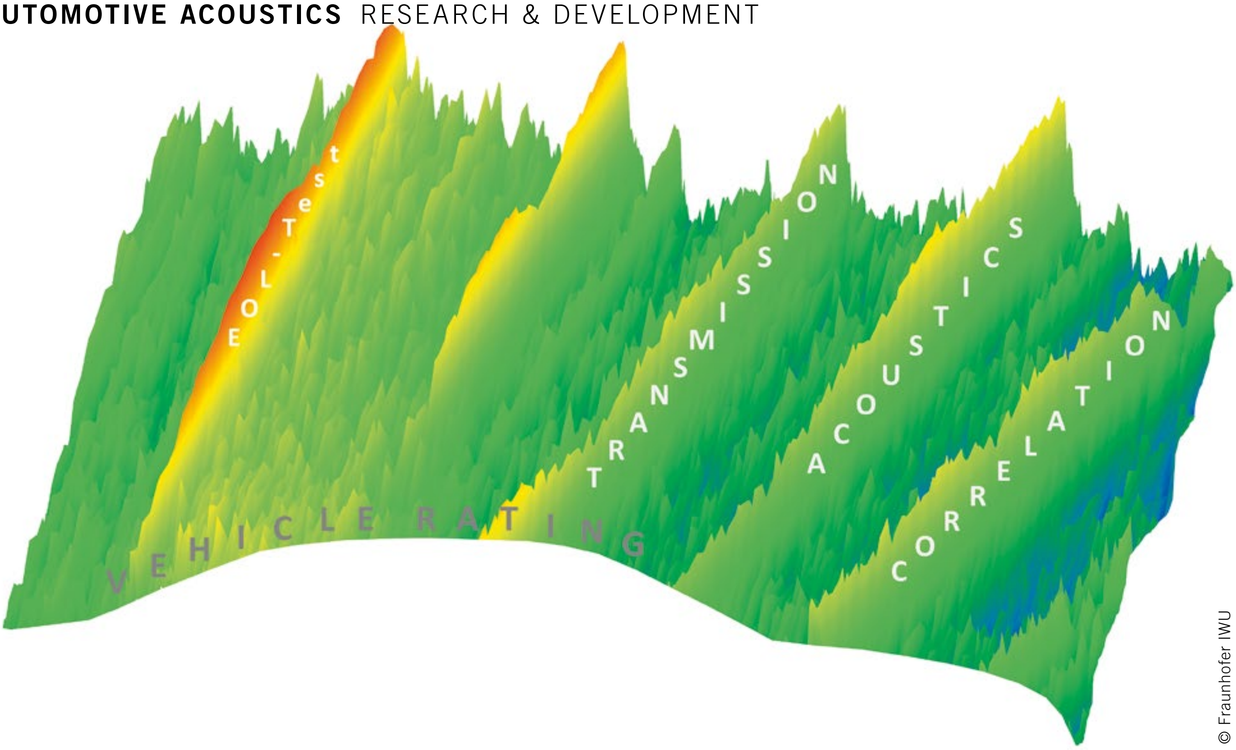

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Transmission Acoustics Between End-of-Line Testing and Vehicle Rating

A research project at the Fraunhofer Institute for Machine Tools and Forming Technology (IWU) utilised a systematic correlation procedure to enhance the prediction of acoustic vehicle quality. The procedure can be applied to predict the NVH behaviour of any vehicle components which are regularly checked on test rigs prior to their installation in vehicles.

INTRODUCTION

Vehicle transmissions as a source of noise and vibration have been the subject of detailed research for many decades. Within that time, the focus with regard to acoustics has continuously changed, from previously airborne noise problems to more comfort-relevant issues today. Electric vehicles and their new sound behaviour as well as decreasing acoustic masking by internal combustion engines emphasise the further research that vehicle manufacturers need to perform. Interior acoustic comfort in vehicles is highly dependent on a sufficient correlation between the acoustic transmission behaviour on a test rig and in the vehicle, since vehicles and transmissions are each subject to statistical variances.

ACOUSTIC TESTING OF TRANSMISSIONS

Originally, end-of-line (EOL) testing was designed only to ensure the correct functioning of a transmission and its components. At a later date, acoustic analysis was also included in EOL testing. A detailed test procedure for the six-speed transmissions considered here has been described in [1].

