting movement (translatory in z-direction), a pitching movement (rotatory about the y-axis) and a rolling movement (rotatory about the x-axis). These movements are damped by the suspension system, but may also be amplified in the natural frequency range. In addition, there are vibrations transmitted from the engine and power transmission to the vehicle body, as well as aerodynamic effects that can also cause the entire body to vibrate. These vibrations are mainly transmitted to the driver via the contact surfaces of the floor, steering wheel, seat and backrest. Other contact surfaces, such as armrests, are also transmission elements for vibrations. With the exception of the steering wheel, the last mentioned transmission paths also apply to the remaining passengers of the vehicle. ◘ Figure 8.13 shows the mentioned vibration sources and transmission paths.

Analogous to the acoustic categorization tone, sound and noise as well as impulse sound ("bang"), one can also distinguish between purely sinusoidal excitations, periodic excitations (superposition of several sinusoidal oscillations), stochastic and impulse-like excitations ("shock") in the area of oscillations. Sinusoidal and periodic excitations in the low frequency range should always be avoided in order to prevent resonance effects with human organs (see below). Stochastic excitations and pulse-like excitations differ fundamentally from their sensory quality.

As the frequency ranges of acoustic and vibration sensation overlap, there are certain phenomena that are both heard and felt. ◘ Fig. 8.14 gives an overview of various characteristic frequency ranges in the vehicle, which Knauer (2010) has compiled by evaluating different literature references.

8.3.2 Perception of Vibrations

The human organism perceives vibrations via various sensory organ systems. In particular, the vestibular organ, various nerve endings in the skin surface and the entire proprioception of the body position are involved (Griffin 1990; see also ► Sect. 3.2.1.3). Each of these systems has its maximum sensitivity at specific frequencies. In addition, the vibration judgment of test persons in a vehicle is significantly influenced by perception from other sensory organs, in particular from the optical

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[8] Mounting loudspeakers on flexible cladding parts can cause them to vibrate mechanically, thereby also reducing the acoustic efficiency of the loudspeaker.

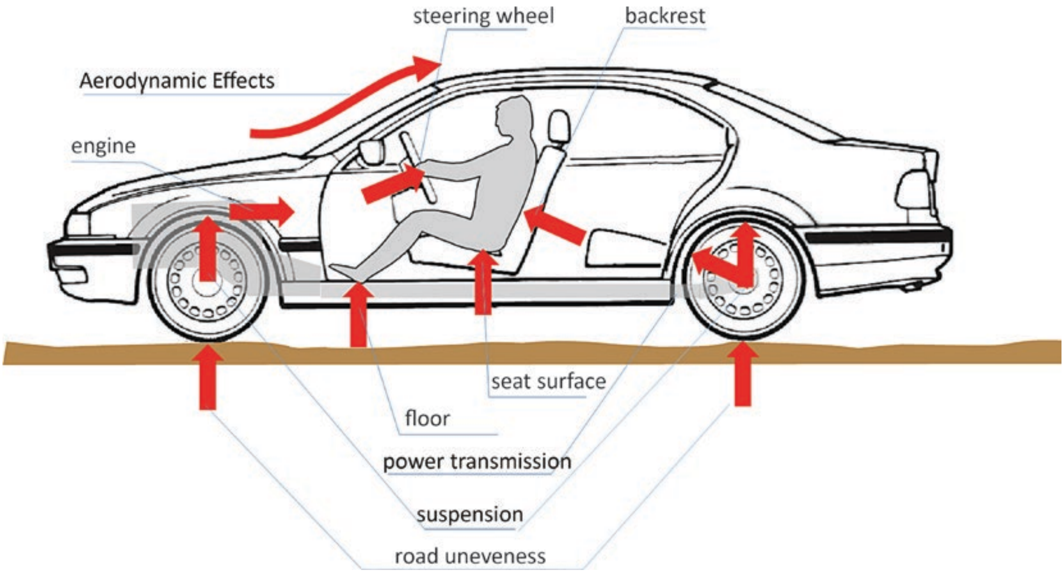


Fig. 8.13 Vibration sources and transmission paths on a vehicle moving on an uneven road. (According to Mansfield 2013)

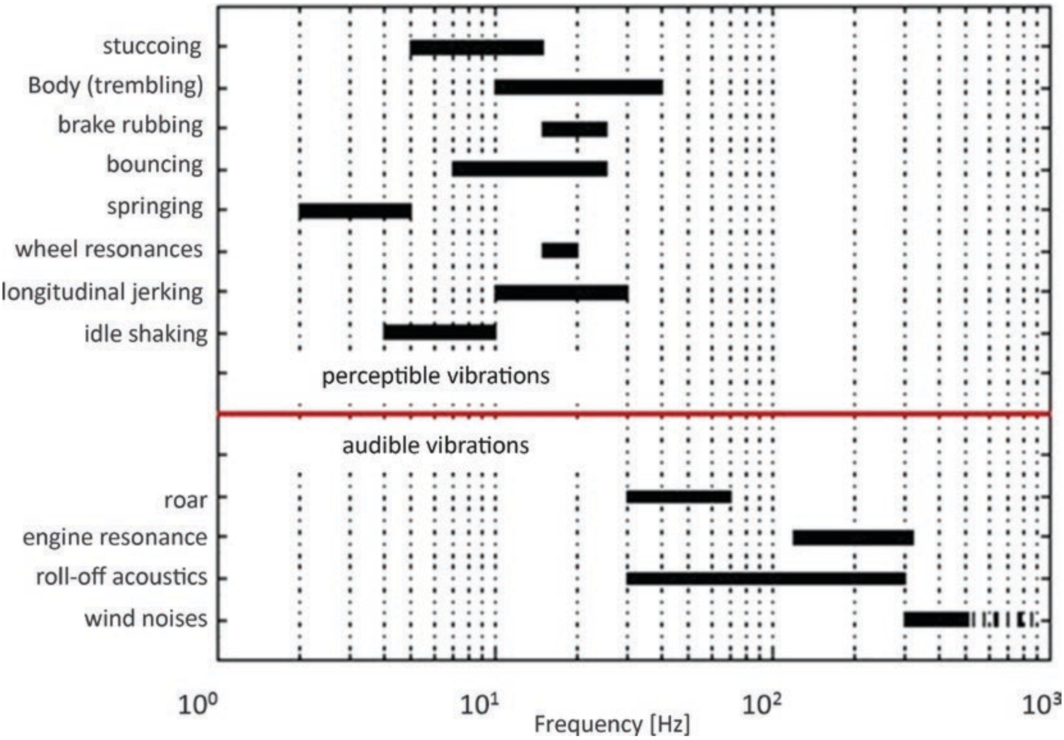


Fig. 8.14 Characteristic frequency ranges in the vehicle. (Knauer 2010)

and acoustic channel. It is therefore difficult to define a single determinant quantity that describes the influence of vibrations in the vehicle (Mansfield et al. 2007). The human response to vibrations has been extensively tested in the laboratory. According to this, the perception of vibrations is particularly sensitive to frequencies in which the human body

8

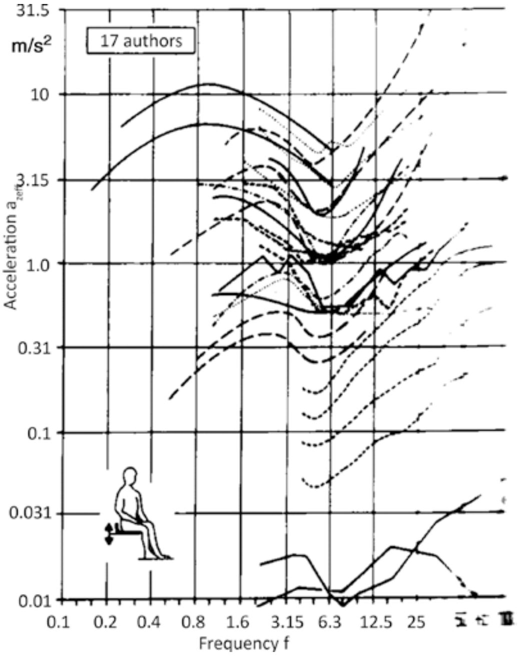
◘ **Fig. 8.15** Human coordinate system

shows biomechanical resonances (Mansfield 2013). To objectify this, one uses the human-related coordinate system shown in ◘ Fig. 8.15. The effective value a_{eff} of the acceleration, which is defined as the square average of the measured acceleration a(t) over the exposure time T, is used as the key figure for the influence of vibration:

$$a_{eff} = \sqrt{\frac{1}{T}\int_0^T a(t)^2 \, dt} \qquad (8.3)$$

Dupuis and Zerlett (1984, 1986) compiled curves of equal strength of perception for the effects of vibrations on the seated person in the z-direction (◘ Fig. 8.16).

From these results it can be seen that, independent of the vibration exposure a_{eff}, a sensitivity maximum lies between 4 Hz and 8 Hz, but is also sensitive to very low frequencies (< 0.4 Hz). Knauer (2010) compiles resonance ranges of the human organism from studies by Dupuis (1969), Dupuis et al. (1974), Hennecke (1994), Recknagel (1995) and Scheibe (1979) (◘ Fig. 8.17). Dupuis (1993) shows in another compilation of literature that the transmission in the z-direction between fuselage and head has a resonance at about 4 Hz and that the eye has a resonance frequency of about 20 Hz.



◘ **Fig. 8.16** Frequency-dependent curves of equally strong vibration perception – research results of 17 authors. (Dupuis 1993)

From all this it can first be concluded that extremely low frequencies should be avoided (see also ► Sect. 8.3.5), that the frequency range around 4 Hz is particularly critical, that frequencies around 20 Hz should also be technically absorbed in order to avoid visual disturbances and that, as explained in more detail in ► Sect. 3.2.1.3, frequencies around 200 Hz should be dammed away as well as possible so that no unpleasant feeling of vibration arises. Within vehicle however, all these areas are subject to vibrations (see ◘ Fig. 8.14).

8.3.3 Vibration Evaluation

In VDI standard 2057–1 and ISO 2631-1 the currently valid evaluation procedures for mechanical vibrations are published. In the

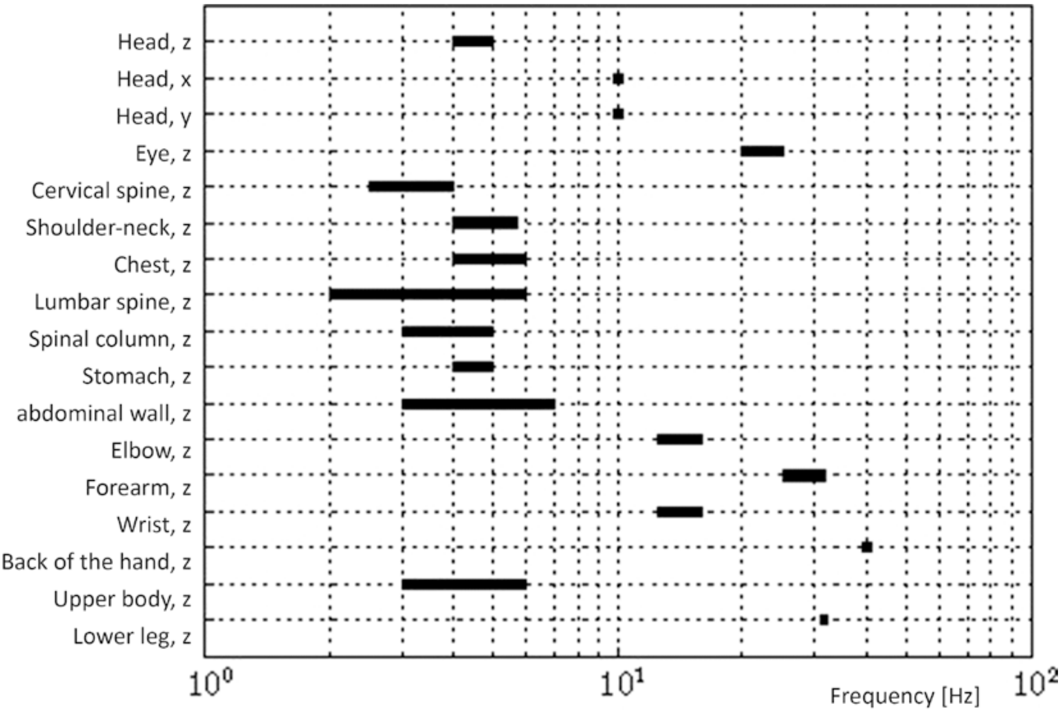


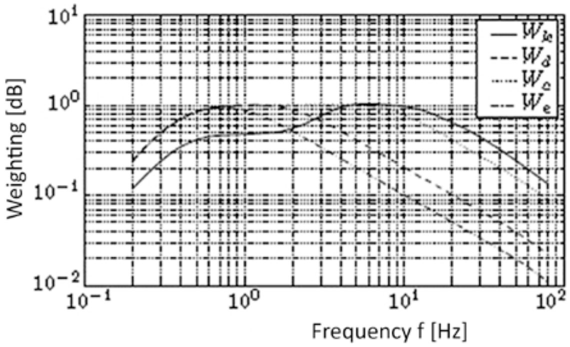
Fig. 8.17 Resonance ranges of various organs and body parts of the human organism compiled by Knauer (2010) from various literature sources

usual field of application in vehicle technology, the acceleration $a_w(t)$ transferred to the human body is measured by means of flat accelerometers mounted between the buttocks and the seat of the test person or at other points to be examined. Depending on the spatial direction of the vibration effect, the measured value is weighted frequency-dependently, whereby dependencies of the sensation, as shown in ◘ Fig. 8.16, are taken into account. From the values obtained in this way, the effective accelerations $\bar{a}_{wx}$, $\bar{a}_{wy}$ and $\bar{a}_{wz}$ are now calculated. The next step is the so-called multi-axis single-point excitation $\bar{a}_{wv}$ calculated. It is obtained by quadratic averaging of the weighted effective values in the individual spatial directions (vectorial addition). A further factor takes into account whether the excitation is via the seat or the backrest. After the excitations on the human body occur via several contact points, the last step the multiaxial multipoint excitation $\bar{a}_{wvges}$ is calculated. The procedure for this calculation and the individual formulas for it are compiled in ◘ Table. 8.2. In addition to the calculation formula for multi-axis multi-point excitation, there is also a tabular assignment of the values obtained to verbally defined discomfort values. A value $\bar{a}_{eff} > 0{,}5\,m/s^2$ can be used as an orientation which represents the trigger limit for damage to health caused by all-day exposure. However, this value is practically never reached in normal passenger car driving.

