Identification and Prediction of Road Features and Their Contribution on Tire Road Noise

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Abstract: Traffic noise has large consequences on the appreciation of the living quality close to roads and is considered as a health problem today. It leads to speech interference, sleep disturbances, and general annoyance. The major contributor to traffic noise is tire/road noise. Many studies show the influence of different road types or vehicles on tire/road noise or on the noise inside the vehicle. This study focuses on the contribution of the overdrive of different road features on the tire/road noise for various velocities. Experimental measurements based on the ISO-13325 Coast-By Method are performed to determine the relative Sound Pressure Level of road features compared to a normal Asphalt road in good condition. The results show, that road features cause at least 4 dB higher Sound Pressure Level than the reference Asphalt road for the investigated velocities, except for manhole cover at 8.3 m/s. Therefore, road features and damages have a significant contribution to tire/road noise and on human health. To identify and predict such road features, we present a method based on vehicle sensors and data mining methods. The sensors are an inertial sensor placed at the centre of gravity of the vehicle and a sound pressure sensor in the tire cavity. The sensors combined with the data analysis method represent a strong system to comprehensively and automatically identify and predict road features, the road infrastructure condition and subsequently road segments with a high value in tire/road noise. With the output of the presented method maintenance and repairs can be done efficiently, which contributes to lower tire/road noise and less disturbance of residents.

Key–Words: Tire/Road Noise, Vehicle Vibration, Tire Vibration, Road Features, Data Mining, Vehicle Sensor, Experimental Study

1 Introduction

The type and condition of the road surfaces have not only various influences on the vehicle itself and the passengers, such as driving comfort, traffic safety and vehicle damages. They also affect people living close to road infrastructure and pedestrians due to the enormous traffic noise. Traffic noise has become one of the most annoying disturbances worldwide, especially owing to the ongoing growth of the road network. This continuing growth causes the problem of traffic noise to even spread to rural areas.

A big contributor to traffic noise is the tire/road noise, not only above 40 km/h, but in all driving conditions [32]. Many studies show the effect of traffic noise on the living quality and found relationships between the level of transportation noise and speech interference, sleep disturbances, and general annoyance [11,13,27,35]. Other studies tested whether there is any influence on psychic or physical health and found effects on children's' cognition and health [36] and increased risk for hypertension [4, 29].

However, less focus was set on the investigation of the influence of road features, such as level crossings, manhole covers, damages, condition, on the tire/road noise. With our paper we close this gap in the literature and provide for the first time a quantitative relation between road features and tire/road noise generation depending on the velocity.

1.1 Relevant Work

Many researchers have investigated the source of the traffic noise. The main factors for the noise generated from the vehicle are for instance, the power train, breaking, or exhaust. Tire/road noise is the main contributor above 40 km/h [34], whereas wind only plays a significant roll at very high velocities [18].

As we are approaching the age of hybrid or fully electric cars the tire/road noise will even play an increasing part in noise generation [30]. During the course of this work we focus on tire and vehicle vibrations, which are mainly caused by surface irregularities and lead to a higher level of tire/road noise [17, 33, 37]. Those structural vibrations can be further divided in adhesion caused stimulations and mechanical vibrations, which can be split up into noise caused by the roadway, the tire profile or the so called flattening of the tires [31]. Another study showed that these structural vibrations account for up to 80 % of the noise generated by tire/road contact [5]. [3] showed a decrease in tire/road noise by 1 to 2 dB on asphalt in contrast to concrete with similar textures. The authors also found that the flexibility of the roadway surface can decrease the noise by up to 4 dB.

[15] investigated the influence of temperature and ageing on tire/road noise and found that the temperature has little to no effect on the noise generation, whereas the age of the road has an effect. Researches [18] showed an increase of 15 dB unweighted sound pressure level inside the car for different road surface discontinuities, which they simulated by placing two tires above one another and then deflect the upper tire. Other literature studies the relationship between mean roughness and tire/road noise and found an increase of up to 5 $dB(A)$ depending on the texture of the road surface [28, 31]. [38] investigated the influence of different truck tires on road traffic noise and found a variance of up to 4 $dB(A)$ depending on the used tire.

In the literature, there have already been presented lots of different methods to measure the noise generated by traffic. For example the widely used Statistical Pass-By Method (SPB Method), which is described in [9]. This method is primarily used for classifying and ranking different types of road surfaces, by measuring the A-weighted sound pressure level of a statistically significant amount of cars. Another very common method to measure tire/road noise is the Coast-By Method (Coast-By Method), which is described in ISO-13325 [16] and will be used during the course of this work.

1.2 Our Contribution

Apart from all the investigations of the tire/road noise studies till today, we focus on what we believe to be one of the most important sources of street noise, which are different roadway damages and road infrastructure features. Firstly, we identify relevant road features based on civil engineering literature and interviews with experts. Secondly, we investigate if these features and damages are significantly louder and quantify their contribution to the overall noise and how much louder these road features and damages are compared to a normal asphalt road. More precisely, we perform experimental measurements based on the international standardized Coast-By Method [16], to characterize the Sound Pressure Level (SPL) of these road features and their contribution to road noise relatively to a road with low level tire/road noise. Since we investigate the tire/road noise for various parameters, such as varied velocities, we make necessary adjustments of the ISO-13325, which is only defined for specific speed ranges for example.