Once a transmission has passed the EOL test, it is installed in a vehicle. Since the transmission mounting in the vehicle is different from that on the test rig, the acoustic behaviour of transmissions can vary to some extent from the EOL test results. To ensure acoustic comfort, noise and vibration measurements in vehicles periodically take place. If a transmission with vibration levels close to the upper thresholds is unremarkable in a vehicle, the acoustic quality of transmissions with lower vibration levels will usually be guaranteed as well.

However, not all identical vehicle models “respond” with the same acoustic behaviour when they are driven with one and the same transmission. Frequency-dependent variations of up to 10 dB among the transfer functions of identical vehicles are not unusual. Therefore, the acoustic quality and variance of the transmissions coincides with the variance of the vehicles. In order to temporarily limit the test procedures to the transmission influence alone, the following measures with five different transmissions took place using one midsize vehicle.

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The airborne noise inside the cabin was measured using a dummy head on the front right-hand side (passenger side) and using two microphones close to the driver's ears. Additionally, the vehicle was equipped with several accelerometers, which were mainly fitted to the transmission housing and its connecting points to the car body. Speed and engine signals were taken from the on-board diagnostics (OBD) interface.

To begin with, the vehicle was driven in real urban and rural environments. These test drives were mainly conducted by at least two drivers with experience in acoustics, since the 1-to-10 scale rating [3] is exceedingly subjective. It provides the perceived acoustic quality of all transmissions which are rated in all gears under driving and coasting conditions at different engine loads and engine speeds. **FIGURE 1** highlights the rating in gears 2 to 4, where higher values indicate better ratings. Transmission 2, which has almost the best ratings in driving and coasting conditions, is the one with which the vehicle was originally delivered. The other four transmissions were chosen for correlation comparisons. In addition to the driver's judgements, 24 persons rated the acoustic quality of the transmission in listening tests of the pre-recorded signals [2].

After the subjective test drives, the vehicle was driven on an acoustic roller test rig. Without interference from the road and traffic conditions encountered in real situations, the test rig measurements were undertaken at miscellaneous constant acceleration levels, from light load to full load and during coasting.

CORRELATION COEFFICIENTS

FIGURE 2 groups the separate sub-correlations into a scheme in which the target correlation is the quantity between the EOL test result (EOL value) and the subjective driver's rating in the vehicle. It is useful to bear in mind that at least three "internal correlations" occur in the chain, namely the correlation at the same EOL point between the EOL test rig measurement and vehicle measurement (correlation of the same physical quantity), the correlation between the EOL point and the sound pressure level (correlation of the same measurement) and the correlation between the driver's rating and the objective sound pressure measurement in the cabin (objective-subjective correlation). As stated above, due to inherent product variations, no single correlation will always be perfect, even in the simplified case of a linear system. To ensure the sound quality that customers expect, all of the single sub-correlations in the scheme of **FIGURE 2** need to be as good as possible.