As Knauer (2010) criticizes, the evaluation of stochastic suggestions according to VDI 2057–1 cannot under all circumstances be reconciled with the judgements of test persons. In addition, the assessment of vibration phenomena containing shocks is not possible by such a purely spectral method. Neither the number of shocks nor their distribution in the time signal are taken into account. A large number of correlative approaches have been developed to improve the characteristic values obtained by the VDI standard using various frequency-dependent weighting factors. Among these, the Hennecke procedure (1994), which provides for a correction via a so-called instationarity factor, deserves special mention. This results in a significantly improved correlation

Table 8.2 Calculations of the evaluated vibration strength according to VDI 2057 (from Knauer 2010)

Single-axis single-point excitation



$\bar{a}_w = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt}$	Measuring location	Direction	Factor
	Seat surface	z	W_k
		x,y	W_d
	Backrest	x	W_c
	Foot platform	x,y,z	W_k
	Rotation	r_x, r_y, r_z	W_e

Multi-axis single-point excitation

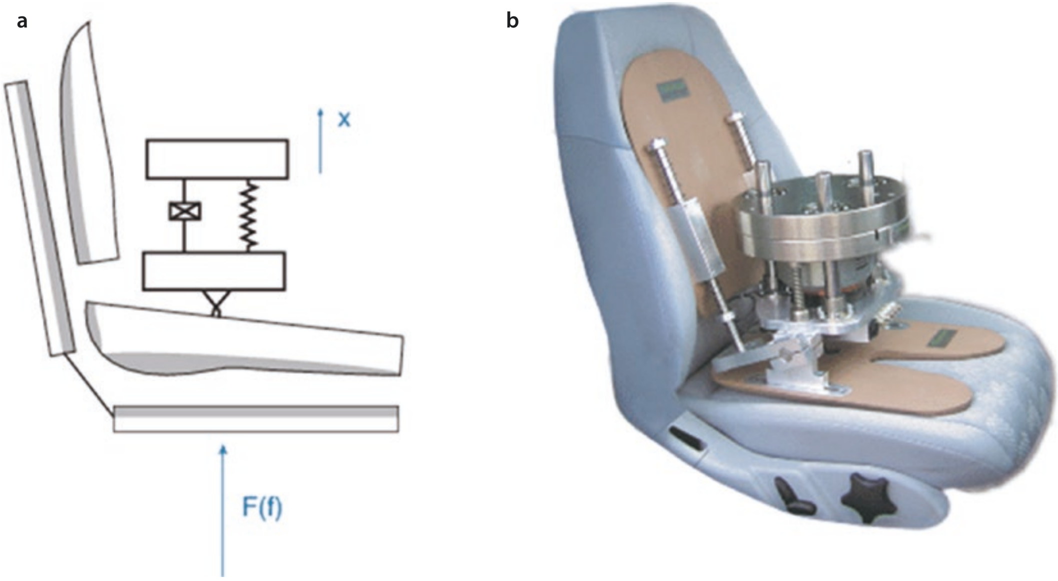
$\bar{a}_{wv} = \sqrt{k_x^2\bar{a}_{wx}^2 + k_y^2\bar{a}_{wy}^2 + k_z^2\bar{a}_{wz}^2}$	Measuring location	Direction	Factor
	Seat surface	x,y,z	1.00
	Backrest	x	0.80
		y	1.50
		z	1.40

Multi-axis multipoint excitation

$\bar{a}_{wv_{ges}} = \sqrt{\bar{a}_{wv_1}^2 + \bar{a}_{wv_2}^2 + \ldots + \bar{a}_{wv_n}^2}$	$\bar{a}_{wv_{ges}} [m/s^2]$	discomfort level
	< 0.315	not unconfortable
	0.315 to 0.63	somewhat unconfortable
	0.5 to 1	distinctly unconfortable
	0.8 to 1.6	unconfortable
	1.25 to 2.5	very uncomfortable
	>2	extremely uncomfortable

to subjective assessments. The literature also describes numerous approaches that determine the comfort judgement with the aid of artificial neural networks. An examination of the known applications of neural networks on the objectivization of the evaluation of vibrations shows the highly experimental procedure in the selection of network parameters. Although very good results can be achieved, the transferability to new unknown data sets is difficult to verify (a compilation of all this work can be found in Knauer 2010).

In connection with vibration influences, the seat is traditionally considered to be of great importance, since it is assumed that good seat suspension combined with appropriate damping properties can absorb the transmission of hard impacts to humans. Since experiments with real persons encounter a variety of difficulties and, particularly because of the individual deviations mentioned above, it is difficult to objectify the behaviour of the seats, attempts are made to resort to technical solutions. In many cases,



◘ **Fig. 8.18** Principle sketch **a** and **b** structure of the Memosik test specimen. (According to Wölfel)

so-called "water dummies" (plastic vessels roughly imitating the shape of a seated person, consisting of thigh and back, which are filled with water so that the seat load corresponds approximately to that of a test person) are used for this purpose and the transmission behavior between the vibration initiation measured on the seat rail and its contact surface to the seat is measured. Since this simple procedure cannot reproduce the complex oscillation behaviour of humans at all, attempts have been made to use appropriate mechanical reproductions of humans for this purpose. The most common and at the same time very practical method is the Memosik test specimen developed by Wölfel (◘ Fig. 8.18). An active control system makes it possible to adapt the so-called mechanical impedance $I = F(\nu)/\dot{x}(\nu)$ to that of humans. This provides a means of objectifying the vibrational behaviour of the seat.

However, the investigations by Bitter et al. (2005) show a high correlation between the vibration influences, as measured on the seat rail, on the vehicle floor and on the steering wheel, and those on the seat surface. In addition, this study shows that there is obviously a kind of constancy performance with regard to static seat pressure and vibration behaviour, i.e. at least in the range relevant for passenger cars, occupants are clearly able to distinguish between the static seat pressure and the dynamic properties resulting from the movement of the vehicle. This observation contradicts the model postulated by Ebe and Griffin (2000), according to which a dynamic factor is based on the static factor, which causes an increase in the overall discomfort with increasing oscillation amplitude (and increasing time).

In all the methods described so far, it is necessary to resort to test persons whose influence on the result is not insignificant due to their individual biomechanical properties. In addition, all these procedures do not allow a prospective evaluation of the vibration influence, i.e. possible already in the planning phase. The greatest progress can therefore be expected in the application of biomechanical human models. Knauer (2010) gives an overview of the possible models (◘ Table 8.3). Especially the model CASIMIR is able to predict the transfer function between seat and human being well, but an evaluation regarding the subjective discomfort is still pending.

However, some studies by Knauer (2010) can provide a basis for the prospective discomfort evaluation of vibrations. The experience with the unbalance of a wheel, which can be clearly perceived on a flat road, but whose perception "disappears in the noise"on

Table 8.3 Overview of biomechanical human models for the calculation of seat contact and vibration influences (from Knauer 2010)

	Circumference	Main points
Moes (2000)	Detailed FE model of a thigh and half of the pelvis	Model for the investigation of seating comfort Imaging of soft tissues and bone structure The measured pressure distribution could not be reproduced with different material laws Model not validated
Brosh and Arcan (2000)	2D-FE model of the seated person	Soft tissue behaviour determined by indentation tests on test persons and transferred to model Good comparison between calculation results and test data Model for investigating tissue properties, less suitable for sitting comfort
Schmale (2002)	MKS model of the human being and FE model of the seat	Man modeled as rigid body on soft seat Buttocks not deformable Pressure distribution on seats cannot therefore be determined
Verver (2004)	MKS total body model and FE model of the buttocks	Bone and soft tissues as FE model based on the analysis of a postmortem male body On real seat and on wooden plate validated model for the evaluation of seat comfort dyn. Seating comfort on the basis of the MKS model in the range 0–15 Hz investigated FE model validated under static conditions
Siefert (2013)	Casimir, FE-model of the seated person	Reproduction of the complete skeletal structure Reproduction of the soft tissues of the thighs, buttocks and the back Reproduction of the abdomen and back muscles Variable in percentile and posture Seat pressure distribution calculable Seat transfer functions determinable

a bad road, shows, for example, that there is also a masking effect in the area of vibration perception. At least with regard to harmonic oscillations, it can also be determined in the experiment that the level difference that can be perceived at the moment hardly depends on the frequency, but the frequency difference that can be perceived at the moment increases with increasing reference frequency. Also in the field of vibrations, the effect of attention is known from the evaluation of acoustic signals. It is repeatedly observed that only when the evaluator consciously concentrates on the corresponding stimulus is he able to detect an overthreshold stimulus. The perceptibility threshold therefore appears to be a useful criterion for discomfort relevance. This also applies to the assessment of transient events, such as those that occur when driving over a pothole in the form of an impulse. In trials, Knauer did not use the steering wheel to transmit the impulses, since the impulses perceived there would rather be referred to as steering shock. It is quite clear that an acceleration signal in the seat surface at least by a factor of 3.50 and in the seat back at least by a factor of 3.24 must be greater than the effective value of the background noise in order to be perceived as an impulse. The result seems quite plausible if you consider that with white noise, to which no outstanding individual impulses would be assigned, already 2% of the signals are 2.5 times higher than its RMS value. The decay process of an

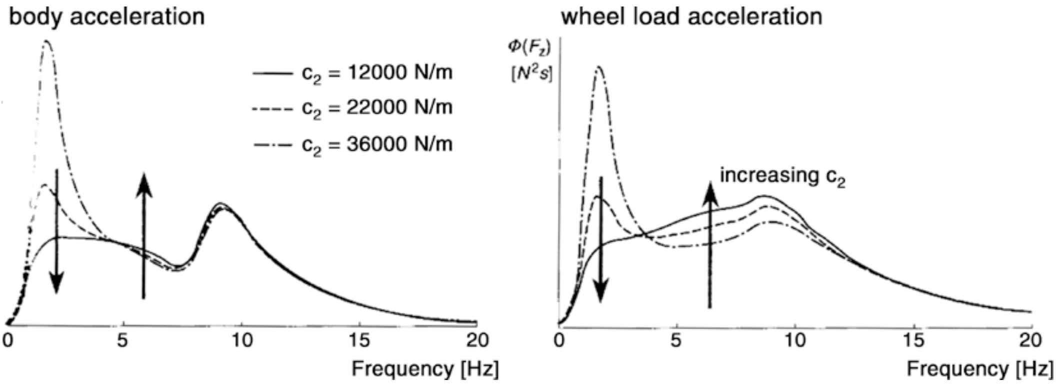
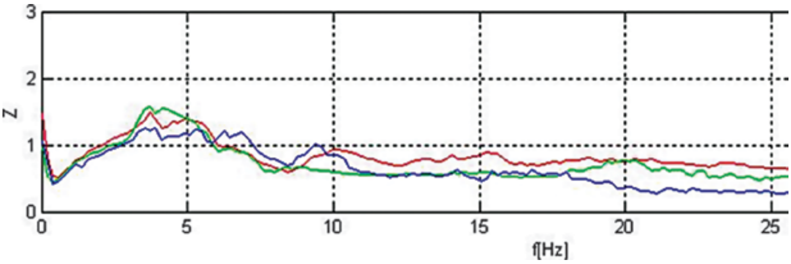


Fig. 8.19 Influence of spring stiffness c_2 on the power spectra of body acceleration and wheel load fluctuations (from Bootz et al. 2011)

Fig. 8.20 Transmission behaviour seat rail – seat surface for three different vehicle seats. (Bitter et al. 2005)



impulse also has an effect on the sense of comfort. This rebound process should be as short as possible.

8.3.4 Comfort and Driving Safety

The aim of a comfort-oriented chassis design is to keep the accelerations transmitted to humans as low as possible and at the same time to avoid natural vibrations as far as possible, i.e. the discomfort caused by acceleration forces should be minimized. Even a simple geometric consideration shows that large wheels and a long wheelbase can achieve a geometric average of the road unevenness transferred to the vehicle. Furthermore, elementary physical considerations indicate that a soft spring (low spring constant) in combination with a high mass (heavy vehicle) shifts the natural frequency of the system to desired low values (out of the range of human natural resonances, see ◘ Fig. 8.17). At the same time, correctly designed damping reduces overshoot when excited in the resonance range. In fact, however, the vehicle represents a complex vibration structure which, even in a simple description, must take into account the spring characteristics of the four tyres and the spring-damper connection of the four wheels to the vehicle body. Bootz et al. (2011) show on the basis of a simplified model that in the frequency range around approx. 1.5 Hz with increasingly softer suspension c_2 the build-up acceleration $\Phi(\hat{Z}_2)$, whereby a second resonance peak at 10 Hz is not influenced by this. The wheel load fluctuations also decrease in the 1.5 Hz range, but increase slightly in the range up to 10 Hz (◘ Fig. 8.19).

In all experiments reported by Bitter et al. (2005), an increase in resonance in the z-direction from seat rail to seat surface was observed at approx. 4 Hz (◘ Fig. 8.20). Since there are many natural resonances of the human organism in this frequency range, excitation by the vehicle body in this range must be avoided. In this respect, the reduction of the build-up acceleration with softening suspension shown in ◘ Fig. 8.19 is a measure to be aimed at.