We chose the Coast-By Method as our measuring method, since it excludes other noise sources, such as the power train and thus it gives us almost only the pure tire/road noise. During the course of this work we identify various measuring sites with different road features and carry out noise measurements for each of the sites at four different speeds with four runs for each velocity. The evaluation and set-up is carried out according to the ISO-13325 [16]. Our results give us and the public institutions, who are in charge of the road construction, the tools and understanding of the interaction between roadway damages or road features and noise generation. Specific road features, which have a big contribution to tire/road noise, should be avoided in inhabited areas or be maintained.

In addition, we present a method on how to comprehensively identify and classify road features with vehicle sensors to monitor the road infrastructure comprehensively. With the output of our proposed method, one can prioritize road segments with high level of noise and repair them specifically and efficiently. Therefore, our paper is a contribution to increase the living quality by understanding the contribution of the overdrive of road features on tire/road noise and the identification and subsequently the maintenance of loud road features.

2 Tire Road Noise and Road Infrastructure Features

2.1 Theoretical Background of Tire/Road Noise

The major source of traffic noise is the tire/road noise. The percental noise intensity of vehicles under operation is shown in Figure 1, which indicates the dominance of the tire/road noise. With velocities over 40 km/h the tire/road noise is the most dominant noise source of the vehicle.

The source of the tire/road noise can be seen as two parts. The first part being the characteristics of the tire and the second part are the characteristics of the road surface itself. The tires are the only contact point the car has with the road surface and they have to carry all the weight and transfer the force onto the road. The necessity for the tire is to provide a safe

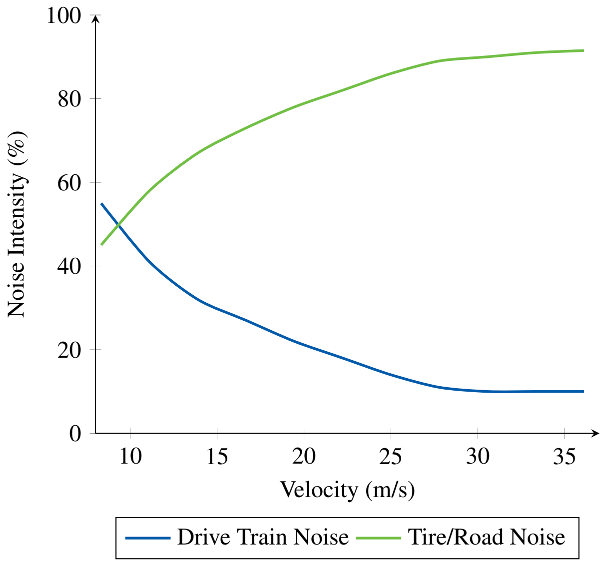

Figure 1: Vehicle noise generation depending on velocity. Adapted from [3].

drive in different weather conditions, to be power efficient as well as acoustical comfortable. To meet these desires and necessities the manufacturer has to adapt the profile, construction and the rubber compound.

[34] divides the noise generating mechanisms into mechanical and aerodynamic stimulation. Aerodynamic stimuli consists of air pumping and resonance effects of the tire. The mechanic stimuli can be subdivided into stimuli caused by the tire profile, tire flattening and roadway surface. According to the investigations of [5], the mechanical stimuli are the main part of the noise generation with up to 80 % and followed by air pumping with only $10-30$ %. The vibration stimulation of the tire results from level crossings, irregularities or the roughness of the roadway surface. The driving force for those vibrations is the tire profile deformation while it hits the ground. After losing contact with the ground the tire profile will oscillate back into its normal position. These stimuli cause the tire profile to start vibrating in a radial direction causing the rest to vibrate too and generating noise. Another mechanical mechanism is the running deflection, which causes vibrations because of the unbalanced load of the tire [34]. The perfect and therefore least noisy tire would have a equal force distribution causing less vibrations because of less running deflection [18]. Air pumping denotes an effect that is caused by air displacement and air induction at the contact surface of the tire with the road. The tire profile and the air within its gaps will get compressed when the tire hits the ground. The thus escaping air causes turbulence, which causes noise. When the tire loses contact with the road, air will flush back in the profile gaps resulting in more turbulence and therefore more noise. Thus the width of the tire also directly influences the amount of noise.

2.2 Road Features

We investigate the following road features and damages, which have an influence on the tire and vehicle vibration:

- Smooth asphalt road
- Railroad crossing
- Manhole cover
- Cobbled road
- Pothole
- Damaged road

3 Experimental Design

The Coast-By Method is a variation of the commonly used SPB Method. The SPB Method is based on measurements of the A-weighted sound pressure level of a statistically significant amount of vehicles passing by the measurement site. This method is usually carried out in three different speed ranges called 'Low speed roads', ' Medium speed roads' and 'High speed roads' with speed ranges from $45-65\ km/h$, $65-99\ km/h$, and greater than $100\ km/h$, respectively [14]. Afterwards a regression line is calculated for all the data in one speed set.

