

PREDICTION OF VEHICLE PASS-BY NOISE

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1 INTRODUCTION

Environmental noise exposure represents a burden to people and can result in cardiovascular disease, sleep disturbance or annoyance¹. Road traffic noise is a main contributor to environmental noise, thus, it is intended to be reduced and limited by legislation in order to increase health and life quality.

Vehicle pass-by noise tests are conducted according to the international standard ISO 362, which is supposed to reflect the noise emission of a vehicle in an urban traffic environment. It is discussed that nowadays urban traffic situation requires a change of the test procedure with accompanying reductions in pass-by noise limits. To achieve compliance with the pass-by noise test it is important that vehicle engineers have access to predictive tools at the design stage.

In this paper the initial development of a pass-by noise predictive tool is reported. To begin with, the vehicle pass-by noise test according to standard ISO 362 is summarized. Existing public domain literature is reviewed and an analysis of the characteristics of the four major noise sources (engine, intake and exhaust system, tyre/road system) contributing to pass-by noise is presented. An experimental set-up involving a point source loudspeaker on a moving trolley is described. Experimental measurements made within an anechoic chamber are used as validation data for the predicted pass-by noise.

2 REGULATION AND LEGISLATION OF VEHICLE PASS-BY NOISE

Vehicle pass-by noise limits exist since the 1970s and have been gradually reduced over the last decades (cf. Figure 1). The reductions are supposed to account for higher traffic densities, urbanization and well-being of the population. For example, the noise emission of a vehicle with a pass-by noise level of 82 dB(A) corresponds to the noise emission of six cars at 74 dB(A) nowadays, i.e. a reduction of 84%. Every recently developed vehicle prior to market launch has to comply with ISO 362, which has to be ensured by the vehicle manufacturer and suppliers during the development process.

Vehicle pass-by noise tests are conducted according to the international standard ISO 362² from 1998, which intention is to reflect the noise emission of a vehicle in an urban traffic environment. In case of a passenger car, the vehicle is driven on a straight line at a constant speed of 50 kph approaching a 20 m acceleration area. When the front of the vehicle reaches the acceleration area, the accelerator is fully floored until the rear of the vehicle leaves the area. Two microphones located midway in the acceleration area and 7.5 m away from the centre line measure the A-weighted pass-by noise level. For a vehicle with manual transmission, the 2nd and 3rd gear are usually applied. The test is repeated four times for each gear. If the recordings are within 2 dB(A), they are averaged for each side and each gear. The average of the highest noise levels of each gear determines the pass-by noise level. To ensure equally equipped test facilities, the surface of the test site consists of

a special tarmac according to ISO 10844³. Further information, exceptions and restrictions can be found in the standard.

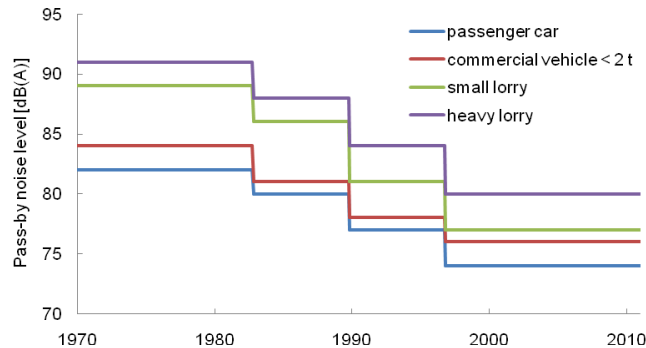


Figure 1: History of type approval noise limits

Pass-by noise limits were reduced gradually over the last decades, while the core test procedure remained the same. Critiques are that the test procedure does not simulate nowadays typical urban traffic conditions. The test is dominated by powertrain noise suppressing tyre/road noise⁴, but urban traffic is not dominated by full accelerating vehicles. However, the standard has been revised recently⁴. After extensive investigations of traffic noise, a constant-speed test of 50 kph is added to the traditional acceleration test in order to simulate urban traffic situations closer to reality. The formula for the determination of the pass-by noise level takes measured sound pressure and engine power into account.

Between 2008 and 2010, pass-by noise tests were conducted according to both versions of the standard in order to establish a comparison database. On average, the pass-by noise level according to ISO 362 (1998) is 72 dB(A), which is 2 dB(A) higher than the noise level of the suggested new test method⁵. Currently, the implementation of the new test and adapted noise limits are still being discussed. New pass-by noise limits could be as low as 68 dB(A) by 2015⁵.