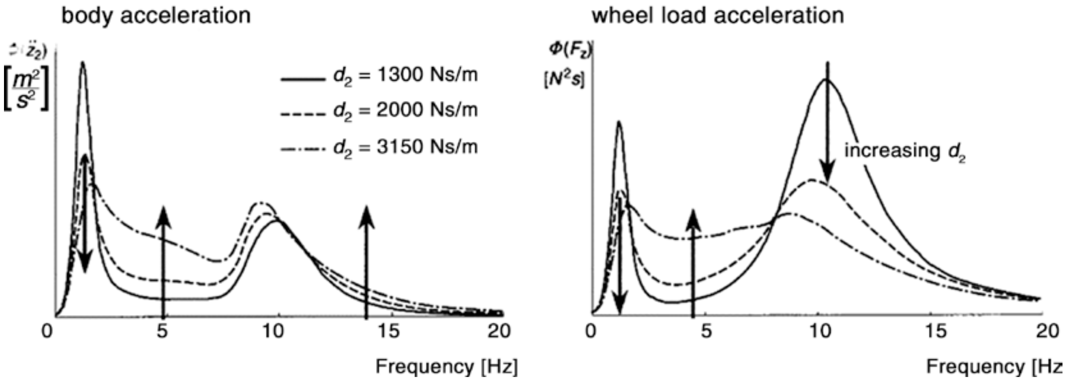


Fig. 8.21 Influence of dampers d_2 on the power spectra of body acceleration and wheel load fluctuations. (From Bootz et al. 2011)

However, the effects of pitch and roll oscillations must also be taken into account in this context. In addition, it plays a major role whether the vehicle is designed more comfortable for the driver or for passengers near the rear axle, so that finally a compromise must be found between the demand for low discomfort due to undesired body movement on the one hand and driving safety on the other, which is only achieved by good and even contact of the wheels with the road surface. For example, the optimum design for the chassis of sports vehicles can be based on small roll angles and lower load fluctuations at the expense of comfort, resulting in significantly harder springs, lower spring travel and correspondingly tighter vibration damping.

Fig. 8.21 shows on the left the power spectra of the vertical body acceleration of the vehicle for different damper characteristics when driving on a middle country road. It can be seen that in the frequency range of approx. 2 to 30 Hz the soft characteristic curve of the damper reduces the build-up acceleration. From 0.3 to approx. 1.5 Hz, however, the hard characteristic curve reduces the acceleration amplitudes and thus the vibration discomfort. With regard to driving stability, wheel load fluctuations in particular must be taken into account, which with increasing damping result in a reduction in the frequency range around 1.2 Hz and around 12 Hz, but at the same time in an increase in the range around 5 Hz (Fig. 8.21 right). In principle, these different requirements can be adjusted by means of adjustable damper systems. As part of the technical development, various adjustable damper systems were developed which are now almost universally used in vehicles of the higher performance classes (see further details in Bootz et al. 2011). An even better adaptation to different requirements is possible by the combination with active springs, by which – depending on the technical design – different loading conditions can be considered. Of all the possible designs for this, the air spring has proven to be particularly favourable because it can achieve an almost constant body natural frequency even under different loading conditions of the vehicle. Bootz et al. (2011) state that today, for cost reasons, most chassis of a conventional nature are still constructed from passive components, but that the next technical evolutionary step in the sector of controlled chassis up to the so-called “previewing” chassis, which contain a temporal and spatial forecast for lane guidance and road unevenness, has to be sought. The Magic Body Control recently introduced by Mercedes in the S-Class represents a first series development for the latter system. Up to a speed of 130 km/h, it is able to adjust the spring and damper rates to the road unevenness detected by a stereo camera, thus minimizing bodywork fluctuations without having to compromise driving safety. Since the system is based on optical detection by a camera, it automatically switches back to reactive active suspension in poor lighting conditions (night, rain, snow and fog).

The vibrations transmitted to the driver by the vehicle body not only affect discomfort, but possibly also driver performance. In their investigations, Baker and Mansfield (2010) found no significant differences between the control power without vibration and the effect of vibration similar to that of off-road driving. If, however, the subjective stress is examined using the NASA TL-X questionnaire, an increase in stress under the influence of vibrations is clearly evident. The same was observed for objective performance in speed maintenance. A particular problem is the handling of a touch screen under the influence of mechanical vibrations. As Moseley and Griffin (1986) state, visual perception is most affected when the display moves relative to the observer and least when the observer and display move in phase. In the vehicle, the target (touch screen) and driver are both in motion, but the relative motion depends on the respective frequency. At the resonance frequency of the driver's arm, for example, there may be significant relative movements between the driver and the controls. Especially with pointing tasks, there can be more than the double movement compared to that of the seat (Griffin 1990). An effective method to improve the driver's performance, to select a small target, is to allow the hand to contact an environmental object while operating. This is easily possible when operating controls on a traditional dashboard, but hardly feasible with a large touchscreen (an effect that, by the way, is barely noticeable when checking in a vehicle salesman's stand or showroom).

8.3.5 Kinetosis

Passengers in a vehicle often suffer from symptoms of the so-called motion sickness (kinetosis). The most common symptoms are: heat, dry mouth, headache, drowsiness, lethargy, unpleasant feelings in the stomach, seasickness and often – vomiting. The generally accepted theory for the occurrence of kinetosis is the "sensory conflict theory"or "sensory rearrangement theory". This theory is based on the idea of the combined processing from different sensory organs described in ► Sect. 3.1.3 (see also ◘ Fig. 3.11). The organism then assembles optical information (foveal and peripheral) and information from kinesthetic, haptic and proprioceptive perception into a single, inherently consistent motion perception. For the existence of everyday demands, perception of movement is also always connected with the expectation: "what information will I receive when I initiate a certain action? (see ► Sect. 3.2.2.4 and specifically ◘ Fig. 3.47). Mansfield (2005) has illustrated this theory by the images shown in ◘ Fig. 8.22 using the example of the driver and a passenger in the same vehicle who does not take care of the driving process (e.g. by reading a book). While the information perceived optically, kinesthetically (vestibular) and haptically (somatically) by the driver is completely consistent with his expectation of what will happen when he turns the steering wheel (a), for the accompanying reading passenger there are inconsistencies in his optical perception between the movement perceived consistently via the vestibular channel and the force via the haptic channel, which are also not compensated by conscious processing (b). This example is typical for many observations of kinetosis (Probst et al. 1982). It is also common experience that the same people who tend to have kinetosis as co-drivers have no complaints of this kind when they themselves act as drivers.

Mansfield (2013) suspects that the cause of these observations is a side effect of the body's defence against dangerous toxins. Many potentially dangerous, even lethal substances affect the sensory organ system before they cause permanent damage. It is then a sensible reaction of the organism to eliminate the cause of this effect from the food tract as quickly as possible. Excessive alcohol consumption is a well-known example of this reaction of the organism. However, this reaction mechanism, which developed over a long period of evolution, loses its meaning in connection with modern means of transport.

In order to prevent kinetosis, it therefore makes sense to provide passengers with as good a view of the road as possible (see ► Sect. 7.2.5.1 for the conflict arising for rear-seat passengers as a result of passive safety regulations). In addition to the aforemen-

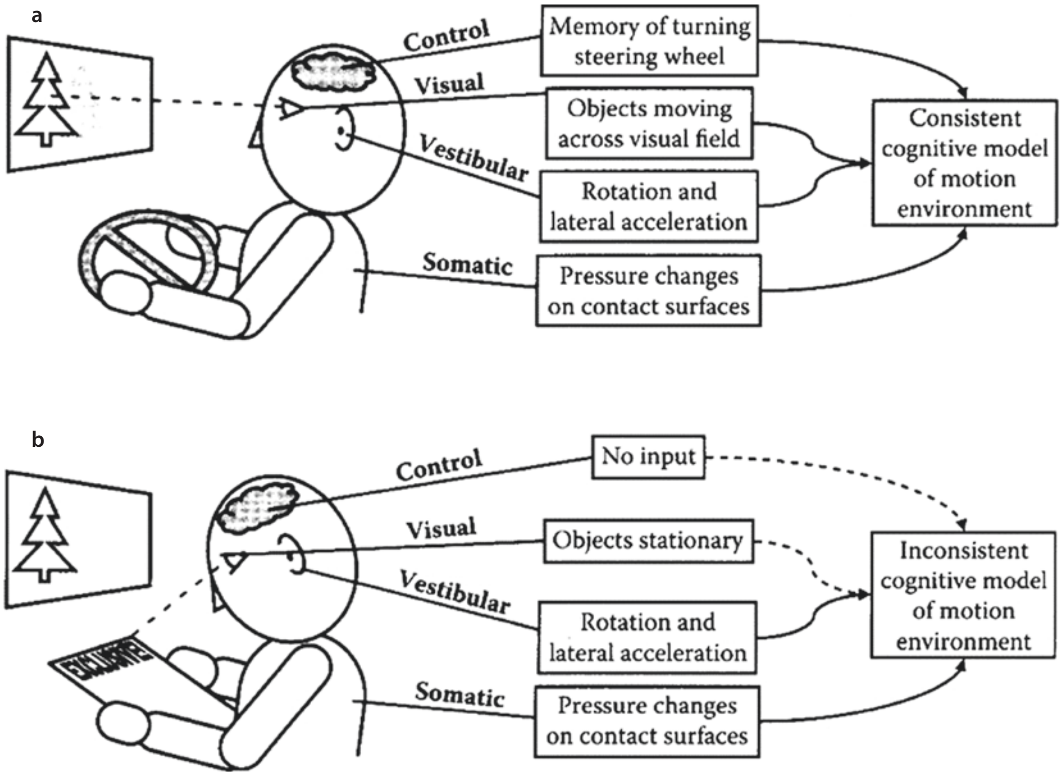


Fig. 8.22 Illustration of information paths for motion perception. (From Mansfield 2013 and 2005)

tioned perception conflict and possibly in connection with it, both laboratory and field studies have found that frequencies in the range of 0.2 Hz in particular cause kinetosis (Lawther and Griffin 1987). These are frequencies that are mainly caused by the formation of the road. So pitching, rolling and lifting movements within this frequency range should be avoided as far as possible. However, a particularly soft – apparently “comfortable” – suspension, which shifts the resonance frequency of the vehicle body to lower frequencies, could imply a rocking of the body movement in this region rather than a hard suspension. Many passengers who have a tendency to kinetosis report that they use soft-suspension vehicles[9] less than vehicles with hard suspension. Since one can assume that especially for these slow movements there is little experience with the coordination of vision and initiative, further scientific experiences have to be awaited, to what extent the previewing suspension (Macic-Body-Control by Mercedes) provides relief for sensitive persons or possibly causes the opposite.

8.4 Climate

For the whole complex issue of climate, see the excellent summaries in Temming (2003); Großmann (2013) and Hodder (2013).

8.4.1 Climate, Performance and Comfort

In contrast to the environmental factors lighting, sound and vibrations, the climate (collective term for the thermal environment of humans) has no feedback character about the driving process. However, as a homeostatic living being, humans have to maintain a body

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[9] A particularly critical vehicle in this context was the Citroën DS 19 with its soft hydropneumatic suspension.

core temperature of 37 °C within relatively narrow limits under all external temperature conditions, the climatic conditions contribute considerably to their well-being and thus also to their performance. In the history of vehicle development, the climate in the vehicle cabin was given relatively late attention. In combination with higher speeds, closed vehicle cabins were initially introduced to protect passengers from disgusting weather conditions. To counter the fogging tendency of the windows in these cabins and to meet the needs of passengers at higher outside temperatures[10] various simple measures were introduced, in particular opening windows (crank windows, windscreen to be raised, opening windows, sliding windows for very simple vehicles).[11] It was not until the 1950s that it became common practice in Europe to use the waste heat from the combustion engine to heat the vehicle in winter. Since 1963 the legislator has prescribed the existence of a heating system. Due to the relatively moderate temperature conditions in Europe, it was customary until the turn of the millennium to deliver vehicles as standard only with this prescribed heating system. From the eighties, however, the desire for better air conditioning became ever greater, especially under summer conditions, possibly also with a view to the USA, where air conditioning systems have been offered as standard since 1953 (the company Packard Motor Car introduced a complete air conditioning system for the vehicle in the USA as early as 1939).

A large number of experiments in the world of work dealt with the relationship between climate and performance. There is a clear link between physical performance and climatic conditions, but this is irrelevant in view of the fact that the driver does not perform at all. Of interest, however, are the motor and cognitive abilities of the driver depending on the climate. For cold conditions, it can be assumed that at an air temperature of <10 °C, the movement speeds of the extremities decrease progressively. The speed of nerve conduction is also reduced at low temperatures, so that at least the output of mental performance is slowed down. Temming provides an excellent overview of heat conditions (2003; FAT Study No. 177). According to this study, cognitive abilities in particular are restricted at temperatures >30° C_{eff} (see 8.4.2), whereby younger persons are obviously less affected than older ones. This study was not able to prove a connection with traffic accidents and conditions that can only be attributed to the climate. Even the expectation that aggressiveness is related to climatic conditions cannot be clearly proven scientifically. However, on the basis of general findings from occupational science, it can be stated that under certain conditions any strain that leads to discomfort at least impairs cognitive performance simply because mental resources are tied to the discomfort and thus capacity for the actual driving task is lost.

8.4.2 Climatic Comfort

8.4.2.1 Thermoregulation

As already described in ▶ Sect. 3.2.1.4, the thermoregulation of the human organism takes place via the warm receptors located mainly in the hypothalamus and the cold receptors distributed on the skin surface. A climatically neutral feeling (comfort = no perceptible discomfort) is achieved when a temperature between 33 °C and 34 °C is reached on the skin surface. The fact that the temperature perceived as comfortable is significantly lower depends essentially on the effect of the clothing, which creates a microclimate in the area of the skin surface that provides this temperature. Based on all scientific findings it can be assumed that comfort is achieved when the effort of the organism to maintain the mentioned skin surface temperature is minimized. This effort depends to a large extent on the climatic conditions. These are first and foremost determined by the *air temperature*. Normally the body emits heat to the environment by convection (exchange of the air

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[10] Until the 1940s it was common practice to immobilise a vehicle in winter.

