SUMMARY

Last year, a new method for the analysis of vehicle interior sound quality, was extended to cover applications to commercial vehicles. With the AVL VOICE system, sound qualities such as the perceived ‘annoyance’ or impressions like ‘powerful’ can be analysed objectively. Due to the fact that in the field of commercial vehicles, the assessment of vibration quality has become equally important, this system is currently being extended by modules for the measurement of vehicle vibration quality. The advantages of this development tool for manufacturers of commercial vehicles lie in the fact that development effort is considerably reduced, quality target parameters are defined and quality ‘benchmarking tests’ can be carried out.

INTRODUCTION

In future, the perception by drivers and passengers of noise or vibration emissions will become an ever more central consideration in the vehicle development process. Vehicle acoustics will develop further in the direction ‘human factor’. As a consequence, there will be a demand for new measurement instruments, with the help of which, manufacturers of vehicles and vehicle components will be able objectively to assess the sound and vibration qualities of their products.

Conventional measurement parameters, such as the A-weighted sound pressure level are, for many reasons, useful indicators for a first assessment of acoustic disturbance situations. In order to comply with the increased demands, it will, however, be necessary to go beyond these simple methods of description, and to define special quality parameters. As far as sound-related quality attributes are concerned, during the past years, sound properties such as annoyance, dynamic, powerful etc. have been analysed. Alongside sound-related considerations, in the commercial vehicle field, the assessment of vibration in the passenger cabin is particularly important. In contrast to most car applications, health risks caused by long-term effects of seat vibrations are of paramount concern. In this field, quality attributes such as the strength of perceptibility or disturbing effect are of primary interest.

Normally the two acoustic aspects of sound and vibration measuring technology are handled separately. Independently of the perception-related connection between noise and vibration, which without doubt exists yet can scarcely be represented in analytical terms, these two important aspects must in future be appropriately harmonised and considered.

For more than 10 years now, AVL has been dealing with the objective recording of sound quality. Starting with the ‘Annoyance Index’ for engine noise [1,2] over the last few years a development tool under the broad heading of ‘Sound Quality Map’ [3,4,5] has been developed, with the purpose of making objective measurements of passenger car interior sound quality. The resulting software package ‘VOICE’ is now being put to practical use by vehicle manufacturers. With this measurement system, it is now for the first time possible to analyse sound qualities like, for example, the level of ‘annoyance’ or the perceived impressions ‘sporty’, ‘luxurious’, ‘reliable’, or ‘powerful’.

The advantages of this development tool are clearly that the acoustic development effort can be significantly reduced, and that quality target parameters can be defined. Thus it is possible to deduce from interim measurements optimising modifications that are targeted on sound quality improvement. In addition, quality ‘benchmarking’ tests can be carried out with this system.

This very successful methodology, originally developed by AVL for passenger car interior noise, is now also finding application in the commercial vehicle sector for objective measurement of vehicle interior sound qualities. In this area the attributes ‘annoyance’ and ‘powerful’ are currently particularly relevant.
In order to meet ever increasing demands, the system is currently being extended by the addition of a module for measuring vehicle vibration quality. The goal of this development is to establish a simple, quick to use instrument for the combined measurement of sound- and vibration-quality. An effective module concept must guarantee the necessary adaptability to the requirements of various vehicle and component manufacturers, as well as vehicle categories.

**NOISE REQUIREMENTS FOR COMMERCIAL VEHICLES**

The requirements for acoustic properties of commercial vehicles largely correspond with those for passenger cars. The reduction of the disturbing effect of vehicle interior noise is also in this case the highest priority goal. In addition, there has been much thorough discussion of driver performance as a function of noise environment [6,7].

First and foremost, for commercial vehicles, an agreeable sound character is sought, that conveys an impression of reliability, refinement and power. The prevailing (core) noise of the diesel engine is advantageous in this context. In this area, ancillaries are often a problem, being perceived as acoustically intrusive components because their noise character doesn’t fit into the expected overall picture.