The main difference to the SPB Method is that for the Coast-By Method the gear shift is switched to neutral while passing by the microphone to avoid noise from the engine. This makes it remarkably suited for our purpose, because we do not want the engine noise to affect our measurement, as we are only interested in tire/road noise created by different features on the road surfaces. For our measurement we use a speed range of $30-60\ km/h$. We could not reach higher speeds for some of the measurement sites, as the test tracks were too short. We have to measure and monitor the following parameters during the performance of our experiment. One important parameter is the velocity of the vehicle while it is in the area of or passes the microphone. The measuring device should have an accuracy of ± 3 %. For later corrections we need to know the air temperature within $\pm 1°C$ and as we have to keep the noise caused by wind low, we need to measure the wind speed, which should not exceed $5\ m/s$. The most important parameter is the sound pressure from which we consequentially calculate the maximum A-weighted sound pressure level $L_{A,max}$. In order to avoid noise by the engine or exhaust, the test vehicle has the transmission set to neutral while it is inside the square $BB'CC'$ and the driver has to follow the *Centerline* as closely as possible, which is shown in Figure 2.

3.1 The equipment

The equipment needed for this method are two microphones, which have to satisfy the requirements of [16]. We use a MK 250 microphone cartridge and measurement microphone preamplifier MV 204, which are calibrated and designed for sound level meters of IEC Type 1 according to IEC 651. Furthermore, we use the vehicle control to regulate the velocity and we monitor the temperature and wind speed. We used a BMW 116d for all our measurements. The calibrations for the equipment is done according to [16].

3.2 Requirements for the test procedure, test site and road surface

The most important requirement for the Coast-By Method is that the test section provides free-field conditions for the sound measurements within a 50 m radius around the centre of the test track. This ensures that no reflecting objects such as barriers, fences or buildings influence the recorded sound pressure and therefore guarantee a correct result for the measured parameters. Further requirements are a test track of at least 60 m with no gradients bigger than 1 %. There should be no objects or men in-between the microphone and the centre of the test track throughout the entire measurements. Any observer shall be positioned outside of the measurement site to not affect the measurements at all. In [16] adiitonal requirements are described, such that all windows must be kept closed during the measurements and that the car has to be clean. Additionally all unnecessary parts hanging of the car, which could create noise must be removed and the tires must be inflated to normal operation pressure as stated by the manufacturer and have to be warmed immediately prior to the test. The driver himself has to ensure that the brakes are not poorly released and may thus cause breaking noise. The last condition is that the A-weighted sound pressure level of the background, including wind noise, should be at least 10 $dB(A)$ below the maximum of the quietest pass-by.

3.3 Measurement setup

We use the setup for the measurement as described in [16] and shown in Figure 2. $P1$ and $P2$ represent the positions for the microphone during the measurements. The distances were chosen according to [16], which means, that the radius r is 50 m and depicts the radius within no reflective objects such as walls or parking cars are allowed. The *Centerline* is the lane where the car is driven. The distance from this *Centerline* to each of the microphones $P1$ or $P2$ has to be exactly 7.5 m. The distance from B' to C' and the distance from B to C have precisely the same length of 20 m. The horizontal distance from A' to B' has to be 10 m, so does the horizontal distance from C' to D', A to B and C to D. The vertical distance of these four line segments are all 10m. The height of the microphone shall be (1.2 ± 0.02) m above the surface of the test area, facing the sound source.

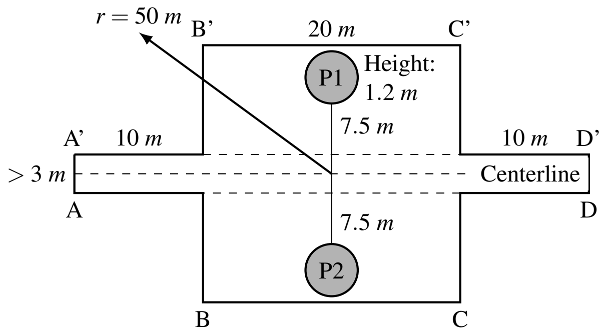

Figure 2: Measurement set-up according to [16].

3.4 Selection of the measuring sites

We selected measuring sites according to the described requirements and where we could find the road features, which are described in Section 2.2 . We chose a common asphalt surface as our reference measuring site. Furthermore, we measured the sound pressure of the tire/road noise for a road with slight damages, with a pothole, a manhole cover, railway crossing and a cobblestoned road. Figure 3 and Figure 4 show a pothole and manhole cover, two of the selected road features to measure, respectively.