[11] In the accessories trade there was also an additional pane of glass with electric wires to be glued to the windscreen, which was intended to create a clear view in this area.

heated on the skin surface by colder air) and body contact (touching low-temperature objects; e.g. cold vehicle seat – this way, of course, heat can also be transferred to the body via the other way round e.g. seat heating). If the air temperature is too low, it can generate heat through body movement (due to the poor efficiency of the muscles, etc. e.g. cold shivering). If the air temperature is too high, the heat dissipation via the path of convection can be increased by increasing the *air velocity* (fan out of air). A further increase in heat dissipation is possible through the release of sweat. The heat necessary for the evaporation of this liquid is extracted from the environment, i.e. especially from the skin surface. The effect of evaporation can also be significantly improved by air movement. However, it depends considerably on how much moisture the air can absorb at all (at 100% humidity, no further moisture can be absorbed. In this case the sweat formation has no effect.) Thus, in addition to the already mentioned air movement, the *relative humidity* an essential factor defining the comfort climate. Like every body, the human body is also in an exchange of radiation with its surroundings (every body emits electromagnetic radiation according to its surface temperature, at the usual ambient temperatures essentially in the long-wave infrared range). If the surface temperature of the surrounding surfaces coincides with the surface temperature of the body (here the surface temperature on the clothing plays the decisive role), then radiation equilibrium prevails, that ver *rays* no heat exchange takes place. If the surface temperature of the surrounding surfaces is significantly higher than that of the body, heat is transferred to the body via this path, which may then have to be released again via the mechanisms mentioned above. Conversely, the body can also emit heat via the path of the radiation if it has a significantly lower temperature than the body surface (especially in winter this is done by cold body parts).

However, the physical process described depends to a large extent on how much heat is actually produced by the body and how the individual body is given the opportunity to retain or release the heat produced. Thus, in addition to the above conditions, the perceived comfort is considerably influenced by the individual energy metabolism and the clothing worn. In addition, the organism has the ability – as with other environmental influences – to acclimatise (adapt) to long-term conditions.

The ***energy turnover*** depends on age, sex and body dimensions (height and weight). Due to the large influence of the body dimensions, the energy conversion [W] is often related to the body surface [m^2] specified [W/m^2]. A medium adult male (70 kg, 1,75 m body height) with a surface area of about 1,8 m^2 has under normal driving conditions a heat emission of about 70 W/m^2. In poorer road conditions, this energy conversion can increase slightly due to the physical activity required (Hodder 2013). This information is valid for temperate climates. In hot environments, due to increased pulse rate and sweating, an increase of 5 to 10 W/m^2 (DIN EN 28996, 1993) can be observed.

The ***clothing*** can make a significant contribution to maintaining thermal comfort. The insulating effect of clothing means that, on the one hand, the effective heat emission of the body at a correspondingly low temperature maintains the conditions of the comfortable surface temperature of the skin. This effect can also be largely regulated by adapting the clothing to the temperature conditions. Under extreme conditions it can even be ensured that the heat transfer from the outside to the body (especially radiant heat) is kept within limits. The effect of clothing is defined by the internationally accepted unit of measurement "clothing unit"(abbreviation clo). The reference value of 1 clo applies by definition to the "typical office suit". Estimated values for typical clothing combinations can be found in ◘ Table 8.4.

Temming (2003) presents the following findings regarding the climatic ***acclimatisation*** different literature results together. After more than eight days it can be expected that a person exposed to the heat climate will experience a notable acclimatisation effect. However, all the literature references found refer to observations of heavy physical work in a heat climate. According to the unanimous opinion of most

Table 8.4 Insulation values of clothing combinations according to DIN ISO 7730 (1987)

Type of clothing combination	Insulation value	
	m^2-°C/Watt	clo
Unclothed	0	0
Shorts (shorts)	0,015	0,1
Typical clothing in tropical areas: Underpants, shorts, short-sleeved shirt with open collar, light stockings and open shoes	0,045	0,3
Light summer clothes: Underpants, long, light trousers, short-sleeved shirt with open collar, light stockings and shoes.	0,08	0,5
Light work clothes: Underwear, cotton work shirt with long sleeves, work trousers, wool socks and shoes	0,11	0,7
Typical winter clothing for interiors: Underwear, shirt with long sleeves, trousers, jacket or pullover with long sleeves, thick stockings and shoes	0,18	1,0
Heavy, traditional, European office clothing: Cotton underwear with long legs and sleeves, shirt, suit consisting of trousers, vest and jacket, woollen stockings and heavy shoes	0,23	1,5

of the authors quoted, acclimatisation is due to the extent of sweating, which is itself controlled by the elevated body temperature. The duration of the heat exposure must be at least 1 hour daily in order to cause an increased body temperature and the associated increased sweating. Comparable acclimatisation gains can also be observed for older people. For persons sitting quietly and exposure times of at least 6 hours, however, only an increase of the tolerance limit by approx. 2 K is possible[12] to observe. It can therefore be assumed that the acclimatisation effects mentioned have no effect on the discomfort sensation in the vehicle.

8.4.2.2 Summary Climate Measures

Due to the complexity of the individual physical quantities influencing climate perception, there have been repeated attempts to combine them into a single quantity describing climate perception. The advantage of such a procedure is to recognize what effect the design change of a physical quantity has and then to derive appropriate measures from it. There are two different approaches to this. One method tries to find climate combinations that lead to the same temperature sensation (e.g. in the sense of curves with the same strength of perception in the acoustic range). The best known and oldest representative of this variant is the effective temperature according to Yaglou (1927). This is followed by a series of modified procedures, which are summarised under the term climate sum measures. The second method is to estimate, on the basis of a kind of energy balance, the proportion of people who feel comfortable with the climate combination in question. The best known system of this version was developed by Fanger (1967 et seq.). This is also followed by a series of modified procedures through which particular aspects of influence are to be taken into account. A comprehensive compilation and discussion of all these procedures can be found in Temming (2003).

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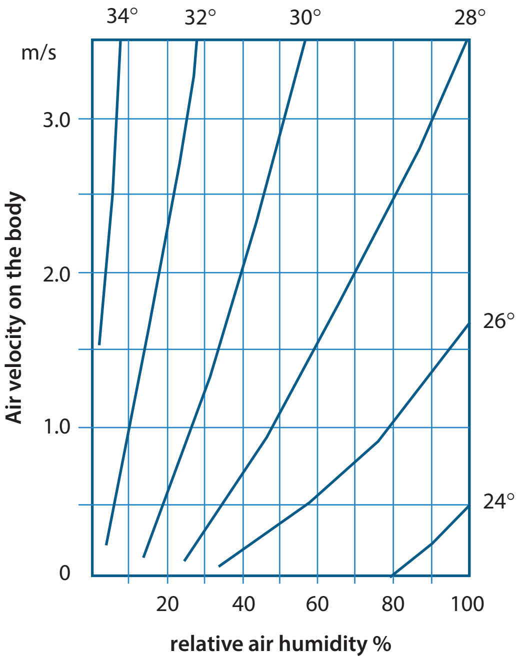
[12] the Celsius scale represents a measure at the interval scale level and therefore only has significance if one wishes to describe the temperature state through it. If one wants to indicate the difference of temperature values, it is therefore correct to use the temperature scale according to Kelvin (K = 273 + x °C). Of course, the same numerical values result.

▪ Climate Sum Measures

In the twenties, Yaglou (1927) developed an integrating climate measure in the USA, which combines all combinations of air temperature, psychometric humid temperature (a measure for the relative humidity of the air, and the temperature of the air.[13]) and flow velocity of the air is indicated by a measurement number, which caused the test subjects to feel the same amount of heat during the experiments. Two nomograms were developed from the test results (one for clothed and one for unclothed persons), with which a single value describing the thermal sensation, the so-called "effective temperature t_{eff}". The diagrams are included in DIN 33403, Part 3 (2000). In the meantime, work has become known which presents the content of nomograms in the form of equations, so that the effective temperature for concrete climate combinations can also be calculated numerically (Müller and Gebhart 1999; Gebhardt et al. 1999). The effective temperature indicates the heat sensation that occurs at the corresponding dry temperature, no air movement and 0% relative humidity. For sitting, practically non-physical work, a range from t_{eff} = 19° C_{eff} to 23° C_{eff} is assumed for neutral temperature sensation. Using the nomograms mentioned above, Bubb & Schmidtke (1984) have compiled the air velocity required to achieve a neutral temperature sensation of 23°C_{eff} as a function of air temperature and relative humidity in a diagram (◘ Figure 8.23).

The nomogram originally developed by Yaglou does not contain the influence of the radiation temperature. Various proposals have been made to take this handicap into account. The recommendation to measure the so-called Globe temperature instead of the dry temperature and to use it instead of the dry temperature in the Yaglou's nomogram has become widely accepted. The probe of the globethermometer is located in the center of a black painted copper ball with a diameter of 150 mm. The value determined in this way is called the "corrected effective temperature". Also concerning the size and definition of this globe thermometer different variants are described in the literature.



◘ Fig. 8.23 The air velocity required to reach an effective temperature of t = 23°C_{eff} depending on the relative humidity and air temperature. (From: Bubb & Schmidtke 1984)

As already mentioned, a large number of other sum measures have been developed. In this regard, reference is made to the compilation in Hodder (2013) and especially Temming (2003).

▪ Comfort Equation According to Fanger

The comfort equation developed by Fanger (1970) is based initially on the body's heat balance: The heat generated by the body due to its basic metabolic rate q_{met} minus the heat flows emitted by the various mechanisms (heat conduction, convection, radiation, diffusion, evaporation of sweat and respiration)

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[13] In an apparatus known as a psychrometer, the temperature is measured with a thermometer, the sensor of which is surrounded by a moistened wad of cotton wool and fanned with prescribed air movement. Evaporative cooling removes heat from the thermometer so that it indicates a lower temperature than the so-called dry temperature measured in parallel. The lower the relative humidity, the greater the difference. The value obtained in this way is called the "wet bulb temperature".

◘ **Table 8.5** Perception and scale of PMV according to DIN EN ISO 7730

Sensation	***PMV***	**Dissatisfied [%]**
Hot	3	100
Warm	2	78
Slightly warm	1	26
Neutral	0	5
Slightly cool	−1	26
Cool	−2	78
Cold	−3	100

$\dot{q}_{ab,.n}$ represents the effort of the organism to maintain the body core temperature of 37 °C.

$$q_{met} - \sum_{n=1}^{n} \dot{q}_{ab,.n} = \sum q \qquad (8.4)$$

On the basis of complex psychophysical experiments with test persons (see also ▶ Sect. 11.3.1.2), he investigated which effort can be assigned to which sensation. Using regression analytical methods, he has developed a “predicted average overall sensation” of the climatic conditions, the PMV (Predicted Mean Vote):

$$PMV = 0.303 \cdot e^{(-0.036 \cdot q_{met} + 0.028)} \cdot \sum q \qquad (8.5)$$

The Fanger method is included in many standards (e.g. DIN EN ISO 7730) and thus represents the “state of the art” of climate assessment. For the calculation of the heat flows there are many detailed data there. Großmann (2013) also provides a clear presentation of this. ◘ Table 8.5 provides the verbal assignment to the *PMV*-values as well as the expected percentage of dissatisfied people in the individual categories after catchers.

According to Großmann’s experience (2013), instead of eq. 8.5 in the automotive-relevant range from metabolic rates to 150 W/m² the following simplified version can also be used:

$$PMV = \frac{3,8}{\dot{q}_{met}} \cdot \sum q \qquad (8.6)$$

In any case, it can be seen that, in the case of the balanced heat balance $\sum q = 0$ also the *PMV*-value becomes 0. However, according to the experience of Fanger, 5% of the test persons are still dissatisfied with the temperature conditions (see ◘ Table. 8.5). Mayer (1998) even found out in his own car-related experiment that the percentage of the dissatisfied even with $PMV = 0$ is still at 15%. In another publication, he notes that most people feel comfortable in the vehicle with a PMV = 0.5, whereby 18% of the people are still dissatisfied (Mayer et al. 2007).

The PMV value developed by Fanger actually refers to air conditioning in immobile work and recreation rooms. Due to the tight conditions in the vehicle, however, the model must be extended for this application. For this purpose, the human surface is divided into surface elements and the absorption of direct solar radiation is taken into account in order to assess the local individual heat flows. On the basis of Fanger’s comfort studies, specific evaluation methods were developed which evaluate local comfort in individual parts of the body with the LMV (Local Mean Vote) instead of global comfort (Bureau et al. 2003; Frühauf 2002; Kühnel et al. 2003; example see ◘ Fig. 8.24). By the way, there are limits to a simple summation of the heat flows: e.g. a cold left and at the same time hot right foot could simulate a neutral feeling in the calculation. This is another reason why local assessments are important (more on this in Großmann 2013). A large number of publications deal with the modification of these comfort equations in order to better adapt them to the conditions of high thermal stress. In this context, reference is made to the detailed presentation in Temming (2003). Due to the uncertainty of the assessment by test persons, climate manikins are increasingly being used to assess the climate in cars in order to objectify the local assessment (◘ Fig. 8.25).

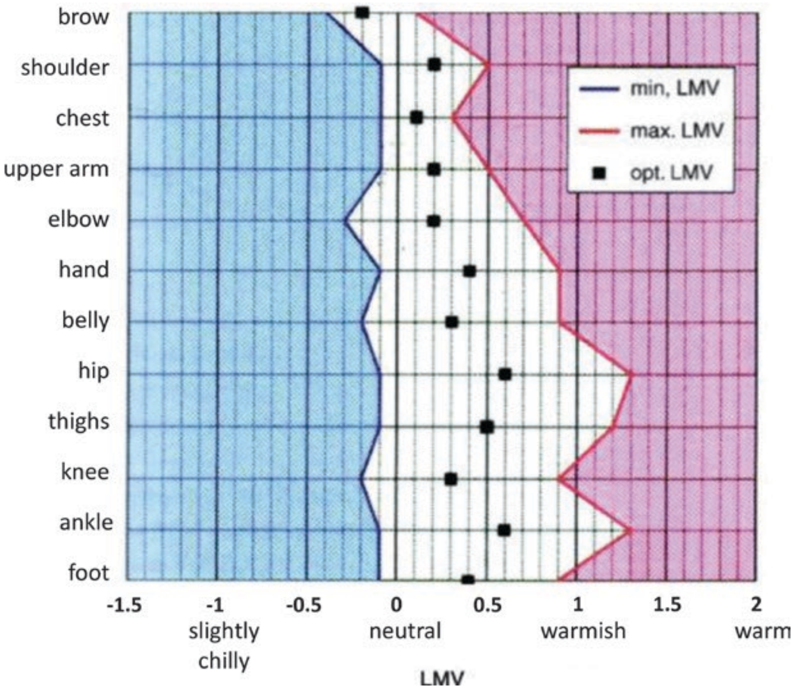

Fig. 8.24 Comfort evaluation on body parts with LMV. (From Wawzyniak 2011)

8.4.3 Environmental Conditions

Vehicles are used worldwide under extreme climatic conditions. Temming (2003) and his working group compile some interesting external climate data, with a focus on conditions in Germany. In this context, reference is also made to the Handbook of Fundamentals (ASHRAE 1997), which is updated every four years by the American Society of Heating, Refrigeriating and Air Conditioning Engineers. Although this basic work contains predominantly climate data for the USA, it also contains orientation data for practically all countries of interest in the world. According to DIN 1946–3 (2006–2007), outdoor air temperatures worldwide can vary between −45 °C and 55 °C. DIN 4710 (2003) compiles extensive meteorological data for Germany. The climate data guideline VDI 4710,1 (2008) describes non-European climate data for building services engineering. As an example, Großmann (2013) gives the values preseted in ◘ Table 8.6.