3 ANALYSIS OF PASS-BY NOISE

This section gives a general overview about vehicle noise emission in both time and frequency domains in the ISO 362 test. The focus is on the acceleration test due to the availability of information in the public domain.

The noise level of the approaching vehicle increases slowly against time or travelled distance of the vehicle, respectively. However, when the accelerator is engaged, the radiated sound pressure increases rapidly, which can be up to 5 dB(A) within 3 m in 2nd gear⁶. The raise can be related to the abrupt change in engine load and constant increase in engine speed and acceleration. Greater pressure pulses from the engine and intake system and a greater amount of air sucked into the intake system occur resulting in a higher noise level. In case of a front engine, this is clearly identifiable in the pass-by noise data. The acceleration capability in 3rd gear is less than in 2nd gear resulting in a smaller sound pressure gradient⁶. The maximum sound pressure level is recorded shortly after the vehicle has passed the microphone⁶ indicating that the exhaust orifice and tyre/road combination are the main contributors. It can be assumed the situation is favoured by the relatively short distance between the receiver microphone and the noise sources. Furthermore, the exhaust orifice noise can almost radiate without any obstacles towards the microphone. In this position, the engine noise is assumed to be screened by the vehicle body. After the peak level, the sound pressure level decreases⁶ as in the case of a point sound source leaving a receiver. The recorded graph of the pass-by noise measurement data appears to be a parabola upside down⁶. For a regular passenger car, the speed difference for the 2nd gear can be about 16 kph, for the 3rd gear it is approximately 12 kph⁶. Engine speeds are in the range of 3000 rpm to 4500 rpm for 2nd gear and

2000 rpm to 3000 rpm for 3rd gear⁷. Generally, engine speeds vary depending on gear ratios and engine power.

The frequency spectrum of a pass-by noise recording is dominated by engine orders below 500 Hz, which consist of the sound radiation of engine, intake and exhaust system⁸. Typical firing or engine orders have their origin in the periodic combustion process of the engine. Due to the aspiration of air and blow-out of exhaust gas, high sound pressure levels at the frequency of firing orders occur also at the intake and exhaust system. The frequency spectrum between 500 Hz and 2 kHz is dominated by tyre/road noise⁸. Depending on the vehicle position, the contribution of each noise source varies. The exhaust orifice noise is dominant when the vehicle has passed the microphone position, because noise can be radiated freely without obstacles towards the microphone. When the vehicle approaches the microphone, exhaust orifice noise is shielded by the vehicle body. The situation is similar regarding engine and intake system radiated noise.

4 NOISE SOURCE CHARACTERISTICS

Vehicle pass-by noise is composed of the four major noise sources comprising engine, intake and exhaust system, tyre/road system. Each noise source has different radiation characteristics and certain frequency content. However, the contributions of each noise source are superposed.

The windowing or shielding technique is the preferred technique to identify noise source contributions to the overall pass-by noise. All noise sources on the vehicle are encapsulated with absorption material or attenuated by high volume mufflers attached to exhaust and intake orifices. Each noise source cover is removed on turn in order to measure its contribution⁹. Investigations show that the engine is the most dominant noise source in the accelerated test followed by tyre/road noise and exhaust system noise¹⁰. The engine and tyre/road almost linearly increase until the vehicle front reaches the microphone line. It then remains almost constant until declining in the final quarter of the test. It can be assumed that the short distance between vehicle and microphone results in high noise levels. The combination of an increasing distance and higher engine speed, which causes higher noise emissions, leads to a slow reduction of the noise level. The maximum tyre/road noise level occurs when presumably the rear axle is on the same height as the microphone. It can be assumed that front and rear tyres in combination with a short distance to the microphone cause the highest noise level. For the leaving vehicle, the noise level gradient is less steep than for the approaching vehicle indicating that a significant portion of sound is radiated towards the rear side of the tyres. This is basically in compliance with investigations of the horn effect¹¹, which describes the noise amplification from the leading and trailing edge of a tyre. The contribution of exhaust orifice noise is rather low at the beginning, but it suddenly rises when the vehicle passes the microphone position. The vehicle body does not screen the radiated exhaust orifice noise anymore, consequently, its noise level increases until the vehicle leaves the test area. Exhaust orifice noise can have a great influence on pass-by noise levels.