3.5 Calculation of the SPL

The data from the microphone were acquired with the data acquisition device NI 9234 from National Instruments and saved as a tdms-file. We calculated the A-weighted sound pressure level in Matlab and perform a Fast-Fourier Transformation (FFT) using a Hanning-Window and 50 % overlap for each interval. According to [10] the A-weighting function for the frequency (in Hz) dependent amplitude is given as

$$R_A(f) = \frac{12200^2 \cdot f^4}{\sqrt{(f^2+107.7^2)\cdot(f^2+737.9^2)}} \cdot \frac{12200^2 \cdot f^4}{(f^2+20.6^2)\cdot(f^2+12200^2)}. \quad (1)$$

Figure 3: Picture of the overdriven pothole to measure the sound pressure level.

Figure 4: Picture of the overdriven manhole cover to measure the sound pressure level.

These weighted amplitudes show an attenuation of 2 dB for 1 kHz. As all the data usually are normalized to 1 kHz, we have to correct for that attenuation using the formula

$$L_A = 20 \cdot log(R_A(f))dB + 2.0dB. \quad (2)$$

In the last step we calculate the moving average, using a small window-size of 5 points of the A-weighted SPL and determine the maximum SPL for each test drive.

3.6 Corrections

There are two major corrections that are applied on the measured data. The first correction is for the temperature and is also taken from [16]. The standard temperature is given as $T_0 = 20°C$ and then the correction can be calculated using the following equation.

$$L_{corr'} = L_{measure} + \eta \cdot (T_0 - T), \quad (3)$$

where η is $-0.03 \dfrac{db(A)}{°C}$ when the measured test surface temperature is $> 20°C$ and $-0.06 \dfrac{db(A)}{°C}$ if the temperature is $< 20°C$.

The second one is the correction for speeds that are not equivalent to the reference speed of the corresponding road-type of [16]. This correction is carried out using a regression analysis and the following equation.

$$L_R = \overline{L} - a\overline{v}, \quad (4)$$

where $\overline{L}$ is the arithmetic mean of the temperature corrected sound pressure levels and $\overline{v}$ is the arithmetic mean of the logarithm of speeds. The slope of the regression is a and can be calculated as follows:

$$a = \frac{\sum_{i=1}^{N} (v_i - \overline{v}) \cdot \left(L_i - \overline{L}\right)}{\sum_{i=1}^{N} (v_i - \overline{v})^2} \quad (5)$$

Its units are decibels per speed decade.

Using equation 4 we get the reported sound pressure level L_R. Given this value we can now calculate any other sound pressure level L_v within the speed range as follows:

$$L_v = L_R + a \cdot \log\left(\frac{v}{v_0}\right), \quad (6)$$

where v_0 is the reference speed for the chosen speed range.

In our case $v_0 = 8.3, 11.1, 13.9, 16.7\ m/s$ respectively.

4 Methods to Identify and Predict Road Features

Since the results our measurements in Section 5.1 show the enormous effect of the overdrive of road features on tire/road noise, we see necessity to identify and predict these features and damages comprehensively to enable an efficient maintenance. Therefore, we present a method, in which we use data from vehicle sensors and apply data mining methods to estimate the road infrastructure condition. The advantage of this method is that vehicles can be used as sensor systems and acquire data comprehensively and automatically.

4.1 Sensors

The main sensors we use for the identification and prediction of road features are

- an inertial sensor in the centre of gravity of the vehicle and
- a sound pressure sensor in tire cavity.

The inertial sensor measures the characteristics of the vehicle dynamics and especially the movement and vibration of the vehicle body due to road features. Figure 5 shows the orientation of the sensor. The signal is damped due to the suspension systems. However, the overdrive of road features, such as railway crossings or manhole show a characteristical course of the vertical acceleration, pitch or roll rate of the vehicle.

To identify small damages on the road, which also have an effect on the tire/road noise, we include a sound pressure sensor in the tire cavity in our method [20]. The idea behind this measurement method is shown in Figure 6. The tire carcass of a road vehicle is stimulated by the road surface and its particular characteristics and damages. Therefore, the tire cavity air oscillates through the vibration of the tire carcass and the sound pressure reaches values higher than 150 dB [6].

The measurement system consists of low-cost components to enable a large scale application and was developed and verified at our Institute [22–24].

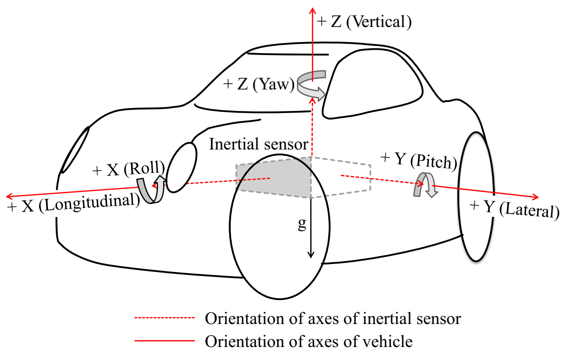

Figure 5: Coordinate systems of the vehicle and the inertial sensor according to ISO 8855:2011.