Vehicles are generally designed to operate in a temperature range between −20 °C and 40 °C. This also corresponds to the temperature conditions measured in Europe (e.g. Russia Kotlas: −18 °C, 30 frost days; Granada: 35 °C). However, there are also extreme deviations, for example in the winter of 2013/14 on the east coast of the USA −45 °C and in the same period in South America +40 °C. Extreme values are also possible in Germany: Großmann (2013) reports that an air temperature of 38.7 °C was measured in Manching (near Ingolstadt) on 27th July 1983 and even 40.2 °C on the same day in Gärmersdorf near Amberg. In Munich, the temperature measured at the airport normally varies over the year between −4 °C in January and 25 °C in July.

Apart from extreme winter conditions, at least for the temperate climatic conditions in Europe, winter operation is ensured by adequate heating up to an external temperature of −10 °C can still produce pleasant interior temperatures, possibly supported by an additional heating system. A particular challenge, however, are the summer climatic conditions. They therefore play a special role in the available publications. Temming (2003) compiles a large number of data sheets for summer outdoor temperatures. Among other things, he notes that local differences in particular arise not only on a large scale due to different alti-

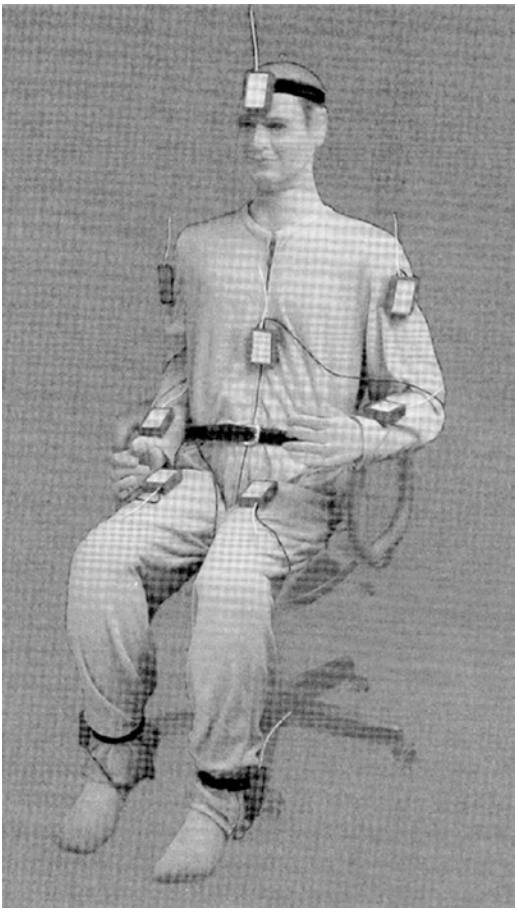

Fig. 8.25 Climate manikin DRESSMAN. (Mayer et al. 2007, source Fraunhofer Institute for Building Physics)

Table 8.6 Examples for air temperatures and relative humidity at different locations (from Großmann 2013).

Location	Air temperature °C	Relative air humidity %.
Phoenix (USA)	43	15
Munich	30	50
Tokyo	30	75

tudes or the effects of sea and land climates, but also as a result of small-scale peculiarities such as building density and vegetation. In this context, he quotes Völksch (1978), who, on the basis of extensive literature research, found that differences of up to 10 °C can be observed in comparison with the surrounding open land during low-exchange nocturnal weather conditions in large cities.

According to the physical connections that air with a higher temperature is able to absorb a larger amount of moisture, the highest moisture contents of the outside air (9 g/kg) are observed on cheerful days in July in contrast to the lowest in January (approx. 3.5 g/kg). According to Dufner et al. (1993), the moisture content of the air in rural areas is typically 8% higher in summer than in urban areas. The differences in both air temperature and moisture content between urban and rural areas are mainly attributed to the water vapour release of the vegetation and the differences in dew formation.

The heat input by the sun represents the greatest challenge, along with extreme cold for the air conditioning of the vehicle. The intensity of the sun's rays depends on the season, the time of day, the degree of latitude on earth and the cloud cover. Großmann (2013) provides detailed information and calculation examples. In general, it can be assumed that the maximum sun intensity in the summer months in Central Europe is between 800 and 1000 W/m^2. The long-wave heat rays of the sun pass through the windows of the vehicle into the interior of the vehicle and heat up the surfaces of the objects located there (dashboard, steering wheel, seats, rear shelf, etc.). The radiation emitted by the heated objects can only be partially emitted to the outside through the window panes, which partially absorb the heat radiation. For the most part, however, the air in the vehicle is heated by convection from the hot surfaces. In a stationary vehicle there is no air exchange with the environment, so that very high air temperatures occur in this way (so-called greenhouse effect). Temming (2003) reports temperatures between 42 °C to 51 °C in the footwell, 55 °C to 67 °C in the headspace and temperatures up to 100 °C on the sheet metal surfaces measured in a vehicle that stood for 2 hours in the midday sun at 26 °C in 52° north latitude (Kassel) and at 43 °C in 33° north latitude (Phoenix, Arizona, USA). Although these extreme temperatures

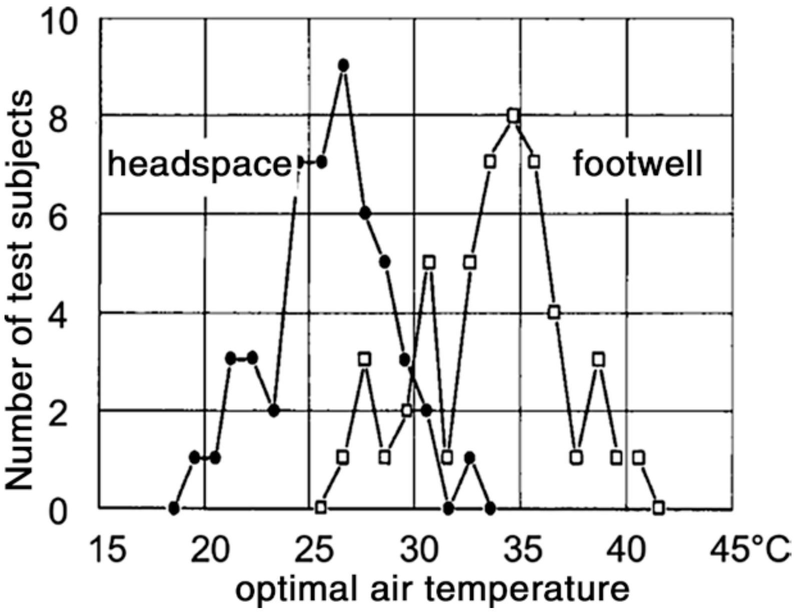

Fig. 8.26 Comfortable head and foot temperature in the car. (After Amano and Imai 1971)

can be reduced more or less quickly (for periods of several minutes) by the operation of the vehicle, since an exchange of the vehicle interior air can now take place via the ventilation system or open windows. However, due to the greenhouse effect described above, the temperature in the passenger cabin always rises by several degrees Celsius in summer (between 5 °C and 10 °C depending on the technical requirements), even during operation. With regard to the heat load in the interior, it is also important that the mentioned temperature rise does not contain the direct effect of the heat radiation, because the quoted values were mostly measured with simple thermometers (Temming 2003).

8.4.4 Technical Requirements

8.4.4.1 Driving Operation

According to Großmann (2013), it is usual to determine the mean interior air temperature in a vehicle as the arithmetic mean of the mean temperature at the level of the footwell and at head height. While according to DIN 1946–2 (1994–2001) an average interior temperature of 22 °C is recommended in residential areas of buildings, according to Großmann's experience the average temperature in the vehicle is higher both in winter and summer. There are several reasons for this.

Winter Operation

Especially in winter, passengers radiate heat to the cold windows. Since the distance between the side windows is very small in comparison to corresponding walls and windows in buildings, the air in the footwell must be considerably warmer than at head height for a comfortable climate in the vehicle. Großmann recommends an air temperature stratification of 5 K to 12 K. Temming (2003) gives temperature differences of 4 K to 8 K based on a literature compilation (see also Fig. 8.26). According to Großmann (2013), with an outside air temperature of −20 °C, an average indoor air temperature of 28 °C can be achieved in the stationary state.

Fig. 8.27 schematically shows the heat flow in a vehicle during winter operation. The air heated by the heating system flows into the interior. According to Großmann (2013), the air mass exchange under blower operation is between 7 to 9 kg/min. Weible and Kern (1984) give maximum values in the range of 8 to 10 kg/min for this purpose. It is also strongly dependent on the driving speed. The entire body mass is in heat exchange with this warm internal air, additional heating by the engine

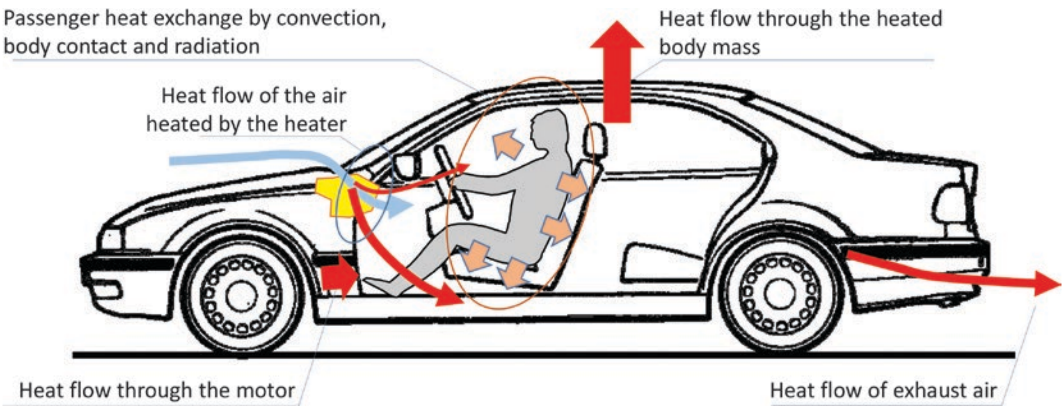

Fig. 8.27 Heat flow through the passenger compartment during winter operation

heat and dissipated heat to the cold external air.[14] Passengers emit heat through radiation to the body parts with low surface temperature and through contact, especially to the seat, but also to other objects that are touched (steering wheel, armrest). From this point of view, it is more comfortable if a vehicle is equipped with seat heating (this also applies to the rear seats; see also Brooks and Parson 1999). For the design it has to be considered that in winter many people use the vehicle with winter clothing, which has a high insulation value. In addition, there is also the insulation value of the seats, which according to Hodder (2013) can be set at 0.2 Clo. Since winter clothing may not be required for longer journeys, it is essential to regulate the output of the seat heating system.

For technical reasons, the heating power of a vehicle depends on many circumstances, such as driving condition (speed, uphill/downhill), surface temperature of the road, air temperature fluctuations, solar radiation. Therefore, regulation of the heating effect is necessary in any case. According to Petzold (1975), the perception threshold for temperature fluctuations is in the range of about 1 K. According to DIN 1946 (2006–2007), the time deviation from the setpoint of the room temperature should not exceed or fall below a value of 2 K. This makes a technical regulation of the outlet temperature of the heating system necessary.

As is relevant for the summer operation described below, it is also true for winter operation that the individual thermal comfort requirements vary greatly (see Table. 8.5). This means that individual regulation of the heating output for the individual seats is necessary. Today, a separate regulation for the driver's and passenger‘s seat is offered – usually in use with air conditioning – at least for the front seats. An air supply to the rear seat area and a regulation independent of the front area is additionally necessary in order to ensure individual thermal comfort for the rear seat passengers.

A problem of winter driving operation for the occupants is the low humidity caused by the low outside temperature (see also ▶ Sect. 8.4.3). As this air is heated by the heating system, the resulting relative humidity in the vehicle interior is correspondingly low. According to various recommendations, an air humidity between 30% and 50% is considered optimal (Sterling et al. 1985; quoted after Temming 2003, see also Deyhle and Bienert 2011). A technical humidification of the vehicle interior air would therefore make sense, especially since the disturbing electrostatic charge can also be largely reduced from an air humidity of approx. 40% (McIntyre 1980). In this context, however, reference should also be made to the requirements described in ▶ Sect. 8.4.4.3, since low humidity can ultimately prevent fogging of the windows.

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[14] For detailed calculations of these data, please refer to the detailed treatment of Großmann (2013).

