

Chapter 2

Sound Optimization for Downsized Engines

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Abstract Today, the number of downsized engines with two or three cylinders is increasing due to an increase in fuel efficiency. However, downsized engines exhibit unbalanced interior sound in the range of their optimal engine speed, largely because of their dominant engine orders. In particular, the sound of two-cylinder engines yields half the perceived engine speed of an equivalent four-cylinder engine at the same engine speed. As a result when driving, the two-cylinder engine would be shifted to higher gears much later, diminishing the expected fuel savings. This chapter presents an active in-car sound generation system that makes a two-cylinder engine sound like the more familiar four-cylinder engine. This is done by active, load-dependent playback of signals extracted from the engine vibration through a shaker mounted on the firewall. A blind test with audio experts indicates a significant reduction of the engine speed when shifting to a higher gear. In the blind test, experts favored the interior sound of the proposed sound generation system and perceived better interaction with the vehicle.

Keywords Downsized engine • Active sound generation • Interaction

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2.1 Introduction

Down-sized engines create a significantly different sound in the passenger cabin in comparison with traditional four-cylinder (and greater) combustion engines [1–4]. The observed differences are mainly caused by the different characteristics of engine orders due to engine structure and combustion sequence. In [5], basic coherences between engine orders and elements of music are discussed. Sound attributes and perceived timbre in regard to consonant and dissonant are treated considering engine order intervals and related harmonics. In addition, it has to be mentioned that the amplitude distribution of engine orders mainly determine the perceived pitch of the overall sound [6].

In regard to reduce the fuel consumption the optimal theoretical gear change should happen at around 2000 revolutions per minute (rpm). Studies under practical conditions show for an examined two-cylinder engine (FIAT 500¹) that the typical gear change occur almost at 4000 rpm.

By comparing measured run-up spectra (cf. Fig. 2.1) of the examined (a) two- and a typical (b) four-cylinder combustion engine under full-load condition we can address the following: Differences of partly missing, reduced or enhanced engine orders can be observed. In case of the two-cylinder engine, the 1st engine order is dominating whereas the 2nd order is most emphasized in case of the four-cylinder engine.

In order to obtain a resulting four-cylinder engine sound in the passenger cabin of the two-cylinder vehicle, we have to acoustically introduce or eliminate several defined engine orders. Subsequently, possible strategies are presented and their feasibility under practical considerations is discussed. Out of these strategies, one promising approach has been selected and implemented. The implementation yields the desired magnitude profile of the most relevant engine orders.

Series of tests show that the average gear change is positively influenced. The switching moment is moved towards lower rotational speeds, i.e. the gear change is executed at lower rpm.

Moreover, subjective evaluation of the drivability considering dynamic handling aspects exhibit improved results without modifications on the vehicle itself but solely acoustically supporting a four-cylinder sound in the passenger cabin.

Conducted experiments partly took place at public transport routes under normal road traffic conditions and at a special dedicated test track.

¹The test car was a Fiat 500 0.9 TwinAir Turbo with 82hp built in 2009.

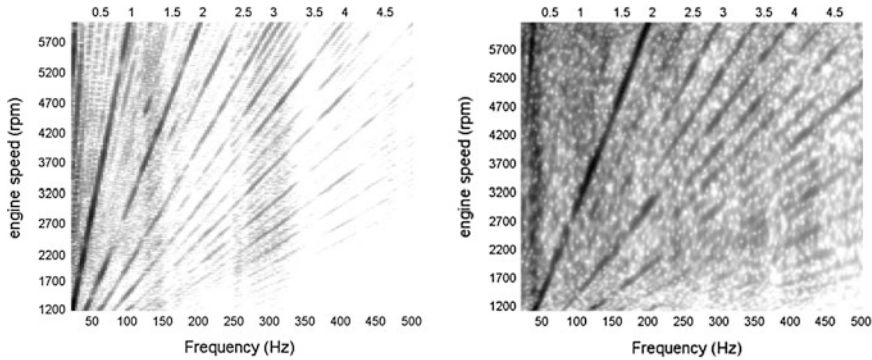


Fig. 2.1 Measured sound pressure spectra in passenger cabin. Spectra are normalized to the corresponding engine order maxima and depicted sound pressure dynamic is limited to 50 dB. Run-up under full-load condition (*left*) at the top, of examined two-cylinder gasoline engine (FIAT 500) and (*right*) at the bottom, an arbitrary four-cylinder gasoline engine (AUDI A3). At first glance, dominant 1st order in the upper and 2nd order in the lower case will be easily recognized