4.2 Data

Besides the inertial and sound pressure sensor, we also acquire control variables with additional sensors in the tire cavity and the vehicle. Figure 7 shows the functional model of our system, the sensors and the data we acquire. Since the temperature T and air pressure *static* p of the tire influences the sound pressure *dynamic* p, we acquire these data with an standardized tire pressure monitoring system (TPMS). The signal

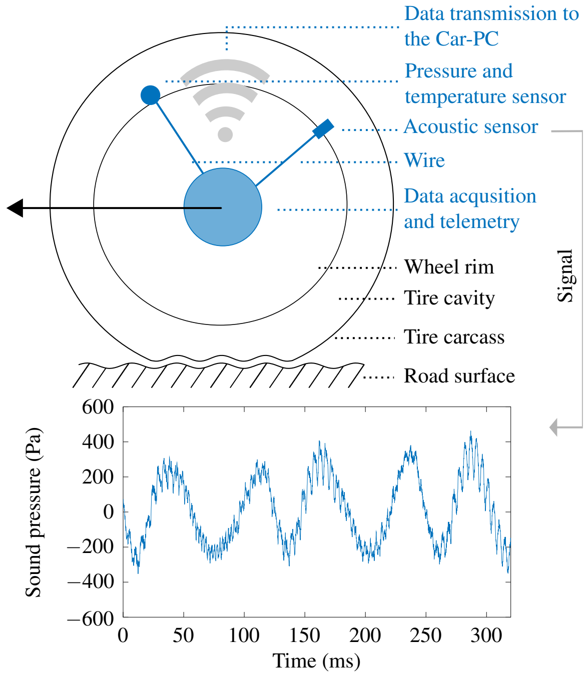

Figure 6: Tire torus sound measurement method and sound pressure raw data [26]. The acoustic sensor measures the sound pressure level inside the tire cavity and additional sensors acquire the static pressure and temperature. The sensors are connected to a telemetry system attached to the rim flange, which transmits the data to a Car-PC. The signal of the tire cavity sound pressure indicates the wheel speed with a frequency of approximately 10 Hz due to the rotation of the acoustic sensor and the superposed tire cavity oscillation from the road surface texture.

from the TPMS is sent via 433 MHz to our data logger based on a Raspberry Pi inside the vehicle and the sound pressure via Bluetooth from the telemetry unit at the wheel rim. In addition to the inertial sensor, we also acquire the position and velocity of the vehicle with a GPS module. As soon as the vehicle returns to its parking area and connects to a nearby supported access point, the software of the data logger is updated and the data are automatically transmitted and stored on a server. On the server, the data are processed and information from the raw data can be extracted with data mining methods to identify road features and damages.

4.3 Data Mining Methods

We apply two different methods to analyse the data from the inertial and sound pressure sensor. Our goal is to find a function f_X, which returns the road feature or condition of the road infrastructure based on the

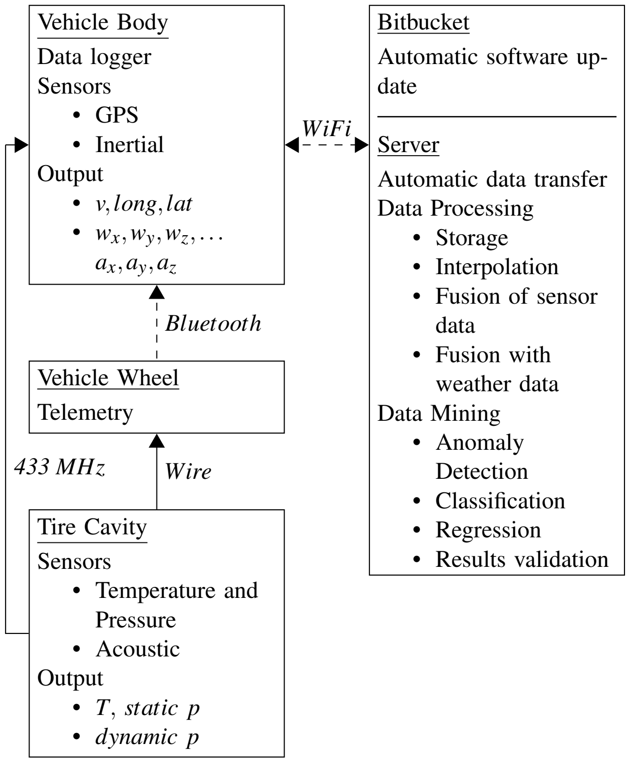

Figure 7: Functional model of our developed measurement system to identify road features and road damages [25]. The data is saved locally on the data logger during vehicle operation. After the vehicle returns to its parking area and to the WiFi access point, the data is transmitted to a server without additional intervention of the driver.

