# Sound Perception inside a Stationary Vehicle in Case of Frontal Audio Source

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*Abstract*—**In case of low speed collisions one of the most important question is the perceptibility. That is based on two fields: detection of sound and impact. This paper represents several problems connected to the sound perception inside a vehicle. Several variables were taken into consideration. To reduce the number of measurements fractional factorial Design of Experiment (DoE) $2^{7-4}$ was used. The following factors were chosen: the state of the windows (each front and rear ones), the engine, the fresh air fan and the position of the person in the automobile. Thus, the mutual condition of man and car was determined. The acoustic appreciability of pure sine wave tones was examined at three directions of the audio source. The different settings of the factors were defined by DoE. By help of Pareto charts significant effects (at a level of 0.95) were selected from the variables studied. In addition, parameters of the case of the worst perceptibility were determined.**

## I. Introduction

In case of low speed vehicle collisions, a fundamental question is the perceptibility. Regarding these incidents, the related audio effect is considered being at the borderline of the human appreciability that is even deteriorated by the disruptive effects of the vehicular operation and use. Furthermore, compared with impacts of a higher speed interval, the collision energy is smaller by several orders of magnitude. Additionally, there are only hardly remarkable visual damages (e. g. the surface varnish is lightly damaged) as most of the impact energy is absorbed by the elastic deformation of the parts.

The perception is primarily based on the human abilities; however, it is reduced by all the problems mentioned above. Moreover, comfort electronic systems (car multimedia, air conditioning system, etc.) and company of others have disruptive effects as well.

The classification of impacts is a key point in those cases where further legal consequences are expected or a bigger amount of property damage is made say Niederer et al. [1]. Minor, medium and severe collisions can be defined. Important criteria are the speed status of the vehicle and the human injury occurred. However, the severity of an incident is completely different in kinematical, medical and biomechanical sense.

Regarding analytical aspects at minor collisions [2] slight surface damages occur on the vehicle involved thus the crash speed is low ($v$=1…5 km/h). Modern bumper systems are expected to absorb impact energy by elastic deformation until a tagged velocity ($v \leq 4$ km/h - $v \leq 8$ km/h in the USA) [3].

The judgement of the perceptibility of low speed crashes is not a clear problem. The process in an analytical opinion is as follows:

Schneider [3] says that here are three different fields of detection to be investigated. The key point of visual perception is whether the driver saw the accident. In case of passenger cars, a critical situation is reversing from a parking place where a quite poor visibility is provided from the driver's seat [2] [5]. The most important point is whether the view of the driver was directed in the way of the contact or not.

Acoustic perception means the audibility of the sound effect the accident is followed by. There are several disturbing factors those can be divided into two groups. Sounds from outer sources are the engine and the environment, inner ones are the comfort electronic systems and other disturbances. The cabin is shaded against outer acoustic disturbances which worsens the detection.

The third opportunity is tactile and kinesthetic perception that is based on the detection of the pushes caused by the impact using the sense of balance. Since the body is a complex construction, it does not have a constant stiffness. That is the reason why a key question is the location of the contact. Weakened parts are the door. Having a contact on a door provides a sound effect 75% lower than in case of crashing the B-pillar. Investigating the perceptibility, the most important viewpoint is the third one.

Irmler [6] [7] investigated 51 minor collisions regarding the perceptibility from the aspects of the driver. Measurements were carried out on common modern vehicles. The driver's view, the accelerations and the damages of the vehicle were registered.

Lazányi [8] and Zeng et al. [9] studied the driver-vehicle unit.

The influence of age, gender, height and educational level on vibratory stimulus detection was investigated by De Michele et al. [10]. A 128 cps tuning fork was used in the tests. After striking the fork to the palm at medium degree intensity, the examiners applied it to bone prominences with the same pressure and measured the perception times. Different regions were studied by analysis of variance. A non-linear age related decrease of vibration sense was defined. What is more, in case of the collarbone, perception times were longer with males and shorter with higher people. Age-gender interaction was not found.