Any acoustic measures have to fit in the overall acoustic appearance of the vehicle, which is mainly focused on the characteristic and customer perception of vehicle interior noise. The development of exterior noise is predominantly driven by legislation not by customer preferences. If the sound radiation of engines is too high, efficient sound damping measures can be applied in order to pass the ISO 362 test. However, additional weight due to damping measures is counterproductive to efforts in fuel consumption saving. Diesel engines have usually higher noise radiation than petrol engines¹⁰. The noise emissions of a combustion engine generally increases with rising engine speed¹⁰. Engine torque influences noise emissions at lower engine speeds.

Investigations utilizing the shielding technique in conjunction with acoustic holography under ISO 362 conditions show that the engine noise radiates into the environment from the bottom of the vehicle¹². Depending on the engine order, one or more sound pressure maxima exist. Reflections and diffractions of the sound waves can be expected due to the vehicle body and the ground. The vehicle body screens the direct radiated engine noise in the engine compartment.

In the past, exhaust orifice noise was dominant for vehicle exterior noise¹³. It was reduced by large volume mufflers and noise limiting legislation. Exhaust and intake system have a similar acoustic characteristic. Both intake and exhaust system contribute significantly, if the engine is run under high load and speed¹⁴. Intake and exhaust system noise are caused by primary and secondary noise sources¹³. Pressure pulses, which are caused by the opening and closing events of engine valves, belong to primary noise sources. They proceed through the ductwork of the intake and exhaust system to the orifices, where they are radiated as noise into the environment. The valve motion is linked to the combustion, so intake and exhaust system noise occur at the engine firing frequency and its multiples depending on the specific design¹⁴. The harmonic noise character depends on engine speed. The secondary noise source is the mass flow inside the intake and exhaust system – the flow noise. The causes are turbulences and vortices of the high speed mass flow around sharp edges, small bends and free jets¹⁴. It is usually effective at higher engine speeds and has a decisive influence on the overall sound pressure level of the exhaust orifice¹⁵. It has a rather broadband character between 1 kHz and 3 kHz. It is possible to tune intake or exhaust system to either attenuate or emphasize pressure waves in order to alter specific amplitudes and frequency content. Half engine orders can be created by uneven pipe lengths from different cylinder banks and uneven firing sequences. Expansion chambers, quarter-wave and Helmholtz resonators belong to the group of reactive mufflers. They cause reflections of the moving sound pressure wave in order to shift its phase; phase cancellation is used to attenuate sound waves¹⁴. Resistive mufflers are filled with absorption material like mineral wool and lower wave amplitudes through absorption. They are predominantly installed in the exhaust system to reduce broadband noise and are very effective in the high frequency range¹⁴. Experiments in free space environment show that the sound pressure radiated from an exhaust orifice approximately decays according to the inverse distance law¹⁶. Furthermore, significant fluctuations of measured sound pressure on a circle around the orifice indicate that sound is not radiated in a pure spherical directive manner. Shell noise from the vibrating structure of intake and exhaust system hardly contributes to exterior noise.

Tyre/road noise is a result of the interaction between tyre and road. Generation mechanisms are divided into structure-borne and air-borne related mechanisms. Structure-borne noise is assumed to be generated by impact mechanisms (e.g. impact of the road surface pattern on the tyre surface) and adhesion mechanisms (e.g. stick/slip effect between tyre tread element and road surface)¹¹. Air-borne noise is presumably caused by air displacement mechanisms (e.g. pumping effect of air in pockets between tyre tread and road surface)¹¹. Tyre type and size, roads, pavement and operating condition influence the overall tyre/road noise as well¹¹. The main noise sources contributing to the overall noise level are located closely to the tyre contact patch in the vicinity of the leading and trailing edge and at the sidewall¹¹. Radiated tyre/road noise is influenced by amplification and reduction mechanisms like the horn effect, the acoustical and mechanical impedance effect and the tyre resonances¹¹. The greatest influence is assumed to be the horn effect with the potential of a decisive contribution to pass-by noise level. The horn effect is geometrically defined by the leading or trailing edge of the tyre and the road surface. It is assumed that the amplification of sound results from the good agreement between acoustic impedance in the horn and the ambient acoustic impedance¹¹. Reciprocally conducted experiments with a single tyre show amplifications of up to 23 dB in the tyre plane¹¹. Measurements involving the whole vehicle result in maximum amplification at angles between 45 deg and 75 deg off the tyre plane. The angles between 45 deg and 90 deg show only a 2 dB difference in the amplification¹¹. The amplification in the tyre plane is low, since the vehicle body presumably presents a screening effect. Varying distances and angles between tyres and pass-by noise microphone location can create favourable conditions for the horn effect to raise pass-by noise level.

