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Zero-Emission Vehicles Sonification Strategy Based on Shepard-Risset Glissando

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Abstract. In this paper, we present a sonification strategy developed for electric vehicles aiming to synthetize a new engine sound to enhance the driver's dynamic perception of the vehicle. We chose to mimic the internal combustion engine (ICE) noise by informing the driver through pitch variations. However, ICE noise pitch variations are correlated to the engine's rotations per minute (RPM) and its dynamics is covered within a limited vehicle speed range. In order to provide the driver with extended pitch variations throughout the full vehicle speed range, we based our sonification strategy on the Shepard-Risset glissando. Such illusory infinite ascending/descending sounds enable to represent accelerations with significant pitch variations for an unlimited range of speeds. In this way, it is possible to conserve the metaphor of ICE noise with unheard gearshifts. We tested this sonification strategy in a perceptual test in a driving simulator and showed that the mapping of this acoustical feedback affects the drivers' perception of vehicle dynamics.

Keywords: sonification, automotive acoustics, multisensory perception

1 Introduction

Car manufacturers are widely expanding their production of electric vehicles, commonly called 'Zero Emission Vehicles' (ZEV), to reduce greenhouse emission gases. If the development of electric motorizations can help improve the automotive environmental footprint, these quieter motorizations also lead to a radical change in the acoustic feedback due to the loss of the engine noise.

This issue has largely been studied in the case of outside feedback alerting pedestrians that a vehicle is approaching [1,2,4,8,10]. At low speeds, when wind and rolling noises are very low, the loss of Internal Combustion Engine (ICE) feedback makes electric vehicles inaudible for pedestrians, leading to potentially dangerous situations. Standards are now imposed to car manufacturers to equip their vehicles with Acoustic Vehicle Alert System (AVAS) in order to generate sounds that enable pedestrians to hear such vehicles.

In the present study, we will focus on inside acoustic feedback. The reduced noise level in the passenger compartment has become a strong selling argument for ZEV, being associated with passenger comfort. However, the ICE noise is the most significant source of information for the driver and its loss can be detrimental for driving. Horswill and Plooy [11] indeed showed that drivers underestimate their speed when the acoustic feedback loudness is reduced. Quieter motorizations can thus deteriorate the drivers' perception of speed and encourage them to drive faster. We also showed in a previous work that the loss of ICE noise could affect the drivers' perception of acceleration [6]. ICE noise is indeed the main acoustic information related to the vehicle dynamics and its loss may influence the driver's motion perception. It has also a strong emotional power and its loss can have a negative impact on the perceived sportiness, driving pleasure and brand identity of the vehicle [22].

With the development of electric motorizations, we thus loose a significant part of the dynamic and emotional acoustical information. To compensate this loss, we developed a sonification strategy to synthetize a new engine sound for electric vehicles to replace the information usually conveyed by engine noise in ICE cars.

2 Sonification Strategy

Adaptive sonification is a powerful tool to inform the user in an action-perception loop [3,5,12,14,20,24], and especially in a driving task in which the sight must be dedicated to the road. We used sonification to inform the driver about the vehicle dynamics to enhance his/her motion perception. With the vanishing of internal combustion engine (ICE) noise, zero emission vehicles (ZEV) also become an amazing playground to shape the soundscape of these quiet(er) vehicles with sonification. Thanks to the freedom offered by sound synthesis, we can design sounds that give character to the vehicle, with a technological or even futuristic dimension. Sonification is therefore becoming a key for car manufacturers to develop acoustic brand identities and tools to enhance the perceived quality inside the cabin.

As a first step, we chose to set aside the esthetic dimension to work on the dynamic feedback and the acoustics invariants of vehicle dynamics. We built our sonification strategy by mimicking time-varying acoustic attributes of the ICE noise to achieve a natural and intuitive way of informing the drivers.

2.1 Objectives

We decided to inform the driver through pitch variations, similarly to the ICE noise behavior, in order to convey information on vehicle dynamics through the same levers as ICE noise, but with its own 'electric' personality. In the case of an ICE noise, the pitch is correlated to the engine rotations per minute (RPM) which describes a piecewise linear function of vehicle speed. During acceleration, the pitch grows up to the higher RPM of a given gear ratio before falling down at each gearshift. The ICE pitch range is thus covered several times over the whole vehicle speed range and remains quite limited within a pitch range of around 2.5 octaves.