Similar considerations apply to agricultural vehicles. For tractors from the lowest price sector, compliance with regulatory noise levels is of primary importance, whilst in the middle and upper price bracket, sound quality is an important factor. An additional requirement for tractors is that proper operation of ancillary machinery attached to the vehicle can be monitored acoustically. This requires both an ‘acoustically transparent’ cabin and a low intrinsic noise level from the driving vehicle itself.

The most important difference between cars and commercial vehicles, in terms of the types of acoustic requirements, is however evident in the fact that a car’s ‘image’ must be reflected in its sound quality. In the passenger car sector, manufacturers deliver not just vehicles but often also ‘images’ and their associated ‘lifestyle’. This factor is indeed also present for commercial vehicles, but in a much diluted form. For them, the acoustic requirements for a workplace are clearly at the forefront though, in future, image attributes will gain importance.

In the following figure, important sound quality attributes are separated into their disturbance and image effects.(Tab. 1).

<table>
<thead>
<tr>
<th>Sound Quality Attributes</th>
<th>Disturbance</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loudness</td>
<td>Dynamic</td>
<td></td>
</tr>
<tr>
<td>Annoyance</td>
<td>Powerful</td>
<td></td>
</tr>
<tr>
<td>Roughness</td>
<td>Reliable</td>
<td></td>
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<tr>
<td>etc.</td>
<td>Etc.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Sound quality attributes for commercial vehicles

These attributes have to be treated differently according to vehicle category and operating condition. Significant criteria for differentiation of operating conditions include not only the relative contributions of engine-tyres-wind-other noises but also driver actions. An action by the driver requires acoustic feedback from the vehicle. For example, actuation of the accelerator pedal without corresponding engine response is perceived as unnatural. This reaction can definitely be traced back to a certain degree to habituation. Nevertheless, the qualitative requirements of the passenger cabin have to be weighted differently depending on this effect.

**SOUND QUALITY ANALYSIS**

Commercial vehicle sound quality is assessed in two stages. Using artificial head recordings, in the first stage the psycho-acoustic fundamental parameters and, in the second stage, the actual psycho-acoustic target parameters are calculated (Fig. 1).

Fig. 1: Block diagram - sound quality assessment

The artificial head recordings are principally carried out using the 2-channel head-related partition stereophony system developed by AVL and Joanneum Research.
Using this system, interior noise recordings can be made that are more faithful to the original sound than has been possible with artificial head systems to date [8,9]. Further advantages include above all the use of conventional microphones, ease of calibration of the whole instrumentation chain, and ease of operation [10]. The stereophonic recordings are differentiated according to type of vehicle, test route and measuring point.

In the first stage of calculation (see Fig. 1), psycho-acoustic fundamental parameters are calculated. Examples include loudness, roughness, articulation index, sharpness, tonality, impulsiveness, etc.. These parameters are based primarily on test results using synthetic sounds such as modulated sine waves for example. In the second stage of calculation, the actual target parameters, such as annoyance or implied power, are finally derived from these fundamental parameters. The algorithms applied are based exclusively on sequences of tests of vehicle interior noise, and differentiate according to operating condition.

Of particular significance in the calculation process shown in Fig. 1 is the effective modular concept, i.e. the system lends itself to application-specific adaptation.

Depicted in the following two figures are the calculated noise parameters ‘Annoyance-Index’ and dB(A)-level for 3 stationary operating conditions of different trucks (Fig. 3). As can be seen, the meaning of the these two measures is significantly different. Furthermore, the ‘Annoyance-Index’ provides a more detailed distinction than the dB(A)-level.

Within Fig. 4, a comparison between the calculated noise parameters ‘Annoyance-Index’ and ‘Powerful-Index’ are shown for a full-load operating condition of 4 different trucks. As can be seen, truck number 5 combines the sound attributes ‘powerful’ with low ‘annoyance’.
VIBRATION REQUIREMENTS ON COMMERCIAL VEHICLES

The perception of low-frequency high amplitude noise is always connected with the perception of vibration. When seeking objectively to define commercial vehicle comfort, it was therefore necessary to include vehicle vibration, above all that transmitted to the occupant through the seat, foot-well and steering wheel, alongside examination of noise. Human perception of vibration differs according to frequency and direction, posture, activity and duration of exposure.