2.2 Strategies

2.2.1 Additional Synthesized Engine Pulses

A straight forward method would be the playback of a four-cylinder sound by the audio system of the car, whereby the played back sound has to mask above all the first order of the original engine sound. However, this means that the level of noise in the car interior increases. Best masking is achieved when every second pulse of the played back sound coincides temporally and locally with the original pulses, at least at the position of the driver. Besides the required complexity of the template related sound synthesis of the additional pulses in order to satisfy a natural-sounding result, both temporal and local coincidences within the vehicle would overexcite a practical solution (cf. [7] for an exhaustive discussion about theoretical limits).

2.2.2 Active Noise Cancellation

To get a controlled condition in the car interior, we want to cancel the engine sound or noise in the frequency areas, where we later want to add the relevant engine orders of a four-cylinder car. This means that we have to cancel the noise in the band between 20 and 80 Hz. Therefore, it is important to know, if we are basically able to cancel the frequencies in that area. For this reason we conducted sweep measurements in the passenger cabin on various positions (with a 10 cm spaced lattice microphone array and a dummy head) in the supposed movement area of the head of the driver and the co-driver.

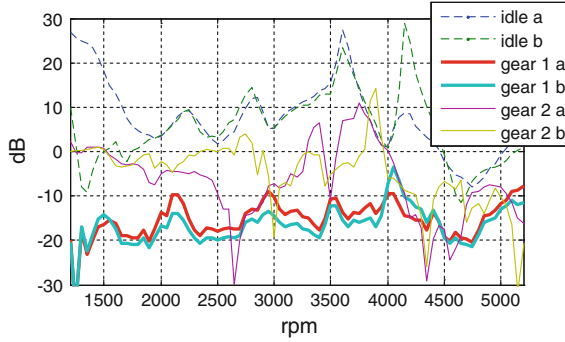


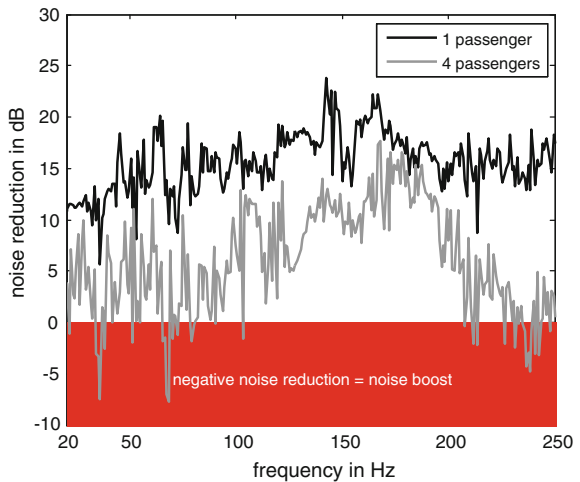
Fig. 2.2 Amplitude of the 1st engine order after noise cancellation. The mean amplitude- and phase relation of two trials (a and b) in the 1st gear is taken as ANC filter. For the two trials in the second gear and especially in the idle mode, there are 1st order enhancements, because the transfer paths from the engine to the car interior are not consistent over different gears and loads

A detailed description of these executed measurements, as well as documented measurement setup, procedure and discussion of the evaluated data in regard to Active Noise Cancellation (ANC), can be found in [7].

Examining the measured sound pressure level at the driver position for various run-ups, considering different gears and loads, attested a huge variability of the transfer function from the engine to the car interior (cf. Fig. 2.2). As a consequence, in order to perform a reliable ANC system, the coupling of the gearbox and the powertrain has to be considered in real time applications.

Moreover, different operating and occupation states will result in different transfer functions as well. If these states are not considered in the ANC coefficients, noise boost can occur, cf. Fig. 2.3 and [7]. Thus, successful ANC requires fast

Fig. 2.3 Maximum noise reduction with 1 or 4 passengers using theoretical ANC coefficients optimized for the condition with 1 passenger only (4 loudspeakers + shaker)



adaptation that is continuously informed by multiple distributed error microphones in the car interior and sensors capturing the engine's vibrations.