Acoustic holography investigations of tyre/road noise during the ISO 362 test show a complex distribution of noise sources around the vehicle surface¹². Noise maxima can be found on the leading and trailing edges of the tyres. Tyre/road noise measurements on a vehicle show a frequency range of interest of 200 Hz to 1 kHz for a wide tyre, whereas the frequency range is reduced to 500 Hz to 1 kHz for a smaller tyre⁸. Generally, higher sound radiation can be expected for accelerating tyres under slip and torque influence^{11,17} in comparison to rolling tyres. However, the acceleration test is dominated by noise from the engine, exhaust and intake system. In the constant-speed test, tyre/road noise is presumably highest.

5 PREDICTION OF PASS-BY NOISE

As seen in the previous sections, the noise source characteristics and radiation characteristics of a vehicle in the ISO 362 pass-by noise test are of a complex nature. Many influences have to be considered in the development of a predictive model for pass-by noise. These influences are not only related to the source characteristics, but also to the transfer behaviour of sound from source to receiver (cf. Figure 2). It can be assumed that strengths and characteristics of all major noise sources change constantly due to the instantaneous, accelerating driving procedure. Rather constant source behaviour can be expected from a constant-speed test; however, the distance between source and receiver is instantaneous for both scenarios. The time delay describes the amount of time between the emission of a signal at the source and the reception at the microphone position. It can be used to relate the vehicle position on the test track to the signal characteristic and its origin. Since the vehicle represents a moving sound source and the microphone is at a stationary position, a frequency shift occurs according to the Doppler effect, which has to be corrected for accurate signal processing. Furthermore, attenuation of sound pressure due to travelling over a certain distance (inverse distance law) occurs. Simultaneously, sound waves are reflected and diffracted from the ground and the complex structure of the vehicle body. The vehicle body insulates sound as well. Absorption occurs e.g. at the porous tarmac and damping material on the vehicle. All of these influences affect the sound propagation.

Previous work on the prediction of vehicle pass-by noise is based on the source-transfer-receiver model. The source strength of each major noise source is determined with each source being separated from the vehicle^{7,18,19}. The transfer path characteristics from each noise source position to the pass-by noise microphone location are determined with loudspeakers replacing original noise sources in the vehicle⁷. Transfer path behaviour has to be known for several positions of the vehicle on the test track⁷. A vehicle prototype is needed. This approach is applied for outdoor^{7,18} and indoor¹⁹ measurements.

For the initial development of a predictive pass-by noise model, a simplified experimental setup representing an exhaust orifice-like assembly with an artificial sound source is developed. It serves in the investigation of moving sound sources and to provide validation data for the predictive model. The experimental setup and the model are introduced in the following sections.

5.1 Experimental apparatus and measurement method

In the ISO 362 pass-by noise test, the vehicle represents a moving system of multiple noise sources. In order to simulate this situation, an experimental setup (Figure 3) is developed with a point source loudspeaker mounted on a moving trolley within an anechoic chamber. The trolley is pulled by a winch, which is driven by an electric motor. Pass-by noise is measured with a microphone in the middle of the track at a distance of 2 m. The motor speed is measured in order to determine the travelled distance of the trolley and, hence, the position of the trolley on the track relative to the microphone. The beginning and the end of recordings are marked by two trigger sensors. The duct opening of the loudspeaker can point to the rear like an exhaust orifice on a vehicle, or to the front like the orifice of an intake system. Reciprocal measurements can be arranged, in which the loudspeaker and the microphone exchange their positions. The experiment serves to provide pass-by noise validation data for the predictive model. Several scenarios with the point source in different positions and different excitation signals can be examined.

Sound pressure measurements are also conducted on a circle around the loudspeaker to determine the directivity characteristic (Figure 4). The results show that the loudspeaker has a characteristic similar to a point source. The sound pressure at the rear of the loudspeaker is 10 dB lower than at the front supporting the assumption of a point source.