In the case of electric vehicles, the situation is different, since there are no gearshifts, as if the whole vehicle speed range was covered by only one gear. In this case, RPM is proportional to vehicle speed. We chose to directly map the pitch to speed, which seemed more relevant for drivers. However, the pitch-based sonification strategy cannot be directly transferred from RPM-dependency in ICE vehicles to speed-dependency in ZEV for several reasons:

- creating frequency drops to simulate gearshifts despite physical reality would be confusing for the driver (fig. 1 (1)),
- keeping the pitch range of an ICE noise to cover the whole vehicle speed range, would infer too low pitch variations for low accelerations and provide information to the driver that would not be sufficiently precise to estimate the vehicle acceleration (fig. 1 (2)),
- duplicating the pitch variation of an ICE noise 5 times to 'unwrap' the pitch and cover the whole vehicle speed range would ensure precise information for low accelerations, but would give too high-pitched sounds at high speeds (Fig. 1 (3)). Choosing a 2.5 octave range for around 30 km/h would even lead to inaudible sounds.

We answered this issue by using the Shepard-Risset glissando illusion of continually ascending or descending pitch. With these peculiar sounds, we can produce large pitch variations to precisely inform the driver, even for low vehicle accelerations while keeping a constrained pitch for the whole speed range of the vehicle.

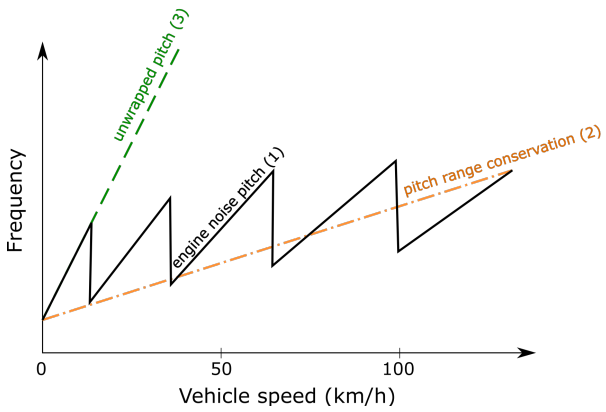

Fig. 1. Schematic representation of the evolution of fundamental frequency of ICE noise over vehicle speed (1). (2) and (3) represent the pitch strategies of pitch range conservation and unwrapped pitch to map pitch to vehicle speed in ZEV.

2.2 Shepard-Risset Glissando Based Sonification Strategy

Principle

Previous experiences within both the visual and auditory domain have revealed the importance of perception of local motion that can be exploited to create both visual and auditory illusions. A well-known example of this effect in the visual domain is Penrose's endless staircase [15]. In the auditory domain Shepard [23] was the first to

create this illusion by synthesizing a bank of complex tones and applying a fixed, bell-shaped spectral envelope that determined the amplitudes of the harmonics.

Shepard tones [23] are made of a sum of ten sinusoidal components each separated by an octave interval. For instance, for a tone corresponding to a C, the tone will consist of the frequencies C1, C2, …, C10. The amplitudes of the components are determined by a fixed, raised cosine function that covers the whole frequency range (10 octaves in Shephard's experiment) as represented in Figure 2. This amplitude function is linked to the log frequency. From these tones, we can construct a scale by shifting all the sinusoidal components by a certain fraction towards higher octaves without moving the amplitude window as represented by the dashed lines in Figure 2. We thus will get a C# with a 1/12 octave shift of each component, a D with another 1/12 octave shift, etc. At the last step, when the comb has been shifted by one octave, the cycle will start again with the C, and the first nine components will replace the components which were one octave higher before shifting (C1 becomes C2, C2 becomes C3…). The previously highest component (C10) drops out the envelope and a new component is introduced one octave below the previously lowest component (C10 thus becomes C1). A shift of one octave thus leads to the exact same note, forming a cyclic scale. Due to the window shape, intermediate frequencies (in the middle of the window) will always dominate while the higher and lower frequency components gradually taper off (vertical solid lines, Figure 2) so that the repetitions are not perceived.

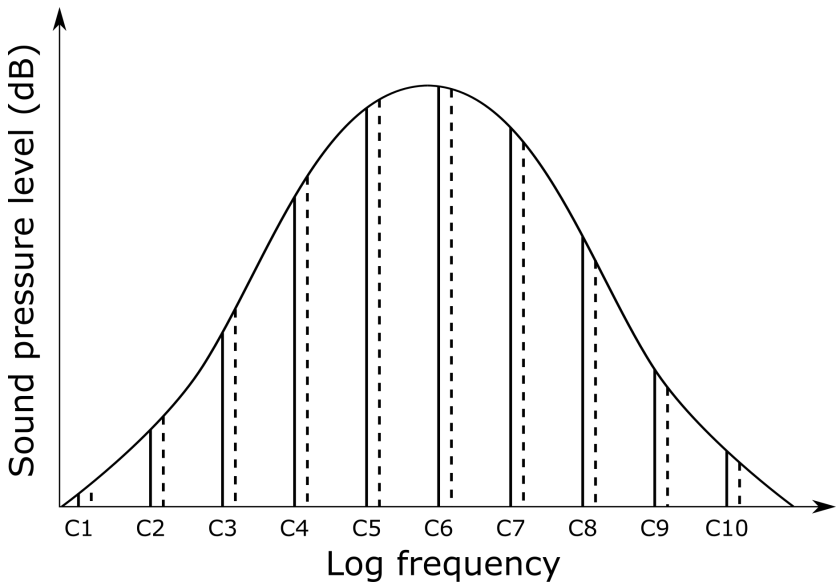

Fig. 2. Construction of a Shepard tone.