2.2.3 Engine Order Emphasis

In order to enrich the existing two-cylinder engine sound in the passenger cabin and result in a perceived four-cylinder engine sound the important engine orders (e.g. 2nd order of the two-cylinder engine sound) are emphasized. This is done by capturing the actual engine load condition, amplifying the relevant (missing) frequency bands, and playing them back to the passenger cabin.

To capture the operational-dependent properties of all relevant engine orders, proper sensor locations have to be determined.

In Fig. 2.4, the Campbell diagram of the most promising and finally selected sensor position is shown. The fully occupied spectrum provides a good chance to retrieve all required engine orders that might be missing in the observed car interior sound.

The playback of the generated sound should be perceived to be coming from the engine (active sound generation, ASG). Therefore, a shaker at the firewall and four loudspeakers of an ordinary in-car sound system were used. According to the carried out measurements described in [7], the shape of the sound field produced by the shaker is more balanced than one produced by the loudspeakers, albeit the shaker's frequency response is limited to low frequencies. As sound field control is

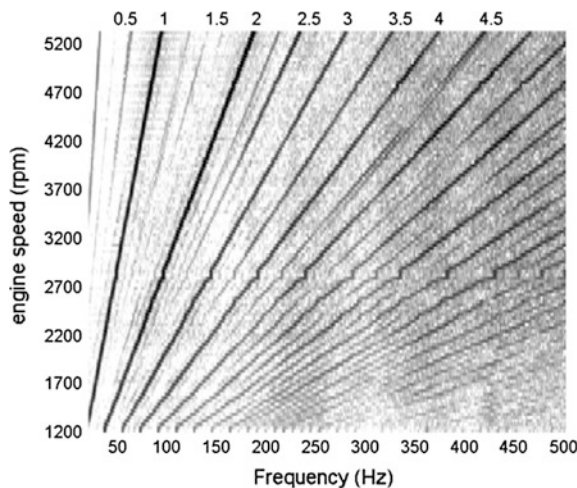


Fig. 2.4 Run-up spectrum under full-load condition of examined two-cylinder gasoline engine (FIAT 500). Measurement with accelerometer sensor mounted on a specific engine position. The resulting Campbell diagram exhibit distinct integral multiple engine orders, as well as half and partly quarter engine orders

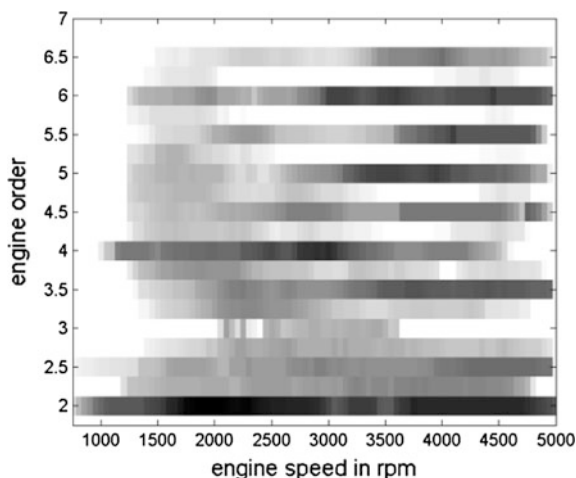


Fig. 2.5 Normalised amplification patterns of individual engine orders. Depicted dynamic range is limited to 50 dB, whereby black indicates 0 dB and white -50 dB or less. Enhancement of the partly missing engine orders is dependent of engine speed (rpm). Various load conditions are tackled via capturing at the specific sensor position mounted on the engine. Transfer functions of sensor and shaker are considered as well

in fact more interesting at those frequencies, our study suggests using shakers for active sound generation rather than loudspeakers.

In order to adjust the required amplification for each of the missing engine orders (cf. Fig. 2.5) the balance of the actual and target Campbell diagram has been determined. Furthermore, the transfer functions of the capturing sensor and reproducing shaker/loudspeakers have been measured and considered, too.

The amplification of the relevant missing engine orders can be controlled via a graphical interface running under the software Pure Data.²

The amplification of the engine orders also depends on the engine speed. Figure 2.5 shows the emphasis of the engine orders over the engine speed for the considered two-cylinder car (FIAT 500) to obtain the intended four-cylinder sound.