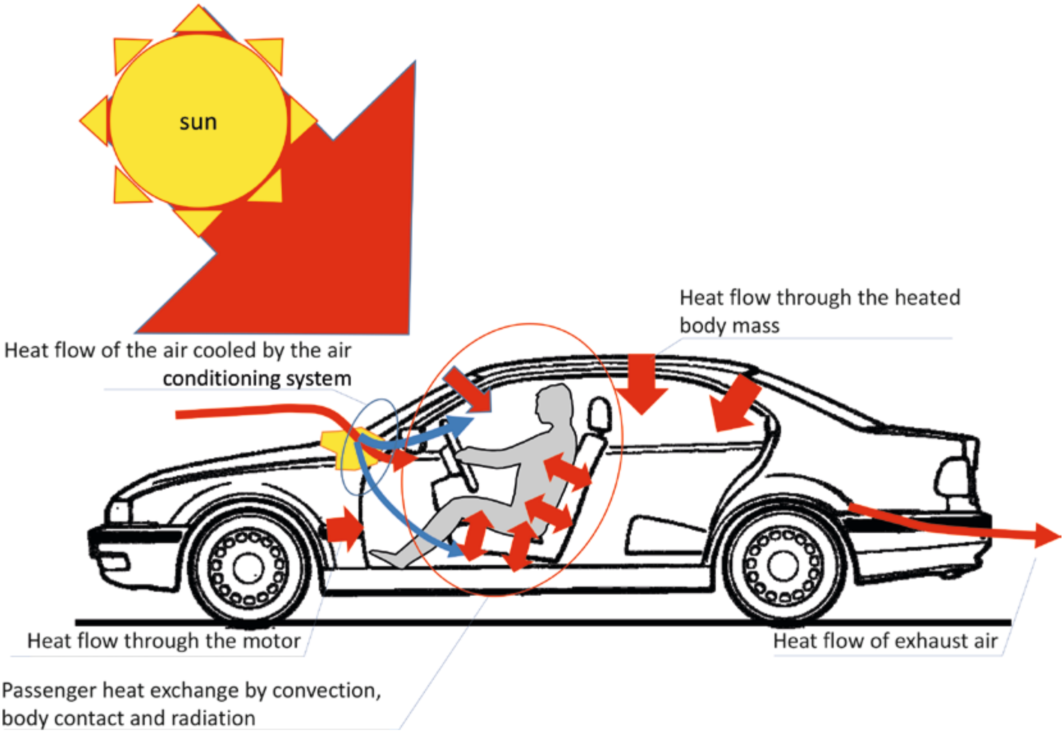

Fig. 8.28 Heat flow through the passenger compartment during summer operation

Summer Operation

In the temperate climate zones of Europe and many other parts of the world, general acclimatisation to summer climatic conditions cannot be assumed, and even if this occurs, the corresponding effect is relatively small (see also ◘ Sect. 8.4.1). Consequently, it is to be assumed that for summer driving conditions, similar requirements are to be placed on the comfort conditions in the vehicle interior as under winter driving conditions.

◘ Fig. 8.28 schematically shows the heat flows through the passenger compartment during summer operation. Without air conditioning, the outside air enters the interior at an almost unchanged temperature. One of the effects of the heated sheet metal housing is that the air drawn in via the ventilation system is additionally heated, which is referred to as “summer air heating on the engine hood”. Since the absorption of solar radiation also depends to a large extent on the paint colour, there are various effects here which have an effect especially in slow stop-and-go operation (Großmann 2013). Apart from the marginal cooling effect caused by the airstream, the body mass has approximately the same temperature as the outside air in stationary driving mode without sunlight. In addition, the sheet metal housing is heated by the motor in the front footwell and especially at the transmission tunnel. In general, an air conditioning system can achieve that the interior temperature is shifted into the comfort range despite a higher outside air temperature.[15]

The conditions change drastically when an additional heat flow is added by the thermal radiation of the sun. In any case, the exchange of radiation with the sun causes the body mass to heat up accordingly, which in turn contributes to the heating of the interior air. However, this is also associated with heat radiation (detailed information and considerations can be found in Temming 2003). Großmann (2013) reports that at an outside

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[15] ◘ Fig. 8.23 shows the sometimes extreme air velocities that are necessary without air conditioning in order to achieve an effective temperature of 23 Ceff.

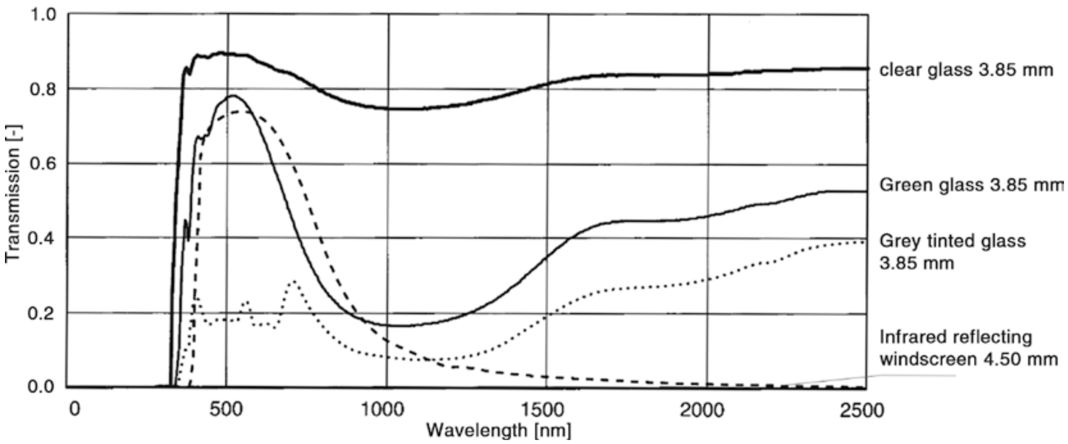


Fig. 8.29 Transmission of different glass types as a function of wavelength. (Source: NSG Group Pilkington Automotive, after Großmann 2013)

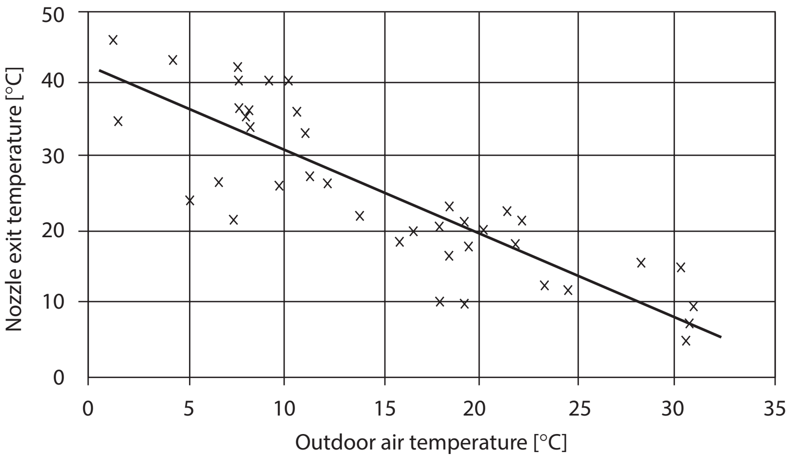
air temperature of 40 °C, solar irradiation of 1000 W/m^2 and a relative humidity of 30% was measured on the nozzles of the air conditioning system 8 °C. As a result of the solar radiation and other effects, the air heated up from these 8 °C to 27 °C as it passed through the passenger compartment, with the average air temperature at head height being 21 °C. The air temperature in the passenger compartment was then reduced to 21 °C.

The decisive influence, however, comes from the direct irradiation of the long-wave electromagnetic solar radiation through the windows. This not only causes the greenhouse effect described above, which is less significant due to the exchange of air in the moving vehicle than the direct irradiation of the body parts of the passengers. This influence naturally depends to a large extent on the weather conditions, the position of the sun and thus the time of day and in relation to it the direction of travel of the vehicle (for more details see Großmann 2013). Due to the large flat window areas, this influence has increased significantly compared to historical vehicles.

Heat-insulating glazing, which is intended to reduce the penetration of thermal radiation, has now become the standard. Absorbing and reflecting panes as well as mixed forms of them are used for this purpose. The absorbing discs contain particles (e.g. iron oxide in classic green glass), which absorb the heat radiation of the sun. This heat is released into the ambient air by the airstream. A thin layer (e.g. tin oxide) is evaporated onto the outside of the reflecting panes. This means that it is possible to prevent part of the solar radiation from penetrating the driver's cab even without wind (Großmann 2013). ▣ Fig. 8.29 shows as an example the effect of different glasses. The high absorption effect of the infrared reflecting glass for the long wavelengths is conspicuous. However, various authors also point out that the influence of radiant heat can be greatly reduced by choosing clothing (e.g. white clothing instead of black) (Schwab 1994). Roller and Goldman (1968) even found that the thickness of the clothing material can reduce the transmission of solar energy to the body. If the body is exposed to direct irradiation, the hair and clothing temperature can rise by 15 K to 18 K, while with correspondingly exposed bare skin only a temperature increase between 5 K and 6 K can be recorded (Clark 1981).

The most effective method to compensate for the thermal radiation effect is to fan the corresponding parts of the body with air cooled by the air conditioner. As Temming (2003) states, car occupants want air inlet temperatures in the passenger compartment to decrease as the outside temperature rises. ▣ Figure 8.30 shows the result of measurements over several months in an air-conditioned vehicle during longer test drives by 8 individual drivers. It clearly shows that

Fig. 8.30 Individually adjusted air inlet temperatures in an air-conditioned passenger car. (From Temming 2003)



with low outside temperatures (winter conditions) high inlet temperatures of the heating system up to 40 °C are required, that already with outside temperatures below 20 °C the air conditioning system was in operation and that with increasing outside temperature the outlet temperature at the air nozzles was adjusted to values up to 10 °C and below. Deyhle and Bienert (2011) also recommend rather low air speeds combined with low exhaust temperatures for vehicle air conditioning. This requires relatively large outlet openings, since high air volumes have to be exchanged in the vehicle via relatively few air outlet cross-sections in order to meet the different thermal requirements. Hinz et al. (1983) require an air flow rate of up to 10 m^3/min for a large car in summer in order to achieve the required maximum high air velocity of 2 to 3 m/s in the interior (see also calculations by Großmann 2000). Asakai and Sakai (1974) indicate values between 1.5 to 2.1 m/s close to the body as necessary to ensure a cooling effect through vehicle ventilation in summer. On the other hand, speeds above about 3 m/s are rejected as uncomfortable. Zipp et al. (1977) have stated that the ventilation of the chest and lap area shows the best results both in terms of objectively measurable effects and subjective assessment. The air flow should be distributed as evenly as possible, which can be achieved by a larger number of nozzles or nozzles with a large outlet opening and by a greater distance of the nozzle from the passenger. In this context, however, it should also be borne in mind that there are quite different requirements with regard to preferences. For example, Europeans and Asians predominantly prefer rather indirect, diffuse air conditioning with low air speeds, while North Americans prefer directly directed large air mass flows combined with corresponding cooling capacity to air conditioning (Deyhle and Bienert 2010). These different requirements are met by special country variants of climate control and by so-called comfort diffusers, which allow adaptation to individual comfort requirements through positions between “diffuse” (draught-free), “conventional” and “spot” (direct air flow) (Fritsche and Feith 2007). Asakai and Sakai (1974) also hold the opinion that a pulsating current, preferably at about 1.2 Hz, can cause a pleasant feeling of coolness. More recent evaluation approaches (e.g. DIN 1946 Teil 2, 2006–2007) require a lower average air velocity at higher turbulence levels in order to avoid tensile sensations. According to Temming (2003), it remains to be seen for the time being whether the increased heat dissipation due to increased turbulence levels could also have positive effects at high ambient temperatures. An application of such considerations in the vehicle has not yet become known.

Contact with the seat in particular creates another problem zone for the occupants of the vehicle that influences their climatic sensation. The body enters into a contact heat exchange with the seat. Madsen (1994) found in a study with a climate manikin that a ventilated seat can improve the removal of heat.

The actual problem, however, is essentially that in a heated vehicle interior the passengers secrete sweat in order to maintain their body core temperature by evaporative cooling. This of course also happens in the back and buttocks area, where the body is in contact with the seat. If the seat is unable to absorb the moisture, an unpleasant feeling may arise, among other things, due to the fact that the sweat itself is not very heat-conductive and that heat accumulates between the skin and the contact surface. Fung and Parson (1993) have done extensive research with different seat materials. Their subjects were exposed to a heat environment (34 °C, humidity 35%) and were asked to evaluate the thermal sensation. The worst rated seats were those that were impermeable to moisture due to their surface material or the foam used. However, later research by Fung (1997) showed that the influence of clothing, the duration of the trial and intra-individual personal preferences made it impossible to find an ideal seat material. Cengiz & Babalik (2007) evaluated the thermal comfort of three different vehicle seats in a field test and found no significant differences between the seats under real conditions (quoted from Hodder 2013).

Electric Vehicles

The air-conditioning (heating and cooling) of electric vehicles poses a particular challenge because, on the one hand, no excess process heat is available from the electric motor and, on the other hand, any energy required to create a comfortable interior climate consumes the energy resources carried along and thus reduces the range of the vehicles. Even a better thermal insulation of the interior, which could reduce heat dissipation to the outside in winter and heat input from the outside in summer, does not have a penetrating effect, because the demand for high air throughput in the small volume of the passenger cabin is still maintained. The technically possible use of combustion systems for air conditioning counteracts the environmentally friendly effect of electric propulsion. It remains a task of future ergonomic research to re-examine the climatic comfort needs of humans under this particular aspect in order to determine which measures can be used to achieve optimum effects with minimum energy input. One could make oneself thereby e. g. the fact to make use of that climatic comfort with a skin surface temperature between 33 and 34 °C adjusts itself. Heating and cooling elements mounted close to the body, which do not have to air-condition the entire room, seem to point the way to success. A very extreme idea in this context would be "climate clothing", in which Peltier elements are woven into the fabric as heating or cooling elements in conjunction with thermal sensors, in which a controller (microprocessor) carried along ensures the specified skin temperature. The energy required for this type of air conditioning is likely to be relatively low, so that a commercially available battery should suffice as a power supply for road operation. For driving, one would connect the clothes to the power supply of the vehicle.

8.4.4.2 Start of the Journey

From a climatic point of view, the entry (dis)-comfort is an essential criterion for the acceptance of the vehicle. In winter, the vehicle takes on the outside temperature after prolonged outdoor parking. When the weather is correspondingly cold, this creates a high discrepancy between the subjective expectation of a "cosy" interior and the actual conditions. In summer, the vehicle heats up considerably due to the greenhouse effect described above, especially in sunshine after prolonged parking. In the interior, the air temperature may then be far above any comfort requirements. In addition, the thermal radiation exchange with the sun causes the surfaces in the interior to reach partial temperatures, which in the worst case can even lead to burns.

