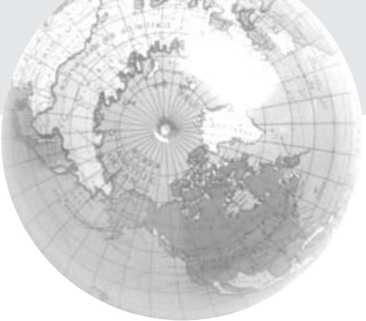

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Das Fahrzeugaußengeräusch
im urbanen Verkehr und seine Bedeutung
für die Interaktion Fußgänger – Fahrzeug

# The Importance of Vehicle Exterior Noise Levels in Urban Traffic for Pedestrian – Vehicle Interaction

In recent years, the comfort and environment consciousness of automotive industry and customers has resulted in a constant reduction of vehicle noise emissions. At the same time, vehicles and pedestrians move closer and closer in urban areas thus increasing the importance of vehicle exterior noise as a warning signal for pedestrians. The present article by a working team of the Munich Technical University (AG Technische Akustik des Lehrstuhls für Mensch Maschine Kommunikation der TU München) deals with this particular aspect of vehicle exterior noise.

## 1 Introduction

The impact of vehicle exterior noise on noise emission levels was frequently studied and has been brought back to mind with the recent publication of draft standard DIN ISO 362 [1]. Another aspect, which is discussed less often is the warning function of vehicle exterior noise for other road users in general and pedestrians and cyclists in particular. In situations with no free sight, this noise is the only possibility of perceiving an approaching vehicle and react adequately. This requires noise levels which are above a certain threshold.

When looking at the German traffic statistics taken from Statistisches Jahrbuch 2004 [2], it can be seen that every eighth person killed (total of 812) and every twelfth person injured (total of 35015) is a pedestrian. The book reveals also the locations where and the reasons why such accidents happen, **Table 1**. Three quarters of those collisions occur while persons cross streets at locations where there are no pedestrian crossings, with the main reasons being that pedestrians suddenly appear from behind an obstacle or simply lack attention. Both are situations where pedestrians strongly depend on their sense of hearing which, in general, is omni-directional and always active in collecting and processing information. So we can assume that most of these accidents happened because pedestrians were not able to hear and react correctly to an approaching vehicle.

**Author:**
Stefan Kerber

## 2 Collision Avoidance in Urban Traffic

### 2.1 Required Minimum Distances for Safe Collision Avoidance

Based on physical knowledge about evenly accelerated movement and investigations of reaction times [3] it is possible to calculate the distance between a pedestrian and a vehicle which is required to safely avoid a collision, i.e. the minimum distance from which the pedestrian must become aware of a vehicle in order to be able to respond. In the following, two different scenarios are being presented:

- The pedestrian only reacts: The pedestrian only is assumed to respond to the vehicle approaching at a constant speed $v_{Fahrzeug}$ The reaction time $t_{Reakt}$ of a pedestrian allows the distance covered by the vehicle during this lapse of time to be calculated after Eq. (1).

  $$s_{Fahrzeug1} = \nu_{Fahrzeug} \cdot t_{Re\,akt}$$

  With pedestrians being among the most agile road users the reaction time needed to come to a stop is assumed to be zero.
- The driver only reacts: The situation gets a bit more complicated when assuming that the driver only responds. A driver, too, needs a certain time $t'_{Reakt}$ to react - i.e. to step on the brakes and bring the constantly moving vehicle to a stop. In this case, however, the time between actuating the brakes and stopping the vehicle must not be neglected. For calculation, it is assumed that the braking process is a movement which is evenly decelerated at a=8 $m/s^2$ . The resulting braking distance is calculated after Eq. (2).

$$s_{Fahrzeug2} = \nu_{Fahrzeug} \cdot t'_{Re\,akt} + \frac{\nu^2_{Fahrzeug}}{2 \cdot a}$$

To safely avoid a collision the pedestrian must be able to hear the vehicle from a distance which corresponds to the stopping distance, see equation (2). At this distance, the pedestrian must respond. If he does not the driver seeing that there is no response must start braking. These "critical distances" are shown in **Fig-**

**ure 1** for different reaction times and speeds. It is assumed that the reaction times of the pedestrian and driver are the same, with the most rapid response ($t_{Reakt}$ =0,7 s) being that of a concentrated road user according to Green [3]. As shown in this study, the response times of distracted persons can be up to 1.5 s long.

## 2.2 Experimental Determination of Reaction Times to Vehicle Exterior Noise

### 2.2.1 Background

To establish a relationship between the above mentioned critical distances and the real reaction times needed to respond to the exterior noise of a vehicle corresponding lab measurements were performed. Attention was paid to simulate real-life situations with attentive road users under most realistic conditions in a lab environment. The test persons were asked to react as quickly as possible to a vehicle exterior noise masked by a background noise. This precisely corresponds to what a pedestrian has to do in a real world situation.