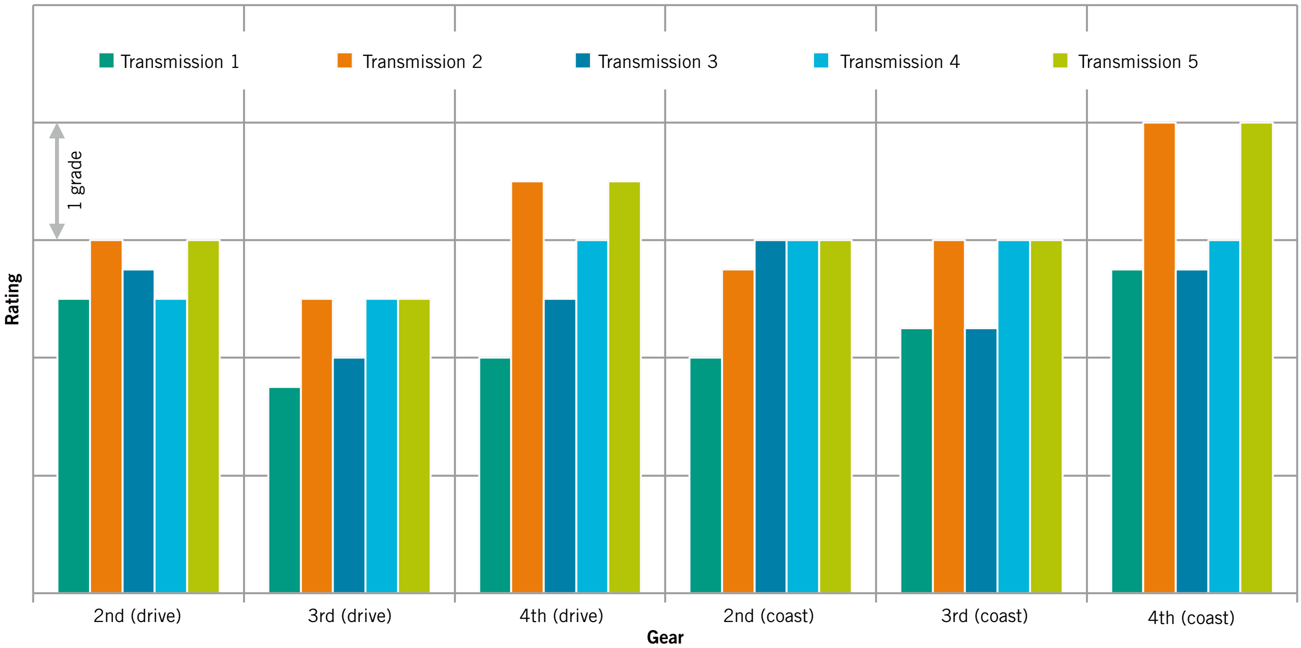

FIGURE 1 Subjective acoustic driver ratings of transmissions during road measurements (gears 2 to 4) (© Fraunhofer IWU)

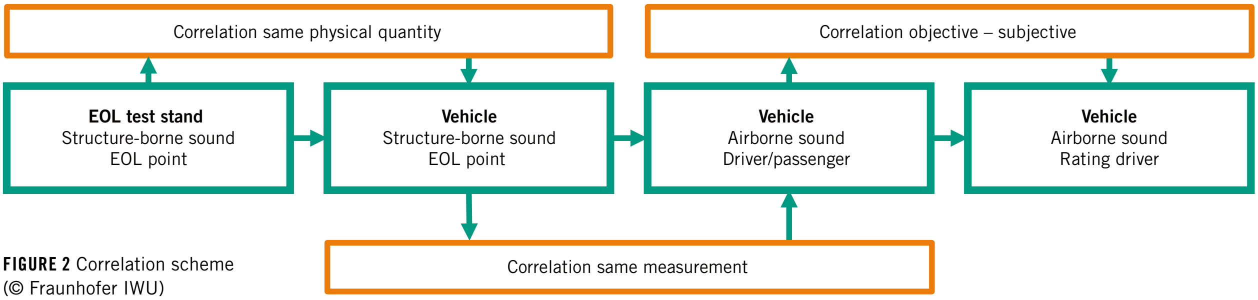

FIGURE 2 Correlation scheme (© Fraunhofer IWU)

The correlation coefficient r_{xy} (often simplified as r) indicates the linear dependency between the two quantities x and y according to Eq. 1.

Eq. 1

$$r_{xy} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})\,(y_i-\bar{y})}{\sqrt{\frac{1}{n}\sum\limits_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\frac{1}{n}\sum\limits_{i=1}^{n}(y_i-\bar{y})^2}}$$

FIGURE 3 shows the acceleration levels of the first gear harmonics (rotational frequency multiplied by the number of teeth on the gear) for the third gear in driving conditions for the EOL test rig and vehicle roller test rig measurements. The speed range and torque are identical between the EOL test rig and the vehicle measurement, with the result that the first two gear harmonics *H1* and *H2* correlate quite well at the EOL sensor position with $r_{H1\ Gear} = 0.85$ and $r_{H2\ Gear} = 0.97$. On the other hand, the levels of the first axle harmonics are comparably low and show only a moderate linear dependency with $r_{H1\ Axle} = 0.30$. It is also obvious that the acceleration level spread of the EOL sensor on the EOL test rig (values on the x-axis) is somewhat higher than the spread of the same sensor during the vehicle measurements on the roller test rig (values on the y-axis). Increasing the speed range in the vehicle will reduce the correlation to the test rig, because the speed range measured at the EOL test rig now covers only a part of the vehicle measurement. Beyond the differences in the speed range at the same torque conditions, there is no distinct correlation when the torque during the vehicle measurements is very different from the EOL test rig measurements.

