

Rolling-noise-relevant classification of pavement based on opportunistic sound and vibration monitoring in cars

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ABSTRACT

As car and truck engines are becoming quieter due to noise emission regulations and new propulsion systems, rolling noise is becoming the dominant contribution of traffic noise. The interaction of tires and pavement causes rolling noise; thus mitigation is possible in both domains. In Europe, quiet tires are promoted at the EU level, amongst others by careful labelling. Pavement choice and maintenance remains the responsibility of local authorities. Typically, the information available on the acoustic quality of these pavements is scarce. Hence, we designed an opportunistic sound and vibration monitoring approach that allows to monitor pavements continuously. Several cars that drive regularly on the roads are equipped with a low-cost sensor box that collects noise, acceleration, and GPS data. Data analytics of the large datasets thus collected allows to classify and label pavements in a way that is relevant for rolling noise production. The classification method combines a set of carefully chosen sound and vibration features using blind clustering algorithms. Spatial connectivity is added to the clustering to represent the higher probability for similar pavements to be found on adjacent road segments. Action plans based on rolling noise labelling of pavements could become an important traffic noise mitigation approach.

Keywords: Road Noise, Pavement Quality, Opportunistic Sensing
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1. INTRODUCTION

Both the increasingly stringent vehicle compliance regulation in the EU and other regions and the introduction of electric and hybrid vehicles have reduced the contribution of engine noise to overall road traffic noise emission and will continue to do so. Rolling noise caused by tire-road interaction therefore will become the next focus in traffic noise mitigation [1]. Both tires and pavements have been and will be designed to lower the noise emission. In Europe tires are labelled for their power consumption, safety and noise emission [2]. A similar labelling could be envisaged for pavements. However, in everyday practice, road surfaces degrade [3], get damaged and repaired, or may not give the expected noise benefits from the start. Hence, a label based on monitoring actual noise performance should be envisaged. Standardised methods for characterisation of road surfaces have been studied in the ROSANNE project [4]. These methods are classically based on close-proximity (CPX) [5], controlled pass-by (CPB) or statistical pass-by (SPB) measurements. The CPX measurement technique has been extensively studied, including round robin tests [6], assessing temperature effects [7], uncertainty consideration [8], etc. On Board Sound Intensity (OBSI) measurement has been proposed as an alternative [9]. CPX and OBSI have the advantage that they allow to assess long stretches of road relatively quickly, yet SPB is more directly related to environmental impact [8].

In this paper, an alternative approach is proposed that at the one hand allows to measure efficiently full road traffic networks, even more efficiently than CPX or OBSI, but at the other hand still averages statistically over a large set of vehicles and typical driving conditions. It extensively relies on opportunistic data collection and big data analytics. Technologically similar approaches for monitoring surface wear, have been suggested in [10] using more intrusive equipment.

2. METHODOLOGY

2.1 Collecting Data in an Opportunistic Way

With the advent of big data methodologies, opportunistic sensing is becoming increasingly popular. For the application at hand, vehicles that are on the road anyhow are used to collect information about the pavement that is relevant for noise emission. In contrast to existing methodologies such as CPX, this approach reduces the labour cost considerably, as no vehicles need to be driven with the sole purpose of collecting data. However, as sensors need to be installed inside vehicles of volunteers, installation should be straightforward and should not interfere with the working of the vehicle. Hence, sensor boxes equipped with a microphone, a 3D accelerometer and a GPS are deployed inside several vehicles, with the microphone positioned as close as possible to one of the rear wheels. Measurement data is transmitted to a server via 3G.

2.2 Relative Emission of Vehicles

Rolling noise not only depends on the type and maintenance state of the pavement, but also on the tire that is used to sample it. Each vehicle has its own set of tires and therefore their noise emission will vary. Moreover, the interaction between road and tires causes differences in the dependence on driving speed [11]. In addition to the source mechanisms, also the transfer function between the tire and the interior microphone may be quite different between vehicles, due to differences in microphone placement and differences in construction between vehicles.

To account for all of the above, the measurement data collected by each vehicle is related to the average measurement over all travelled roads by removing the speed dependent mean value, for each 1/3-octave band:

$$dL(f, i, t, c) = L(f, i, t, c) - GAM(f, c, v(t)), \quad (1)$$

where the indices f , i , t , and c refer to the central frequency of the band, the road segment, the vehicle trip, and the vehicle respectively. GAM refers to a generalized additive model fit on all data collected by car c for each frequency f , as a function of vehicle speed v .