With the peculiar construction of his tones, Shepard built the illusion of a cyclic scale that can be played up and down "infinitely".

Pitch perception has two dimensions. If pitch is correlated to the log frequency of the sound as described for instance by the mel scale (pitch height), we can also notice a circular dimension well known in music (pitch class) representing a strong perceptual proximity of tones in an octave relationship. Pitch is thus often represented as a helix to illustrate these two dimensions, with a complete turn by octave to ensure spatial proximity of tones separated by an octave (Figure 3). With his tones, Shepard managed to scramble these two dimensions. By constructing a scale of ten of these complex tones dividing one octave into ten equal intervals on a scale in log frequency, and turning around the chromatic scale, he showed that listeners felt the pitch growing while playing up this scale, but also while looping this scale from the last tone of the scale to the first. These tones preserve pitch class but cannot be ordered with respect to height. The exact same tone can be perceived at different heights depending on the preceding sequence.

Risset further used this illusion to create an infinite glissando with continuous transitions between tones and played with the two pitch dimensions to choose opposite directions for spectral envelope movements and pitch class movements, hereby creating sequences that ascended and descended at the same time [18,19].

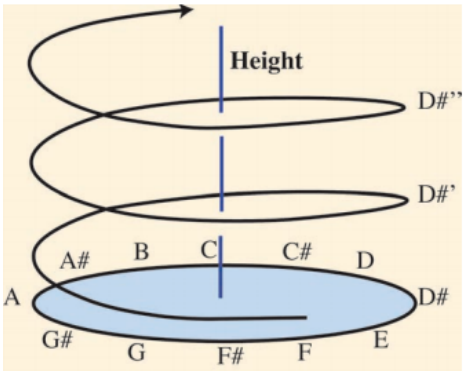

Fig. 3. Helical representation of pitch, varying linearly in the vertical dimension (pitch height) with frequency and describing a circular dimension of pitch class on the musical scale, showing spatial proximity of tones in an octave relation (from [7])

In the present study, we adapted this illusion to our sonification application and made it possible to control both pitch dimensions. We reduced the bandwidth of the window to few octaves to be able to move this window in the frequency domain to change the pitch height through the central spectroid of the generated sounds. But this reduction of bandwidth mechanically leads to the reduction of the number of sinusoidal components of the tone and can weaken the illusion. We thus chose to modify the Shephard tones by adding some components between the sinusoidal components that originally were separated by one octave. Adding more components in a different relation than an octave creates the sensation of chords and also opens

new design possibilities related to the pitch class that conveys the desired identity with this sound feedback.

Synthesizer Development

We developed a synthesizer in Max/MSP to generate these sounds and map our feedback to the vehicle speed and acceleration in real-time. The sine wave components are hereby tuned to form the time-varying scale and the raised cosine function is configured to set the loudness window.

Harmonic comb: The user can create the chord-like tone by selecting the components to be added between the octaves that originally separate the components that form the Shephard tone. These components are then duplicated to each octave to generate the complete harmonic comb. The frequencies of the components of this harmonic comb are controlled by a saw tooth function that browses the scale periodically. The amplitude of each component is defined by the loudness window.

Loudness window: The shape of this window corresponds to a raised cosine function and defines the amplitude of each harmonic component of the comb. The user can define its bandwidth, which may span over one or several octaves, and its central frequency which determines the pitch height of the perceived scale.