The range of frequency between around 0.5Hz and 100Hz is the most significant. Accelerometer amplitudes fall within the range up to around 3 ms$^{-2}$ r.m.s.. Vibration levels above around 1 ms$^{-2}$ r.m.s. are already sufficient to be perceived as extremely bothersome. This level is sometimes far exceeded in commercial vehicles [11,12,13].

Vehicle occupants are mostly exposed to whole-body vibration, i.e. low frequency ‘infra-sound’ frequencies (below around 2Hz) at several contact points (seat squab, back rest, head rest, steering wheel, arm rest, foot-well, etc.) enter and pass throughout the body. The effect of this whole-body vibration on the person manifests itself less as an overloading of this specific sense, but rather more as an irritation of the person in the sense of a reduced feeling of well-being, that can lead to compromised performance or capability. Alongside this psychological irritation, physical damage to the spinal column is observed, above all among full-time truck drivers. Slipped discs occur two to four times more frequently in this group than average. This can be traced back to the fact that lorries exhibit vibration resonances mostly around 4-5 Hz, which corresponds with the fundamental resonant frequency of a seated person. It is not only mechanical parts that can be destroyed by vibration at their resonant frequency; damage to the spinal column can also be attributed to this effect [14,15,16].

Thanks to acoustic improvements to lorries, such as improved cabin suspension for example, significant improvements have already been made in the levels of cabin vibration and associated driver well-being. Nevertheless, the levels of vibration at the man-machine contact points are in many cases still clearly too high. In the light of this fact, it is essential to pay urgent attention to the improvement of comfort where compromised by vibration.

The measurement system described in the following section is aimed at accelerating the analysis and development effort associated with improving vibration quality. Quality target levels and benchmarking make it possible to derive the necessary hardware modifications.

VIBRATION QUALITY ANALYSIS

CALCULATION OF VIBRATION QUALITY

The analysis of the vibration quality is carried out in a multi-stage, modular calculation sequence (Fig. 5).

![Vibration Quality Calculation Diagram]

Fig. 5: Block diagram - vibration quality assessment

The vibration recordings are made on the one hand at vehicle-related points such as seat mountings and, on the other hand, directly at man-machine contact points such as the seat surface or the steering wheel. Depending on different requirements, the following points are used: seat mounting, seat surface, back rest, foot-well, pedals, steering wheel, gear lever, arm rest, etc.. Different test routes, operating conditions and vehicle categories are distinguished by the system operator. For those points that do not constitute direct man-machine contact, transformations to body-contact points are provided. For example seat transfer functions can be applied to seat mounting measurements to estimate the actual vibrations on the seat surface.

The vibration frequency weighting is carried out by filtering with inverse curves of equal vibration comfort. Distinct contact points and vibration directions are filtered differently. In a post processing stage the multidimensional resultant vector is reduced to a single value of vibration quality. On the basis of combinatorial rules, weighted maxima and various types of mean values are offered. By this means, the algorithms can be adapted to different applications easily. Depending on the application, this stage is not obligatory, i.e. multidimensional results of the calculation procedure are supported by the system in addition.

The dependencies between duration of exposure and resulting influence on the occupant are modelled according to a power law. Again, quick adaptations of this processing stage are provided by the system.
SUBJECTIVE TEST SERIES - VIBRATION QUALITY

In order to validate and modify algorithms from literature, it is necessary to carry out subjective tests regarding the attribute 'vibration quality'. These tests were carried out at the AVL acoustic chassis dynamometer. The test persons were driving with the vehicles and assessed the vibration quality using the direct magnitude estimation method. The chassis dynamometer was chosen in order to combine a realistic impression of the vehicle vibrations with an efficient test execution. A questionnaire for 7 man-machine contact points is shown in Figure 6.

After each test, the test persons were interviewed by the test manager in order to optimize the test method. The following items turned out to have a significant influence on the response behaviour of the test persons.