In Fig. 2.6 the principle implementation concept is sketched for one engine order. Missing engine orders are obtained from the above introduced acceleration sensor signal via dynamic band-pass filters.

The required extremely narrow-band filter characteristics are implemented with cascaded low- and high-pass filters. In order to prevent audible clicks (artefacts) during dynamic adjustments the subsequent sections are adapted at different time stamps (cf. indicated timing periods in (ms) in Fig. 2.6). Therefore, artefacts will

²Pure Data (Pd) is a visual programming language for creating interactive computer music and multimedia works. Pd is an open source project with a large developer base working on new extensions. It is released under a license similar to the BSD license. It runs on GNU/Linux, Mac OS X, iOS, Android and Windows.

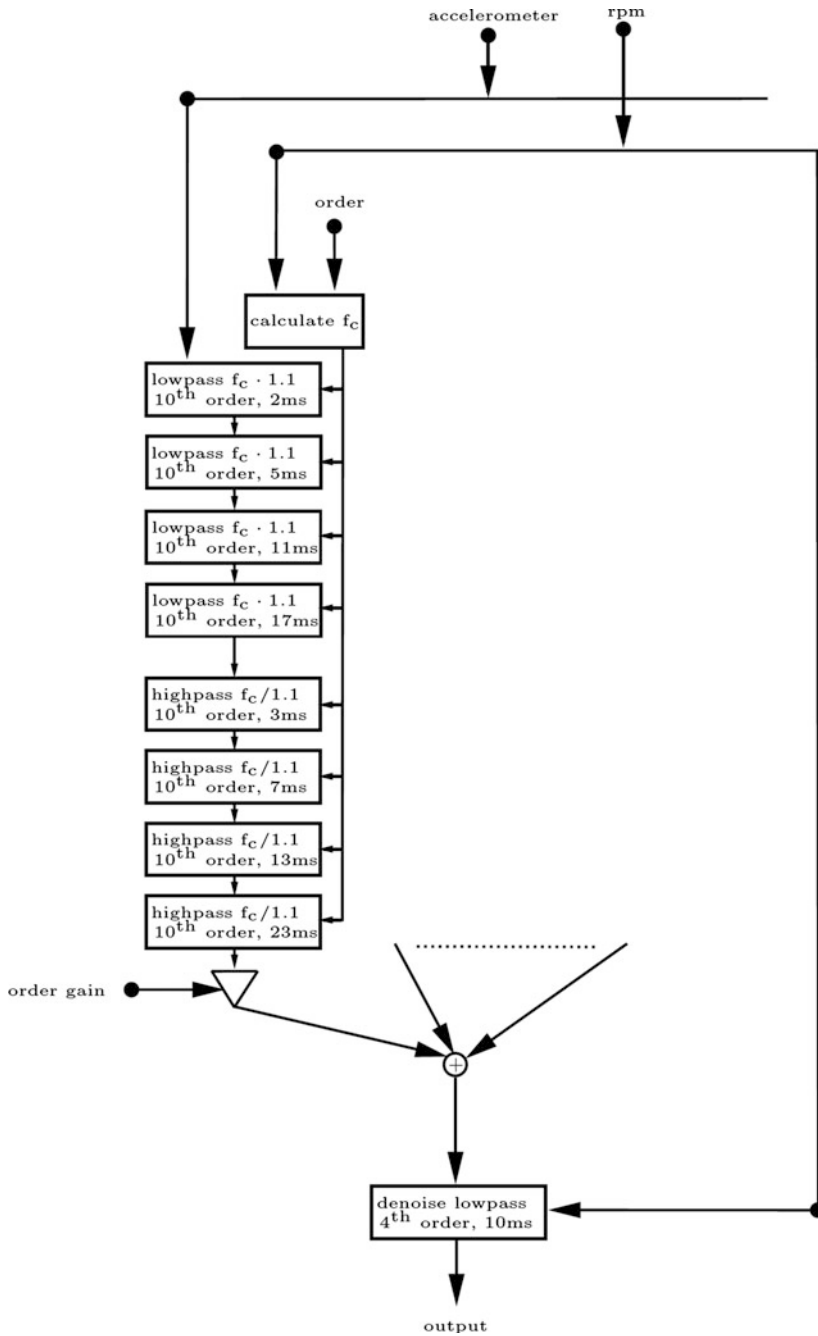


Fig. 2.6 Block diagram of the engine order enhancement. Four 10th order low- and high-pass filters extract the predefined orders from the accelerometer signal from the engine

result in a low-frequency band-limited noise that can be further reduced with a subsequent low-pass filter (denoise-stage).