Mapping We mapped the pitch height of the generated sounds to the vehicle speed. We chose a generic linear mapping between the pitch and the vehicle speed (S_v):

$$\text{Pitch} = kS_v + c \qquad (\mathbf{1})$$

With the specific construction of our sound feedback that relies on two attributes, (pitch class and pitch height), we have two independent ways to vary the pitch of the generated sounds: with the center frequency of the loudness window (F_c), i.e. the pitch height, and with the sweeping speed (S_s) of the harmonic comb (i.e. the frequency of the sawtooth function). We declined our mapping to these two parameters, linking the logarithm of the center frequency of the loudness window to the vehicle speed (S_v), and deriving this formula to map the sweeping speed of the harmonic comb to the acceleration (A_v) (Fig. 4.).

$$\log (F_c) = k_1 S_v + c_1 \qquad (\mathbf{2})$$

$$S_s = k_2 A_v \qquad (\mathbf{3})$$

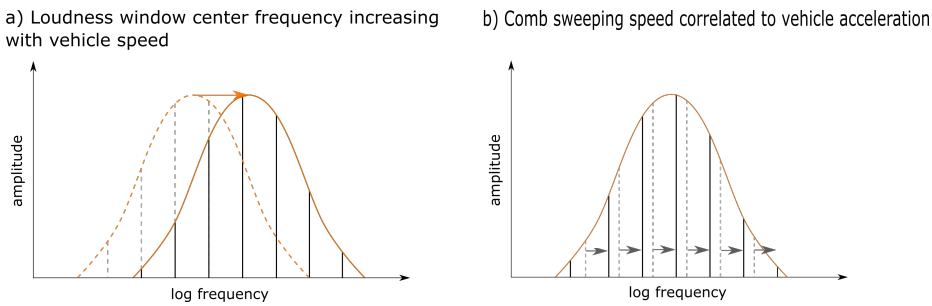

Fig. 4. Representation of the mapping of pitch with vehicule dynamics. The pitch height is controlled through the center frequency of the loudness window mapped to the vehicle speed (a) while the pitch class is mapped through the sweeping speed of the harmonic comb mapped to the vehicle acceleration

Information feedback

As described above, pitch variations can be induced through two pitch attributes. Hence, the sweeping speed of the harmonic comb controls the pitch class variations while the moving center frequency of the loudness window controls the pitch height variations in the generated sounds.

The sweeping speed of the harmonic comb informs the driver on the vehicle acceleration. As for the ICE noise, the faster the frequency variation, the larger the acceleration is perceived by the driver. It is interesting to notice that our glissando is controlled by a sawtooth function. As for the pitch of the ICE noise, the frequency of the generated sound increases during acceleration before decreasing to its original frequency, like it does in ICE noise at gearshift (Figure 1(1)). With the Shepard-Risset glissando illusion, we thus kind of reproduce 'unheard' gearshifts that enable large pitch variations even at low accelerations, but with a constrained pitch range in the whole vehicle speed range.

In addition to this ICE noise metaphor, we also added a second vehicle speed information (i.e. the height attribute of the pitch) by enabling the control of the center frequency of the loudness function.

We tested this sonification strategy in a perceptual test in a driving simulator to evaluate the impact of this pitch attribute on the drivers' perception of vehicle dynamics.

3 Impact of Shepard-Risset Based Sonification Strategy on the Drivers' Perception of Vehicle Speed and Acceleration

ICE noise represents an important feedback on vehicle acceleration for drivers. This information is useful in the perception of vehicle dynamics and particularly important in speed maintenance. We thus focused our strategy on acceleration feedback through the sweeping speed of the harmonic comb. To evaluate the impact of the proposed sonification strategy on drivers' perception, we ran a perceptual test in a driving simulator.

3.1 Experiment Objectives

The main goal of this experiment was to evaluate the impact of the sonification strategy on the drivers' perception of vehicle dynamics through their perception of the vehicle speed. Speed perception indeed strongly depends on the preceding acceleration [17,21].

We designed our sonification strategy relying on this information. The proposed sound, based on the Shepard-Risset glissando, is well suited to give strong acceleration information with the variation of pitch, but can give fuzzy information about absolute speed with its paradoxical pitch, even if we correlate the spectral centroid to vehicle speed. We assumed that the sonification mapping would affect the drivers' perceived acceleration, and thus their speed production. In particular, we hypothesized that increased pitch variations would induce stronger perceived acceleration among the drivers, hereby inciting them to produce slower speeds.

To validate this hypothesis, we focused on the mapping between the sweeping speed of the harmonic comb and the vehicle acceleration. We fixed the mapping between the filtering window displacement and the speed, and tested different mappings between the sweeping speed of the harmonic comb and the acceleration. We asked participants to accelerate or decelerate without the speedometer information to a given target speed in different sound conditions.

3.2 Method

Participants

29 volunteers (3 women and 26 men), employees of the PSA group, participated in this study. They all held a valid driver license and declared to have normal or corrected to normal vision and normal audition.

Experimental Device

We chose to run this perceptual experiment on a driving simulator to control the stimuli presented to the participants and ensure their repeatability. For this experiment, we used a fixed-based driving simulator composed of the front half of a car disposed in front of a hemi-cylindrical screen. The scene used for the simulation represented a straight two-lane urban road. A picture of the driving simulator and an extraction of the scene are presented in Fig. 4.