Another important research field is to determine the influential factors of sound propagation in the atmosphere. Liptai et al. [11] give a mathematical model for the connection between the intensity of the sound and atmospheric conditions such as air temperature, relative humidity, wind speed and its direction.

This article aims to study the internal human sound appreciability of a stationary vehicle. The following variables (factors) were examined, how they influence the acoustic perceptibility: the windows (all of front and rear ones), the operation of the engine and the fresh air fan and the position of the person in the vehicle interior.

Theoretically, starting the internal combustion engine and the fan were expected to worsen the appreciability. Further, above mentioned parameters were investigated to decide which of them might also have to be taken into consideration.

In order to determine the most influential, significant effects, Pareto analysis was carried out.

## II. MATERIALS AND METHODS

### A. *Vehicle examined*

Investigations were carried out on a SKODA FABIA COMBI vehicle which is a B-segment estate car. There are more than 170000 vehicles of the same make on the roads of Hungary [12].

Acoustic perception was tested in three different positions of the audio source (see Figure 1).

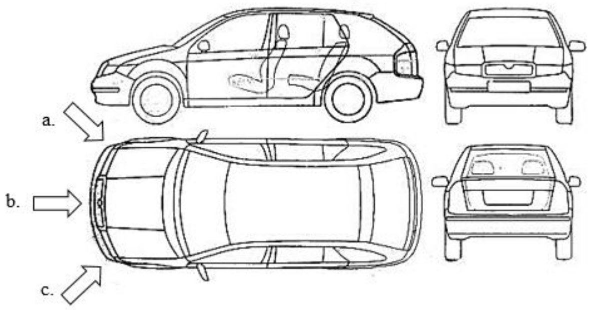



Figure 1. Vehicle examined
The directions of the audio source: a. front right; b. front middle; c. front left

### B. *People examined*

20 people were taken under the tests. Experienced drivers were chosen, having a driving license at least for ten years. Their age was between 28 and 55.

None of them was diagnosed with hearing damages or hearing loss.

### C. *Devices used*

The online tone generator of Tomasz P. Szynalski [13] was used as audio source that can pay constant pure, sine wave tones.

The frequency can be adjusted in a wide interval ($f$=1…20000 Hz).

For evaluating the data Minitab 17 was used.

### D. *Design of Experiment determined*

The aim of design of experiment (DoE) is to gain information about the effect of the variables involved in the investigations furthermore a reduced number of experimental runs is another advantage of the method.

Factors are the variables, their effects main the change of the response affected by the change of the levels.

Full factorial designs involve all the possible combinations of levels of factors mentioned, are studying the effects of two or more factors. The number of experimental runs is $l^p$, where $l$ is the number of the levels and $p$ is the number of factors examined [14].

During the examination 7 factors are varied at 2 levels. Table 1 shows the names and levels of the factors.

TABLE 1.
FACTORS AND THEIR LEVELS

| Factor | Name | +1 | -1 |
|---|---|---|---|
| A | front right window (FR w) | closed | open |
| B | front left window (FL w) | closed | open |
| C | rear right window (RR w) | closed | open |
| D | rear left window (RL w) | closed | open |
| E | engine | stopped | started |
| F | position | driver seat | passenger seat |
| G | fresh air fan (FAF) | off | level 1 |

The case of a full factorial design would mean $2^7$=128 combinations.

To reduce the number of measurements a fractional design was chosen [15]. A fractional Design of Experiment $2^{7-4}$ was used (see Table 2 and 3) where main effects are not aliased with each other. However, those are aliased with two-factor interactions.