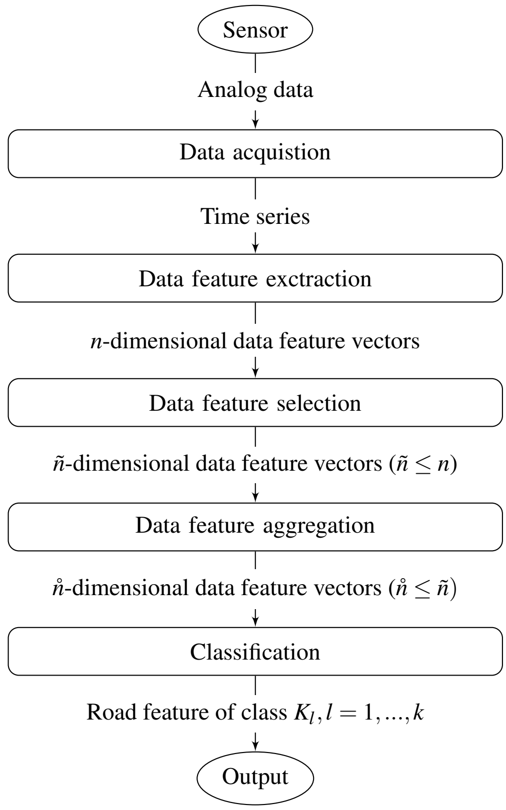

Figure 8: Overview of our method to predict the road feature based on time series data from the inertial sensor [26].

time series data from the two sensors. Therefore, we use a training set with data features calculated from the raw data labeled with the overdriven road feature or damage to automatically find a function with a good generalization. With this function we can predict measurement data, which were not used for training or which will be acquired in the future.

For the inertial sensor we apply a classification model to detect the road features and for the sound pressure sensor we apply a regression model to predict the road condition. A support vector machine (SVM) is a model to find such a function f_X [7]. It is known as a top performer and it finds a global optimum, maximizes the generalization ability, is robust to outliers, and is geometrically explicable [1]. The disadvantages are, that a SVM needs a training process and that we have to extend the model to a multiclass problem for the inertial sensor data, since it uses a direct decision function [1]. We want to predict seven different road features as discussed in Section 2.2 and therefore have a multiclass classification problem. We use a one-against-one method to classify multiple outputs, which was introduced in [19] and firstly applied on SVMs in [12], and [21]. Figure 8 shows the signal processing and data mining method for the inertial sensor.

We predict a Roud Roughness Index from the sound pressure in the tire cavity and apply a Support Vector Machine Regression, which has the advantage of the possibility to use non-linear functions. Road damages excite the tire, which results in a high SPL in the tire cavity. Therefore, the Roud Roughness Index is a function of the tire cavity SPL. Since the vehicle velocity v, wheel load P, tire pressure p and tire temperature T influence the SPL we have to control the function for these variables. Overall, our regression model can be described with the following function

$$RRI(SPL, \boldsymbol{x}) = \omega_1 \cdot SPL + \omega_2 \cdot v + \omega_3 \cdot p + \omega_4 \cdot T + \omega_5 \cdot P + b, \quad (7)$$

with the dependent variable RRI, the independent variables SPL, v, p, T, P, and the coefficients $\omega_1 \dots \omega_5$ and the intercept b.

5 Results

5.1 Contribution of Road Features on Tire Road Noise

For each speed and each event we perform four runs. The corrected results of our measurements can be found graphically in Figure 9 to illustrate trends. For this plot, we determine all data points relative to the SPL of the asphalt road at 8.3 m/s, which represents the road feature and vehicle velocity with the lowest SPL. The marker in the bar chart represents the mean and the error bars show the standard deviation of the SPL for the four runs. The results are quantitatively summarized in Table 1 to precisely show the differences in SPL for the road features and velocities. For this table, we determine the data points relative to the SPL of the asphalt road for each velocity. For each value we report the mean value and the Standard Deviation (SD) written as $Mean\ (SD)$ as introduced by Barde et al. [2] and Curran-Everett et al. [8].

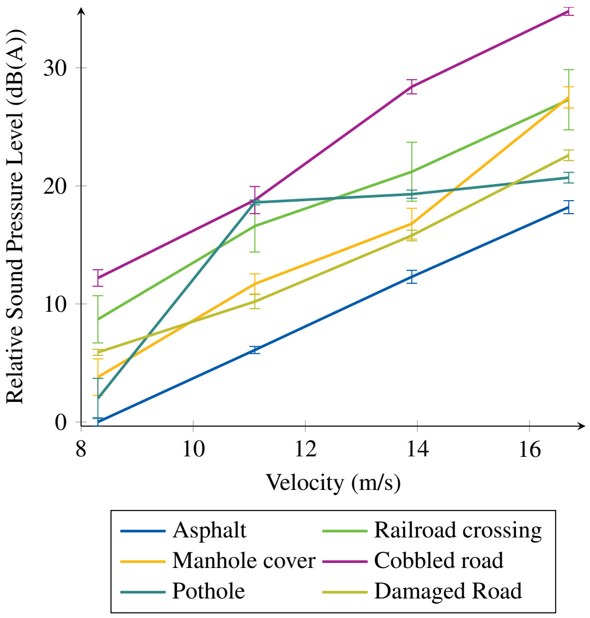

Figure 9: Graphical results of Coast-By Measurements for different road surfaces and roadway damages.