Amplification of the individual engine orders takes places as depicted in Fig. 2.5. Dynamic adaptation towards engine speed is tackled with the rpm signal from an inductive voltage transformer mounted on the drive line and measured entries in a table look-up scheme.

Playback in the passenger cabin mainly employs with the shaker at the firewall and the in-car sound system. As loudspeakers, the 4 loudspeakers of the Fiat's stock in-car sound systems were used on an Alpine PMX F460 4-channel amplifier. The shaker was a Sinuslive Buss-Pump II on a Raveland XCA-400 4-channel amplifier.

2.3 Resulting Sound

In Fig. 2.7, the measured spectra of a run-up under full-load condition are shown. The upper spectrum (a) depicts the two-cylinder sound in the passenger cabin. Spectrum (b), at the bottom, exhibits the resulting modified sound with active sound generation in parallel.

A visual comparison of both spectra lets distinguish a significant enhancement of the 2nd engine order at least within the important speed range from 1500 up to 3000 rpm.

Within this speed range the active sound generation causes an increased loudness level. However, the resulting loudness trend over engine speed (rpm) is much more stable and balanced (cf. Fig. 2.8). In addition, the resulting loudness trend over engine speed much better fits to the intended four-cylinder target sound.

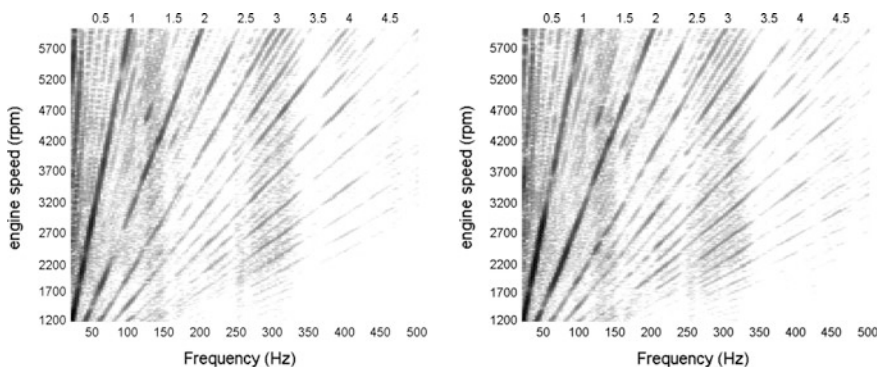
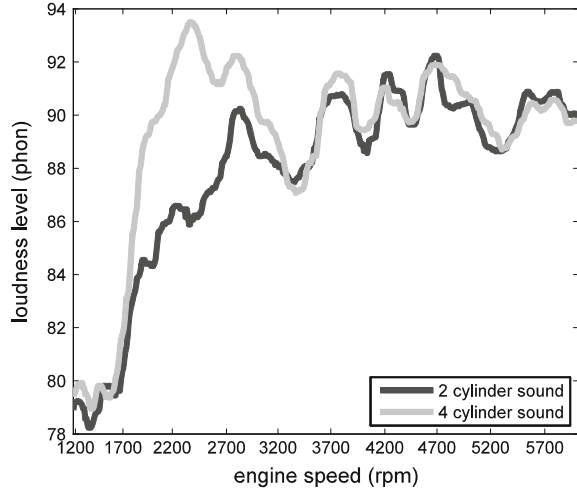


Fig. 2.7 Measured sound pressure spectra in passenger cabin. Spectra are normalized to the corresponding engine order maxima and depicted sound pressure dynamic is limited to 50 dB. Run-up under full-load condition (*left*) at the top, of examined two-cylinder gasoline engine (FIAT 500) without active sound generation and (*right*) at the bottom, resulting sound spectrum of examined engine superimposed with active sound generation

Fig. 2.8 Measured loudness trend over engine speed for both real two-cylinder sound (*black curve*) and resulting sound with active sound generation mimicking the target four-cylinder sound (*gray curve*)



2.4 Experiment

2.4.1 Method

The implemented sound enhancement from the previous section has been evaluated by 10 subjects. The subjects were asked to drive the test car at two different dates. For both rides, the subjects drove the same two-cylinder car (FIAT 500), but for one of the two tours, the four-cylinder sound was played back. However, the subjects were not informed about the changes made to the car—solely active sound generation was activated or turned off. Conducted experiments partly took place at public transport routes under normal road traffic conditions and at a special dedicated test track. Although the subjects were asked to drive rounds on a test circuit, only the way to the test circuit is considered for the analysis of gear shifts in the following. This specific test design is caused by the fact that the driving behavior under common conditions shall be investigated.