TABLE 2.
SETTINGS OF THE EXPERIMENTAL RUNS

| $2^{7-4}$ | | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|---|
| | $x_0$ | $x_1$ | $x_2$ | $x_3$ | $x_1x_2$ | $x_1x_3$ | $x_2x_3$ | $x_1x_2x_3$ |
| 1. | +1 | +1 | +1 | +1 | +1 | +1 | +1 | +1 |
| 2. | +1 | +1 | +1 | -1 | +1 | -1 | -1 | -1 |
| 3. | +1 | +1 | -1 | +1 | -1 | +1 | -1 | -1 |
| 4. | +1 | +1 | -1 | -1 | -1 | -1 | +1 | +1 |
| 5. | +1 | -1 | +1 | +1 | -1 | -1 | +1 | -1 |
| 6. | +1 | -1 | +1 | -1 | -1 | +1 | -1 | +1 |
| 7. | +1 | -1 | -1 | +1 | +1 | -1 | -1 | +1 |
| 8. | +1 | -1 | -1 | -1 | +1 | +1 | +1 | -1 |

TABLE 3.
EXPERIMENTAL RUNS

| $2^{7-4}$ | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| | FR w | FL w | RR w | RL w | engine | position | FAF |
| 1. | closed | closed | closed | closed | stop | driver s. | off |

| $2^{7-4}$ | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| | FR w | FL w | RR w | RL w | engine | position | FAF |
| 2. | closed | closed | open | closed | start | pass. s. | level 1 |
| 3. | closed | open | closed | open | stop | pass. s. | level 1 |
| 4. | closed | open | open | open | start | driver s | off |
| 5. | open | closed | closed | open | start | driver s | level 1 |
| 6. | open | closed | open | open | stop | pass. s. | off |
| 7. | open | open | closed | closed | start | pass. s. | off |
| 8. | open | open | open | closed | stop | driver s | level 1 |

## III. Investigations

### A. *Measurements*

The studies were carried out in three different positions of the audio source: the front right, the front middle and the front left part of the vehicle (see Figure 1).

The tests were performed in random order, in a quiet area without any car traffic.

Table 4 shows the means of the measurement results rounded to integer values and the standard deviations ($s_a$ for Direction a., $s_b$ for Direction b. and $s_c$ for Direction c.).

Table 4.
Results and standard deviations

| $2^{7-4}$ | *a* (Hz) | $s_a$ | *b* (Hz) | $s_b$ | *c* (Hz) | $s_c$ |
|---|---|---|---|---|---|---|
| 1. | 200 | 5.1 | 203 | 6.2 | 205 | 5.0 |
| 2. | 565 | 9.8 | 682 | 28.7 | 638 | 12.4 |
| 3. | 573 | 57.5 | 377 | 44.8 | 228 | 7.5 |
| 4. | 393 | 17.5 | 312 | 45.9 | 223 | 22.7 |
| 5. | 520 | 55.0 | 620 | 10.8 | 560 | 15.2 |
| 6. | 168 | 2.4 | 193 | 8.5 | 245 | 10.1 |
| 7. | 200 | 15.1 | 293 | 6.2 | 273 | 2.5 |
| 8. | 228 | 2.6 | 252 | 8.5 | 208 | 2.3 |

Higher values of standard deviation were caused by the same person who detected considerably lower frequencies than the others.

### B. *Results*

Table 4 shows big differences between the three positions that are graphically shown on Figure 2.

However, in case of the measurement point 1 nearly the same values were provided. That case can be interpreted as the static sound shading capability of the vehicle.

Pareto charts of the effects show which factors have a significant effect on the perceptibility (see Figure 3) at a level of 95% (α=0.05).