As we can see from Figure 9 an Asphalt road in good condition is the most quiet feature throughout all the speeds measured and increases with higher velocities. Latter finding is consistent with other studies, e.g [31]. The increase of the SPL is also true for all the other events except for the pothole, where we can see a constant relative A-weighted SPL of about 20 $dB(A)$ at speeds above 11.1 m/s. The noisiest road surface we measured is the cobbled road, which is true for all investigated velocities. Even at only 8.3 m/s cobblestone is as noisy as a road in good condition at 16.7 m/s or a manhole at 13.9 m/s. The second most noisy road feature throughout the entire speed range is the railroad crossing, except for 11.1 m/s, where the pothole is louder. The SPL of a manhole cover exceeds the SPL of a damaged road for velocities equal or greater than 11.1 m/s.

Table 1 indicates that the SPLs of the road features are at least 2.5 $dB(A)$ higher than for a normal Asphalt road for each velocity, except for a pothole at 8.3 m/s. However, the SPL for the pothole disproportionately increases with the velocity compared to Asphalt. Damaged road is 4.6 $dB(A)$ louder than a good road on average and a railroad crossing even 9.25 $dB(A)$.

In the following we draw some comparisons of our result to underline the importance of the tire/road noise contribution of the investigated feautres. For example the increase of roughly 10 $dB(A)$ for the railroad crossing at 16.7 m/s in comparison to the asphalt would be equal to double the noise or doubled the amount of cars driving over the asphalt road according to [14]. Another example would be the repair of a damaged road or manhole cover at 8.3 m/s, which results in a noise reduction of about 6 $dB(A)$ or equals being twice as far away from the source of the noise. For a linear extended source of noise, like a crowded road, twice the distance from the source of noise equals to a reduction of 3 $dB(A)$. One extreme example we want to show is the difference between the cobbled road and the asphalt road at 16.7 m/s for which we measured a difference of 16.6 $dB(A)$. A car driving in 10 m distance causes about 65 $dB(A)$ of noise. Now having the same car drive over a cobbled road would add about another 17 $dB(A)$ resulting in a total SPL of 82 $dB(A)$, which would cause hearing damages if exposed to this noise for a longer period, to be exact above 40 $h/week$. Above 85 $dB(A)$ the exposure time which we can tolerate before we experience a hearing damage will cut in halves every 3 $dB(A)$.

5.2 Identification and Prediction of Road Features

Besides the Sound Pressure Level from the Coast-By Measurements, we also analyze the data from the inertial sensor in the vehicle and the acoustic sensor in the tire tours. Figure 10 a and b shows the standard deviation of the vertical acceleration and the roll rate of the vehicle. All road features except for railroad crossings have a big influence on the vehicle vibration. The results suggest that the excitation of the vehicle body due to cobbled road and damaged road are similar.

Figure 10 c shows the sound pressure level in the tire torus. Here, the level of the excitement of the tire for the various road features can be clearly dis-

Table 1: Quantitative Results for Different Road Surfaces and Roadway Features.

Velocity (m/s)	**8.3**	**11.1**	**13.9**	**16.7**
	rel. SPL (SD)	rel. SPL (SD)	rel. SPL (SD)	rel. SPL (SD)
Asphalt	0.0 (0.7)	0.0 (0.6)	0.0 (1.1)	0.0 (1.1)
Railroad crossing	8.7 (4.1)	10.5 (4.4)	8.7 (5)	9.1 (5.1)
Manhole cover	3.8 (3.1)	5.6 (1.7)	4.3 (2.6)	9.3 (1.8)
Cobbled road	12.2 (1.4)	12.7 (2.3)	15.9 (1.2)	16.6 (0.7)
Pothole	2.0 (3.4)	12.5 (0.4)	6.8 (0.7)	2.5 (0.9)
Damaged road	5.9 (0.5)	4.9 (1.2)	3.3 (0.9)	4.4 (0.9)

Table 2: Results of 5 class classification on training and test data set

Road Feature	**without tire torus**		**with tire torus**	
	Precision (%)	**Recall** (%)	**Precision** (%)	**Recall** (%)
Asphalt	99	100	99	100
Cobbled Road	68	79	73	85
Damaged Road	73	69	82	74
Pothole	88	61	85	64
Manhole Cover	96	84	93	92
Level Crossing	92	88	93	88
Average	86	80	88	84
Accuracy	82		85	

tinguished.

The results of our classifier to predict the road features are shown in Table 2, which represents performance measures from our training process with a 5-fold cross-validation. For this purpose we drove over the above mentioned road features on different measurement sites and with various velocities. The input of the classifier are the standard deviation of the vertical acceleration, pitch rate and roll rate, as well as the speed. With the sound pressure level in the tire torus the performance measures could be increased.