Figure 1 illustrates the GAM fit for different cars. To construct the GAM fit, A dataset of the first hours driven is used for every car. To make sure all speeds occur in the training set, a minimum driving time of 30 minutes has been decided for speed intervals (0-30 km/h, 30-50 km/h, ..., 110 km/h-130 km/h). This results in a minimum driving time of 10 hours of all devices, since not all speeds are equally distributed in driving time. At low driving speeds, engine noise may dominate rolling noise, even at the back of the car where the microphone is installed, hence the GAM model was fitted to measurements taken at speeds larger than 20km/h only. The vehicles shown have various engine types (gasoline, diesel, hybrid) and cover a range of manufacturing year. The mobile sensing devices are installed in the trunks of all cars, yet the curve labelled “CPX trailer” was obtained from a microphone in the CPX trailer. The levels obtained under the cap of the CPX trailer are higher due to the lack of sound insulation.

Theoretically, the rolling noise is expected to increase with a slope proportional to v^2 at lower frequencies and lower speeds, but may show a v^4 behaviour at higher frequencies and speeds [11]. This main trend can be observed, but the detailed shape of the fit deviates. Hence, a theoretical curve cannot be used to replace the fit, in particular at the lower frequencies. At lower frequencies, the road surface has a stronger influence where at higher frequencies the tire grooving pattern resulting in air pumping effects may become more important. As road surface is correlated to driving speed, a more complicated trend is observed.

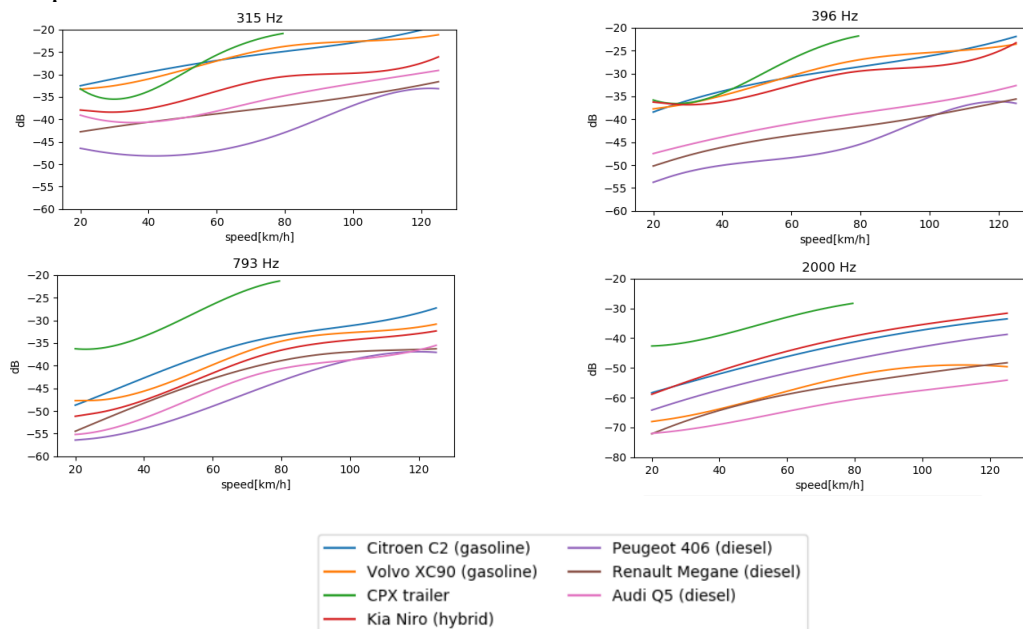


Figure 1 $GAM(f,c,v(t))$ plotted as a function of v for different vehicles and 1/3 octave bands (315 Hz, 396 Hz, 793 Hz and 2000 Hz).

2.3 Relative Noisiness Index by Road

If it can be assumed that each measurement vehicle on average drives the same roads and that the speed dependence of each tire noise emission does not differ significantly, the calibration above would lead to a relative noise emission for each road segment which could be used directly for road labelling.

$$dL_i(f, i) = \frac{1}{N} \sum_{t,c} dL(f, i, t, c), \text{ for } t, c | v(t, i) \in [v_{i,85}, v_{i,lim}], \quad (2)$$

where N is the total number of trips by all cars passing segment i , $v_{i,85}$ is the speed driven during 85% of the trips on that segment and $v_{i,lim}$ is the speed limit of that segment (possibly simplified to the speed limit for that type of road). To check the above hypothesis, the sub-sum by vehicle is made and shown for a few selected 20m road segments in Figure 2. For some vehicles such as the Peugeot 406 or the Volvo XC90 there is a systematic overestimation or underestimation of the relative noisiness of the road in the important mid-frequency region, which could be due to hypothesis underlying the calibration. In addition, some non-systematic differences are also observed, which are due to the different tires of the cars. Spectrum differences between the road segments with relatively new SMA compared to worn asphalt and concrete plates proves that the opportunistic method is capable of making a distinction between different pavements.