Fig. 4. Picture of the driving simulator and the driving scene used for the perceptual study.

The vehicle noise played to the participants in the driving simulator was based on recordings in an actual car with a binaural dummy head. It was replayed using granular synthesis as a function of the vehicle speed, and our sonification proposals were mixed with this noise. This global mix was reproduced in the simulator thanks to a five-loudspeaker sound system.

Experimental Variables

Vehicle speed and acceleration Participants had to reach 2 target speeds, 50 and 70 km/h, either accelerating from 30 km/h below the target (acceleration condition) or decelerating from 30 km/h above the target (deceleration condition). The acceleration was controlled and fixed to 2 values in the acceleration and deceleration conditions: +/- 0.75 m/s^2 or +/- 1.5 m/s^2. We thus tested 4 acceleration -and 4 deceleration conditions.

Sonification parameters To focus on the impact of the harmonic comb speed variation on the perceived dynamics, all the other sonification parameters were fixed. The harmonic comb was composed of a major triad (tonal, major third and fifth) duplicated to the other octaves and served as a basis for the sound feedback. This harmonic comb was filtered with a 4-octave length Gaussian window (see Figure 2) with a central frequency varying exponentially with vehicle speed from 120 Hz at idle to 660 Hz at 130 km/h (approximately 1 octave every 55 km/h).

The mapping between the sweeping speed of the harmonic comb and the vehicle acceleration, was tested with 3 linear mappings with three different values of the constant k_2 (k_2= 0.04, 0.08 and 0.16). In the rest of this paper, we will use the mapping with a constant k_2 =0.08 as reference (mapping1) and refer to the other mappings as mapping 0.5 (k_2 = 0.04) and mapping 2 (k_2 = 0.16). It should be noted that we will encounter situations in which the sound feedback is the same at different visual accelerations, with mapping 1 at 0.75 m/s^2 and mapping 0.5 at 1.5 m/s^2, or mapping 1 at 1.5 m/s^2 and mapping 2 at 0.75 m/s^2.

The influence of this mapping can be observed in Fig. 5 in which we represented the spectrogram of the sounds obtained during a constant acceleration from 0 to 90 km/h. The loudness window is moving from 120 Hz at idle to around 450 Hz at 90 km/h and the harmonic comb sweeping speed is mapped to acceleration with low constant (mapping 0.5, Figure 5a) or high constant (mapping 2, Figure 5b).

We also added a control condition without sonification to the 3 previous conditions.

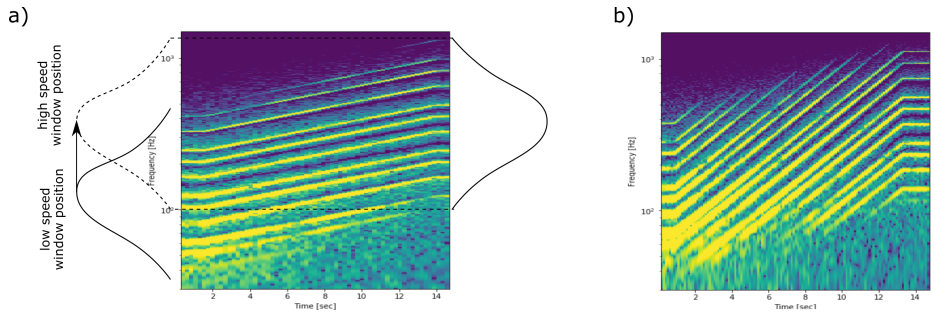

Fig. 5. Spectrograms of two sounds given by our sonification strategy with the same constant vehicle acceleration from 0 to 90 km/h. The central frequency of the loudness window is increasing linearly with speed from 120 Hz at idle to 450 Hz at max speed in both figures. The harmonic comb sweeping speed is mapped with a low constant to vehicle acceleration (mapping 0.5) in (a) and high constant (mapping 2) in (b)

Experimental variables summary These experimental variables that are summed up in Table 1 have been crossed into a full factorial design. Each stimulus has been repeated 3 times, leading to a complete experimental design of 96 stimuli.

Table 1. Experimental variable summary. All variables were crossed in a complete experimental design and each stimulus was repeated 3 times leading to 96 stimuli tested by each participant.

Use case	Target speed	Acceleration level	Sound feedback
Acceleration	50 km/h	+/- 0.75 m/s²	Mapping 0.5 ($k_2 = 0.04$) Mapping 1 ($k_2 = 0.08$)
Deceleration	70 km/h	+/- 1.5 m/s²	Mapping 2 ($k_2 = 0.16$) Electric vehicle (no sonification)

Procedure

Participant tasks Participants were to perform a symmetric task during the acceleration and deceleration conditions.