Winter Conditions

According to Großmann (2013), the combustion engine heats up after 10 to 20 minutes to such an extent that the occupants feel the transferred heat in the passenger compartment. ◘ Fig. 8.31 shows the course of the mean interior temperature during a controlled measurement in a climatic chamber with roller test bench (described in more detail in Großmann 2013). More practical measure-

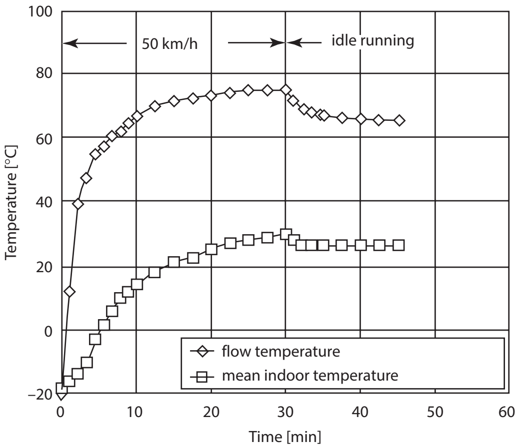


Fig. 8.31 Heating power measurements on a passenger car with a 1.81 petrol engine with direct injection; outside air temperature −20 °C, 30 min Travel speed 50 km/h, then idle; air-side electric auxiliary heater with 800 W; the flow temperature is the cooling water temperature: measurement on a roller test bench. (From Großmann 2013)

ments were carried out by the magazine Auto-Motor-und-Sport in January 2013 (Übler 2013). The tested test vehicles stood one night at −15 °C outdoors. At the beginning of the test the outside temperature was −11 °C. The temperatures in the head area (interior mirror) and in the foot area (passenger foot area) were measured. The vehicles were moved in convoy in steady, restrained travel (max. 80 km/h). Fig. 8.32 shows the temperature curves for the vehicle with the fastest temperature rise (left) and the slowest temperature rise (right). In all vehicles, an almost linear increase in temperature can be observed, especially in the headspace. Even in the best vehicle, under these realistic conditions, which also provided more favourable temperatures than the laboratory measurement documented in Fig. 8.31, no temperature corresponding to the above comfort recommendations was reached after 20 minutes. Großmann (2013) therefore recommends various auxiliary heaters (e.g. electric auxiliary heating, heat storage, electric pre-heating of the coolant, use of residual engine heat), the technology of which is described in detail. According to his argumentation, the parking heater in particular represents the most convenient solution. Due to the sluggish rise in temperature under winter conditions, additional seat and steering wheel heating are recommended to prevent the discomfort caused by extremely low temperatures when starting up the cold vehicle.

Summer Conditions

A vehicle parked in the sun heats up considerably under summer conditions due to the greenhouse effect and can reach temperatures that can even lead to burns (see above and Table 8.7). Temming (2003) quotes a study by Shimizu et al. (1982), which shows heating curves when parking under summer heat radiation and cooling curves after the subsequent start of the journey using an air conditioning system (see Fig. 8.33). It is noteworthy that in the heating-up phase, the surface temperature of the outer skin (e.g. the roof surface) already reaches a constant level after about 20 minutes, while the interior temperatures continue to rise even after 40 minutes. Temming refers to studies according to which the increase in indoor temperatures continues even after 2 hours. In general, the air conditioning system reaches an indoor temperature of around 20 °C within 20 minutes of the start of the journey.

The heating effect depends considerably on the colour design of the vehicle. Großmann (2013) describes a test under controlled conditions in which two vehicles (a white one with a completely white interior and a black one with completely black interior equipment) are tested on the same vehicle.[16] The results are summarized in Table 8.7. Under the health aspect mentioned above, the temperatures at the steering wheel, front passenger seat and armrest in the front door are highlighted.

A particularly effective method of avoiding such extreme temperatures, which are associated with considerable discomfort, is, according to Großmann (2013), the use of stand ventilation with solar technology. With a so-called solar roof (sliding roof with inte-

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[16] Großmann points out in particular that the white dashboard surface and rear parcel shelf, which are favourable for reasons of radiation absorption, lead to extremely annoying reflections in the windscreen and rear window (rear-view mirror).

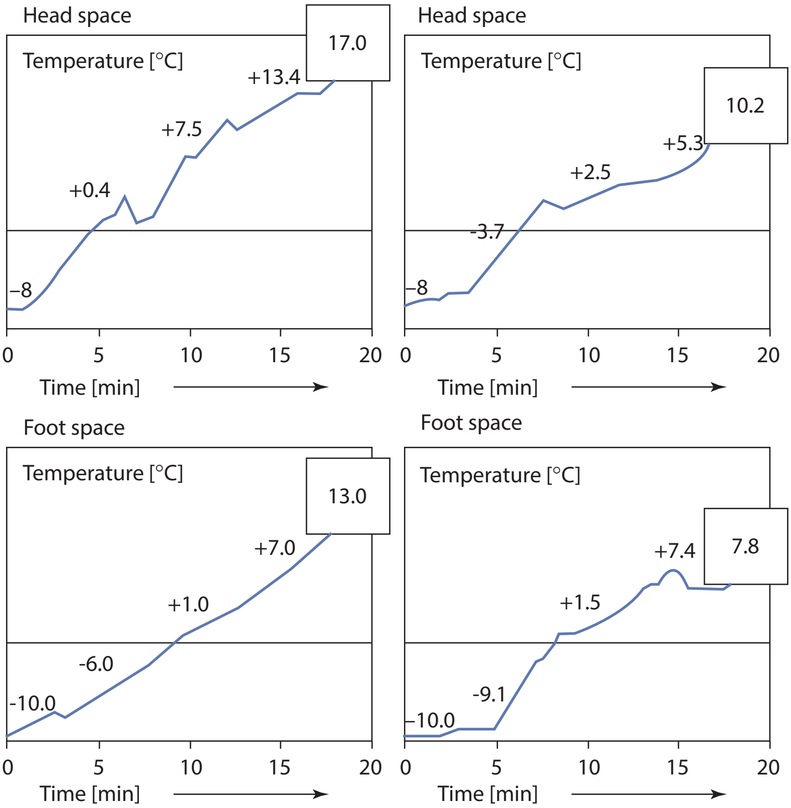

Fig. 8.32 Temperature curves in the head and foot area of two vehicles at an outside temperature of −11 °C and a real ride with a maximum of 80 km/h. (Übler 2013)

grated solar cells), electrical power is generated when the sun is shining, which is made available for blower operation and thus constantly exchanges the air in the parked vehicle. This prevents an essential part of the heating of the interior air by the high surface temperature of the components in the interior (Fig. 8.34).

8.4.4.3 Driving Safety Requirements

The previous discourse dealt with vehicle air conditioning with a special focus on the discomfort felt by drivers and passengers and on the climatic comfort. However, the air conditioning of the vehicle also has an essential safety aspect. The ability of air to absorb water vapour depends significantly on air pressure and temperature. At low temperatures it can absorb significantly less water vapor than at high temperatures. As a result, whenever warm air – possibly with high relative humidity – meets cold vehicle windows, the air cooled in the contact zone condenses the water contained. The pane is thus fogged with water and opaque. If the temperature of the panes is correspondingly low, ice will also form. This is, of course, especially important for the windscreen, but also for the front side windows and the rear window. Fogging is possible both on the inside and outside of the panes.

For fogging the windows of *on the outside* occurs when warmer outside air or air with a high moisture content hits the cold vehicle windows. This is generally the case when the vehicle is parked outdoors in winter weather conditions and is correspondingly cold. As is well known, it is then the driver's task to make the windows free of ice and fog before the vehicle starts. There may also be a sudden formation of external fog if the vehicle parked in a cold garage encounters the warmer and more humid outside air on its way out (under unfavourable conditions, this effect may also occur after a long tunnel journey). If there is no ice formation under these conditions, which is very rarely the case, a clear view can be restored very quickly by pressing the wiper.

Table 8.7 Component and air temperatures in a parked black car (including black interior) and a white car (including white interior) in sunlight, outside air temperature 30 °C, sun intensity 1000 W/m^2 (from Großmann 2013)

Designation of the measuring point	Temperatures in a white car [°C]	Temperatures in a black passenger car [°C]
Air at head height	67	75
Air in the footwell	44	46
Instrument panel, centre	72	99
Instrument panel, hat	78	102
Roof lining, centre	67	46
Hat shelf, centre	73	100
Trunk lid, interior	64	86
Front passenger seat	62	74
Armrest in the front door	61	73
Steering wheel	70	90
Gearshift	62	72
Rear seat backrest, centre	78	95

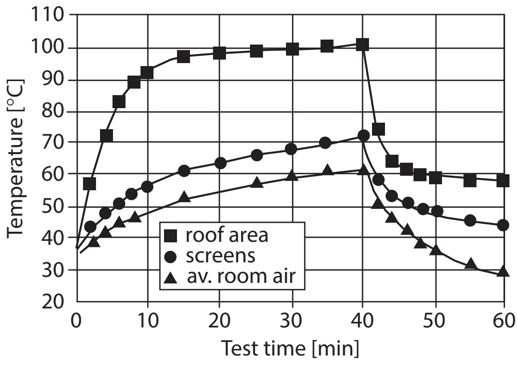

Fig. 8.33 Temperature curves in a stationary and air-conditioned passenger car with summer heat radiation. (After Shimizu et al. 1982; quoted in Temming 2003)

A fitting of the windows *inboard* occurs when there is warmer air inside the vehicle that carries more moisture and condenses on the cold windows. This is particularly the case at low outside temperatures, when the warm air breathing through the windows is subject to high relative humidity, but also when there are other moisture-carrying objects inside the vehicle (e.g. wet clothing, wet carpets, open bottles, etc.). As Großmann (2013) describes it, recirculation operation at low ambient temperatures is particularly critical. Occasionally, this can also occur during mountain passes, when the temperature of the outside air decreases with increasing altitude and the windows are cooled down accordingly. However, the water separated from the evaporator of the air conditioning system and stored there can also be the reason for the interior misting of the windows. Even at outside temperatures of 20 °C, the water stored in the evaporator may condense on the cool panes after a motorway drive and subsequent slow drive. Otherwise, however, an air conditioning system is favourable with regard to the tendency of the windows to fog up, as the cooling of the outside air is also associated with dehumidification, so that relatively dry air enters the vehicle interior. Internal fittings are particularly critical because they can occur suddenly. Due to the large distance of the windscreen from the driver due to the current design, it is also extremely difficult and even impossible to remove the fitting manually.

The traditional technical measure to make the panes fog-free and to keep them fog-free is to heat them. Usually, special ventilation nozzles are installed under the windscreen and in the lateral dashboard area, which direct the air heated by the heating system onto the windows. Various legal regulations exist for window de-icing and dehumidification (USA: FMVSS 103, EU 78/317/EEC; Australia ADR 15; quoted after Großmann 2013). Fig. 8.35 shows the measurement of the time curves up to freedom from fog in accordance with US regulation FMVSS 103. The driver's field of vision (see also ▶ Sect. 7.3.1) must then be free from ice and fog after 20 minutes at the latest (for a more detailed description, see Großmann 2013). In princi-

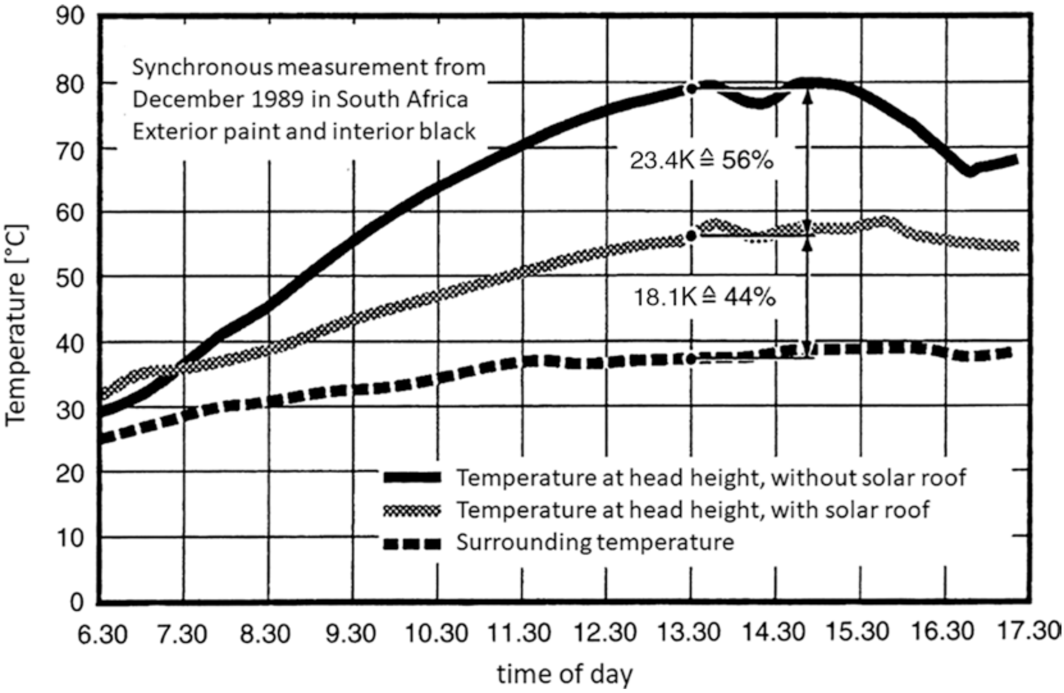

Fig. 8.34 Effect of a solar-powered stand ventilation system. Synchronous measurements of air temperatures at head height as a function of daily variation; Audi Coupé, 1989. (Ater Großmann 1992; quoted in Großmann 2013)

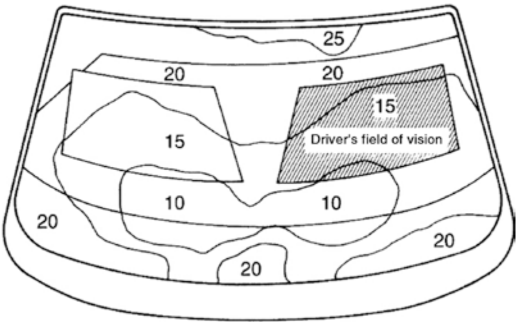

Fig. 8.35 Defrost lines as a function of time according to FMVSS 103. (Großmann 2005)

ple, the hotter the air flowing from the nozzles, the more effective de-icing and dehumidification is. Today, depending on the vehicle type, a completely defrosted windscreen can be reached in less than 7 minutes (Brinkkötter et al. 2007).