### 2.2.2 Test Persons

The tests were performed with seventeen normal-hearing persons aged 24 to 61 (average: 27). Two of the persons were female, the rest were male. Each test was split in two parts and took about 10 minutes.

### 2.2.3 Sounds

All the sounds used in the tests were recordings of real sounds. The masker was a babble of voices recorded at Munich Marienplatz. The sound/loudness level versus time is shown in **Figure 2** while the corresponding loudness/critical band rate pattern is given in **Figure 3**. The 14-second noise record was looped and continuously played to the test persons.

The test sounds used were the pass-by noises (pass by in our context always refers to a vehicle passing by with constant speed) of two different vehicles (one diesel and gasoline-engine-powered version each) recorded at three different speeds. All pass-by modes were recorded twice - i.e. as coasting noise and as constant-speed noise with gear D engaged. The recordings were made on a standard test track used for the measurement of standard pass-by noise levels (DIN ISO 362). The test setup is shown in **Figure 4**.

The two microphones were placed on a line along the middle of the test track at a lateral distance of 2 and 7.5 m respectively to the left and right of the vehicle and 1.2 m above the ground. During the test, the test persons heard a two-second phase only of the sound recorded by the closest microphone before the vehicle reached the connecting line between the microphones. This sound corresponds to what a pedestrian will hear before eventually colliding with a vehicle. The noise level/loudness versus displacement curves in pass-by mode (diesel-engine-powered vehicle, driving speed: 50 km/h) are shown in **Figure 5**.

### 2.2.4 Psycho-acoustic Test

Prior to the beginning of the test all test persons were informed about their tasks which consisted of two parts: First a short sound pulse (75 dB, 1 kHz, duration: 0.1 s) was played to the persons in an anechoic chamber via a loudspeaker. The persons had to respond to this sound pulse as quickly as possible by pressing a button. The loudspeaker (Klein & Hummel type O98) was hidden by an acoustically transparent curtain and placed at a distance of two meters in front of the test person. This part of the test served to determine the persons' shortest possible response times to an acoustical stimulus.

During the second part of the test, the test persons were continuously exposed to the background noise described in section 2.2.3. The mechanical and electrical setups of the first and second parts of the test were identical. In addition to the background noise the recorded pass-by noises were played at random times with the test persons having to respond to these noises as quickly as possible again. The moment of reaction – adjusted for the minimum reaction time determined in the first part of the test – allowed the distance of the vehicle at the moment of noise perception to be calculated. It should be possible to perceive a vehicle at the moment when the summed-up noise level of the approaching vehicle and the background noise has increased by 1 dB(A).

## 3 Results

### 3.1 Reactions to approaching Vehicles

**Figure 6** shows the reaction times recorded for various approaching vehicles. It is interesting to note the differences between the responses to vehicles coasting by and passing-by at constant speed. As can be seen, the reaction time is longer at low vehicle speeds - i.e. exactly in a phase where there is no engine noise and the rolling noise is very low. As driving speed increases, the reaction times for both operating modes are almost similar, which is due to the fact that noise level mainly depends on the tire/road noise.

**Figure 7** shows the critical distances (hatched areas) known from Figure 1, with the upper limit representing diverted road users and the lower limit representing persons who are concentrated on road traffic. In addition, the median distances before collision including their probable scatters have been plotted for both vehicles and both operating modes and for three different

**Table 1:** Typical lapses and locations of pedestrian accidents determined by the police in Germany in 2003 [2]

| | |
|---|---|
| Lack of road fitness | 9.09 % |
| Wrong behaviour when crossing the street | 77.92 % |
| No use of the sidewalk | 1.68 % |
| No use of the correct road side | 0.89 % |
| Playing on or next to the road | 1.36 % |
| Other pedestrian errors | 9.06 % |
| | |
| At controlled pedestrian crossings | 8.92 % |
| At uncontrolled pedestrian crossings | 0.76 % |
| Near intersections, pedestrian crossings, in dense traffic situations | 7.37 % |
| In other places: | |
| – by sudden appearance behind obstacles | 20.12 % |
| – by not paying attention to vehicle traffic | 55.12% |
| – by other misguided behaviour | 7.70 % |

**Table 2:** Vehicle noise levels at the moment of perception recorded at the closer microphone position

| | **Diesel-powered** | | | **Gasoline-powered** | | |
|---|---|---|---|---|---|---|
| | 20 km/h | 30 km/h | 50 km/h | 20 km/h | 30 km/h | 50 km/h |
| **Coast-by** | 56.5 dB(A) | 59 db(A) | 59 db(A) | 56.5 dB(A) | 58.5 dB(A) | 59 db(A) |
| **Constant-speed pass-by** | 58 db(A) | 58.5 db(A) | 59 db(A) | 56.5 db(A) | 59 db(A) | 59 db(A) |

driving speeds. These median values are obtained by calculating the product of the reaction time and vehicle speed.