During acceleration, subjects were launched at a constant speed (20 or 40 km/h) depending on the target speed (50 or 70 km/h). The driving simulator regulated the vehicle speed and the driver did not press the accelerator pedal in the constant speed situation, as if a speed regulator was used. When entering the acceleration zone, the subject pressed the accelerator pedal to accelerate. The vehicle acceleration was regulated by the simulation (at 0.75 or 1.5 m/s²) and the driver had to stop the acceleration by releasing the pressure on the accelerator when he/she thought the target speed had been reached. After the acceleration, the vehicle speed was kept constant by the driving simulator.

In the deceleration condition, the task was symmetrical, and the participants were asked to press the accelerator pedal to keep the speed constant (at 80 or 100 km/h depending on the target speed). When they were ready to start, they reduced the pressure on the accelerator to begin the deceleration (at 0.75 or 1.5 m/s² depending on

test condition) and had to press the accelerator again when they thought they had reached the target speed.

Both conditions are summarized in Fig. 56.

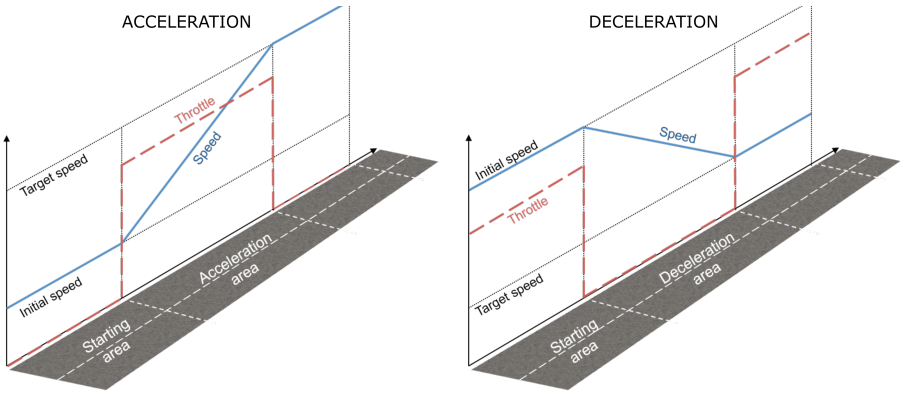

Fig. 5. Test procedure for acceleration and deceleration conditions.

Test sessions Stimuli were divided in two blocs by the acceleration/deceleration condition. To avoid learning effects, half of the participants began with the acceleration condition and the other half with the deceleration condition. The whole test lasted for approximately 1h45.

At the beginning of the test session, the experimenter presented the experiment to the participant. The experimenter explained that the participant would have to evaluate the vehicle speed without a speedometer feedback at different speeds. He also explained that different acoustic feedbacks would be provided, but without mentioning the nature or the type of control of these sounds.

Before the beginning of the test, the participants underwent a training phase. The first training phase aimed to familiarize each participant with the driving simulator: the participant drove freely within roads on the map used for the test. During this phase, the speedometer was visible and the participant could calibrate his/her speed perception without the sonification, with only the natural electric vehicle acoustic feedback *i.e.* in the sound control condition. When the participant felt comfortable with the driving simulator, the test began.

Each test bloc (acceleration and deceleration) began with a task-learning phase. The experimenter explained the subject's task and a couple of additional tasks were tested to make sure the participant fully understood the task. Stimuli corresponding to the different acceleration intensities, target speeds and sounds were presented with a pseudo-randomized experimental design based on a Latin-square to reduce learning effects.

3.3 Results

We recorded the speed reached by the participants after the acceleration/deceleration phase and considered it as their perceived target speed. We calculated the error between the speed reached by the driver and the target speed to compare the results between the two target speeds tested.

Analysis of Variance (ANOVA) was ran on acceleration and deceleration conditions to determine the experiment parameters that had a significant impact on the speed reached by the drivers in each condition.

Acceleration condition

Sound condition In the case of acceleration, the ANOVA showed a significant effect of the sound condition ($p < 0.001$). A Scheffé post-hoc test separated these four conditions (3 mappings and one electric – without sonification - condition) in three groups:

- mapping 2 (mean error -1.6 km/h),
- mapping 1 (mean error -0.1 km/h) and electric condition (mean error 0.8 km/h),
- mapping 0.5 (mean error 1.1 km/h) and electric condition.

Intensity of vehicle acceleration The intensity of the acceleration had a significant impact on the speed reached by the drivers ($p < 0.001$), with a speed error of -2.8 km/h during acceleration and 3 km/h during deceleration.