After the EOL sensor of the test rig has been correlated to the vehicle measurements, the next step is the correlation of the EOL sensor signals in the vehicle to the sound pressure measurements inside the cabin. Calculated again for third gear in driving conditions, the first gear and axle harmonics correlate in **FIGURE 4** with $r_{H1\ Gear} = 0.68$ and $r_{H1\ Axle} = 0.89$, while the dominant audible gear mesh in the vehicle in that working condition is the gear mesh of the axle gears. Although the first gear harmonics exhibit a higher acceleration level compared to the axle harmonics, they are less audible in the cabin because of the frequency-dependent filtering by the vehicle transfer paths. In contrast to the test rig vibration signals, the second gear harmonics *H2* of the five transmissions are not audible inside the cabin, which means that they cannot be correlated to their corresponding EOL sensor harmonics.

Leaving the acceleration levels of the EOL sensor aside and staying at the air-

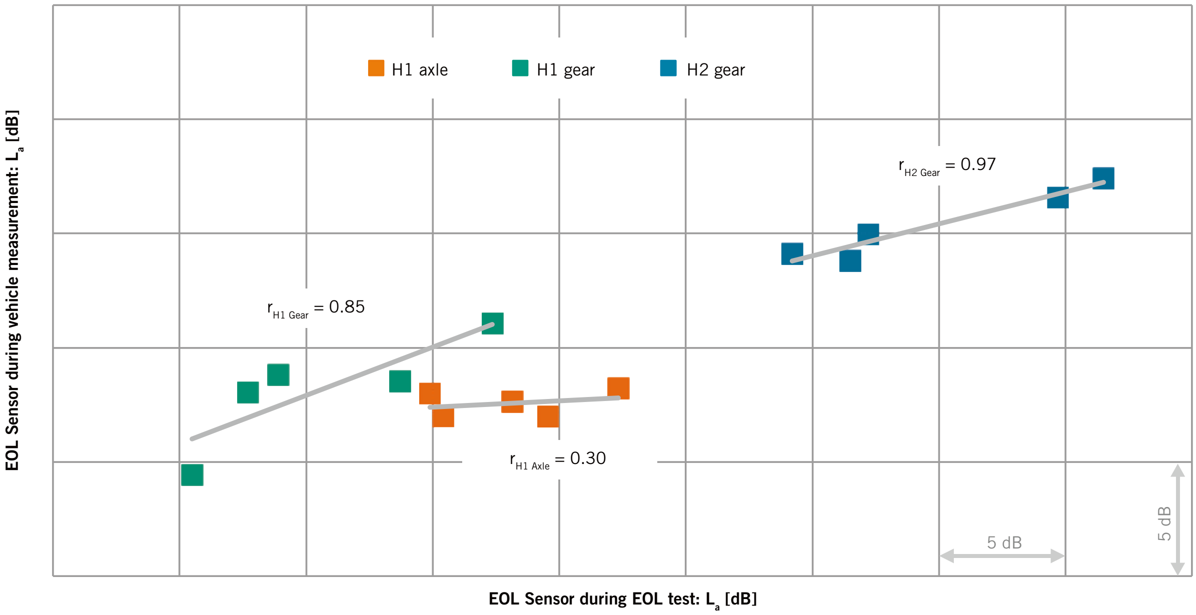

FIGURE 3 EOL-sensor at same working conditions, comparison EOL-test rig and vehicle measurement (3rd gear, drive) (© Fraunhofer IWU)