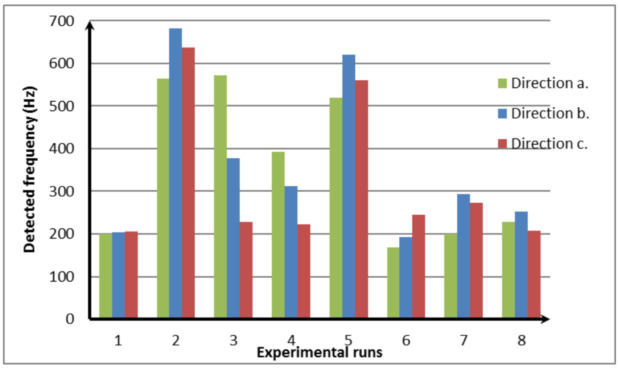
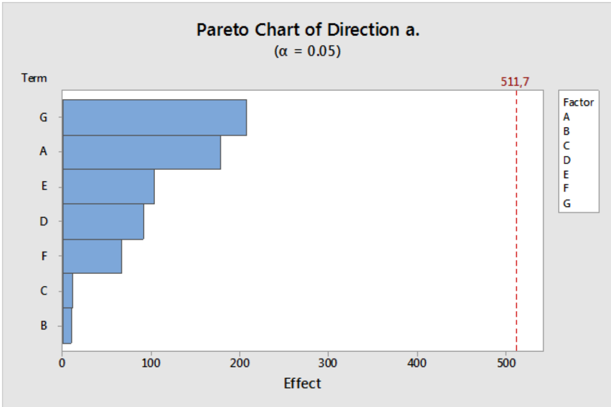
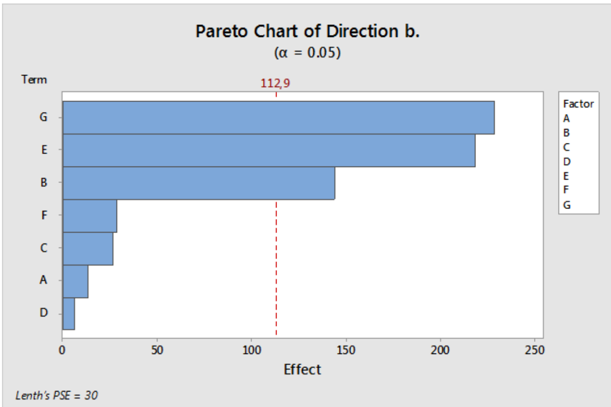


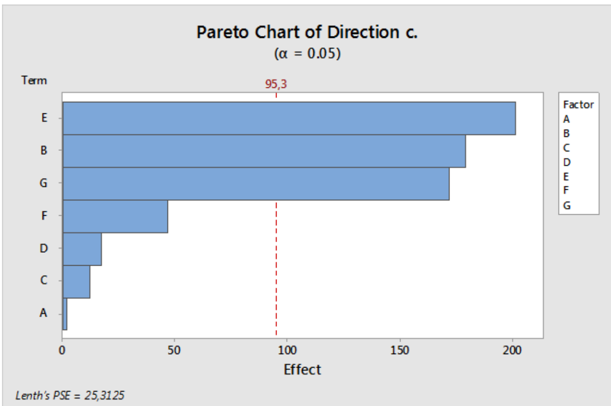

Figure 2. Means of the results shown graphically




a.




b.




c.

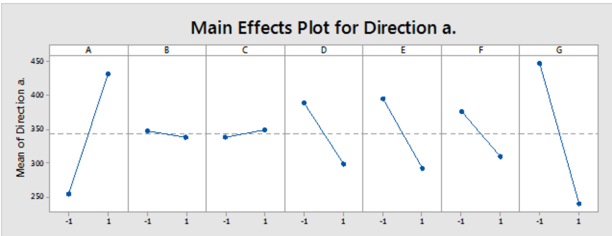
Figure 3. Investigation of human perceptibility by Pareto charts
a. Direction a.; b. Direction b.; c. Direction c. (see Figure 1)

In case of the front right position, none of the effects of the factors examined was proved to be significant.