6 Discussion

The explanation for the almost constant SPL for a pothole for velocities from 11.1 m/s is that the tire slips over the pothole resulting in a reduced or constant noise generation. For us this result is even more surprising as we even expected the noise to decrease after 13.9 m/s from what we heard both inside and outside the car during the measurements. This phenomena could be explained considering the fact that the A-weighting of the SPL tries to recreate the noise perception of the human ear, but is not perfect itself. This inaccuracy carries weight especially as the A-weighted SPL is less sensitive to very high and very low frequencies, which might be part of what we heard during the measurements and thus differs from what we would have expected right after the measurements.

The measurements are performed with only one single vehicle and the test track was not surrounded by reflective objects like buildings or parking cars, as they occur in urban areas. Assuming we have a huge amount of traffic, especially during the rush hours, and buildings left and right, the noise exposure of road features for the residents would be even more uncomfortable. Furthermore the type of vehicle also plays an important role, as trucks or motorcycles typically are louder than cars. Furthermore, we need to have in mind, that for example the measured pothole had a certain height, length and width and every pothole is different and might result in different tire/road noise generation. One further parameter that surely affects the noise generation is the vehicle, the tire and the tire inflation pressure used while testing, as this can be seen from the measurements taken out by [38].

7 Conclusion

In this paper we quantitatively present the contribution of road features and damages on tire/road noise with data from experimental measurements. The results show, that road features are at least 4 dB higher than an Asphalt road in a good condition for the investigated velocities, except for manhole cover at 8.3 m/s. Therefore, road features and damages have a significant contribution to tire/road noise and therefore on human health. They also have a big influence on the ride comfort, safety and rolling resistance. Overall, our study motivates that road features should be avoided in urban areas or should be maintained to reduce the tire/road noise contribution.

To identify and predict road features with an large effect on tire/road noise, we present a method based on vehicle sensors and data minings methods. Firstly, the data from an inertial sensor placed in the centre of gravity in the vehicle can be used to acquire the movement and vibration of the vehicle body due to road fea-

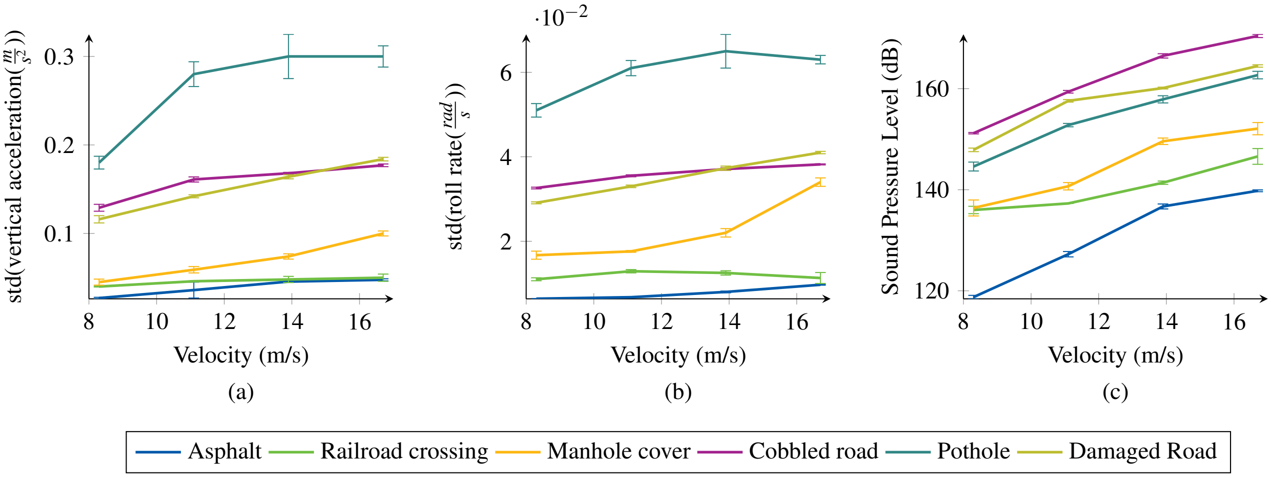

Figure 10: Results of vehicle sensor measurements for different road surfaces and roadway damages. (a) shows the standard deviation of vertical acceleration and (b) the roll rate of the vehicle body, (c) the sound pressure level in the tire torus.

tures. With the presented classification approach, one can estimate the road feature or identify road damages and hazards, such as potholes.

With our sound pressure sensor in the tire cavity we can even detect smaller damages and roud roughness and estimate a Roud Roughness Index, which is a function of the tire cavity SPL and control variables, such as the vehicle velocity and tire pressure. The sensors combined with the data analysis represent a strong method to comprehensively and automatically identify and predict road features, the road infrastructure condition and subsequently road segments with a high value in tire/road noise. Therefore, maintenance and repairs can be done efficiently. Proceeding studies could include different types of vehicles such as trucks or motorcycles or tires in their measurements. Furthermore, we will collect data with our sensor system and apply the presented data mining methods.

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