Target speed We can notice a significant effect of the target speed ($p < 0.001$) with a mean error of 0.9 km/h at 50 km/h and -0.7 km/h at 70 km/h.

Repetition Repetitions showed significant effects ($p < 0.001$) with a mean speed error of -0.7 km/h for the first repetition, 0 km/h for the second and 1 km/h for the third repetition.

Interactions No interaction between these parameters reached a significance level of 5 %.

Deceleration condition

In the deceleration condition, the ANOVA showed the same significant effects.

Sound condition The sound condition had a significant effect on the speed reached by the drivers ($p < 0.001$) and Scheffé post-hoc test sorted the conditions in three groups:

- mapping 0.5 (mean error 8.5 km/h),
- mapping 1 (mean error 10.2 km/h) and electric condition (mean error 10.6 km/h),
- mapping 2 (mean error 12.4 km/h).

Intensity of vehicle acceleration We can notice a significant effect of the intensity of the acceleration ($p < 0.001$) with lower speeds reached at higher decelerations (mean error of 7.5 km/h at -1.5 m/s^2 and 13.3 km/h at -0.75 m/s^2).

Target speed The target speed significantly influences the speed reached by the participants ($p < 0.001$), with a mean error of 10.8 km/h at 50 km/h and 10 km/h at 70 km/h.

Repetition As for the acceleration condition, repetition also has a significant influence on mean speed errors of 11 km/h for first, 10.6 km/h for the second and 9.6 km/h for the third repetition.

Interactions No interaction between these parameters reached a significance level of 5 %.

3.4 Discussion

Speed perception and influence of acceleration

In Fig. 6, we plotted the mean speeds reached by the participants in the acceleration and deceleration conditions for target speeds of 50 km/h and both acceleration intensities 0.75 and 1.5 m/s².

Consistently with the literature on speed perception, this study highlighted a global overproduction of speed by the participants, suggesting that they compensated their underestimation of the speed by reaching higher speeds than the target [16]. We can notice that this underestimation of the speed is higher at lower speeds, in line with

[9,13,16,17], with a mean speed of 56 km/h reached for a target speed of 50 km/h (fig. 4) and 77 km/h for a target speed of 70 km/h.

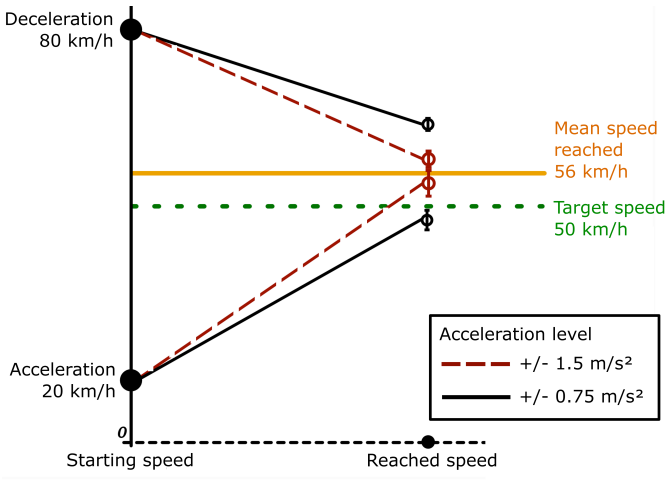

Fig. 6. Mean speeds reached by participants for a 50 km/h target speed during acceleration and deceleration for both acceleration levels.

We also notice that the speed reached by the participants is modulated with the intensity and sign of the acceleration.

Regarding the sign of the acceleration, we can see that the drivers tend to reach higher speeds when decelerating than when accelerating, suggesting that they tend to overestimate their acceleration (Fig. 6). This overestimation of the acceleration makes them think that they accelerated (resp. decelerated) more than they actually did and stopped the acceleration (resp. deceleration) before they should, inducing them to reach lower (resp. higher) speeds.

Regarding the intensity of the acceleration, we can notice that the situation is symmetrical. In the acceleration condition, the drivers tended to reach lower speeds at lower accelerations (**Fig. 6**). Focusing on speed, we can infer that drivers underestimate their speed more after stronger accelerations, consistently with the study of Salvatore [21]. However, during deceleration, the opposite effect can be observed, with lower speeds reached with higher decelerations. This symmetrical result suggests that drivers tend to overestimate their acceleration and even more when its intensity its lower. Drivers thus tend to reach higher speeds at strong accelerations and lower at high decelerations.

This result confirms the major role of acceleration in drivers' speed perception.

Influence of sound feedback

Our sonification strategy based on the Shepard-Risset illusion is particularly well suited to inform on vehicle acceleration. More than the association of a pitch to a particular speed, this feedback enables to control the variation of the pitch according to vehicle acceleration.