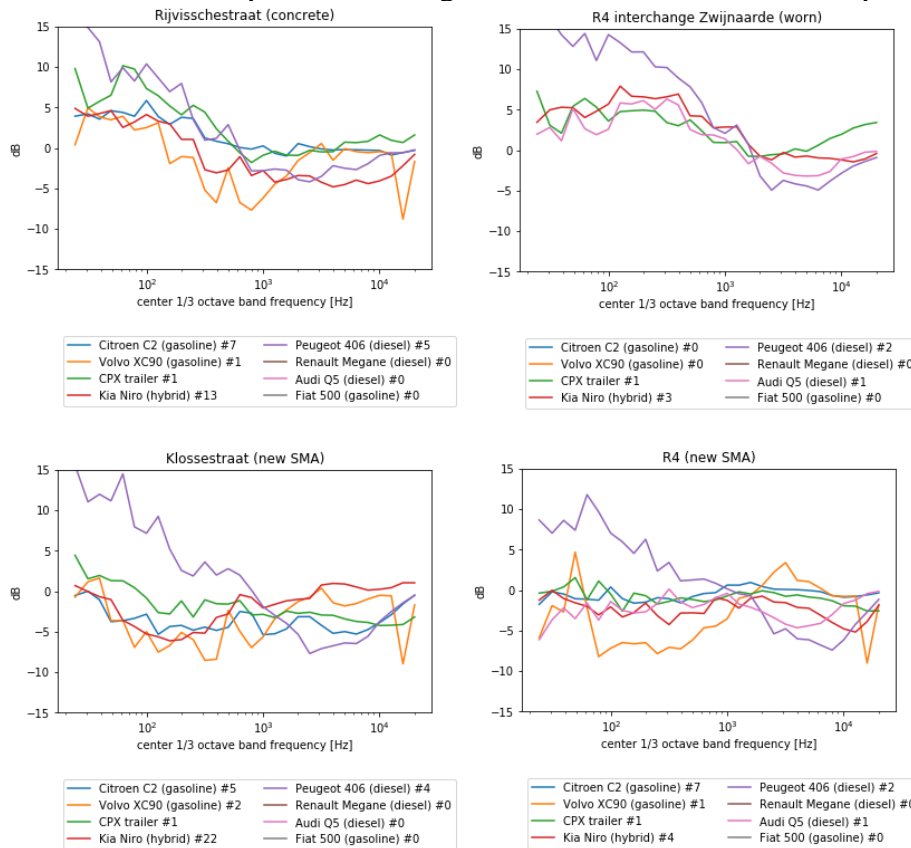


Figure 2 1/3 octave band spectra taken at various 20 m road segments in the Ghent area by vehicle $dL_{i,c}(f, i, c)$. Number following the #-sign gives the amount of trips of a car crossing the particular road segment.

For calibrating out the differences between individual cars, the following options are investigated: (1) setting values of $dL_{i,c}$ equal at common segments; (2) clustering based on the road type.

(1) Setting values equal at common segments

As the absolute value of noise emission is of no immediate use, a straight forward way of making $dL_{i,c}(f, i, c)$ comparable for all cars is to calculate the offset dL_c – due to

different roads typically driven – on segments where all cars have passed. This would lead to a more accurate estimate:

$$dL_i(f, i) = \frac{1}{N} \sum_{t,c} [dL(f, i, t, c) - dL_c(f, c, v(t))]. \quad (3)$$

But this approach requires that the test vehicles drive the same segments at a range of speeds. Obtaining the required amount of data might be difficult in many cases.

(2) Clustering based on road type and averaging

The above-mentioned difficulty to identify road segments where multiple measurement cars have passed at a range of driving speeds could be avoided if road segments with similar pavement and pavement state, could be identified. Hence, a clustering algorithm is used to group similar roads. This clustering is not (only) based on noise levels, but on a variety of spectrotemporal indicators that allow identifying type of surface and surface wear. In this work, hierarchical clustering with a road segment connectivity matrix is used. Within each cluster, the measurements from different cars are then averaged to obtain the estimate of the relative noisiness of the surface:

$$dL_i(f, i) = dL_{cl}(f, cl_i) = \frac{1}{M} \sum_{t,c,j \in cl_i} dL(f, j, t, c), \quad (4)$$

where cl_i is the cluster that segment i belongs to.