Another very effective method of heating the windows is electric heating. The best known is the electric heating of the rear window, which has been a standard feature since the seventies. In some vehicles, electric heating is also provided for the windscreen (e.g. Ford Focus). Instead of the few wires of the rear window, many very thin wires are used which are embedded in the foil of the laminated safety glass. Particularly in darkness, rain and oncoming traffic, however, optical diffraction effects on these wires can cause slight visual distortions, which is why this type of heating has not yet become generally accepted. According to Großmann (2013), this can be remedied by electrically conductive films, which are also integrated in laminated safety glass. It remains to be seen for future developments to what extent nanocoated panes can basically prevent fogging, because this avoids the crystallization points necessary for condensation of the water.

The annoying fogging and ice formation described also apply to the exterior mirrors. It is therefore a further safety benefit if electrical heating is also provided for this purpose. The water of the windscreen washer tends to travel at the outlet nozzles at correspondingly low temperatures. For this purpose, too, an externally temperature-controlled heating system should be provided wherever possible.

8.4.4.4 Vehicle Air Conditioning Design

After already noticing temperature differences from 1 K, a constant readjustment of the air-conditioning performance is necessary, depending on the driving conditions. A distinction is made between manual, semi-automatic and fully automatic systems. Manual systems, in which the individual technical elements such as heating/cooling capacity, air distribution and fan speed have to be set directly by the user, are nowadays usually only offered in small vehicles. In semi-automatic air conditioning systems, the interior temperature is measured by appropriate sensors and the necessary blow-out temperature is controlled via these sensors. In addition to the temperature, fully automatic air conditioning systems regulate the blower output and thus the air volume and, in the best versions, also the air distribution. Additional data such as outside temperature, driving speed, engine speed, coolant temperature and similar are included in the control process (Wawzyniak 2011).

As already explained in ► Sect. 8.4.2, the individual demands of passengers on the climatic conditions to achieve comfort vary greatly. The design of the vehicle air-conditioning system must take this into account. At the very least, different adjustment possibilities shall be provided for the driver and the passenger. In addition, it has been customary since the beginning of the introduction of heating systems in vehicles to provide separate regulation for the head and foot areas. However, heated or cooled air should also be led into the rear compartment, where it should be individually regulated, including special ventilation nozzles. Wawzyniak (2011) explains that for people with cold-sensitive feet, the so-called "variable layering" allows the footwell exit temperature to be raised without changing the basic setting.

There is no standard for the operation of air conditioning systems. The operation should therefore be integrated into the overall operating and design concept. However, actuators which are related to possibly rapidly changing conditions must be immediately available. For example, all controls that have something to do with safe vehicle guidance (removal of windscreen condensation and ice) must be immediately available and, if possible, can be initiated with a single operating step (e.g. "defrost button"). Also the adjustment of the temperature must not be hidden in any menu of the on-board computer. The term "blue" for cold and "red" for warm is internationally understood and should be placed on the reference surface of the actuator (not on the actuator itself, see ► Sect. 6.1.3; ◘ Fig. 6.12). With controlled air conditioning systems, it makes sense to display the set target temperature in degrees Celsius or Fahrenheit (can be changed if possible), as this enables the respective user to assign his individual preference to a specific number. Similarly, direct access to the air distribution (top – middle – bottom) and the intensity of the air velocity is recommended. In combination with the possibility of directly influencing the air flow at the outlet openings, the user can quickly achieve a satisfactory result even under extreme climatic conditions. More complex setting options for the air-conditioning system can then be accommodated in a submenu of the vehicle setting.

Modern air conditioning systems not only change the temperature of the incoming air, they also ensure air quality through appropriate filtering by largely keeping air impurities and unpleasant odours out of the cabin. In view of the increasing number of allergy sufferers, the use of pollen filters in particular makes sense (Herzog 2007). This shows that not only the fresh air, but also the circulating air must be filtered. Wawzyniak (2011) describes the different filter materials and their separation efficiencies required to absorb the different particle sizes. Since the separated particles remain suspended in the filter material, they must be replaced at regular intervals. The service life of the filters is generally approx. 30.000–50.000 km driving performance, but should not exceed two years. From an ergonomic point of view, it must be demanded in this context that this replacement can also be carried out independently.

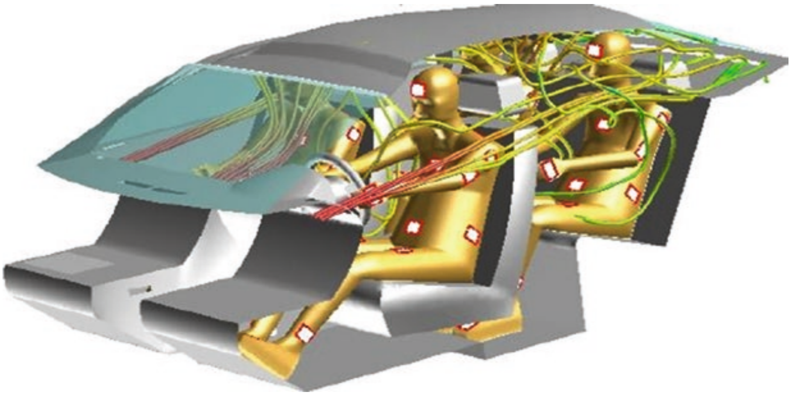

Fig. 8.36 CFD simulation of the flow conditions in the vehicle interior including virtual climate dummies. (Binder 2004)

This creates an additional acoustic entry, not least because of the fan required in every air-conditioning system. Due to considerable development effort, the noise nuisance caused by the air conditioning system is kept as low as possible (examples: Herzog 2007).

8.4.4.5 Air Conditioning Systems in the Product Development Process

The development of a climate control system for the vehicle is an extremely complex process. This is not only due to the requirements of the passengers discussed above, but also to the complex flow conditions in the interior of a vehicle. As in other areas of product development, simulation technology also plays an important role here. Computional Fluid Dynamic (CDF) analysis, which helps, among other things, to make a selection from a series of competing design drafts, is one method that can be used to optimize the flow of components at an early stage (Huco 2005). ◘ Fig. 8.36 shows a simulation of the flow conditions in the vehicle interior using this program system. Binder (2004) reports that the data on speed, temperature, radiation and body heat available in CFD analysis can be used to calculate all the data needed to determine thermal comfort using a specially developed virtual thermal dummy. It could be shown that the values calculated in the simulation show a high correlation to the values measured with the real climate dummy MARCO under comparable conditions (MARCO is very similar to the climate dummy DRESSMAN developed by the Fraunhofer Gesellschaft shown in ◘ Fig. 8.25).

Despite these very good simulation results, the degree of maturity of the vehicle air conditioning system must be examined at every stage during the entire development period from concept development to series production. Deyhle and Bienert (2011) report on a recording and evaluation system (PEA) specially developed by Porsche for objective evaluation, with the aid of which up to 200 air and fluid temperatures can be recorded in the test vehicle using thermocouples, enabling a comprehensive analysis of the functions of the air conditioning system under a wide variety of conditions, particularly with regard to automatic air conditioning control. A further development tool at all automotive companies is the climatic wind tunnel, in which reproducible and constant conditions can be generated and thus differences between different solution possibilities can be determined and optimizations with regard to the objectives can be carried out systematically.

Whether the development goal of “comfort in the interior” has really been achieved can only be determined by comparing the objective measurement results with the subjective assessments of test persons. For this purpose, field driver tests under different weather conditions in different climate zones are necessary. As Deyhle and Bienert (2011) argue, such surveys require on the one hand a statistically reliable basic population (e.g. 100 test persons) and on the other hand the broadest possible range of persons of dif-

Table 8.8 Evaluation scale according to ISO 1405-3 (2006)

ISO scale for temperature perception		**Extended temperature perception scale**	
		+5	**Extremely hot**
		+4	Very hot
+3	Hot	+3	Hot
+2	Warm	+2	Warm
+1	Slightly warm	+1	Slightly warm
±0	Neutral	±0	Neutral
−1	Slightly cool	−1	Slightly cool
−2	Cool	−2	Cool
−3	Cold	−3	Cold
		−4	Very cold
		−5	Extremely cold

Table 8.9 Discomfort verbalisation of the valuation figures in Table 8.8

"Uncomfortable scale.		**Sultriness scale**		**Preference scale**	
3	**Very uncomfortable**	**3**	**Very sultry**	**+3**	**Much warmer**
2	Uncomfortable	2	Sultry	+2	Warmer
1	Slightly uncomfortable	1	Slightly sultry	+1	Slightly warmer
0	Not uncomfortable	0	Not sultry	0	No change
				−1	Slightly cooler
				−2	Cooler
				−3	Much cooler

ferent ethnic origins. The subjects should be representative of the expected user population in terms of age, gender, driving experience and anthropometry. In order to arrive at statistically verified results, it is necessary to use questionnaires which make the subjective evaluation quantitatively describable. Hodder (2013) observes that over a long period of time the investigators often developed their own questionnaire techniques for this purpose. In recent years, however, standardized measurement and evaluation methods have been developed by ergonomists. The advantage of these standardised methods is, among other things, that valid protocols and measurement scales can be used for the evaluation, which also enable a comparison with the results found by another department. ISO 1405-3 (2006) deals directly with the subjective evaluation of vehicles. Table 8.8 shows the rating scales published in ISO. With regard to temperature perception, the scale shown on the left in the first table should normally be sufficient. For extreme environmental conditions, it may be useful to extend this scale from 7 to 11 points (right-hand part of the table). The "uncomfortable" and "sultriness" scales refer to the negative aspects associated with thermal discomfort and sweating (Table 8.9). The preference scale indicates how a person would like to feel. It may happen that a person e.g. reports in his temperature perception that it is warm, but that he/she nevertheless indicates "no change" in the preference scale.

With such attempts it is useful to add an overall survey in which the respondents express their satisfaction and acceptance by answering "yes" and "no". These answers can be used to quantify the degree of achievement across the board.

8.5 Odour

The comfort pyramid presented in ► Sect. 3.3.4 shows that odour is the decisive factor for discomfort perception and can mask all other influences if necessary. Due to the high adaptability of the sense of smell, the first impression plays an important role. If you enter a new vehicle, the perceived smell fundamentally influences the impression positively or negatively. It is therefore extremely important to ensure that odours to be rejected are

Fig. 8.37 Vehicle equipped with gas sensors to objectify the emissions of the components used. (Source: Daimler Global Media Site)

avoided under all circumstances. (See also the comments on “craftsmanship“in ► Sect. 7.9). Objectifying the odour with technical measuring methods encounters considerable difficulties because – due to the evolutionary character – there is a connection of high complexity between the triggering gaseous signal substance and the triggered odour perception (Boeker 2004). Today, there are a number of gas sensors that can be used to objectively determine the evaporation of substances. Since there is no possibility to verify the emotional effect of odours by objective measurements so far, the vehicle companies employ olfactory experts, who decide about the odour emissions of the different materials. For this purpose, the materials to be used in a new vehicle are heated separately in glass containers at 80 °C in order to simulate the maximum evaporation that can occur in a sunlit parked vehicle. After cooling down to 60 °C, the olfactory experts evaluate the odours in the glasses according to a school grading system (1 = odourless ... 6 = unbearable; Laukart 2011). Only materials with an average grade of 1 and 2 are normally considered for series production. The materials to be tested must be manufactured with the tools that are also used for series production. For a final test the complete vehicle will be equipped beside others with gas sensors (see ◘ Fig. 8.37). In detail, an inspection can be carried out according to various standards, for example VDA 276 or FAT AK 26. In addition, the materials used must be tested for possible inhalation allergies and potential skin contact allergies.

Due to the already mentioned high adaptability of the sense of smell, the odour nuisance no longer plays the serious role during the ride as it does when boarding. However, here too unpleasant odours can penetrate the consciousness again and again due to fanning effects. It is a triviality to demand that odours from the fuel system (petrol or diesel odours) must be eliminated in any case. However, the heating system and especially the air conditioning system can also be a cause of unpleasant odours. The condensate generated by the evaporator is separated during operation. However, a residual quantity remains in the evaporator even when the air conditioning system is switched off (Großmann 2013). In particular, if the air conditioning system is rarely operated, mould formation and the like can cause considerable odour and health nuisance. In general, materials which are deposited in the vehicle during use and which secrete perfumes (fruit, food and drink residues, ash residues, stale nicotine odour, dog odours, vomit, etc.) are the subject of odour nuisance, especially in older vehicles. However, unpleasant odours can also be caused by the filters themselves used for air cleaning, if they are clogged and possibly contaminated with moisture for some reason. In the internet different house prescriptions are called, with whose assistance one should be able to eliminate such smells again. A decisive prerequisite for all measures is that the vehicle is thoroughly cleaned beforehand. A treatment with ozone seems to be a particularly good effect. Ozone (O_3) is a radical that reacts among other things with microorganisms, i.e. also with odour molecules, thereby inactivating them. After such ozone treatment, the vehicle must be well ventilated so that the ozone which causes coughing is removed from the vehicle again.

But also an active treatment of the air while driving can have a positive effect on the reduction of odour nuisance. In particular, the positive effect of air ionization is reported here (Taxis-Reischl 1999). Artificial ionisation restores the natural concentration of negative air ions, which is lost when the weather changes or the hair dryer is used, for example. The effect of the electric field can cause suspended matter, especially very small particles such as dust, cigarette smoke, pollen and the like, to be excreted from the air. In addition, negative ionization is attributed to an increase in resilience, concentration, energy and vitality, although this has not been scientifically proven.

The artificial introduction of fragrances into the passenger compartment has also recently been added to the product range by various manufacturers. For example, Citroën offers a fragrance dispenser for the passenger compartment of various vehicles. The fragrance intensity can be regulated and also turned off. There are different fragrances to choose from, so that you can choose the fragrance you want. Mercedes also offers a fragrance dispenser for the new S-Class model, with four fragrances available. A special technology (clocked control) and the use of special fragrances ensure that the fragrance evaporates quickly after deactivation. With the emotional effect that every fragrance has in both the positive and negative sense, however, it must also be borne in mind that with additional scenting, unpleasant existing smells can only be masked, but not eliminated. When the masking fragrance loses its effect, the old unpleasant fragrances regain their effectiveness.

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