Arrived at the test side, the subjects had to perform a reduced AVL standard drivability test procedure at the test circuit. Afterwards, the subjects were asked to evaluate the car in terms of drivability and acoustical aspects (cf. Fig. 2.14).

2.4.2 Test Track

The route is presented in Fig. 2.9 and has a length of 16.1 km from which 4.5 km are city roads and 11.6 km are outside the city limits. The vehicle speed over the driven distance is shown in the subsequent Fig. 2.9 for all subjects. From the CAN-bus of the car, the consumption, the vehicle- and the engine speed were recorded as depicted in Fig. 2.10.

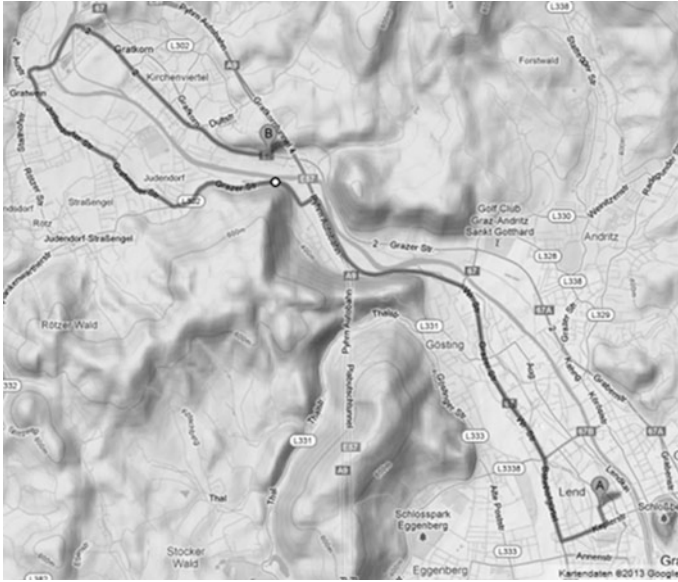


Fig. 2.9 The test track leads from AVL in Graz to the test circuit in Gratkorn. It has a length of 16.1 km [map from Google Maps: <https://www.google.at/maps>]

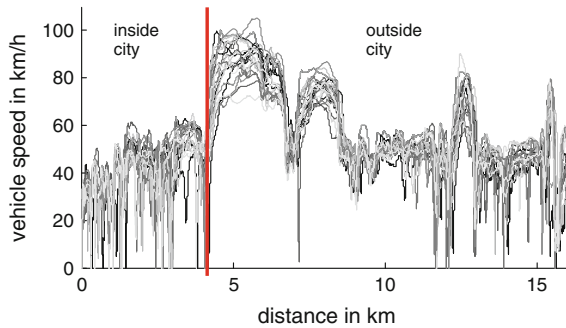


Fig. 2.10 Vehicle speed over driven distance. The first 4.5 km are driven within the city limits with a maximal speed of 60 km/h. The remaining distance is driven outside the city limits with maximal speed up to 100 km/h

Finally, after both tours, subjects were asked to fill in a general form about date of driving licence, approved driving licence categories, driving experience (amount of kilometres), driving performance per annum, ownership of a car (in case of affirmation: brand, driving performance p.a., typical driving profile: city, country side, motorway).

2.4.3 Engine Speed at Gear Shift

Besides a subjective evaluation of the test persons, the driving test investigated if the subjects shift into higher gears at lower rpm. Since no real time information about the gear is available, the gear shift event (in regard to the fuel consumption: only into higher gear) has to be detected over a discontinuity in the ratio between the engine speed and the vehicle velocity. Figure 2.11 shows this gear-shift ratio together with the normalized engine speed in rpm.

More interesting is the rpm-value at which the subjects shift into the higher gears. Therefore, we determine the maximum engine speed in the last 2.5 s before every gear-shift as sketched in Fig. 2.12.