The sitting positions have to be exactly the same for all test persons in order to avoid inaccuracies caused by masking effects. For example, the seat vibrations are judged significantly different when holding the vibrating steering wheel in contradiction to putting the hands on the knees. By holding the steering wheel, the vibration perception of the hands masks the vibration perception caused by the seat.

Another important point is the chosen vehicle ensemble. The vehicles within a test trial should represent approximately the range of existing vibration qualities. By this means the bandwidth of possible judgements is used correctly by the test persons. In case of using, for example, only vehicles with a good vibration behaviour, the worst vehicles within this 'good' ensemble are judged comparatively bad. In that case the assessments of different test trials can only be compared by normalizing the results within each test trial. Nevertheless, in that case inaccuracies caused by the vehicle assembly can not be avoided.

Different man-machine contact points have to be treated differently. For example the vehicle driver is much more sensitive to vibrations of the steering wheel than to the vibrations of the gear stick. First, the steering wheel is held permanently while driving the vehicle, this means that the 'vibration dose' is much higher than from the gear stick. Second the gear stick is intended to be directly connected to the powertrain and therefore the test persons grant a larger vibration level compared to the steering wheel which is not intended to be connected to the powertrain.

Equal to air-borne test series [4], the ability of test persons to assess vibrations is different. Some test persons have strong inaccuracies within their assessments, i.e. they are not able to reproduce their assessments. The subjective judgements of these persons can not be considered for further analysis like the correlation with objective parameters.

Within Fig. 7, a comparison between the subjective ratings of 9 test persons is shown for 4 different vehicles. The standard deviations are typically in the range of 1 to 1.7 points. These results are based on the questionnaire shown in figure 6. The 'overall assessment' (upper left corner) gives the overall impression of the vehicle interior vibration quality.

Fig. 6: Questionnaire Vibration Quality

<table>
<thead>
<tr>
<th>Item</th>
<th>Perceptible</th>
<th>Yes/No</th>
<th>Not Annoying</th>
<th>Very Annoying</th>
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<tbody>
<tr>
<td>Seat Surface</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Left Armrest</td>
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<tr>
<td>Gear Stick</td>
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<td></td>
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<tr>
<td>Right Foot Heel</td>
<td></td>
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<tr>
<td>Right Foot Base</td>
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<tr>
<td>Left Foot Base</td>
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<td></td>
</tr>
<tr>
<td>Left Foot (on floor)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seat Backrest</td>
<td></td>
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<tr>
<td>Seat Surface</td>
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<tr>
<td>Left Foot (on floor)</td>
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OVERALL ASSESSMENT OF VIBRATION QUALITY

Fig. 7: Subjective Assessment - Vibration Quality
Analysis results from the newly developed ‘AVL Vibration Quality Index’ for the operating conditions ‘Low Idle’ and 2nd gear 3000 rpm are shown in Fig. 8. The subjective data of the jury trials (solid line with standard deviations) are compared to the objective i.e. the calculated vibration quality profile (dashed lines). As can be seen, there is a high correlation between the subjective data and the objective vibration quality profile.

Alongside this sound-related assessment method, the evaluation of cabin interior vibration takes on particular significance, particularly in the commercial vehicle sector where vibration has been shown to damage health.

In the past, the two acoustic aspects of sound and vibration measuring technology were handled separately. Independently of the perception-related connection between noise and vibration, which without doubt exists yet can scarcely be represented in analytical terms, these two important aspects must in future be appropriately harmonised and considered.

In order to meet these needs, the psycho-acoustic analysis methodology which proved itself in the practical use was extended by modules for the measurement of vehicle vibration quality. The goal of this development is to establish a simple, quick to use and reliable instrument for the combined measurement of sound- and vibration-quality. First results of this combined system are very promising. An effective module concept guarantees the necessary adaptability to the requirements of various vehicle and component manufacturers.

Future activities will be concentrated on the refinement of the already implemented algorithms towards individual, specific operating conditions and the development of an over-all acoustic quality-index for different vehicle categories. Moreover, the intention is further to extend and stock the acoustic vehicle database, as a basis for comparative quality analysis.

**REFERENCES**


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