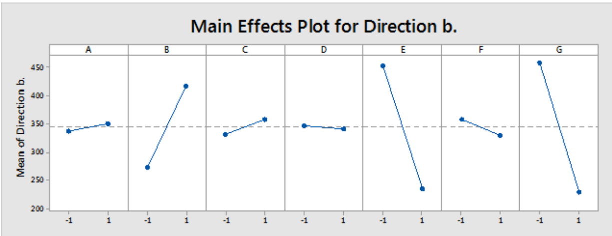
Positioning the tone generator to the front middle part of the vehicle, the operation of the fan is determined as the only significant factor. Nevertheless, the engine has an important effect as well.

In case of the front left position of the audio source, in line with the expectations, starting the engine has the greatest effect (see Figure 3/a.), moreover the status of the front left window and the operation of the fan are significant as well.

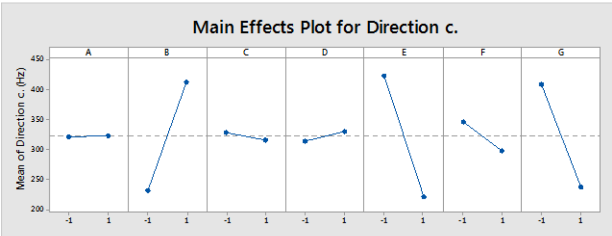
The same results can be shown on the main effects plots (see Figure 4).




a.




b.




c.

Figure 4. Main effects plots
a. Direction a.; b. Direction b.; c. Direction c. (see Figure 1)

In addition, the effect of a given factor can be seen. The impacts are divided into three groups.

Having a line with a positive slope, the higher level of the factor results worse perceptibility (factor A at Direction a., factors B and C at Direction b. and factor B at Direction c.)

Being nearly horizontal, the different levels do not give relevant differences in the detected frequencies (factors B and C at Direction a., factors A and D at Direction b and factors A, C and D at Direction c.).

Having a negative tilt angle, appreciability gets better with the decrease of the level (factors D, E, F and G at Direction a., factors E, F and G at Directions b. and c.).

### C. *Settings of the worst perceptibility*

Furthermore, settings of the worst acoustic appreciability were determined.

The experimental data showed that the levels of the maximum of the detected frequency were defined for each factor. It can be said that starting the engine and the fan both worsen the perceptibility by their disturbing noises. Moreover, sitting in the passenger seat means inattention because of the lower level of responsibility.

What is more, opening the windows on the opposite side to the audio source means worse detection.

In case of sitting in the driver seat showed several differences.

Having placed the tone generator to the front left side the highest frequency was resulted when the rear left window was open.

Moreover, in the front left position the worst perceptibility was experienced by opening the rear right window.

Comparing the placements (see Figure 1) the highest frequency is to be detected in case of Direction b.

## IV. Conclusion

The article was aimed to investigate several parameters affecting the human acoustic perceptibility inside a stationary vehicle. The status of the windows, the engine, the fan and the position of the person were the factors examined.

The audio source emitting pure sine waved tones was placed in the front part of the outside of the vehicle in three different siting (left, middle, right).

Theoretically, starting the engine and operating the fan were expected to worsen the appreciability.

In all three cases, significant factors were determined.

In the front left position, in line with the expectations, starting the engine and the fan the greatest effect, moreover, opening the front left window was proved to be significant as well.

Having placed the audio source in the front middle part, the same three factors had the most important impact on the frequency detected however operating the fan was the only significant one.

In case of the front right position none of the factors investigated had a significant effect at a level of 95%, but the engine, the fan and opening the front right window had the most influential ones.

In addition, factor levels of the worst acoustic perceptibility were defined.

Starting the engine and operating the fan both worsened the appreciability by their disturbing noises. Furthermore, sitting in the passenger seat instead of the driver seat meant less attention paid to the sound effects coming from the environment. That can be explained by the lower level of responsibility.

Another fact is that opening the rear window on the opposite side of the vehicle to the position of the person examined needs a higher frequency to be detected from the inside. Furthermore, in case of the front right position the front left window has the same effect.

The worst perceptibility was experienced when the audio source was placed to the front middle part.

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