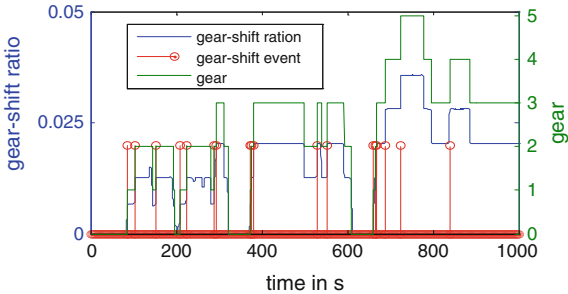
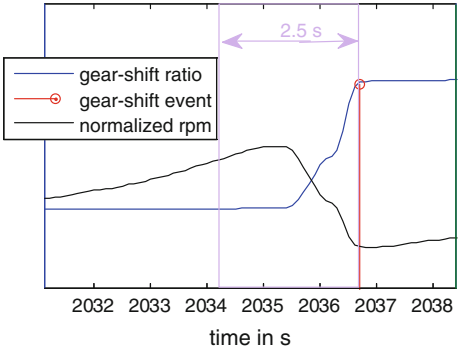


Fig. 2.11 The gear shift is detected over discontinuities in the gear-shift ratio, which is the ratio between the engine speed and vehicle velocity

Fig. 2.12 At every gear-shift event, the maximal engine speed in the last 2.5 s is determined



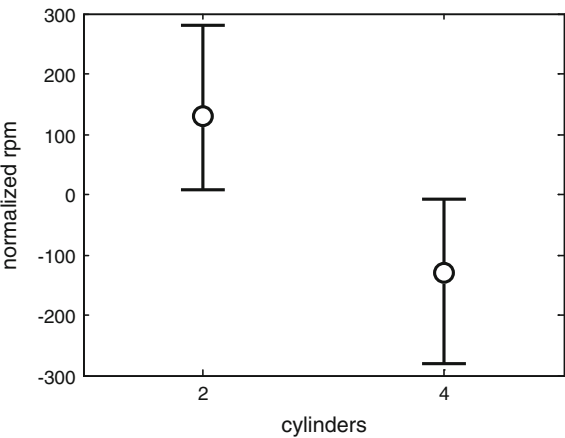
2.5 Results

For every subject and for every gear, these determined engine-speeds are compared between the test drives with the two- and the four-cylinder sound. In the fourth gear, there is a significant difference in the maximal engine speed between the two- and the four-cylinder sound. Figure 2.13 shows that the subjects in median shift at about 260 rpm earlier into the 4th gear when driving with the four-cylinder sound. For all other gears, no statistically significant improvement can be observed. This can be explained because the first three gears are mainly used in city traffic, where gear shifting depends on outer circumstances and the 5th gear has hardly been used on this test track. The shift into the 4th gear however mainly depends on personal decisions. The result of the test thus supports the hypothesis that the sound of the car is a major indication for the gear shift.

The same tendency can be observed when examining the average engine speed in each gear for individual subjects, cf. Fig. 2.14. The average speed in the 2nd and 4th gear decreases in the case of the four-cylinder sound. Moreover, subjects spent more time in the 4th gear.

After both test drives, the subjects were asked to evaluate the car in terms of drivability and acoustical aspects. The mean evaluation of all aspects is shown in Fig. 2.15. For most aspects, no significant difference can be observed. However, in all cases with significant differences, the car with the four-cylinder sound was perceived as better. Especially the car interior noise was evaluated as better with a p-value <0.01. It is notable that also the tip-in and tip-out are perceived as better when driving with the four-cylinder sound, although no changes have been made to the engine itself. This again emphasizes the importance of the engine sound for the driving experience and that a four-cylinder sound is perceived as having better quality than a two-cylinder sound.