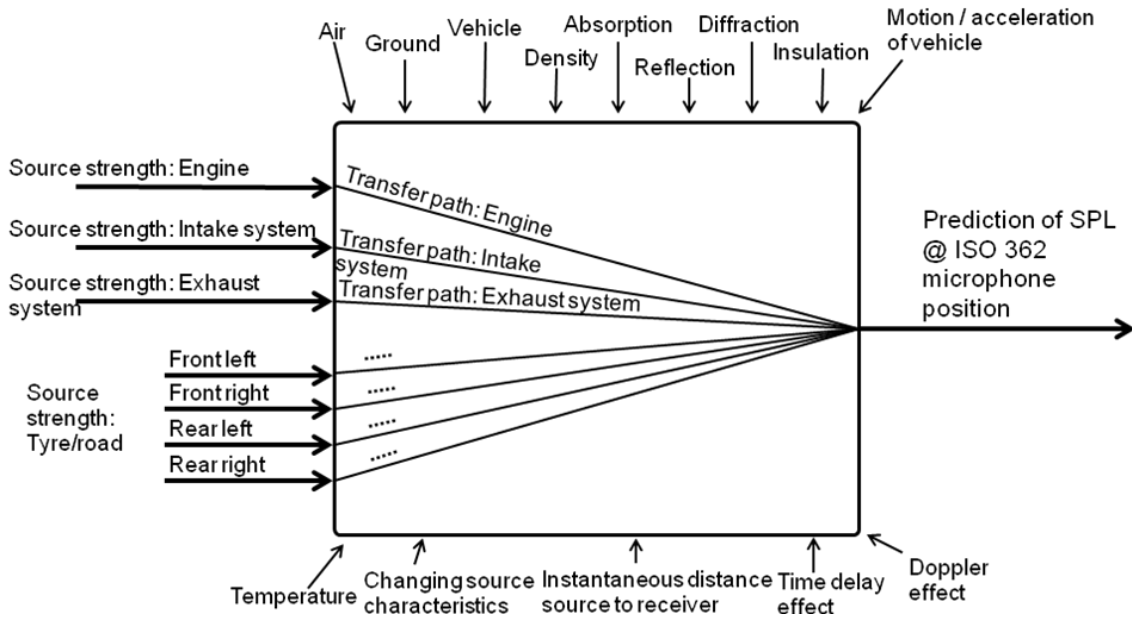


Figure 2: Influences on the prediction of vehicle pass-by noise

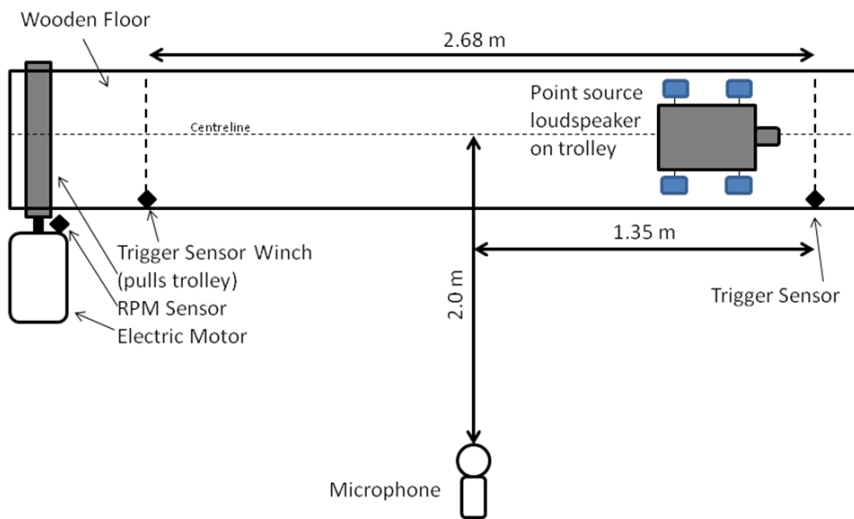


Figure 3: Schematic of experiment

5.2 Initial Development of a Predictive Model

For the initial development of a model to predict pass-by noise of the moving point source loudspeaker in an anechoic environment, the formula of the volume velocity of a point source is selected.

$$p_r(\theta(t_i), x_s(t_i), f) = \frac{Q_s(\theta(t_i)) * \rho * f}{2 * x_s(t_i)} \tag{1}$$

As source strength, the volume velocity Q_s is determined from directivity measurements. Density of air is ρ , frequency is f , and time is denoted t . The instantaneous distance between loudspeaker and microphone is denoted x_s ; it is determined from the recorded motor speed and the fixed geometrically dimensions of the track and the position of the microphone relative to it. The angle θ describes the instantaneous angle between the duct of the point source loudspeaker and the microphone. It assists in selecting the correct value of source strength from the directivity measurements. Figure 5 presents the comparison of predicted and measured pass-by noise of a

white noise signal. The agreement of both curves is mostly within 1 dB and thus very good; a difference of 1.5 dB only occurs at the distance of 0.7 m. It shows that the experimental set-up and the point source loudspeaker work accurately in the anechoic chamber.