We assumed that this feedback could modify the perceived acceleration among drivers and modify their speed production. The plot of speeds reached by participants in the different sound conditions (Fig. 7) confirms this hypothesis. Similarly, to the effect of the intensity of acceleration, we can notice that the effect of sound mapping is symmetrical during acceleration and deceleration. During acceleration, drivers tended to reach lower speeds with a sound mapping that had a faster comb sweeping. In deceleration, they reached higher speeds with faster comb sweeping.

This result suggests that the sound information influenced the perceived acceleration among participants, with a perception of acceleration that increased with the comb sweeping.

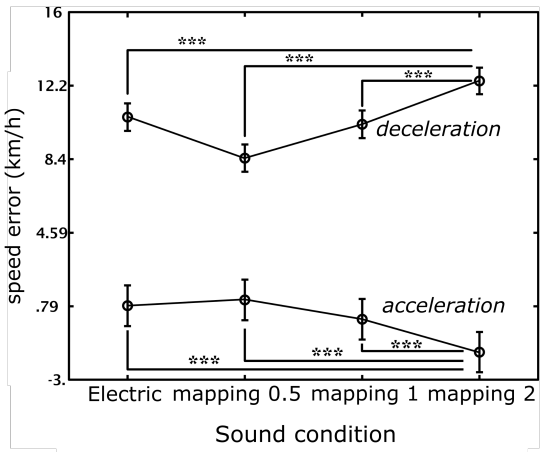

Fig. 7. Errors between speed reached by participants and target speed during acceleration and deceleration in the different sound conditions

It is also interesting to observe that the control condition without sonification is included between the conditions with sonification. The comparison with the sonification conditions suggests than we can increase or decrease drivers' perceived acceleration according to the sound mapping.

With only one mapping of the central frequency of the Gaussian loudness window (i.e. the pitch height) with the vehicle speed tested, we cannot conclude on its effect on the drivers' perceived speed. Even if this information might be too fuzzy to improve the drivers' speed perception (only one octave height change for around 50 km/h), it might contribute to increase the effect of the comb sweeping, i.e. the pitch class increase, when pitch height is linearly mapped to speed as in the present study. However, we can also imagine different mapping strategies of the Gaussian window's central frequency with the vehicle speed to enhance the information, for instance with piecewise mapping functions to more clearly influence typical speeds for city, road or highway driving.

Even if the effect of our sonification strategy is naturally lower than the effect of the vehicle acceleration intensity, it can contribute to change the drivers' perception of the vehicle dynamics. We saw that the drivers tend to overestimate their acceleration and mostly at low acceleration intensities. An exponential mapping can then be used to reduce this overestimation for low accelerations, hence adjusting the mapping to the way acceleration is perceived.

4. Conclusion

The development of quieter electric motorizations changes the soundscape perceived by drivers in their vehicles, and this "silence" is often praised for these zero emission vehicles (ZEV). However, Internal Combustion Engine (ICE) noise is an important feedback for drivers. It gives precious information about vehicle dynamics and has an important impact on the emotional level, since it contributes to the evocation of sportiness and driving pleasure.

In this study we developed a sonification strategy to enhance drivers' perception of vehicle dynamics and improve the pleasure of the driving experience in electric vehicles. We decided to focus on speed and acceleration information, which are of major interest for driving control. The proposed strategy is based on the engine noise metaphor, with a pitch that increases with acceleration, to provide natural and intuitive feedback to the driver. We found that the Shepard-Risset glissando illusion was perfectly suited for this aim. We used both height and pitch class variations to inform respectively on speed and acceleration.

Acceleration has been shown in literature to have a strong impact on speed perception. We thus focused our sonification strategy to enhance this information, giving more information to the variation of the parameter of interest than to this parameter itself. We mapped the infinite glissando speed proportionally to the vehicle acceleration to give salient information to the driver. With this illusion, we could precisely provide information on the vehicle acceleration with fast pitch variations that could be maintained over the whole speed range of the vehicle.

This is, to our knowledge, the first time that the Shepard-Risset illusion has been used as a sonification strategy in an action-perception loop. With the two dimensions

of pitch (height and pitch class) which can be controlled independently, this illusion can also be a very powerful tool to investigate human perception and cognition in an action-perception loop with two independent aspects linked to the same sensation. In our application, we used both dimensions consistently to provide information on speed and its derivative through a new and original sonification strategy.

We tested different mappings of this sonification strategy with vehicle dynamics and showed that this had an impact on the drivers' acceleration perception and speed production. This sonification strategy can also be designed to generate more technological sounds than ICE noise and is particularly well suited to answer the issue of interior sonification of ZEV.

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