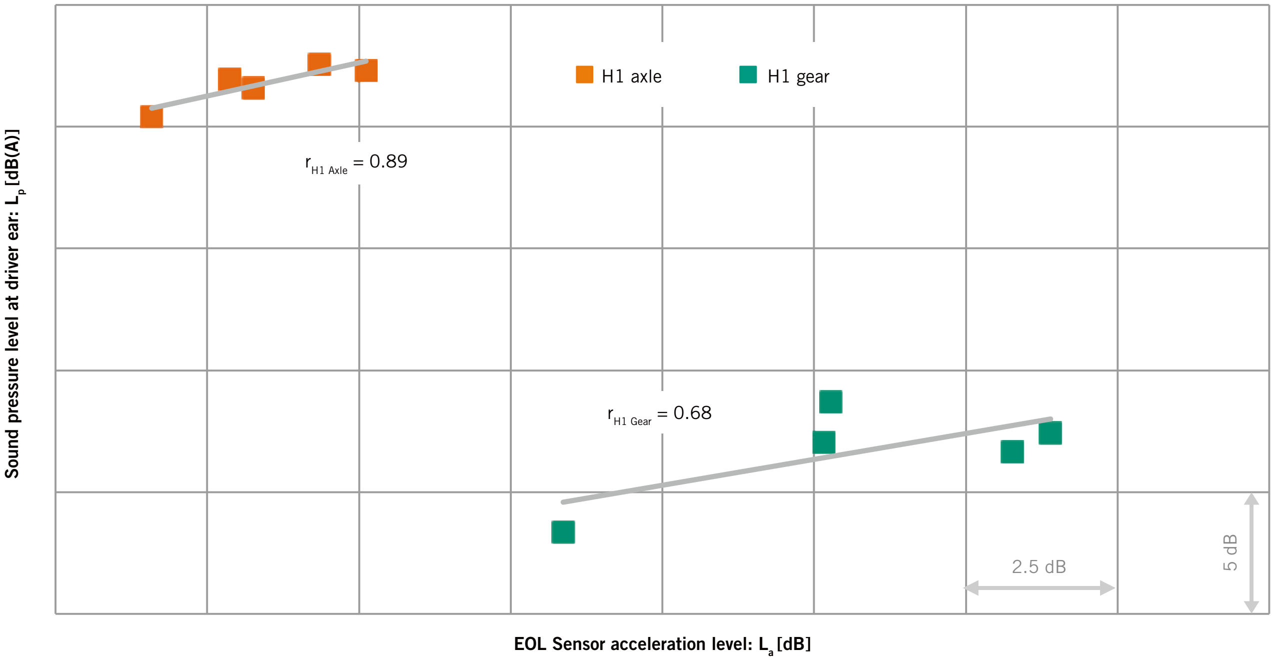

FIGURE 4 Vehicle on roller test rig, comparison EOL sensor and sound pressure level (3rd gear, drive) (© Fraunhofer IWU)

borne sound inside the cabin, the correlation between the objective sound pressure measurement with the subjective driver's rating will complete the calculation of single correlation coefficients. The third gear in driving conditions achieves a good objective-subjective correlation of $r_{Obj.Subj.}$ = 0.77, with the sound pressure level being the energy sum of the axle and gear harmonic levels. The minus sign takes into account that low sound pressure levels correspond to better ratings using higher grades.

TABLE 1 summarises the calculated single correlation coefficients r_{AB} arranged according to **FIGURE 2**. Green colours highlight the expected dependencies of the quantities A and B, while values close to zero do not have a linear dependency between A and B.

From the table, it can be concluded that it is crucial to regard single correlation coefficients always in the same working condition. If this is not done, too many influences on the EOL vehicle chain can dramatically limit the correlation coefficients, which can be seen in the "EOL test rig – driver rating" line. Also, as stated above, it is essential to have at least a sufficient spread of the acceleration levels and sound pressure levels among the transmissions considered. Correlating the sum of single harmonics (row H_{sum}) might enhance the objective-subjective correlation, since the driver usually rates the acoustic quality of the transmission as a whole.

CONCLUSION

A research project at the Fraunhofer Institute for Machine Tools and Forming Technology (IWU) has examined the acoustic quality of vehicle transmissions. The analysis started with five transmissions, which were measured in detail on an EOL test rig and in a vehicle.

A systematic correlation procedure, as a combination of known techniques and new variations, enhances the prediction of acoustic vehicle quality by limiting the process statistics to single sub-correlations. The investigation continues by focusing on the statistical variances at each stage of the chain from the EOL test rig to the vehicle, with the aim of achieving confidence intervals for the correlation coefficients, in which the vehicle influence is observed in comparison to identical and similar vehicles.

Quantity A	Quantity B	H_{1axle}	H_{1gear}	H_{2gear}	H_{Sum}	Name
Test rig (L_a [dB])	Driver rating	0.13	0.4	-0.13	-0.02	EOL test rig – driver rating
Test rig (L_a [dB])	Vehicle (La [dB])	0.30	0.85	0.97	0.97	Same physical quantity
Vehicle (L_a [dB])	Vehicle (Lp [dB(A)])	0.89	0.68	–	-0.54	Same measurement
Vehicle (L_p [dB(A)])	Driver rating	-0.74	-0.62	–	-0.77	Objective – subjective

TABLE 1: Matrix of separate correlation coefficients r_{AB} (© Fraunhofer IWU)

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