2.4 Labelling

Noise exposure caused by road traffic is most commonly assessed using an A-weighted noise level. To construct a single number road surface label, the most relevant spectral weighting at the source needs to be found. For roads immediately adjacent to the dwellings, the spectrum of façade noise exposure will be very similar to the emission spectrum. For major roads at a larger distance, the highest frequencies get absorbed by the air, while interference with the natural ground surface surrounding the road may reduce levels at a few hundred Hz. More importantly, the façade of the dwelling will typically insulate high frequencies better than low frequencies. For all these reasons it is proposed to consider frequency bands in the range 350Hz till 1250Hz in the labelling and give each third octave band in this range the same weight.

The selected frequency range is typically also the range where road degradation has the strongest impact on the above defined noisiness index.

Labels (A, B, C, ...) are assigned in 2 dB interval steps of $\sum_f dL_i(f, i)$. To calibrate the scale, an agreement between experts will need to be reached. For now, we propose to use the label B for a newly laid SMA-D surface.

3. RESULTS AND DISCUSSION

As the number of cars equipped with the sensor box in the Mobisense project is growing, the amount of data and hence the statistical precision of the classification is continuously improving. Figure 3 shows a snapshot of the road noisiness labelling map around Ghent in the end of February 2019. Most of the changes visible on the map have been identified by local field experts as changes in type and wear of road surfaces. Fast variations from segment to segment vanish when the clustering method is used (not shown).

These first results show that the opportunistic sensing approach allows to classify pavements according to their assumed noisiness. The proposed method complements standardised CPX and OBSI measurements. Due to their standardisation, the spread between measurements on the same road using CPX and OBSI methods is expected to be limited [8]. Yet, it has also been shown that the choice of tire has an important influence on the classification of roads [12]. The proposed opportunistic method by design includes:

a broad and typical spread in tires; an assessment of relative emission at the typical driving speed for that road; a statistical spread in weather conditions.

Future work will include validating relative emissions against SPB measurements at a set of well-chosen locations.

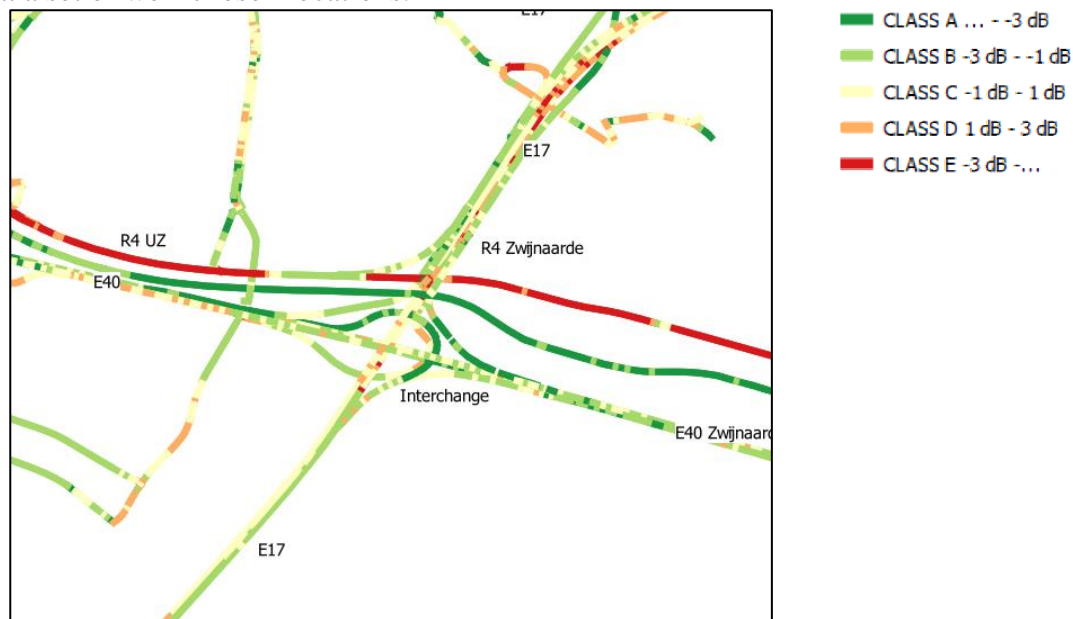


Figure 3: Noisiness index map around the area of interchange E40–E17 (Gent).

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