Fig. 2.13 Engine-speed difference when subjects shifted to the fourth gear for the test car with a two- and a four-cylinder sound



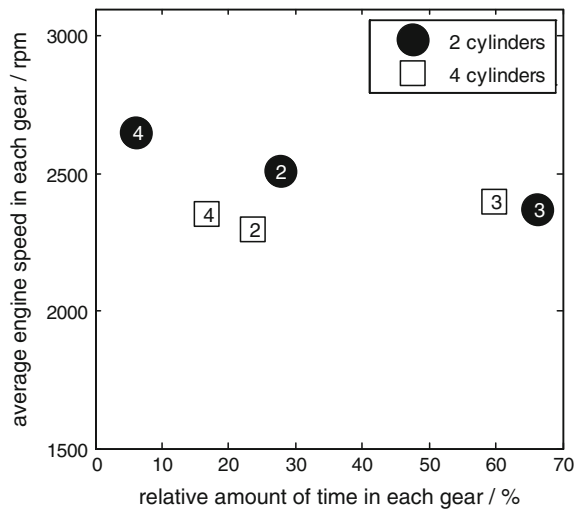


Fig. 2.14 Average engine speed in each gear and relative amount of time in each gear for the test car with a two- and a four-cylinder sound, exemplarily for one subject

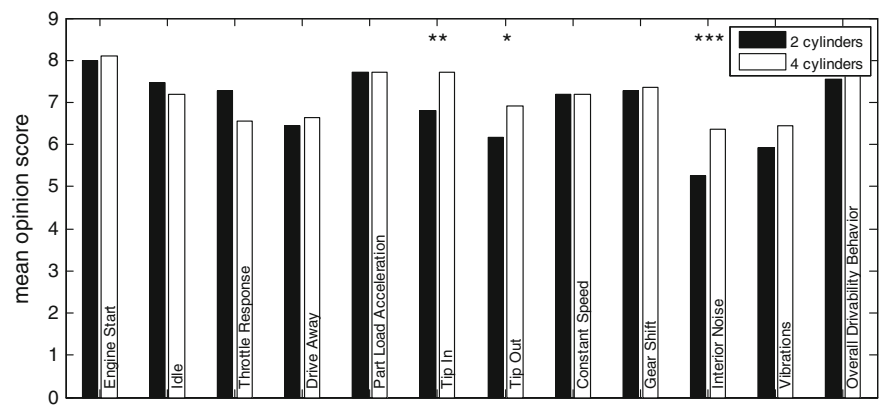


Fig. 2.15 Mean results of the questionnaire, asterisks indicate the significance level of a Mann–Whitney U-test: * p < 0.1, ** p < 0.05, ***p < 0.01

2.6 Conclusion

Three strategies were investigated to create a two-cylinder sound. In all strategies a shaker at the firewall is used as additional sound source. The first strategy is to play back synthesized combustion pulses, the second is to cancel the 1st engine order by destructive superposition and the third is to enhance engine orders which emphasises a four-cylinder sound.

For the first strategy, we recorded combustion pulses up to 3000 rpm in order to extract template pulses for the synthesis playback. However, for a single full-load condition already 40 templates would be necessary to explain 90 % of the variations in the combustion pulses. Moreover, to achieve perfect masking the played back sound must fulfil temporally and locally constraints that can be hardly tackled at all passengers positions nor in various realistic conditions at the driver position itself.

For the second strategy, it is important that the engine as well as the shaker on the firewall create a homogeneous sound field in the car interior especially around the position of the driver. We therefore measured the phase relation between the shaker and specific positions in the car interior with a 24-channel microphone array in a dimension of 50×30 cm. The phase deviations in the measured area are small enough for the relevant frequencies (which are lower than 100 Hz). However, the amplitude and phase relation between engine vibrations and the interior noise is not consistent over different gears and loads. A mean amplitude and phase relation has to be chosen since information about the current gear is not available in real time. In some cases, this mean amplitude and phase relation leads to amplification instead of a cancellation of the 1st order.

The more promising strategy of the four-cylinder sound enhancement has been evaluated in a test scenario. Ten people drove a test track once with the original two-cylinder sound and on a different date with the four-cylinder sound enhancement without being informed about the changes made to the car. The subjects found that the tip-in and tip-out responded better in the car with the four-cylinder sound and they perceived the sound as better. The recorded rpm also show that the subjects shifted into the 4th gear at a lower rpm with the four-cylinder sound as. For the other gears, there are no significant differences between the rpm values because the first three gears are mainly used in city traffic, where gear shifting depends on outer circumstances and the 5th gear has hardly been used. The shift into the 4th gear however mainly depends on personal decisions. The result of the test thus supports the hypothesis that the sound of the car is a major cue for the gear shift. Furthermore, the proposed active sound generation system will also improve the driving comfort in case of automatic transmission with downsized engines.

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