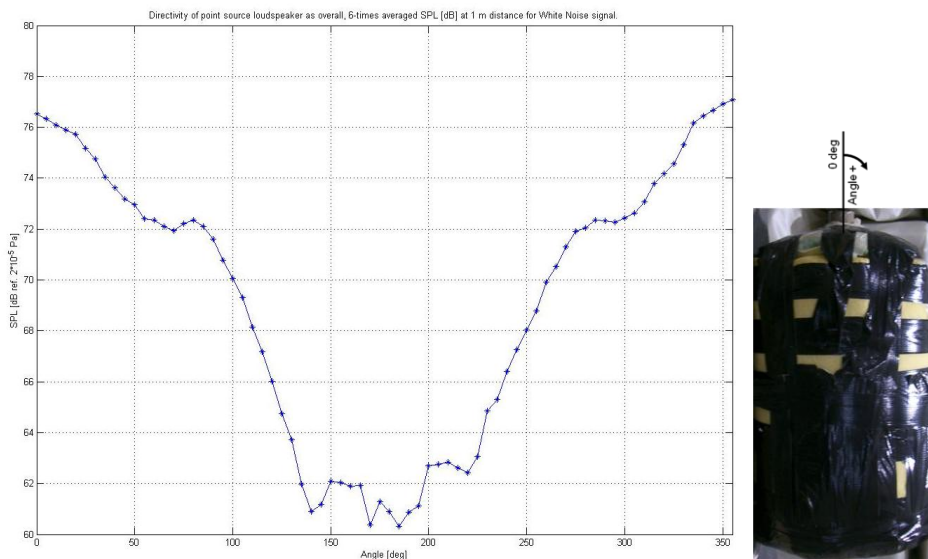


Figure 4: Directivity of point source loudspeaker for a white noise signal

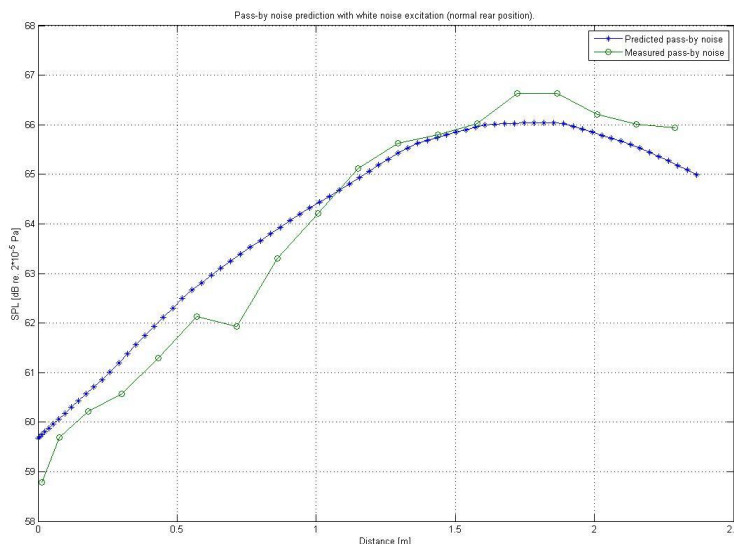


Figure 5: Comparison of predicted and measured pass-by noise for a white noise excitation signal

6 SUMMARY

In this report, current regulation and legislation of the ISO 362 vehicle pass-by noise test are presented. Pass-by noise in time and frequency domains is described, and the characteristics of the four major noise sources (engine, intake and exhaust system, tyre/road) are discussed. For the development of a predictive model, an experimental setup involving a moving point source loudspeaker is developed. The pass-by noise of the predictive model shows good correlation with

the measured noise of the point source loudspeaker for a white noise signal. An enhancement of further noise sources to the moving trolley representing a vehicle-like noise source distribution and the installation of reverberant plates simulating a ground surface is planned.

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