As can be seen, none of the vehicles is perceived in time if the pedestrian is lacking concentration. At best, vehicle noises would be perceived in good time by concentrated pedestrians allowing accidents to be only just avoided. Under such circumstances, vehicle speed, too, has a certain influence: vehicles driving faster are more difficult to perceive in time.

Another interesting aspect is the noise level generated by a vehicle at the moment of perception at the microfon with 2 meters displacement. The noise levels measured with the two test vehicles at various velocities and in the two operating modes have been summarized in **Table 2**.

### 3.2 Perception Levels at Critical Distances

Based on the results of these tests it might be interesting for users to predict the noise level a vehicle should produce at a critical distance to be only just perceptible. With the help of the test data it is possible to calculate the noise levels required at the critical distances to make sure that the vehicles to be perceived. To simplify things, it is assumed that the tone colour of a vehicle changes only slightly as the distance from the microphone varies which means that the perception threshold is almost independent of the distance from the vehicle. As the critical distance is known from physical observation, it is possible to obtain the actual noise level at the given distance from the level/displacement diagram in Figure 5. To do so, the noise level has been interpolated using Eq. (3) (x in meters).

$$L(\mathrm{x}) = \mathrm{A} - 10 \cdot n \cdot \log(2^2 + \mathrm{x}^2)$$

This equation basically describes a hypothetical sound source whose level decreases by the decuple of n each time the distance is doubled. For both vehicles, both operating modes and all driving speeds the parameters A and n of Eq. (3) were calculated using the Gauß-Newton algorithm. This interpolation is necessary because the critical distances increase with increasing driving speed. At that, it is not always possible to obtain noise level values of far-away vehicles.

For a vehicle to be just only perceptible, the noise level at the critical distance must reach at least the perception threshold (Table 2). The limit noise levels which a vehicle should radiate according to ISO 362 in a lateral distance of 7,5 m to be remarked by a pedestrian in the listening test were obtained by way of calculation and are shown in Figure 8. Thus, **Figure 8** provides the users with a tool allowing the perceptibility of a particular vehicle to be checked.

## 4 Conclusions

The methods described so far allow the perception distances to be estimated for vehicles which have similar acoustic properties and whose maximum constant-speed noise levels are known. This noise levels are obtained from corresponding pass-by measurements (test track and microphone positions according to DIN 362, constant-speed driving in city-relevant gears and coasting at 50 km/h). In the following, the results obtained with vehicles of various manufacturers are compared with the critical distances known from physical observation. The conversion of the noise levels into critical perception distances is made in two steps:

1. The approximations obtained from Eq. (3) must be applied to the respective vehicle. In doing so, the parameter n remains unchanged. Only parameter A has to be adapted in such a way that the original noise level of the vehicle under investigation ends up on the interpolated curve.
2. Thereafter, the perception distance - i.e. the distance at which the vehicle produces a noise level loud enough to be perceived - can be read off the re-interpolated curve. The perception level corresponding to the respective approximation and speed can be taken from Table 2.

To assess the quality of this method for the prediction of critical distances the results of the auditory test were compared with the values calculated in the aforementioned way. To this end, the noise levels additionally measured at a 7.5 m lateral distance were used to mathematically predict the perception distances. These predictions can then be directly compared with the results of the auditory test (see the rectangles in Figure 8): Safe for one single exception value at 20 km/h, all the predicted values are in excellent compliance with the results of the auditory test. It remains to clarify, how the method is capable to predict perception distances for slow vehicles.

After having explained and validated the prediction method, the perception distances were calculated for various vehicles at a speed of 50 km/h and compared to the critical distances. The results have been plotted in the histogram in **Figure 9** together with the critical distances. As can be seen, most of the perception distances are beneath the critical distance for concentrated pedestrians and this regardless of the vehicle type and manufacturer. It must therefore be concluded that collisions can be safely avoided only if the vehicle is not perceived by merely acoustical signals only. None of the examined vehicles shows an exterior noise level which is high enough to be distinguished from the given background noise by diverted persons early enough for a collision to be avoided.

## 5 Summary

Based on the observation of reaction times and physical relationships, the present article deals with the critical distances at which approaching vehicles must be perceived in order to safely avoid collisions with pedestrians. An auditory test was performed using two vehicles operated at various speeds and in different operating modes to find out at what distance the vehicles are acoustically perceived by persons in an urban environment. Taking the reaction times obtained as a starting point, a method has been developed which uses the noise levels of a vehicle to determine the distance at which a vehicle passing by at constant speed can be acoustically perceived by a pedestrian. This method was used to find out whether pedestrians are able of perceiving vehicles passing by at 50 km/h and in different operating modes early enough to avoid a collision. It has been found that most vehicles cannot be acoustically distinguished from the typical background noises early enough to safely avoid an accident. Further investigations will be required using, among others, additional background noise levels in order to validate these results. These investigations will provide a basis for finding a sound compromise between the conflicting objectives of pedestrian safety and vehicle noise-level reduction.

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