NEMO project: developing a N-RSD (Noise Remote Sensing Device) to identify high noise emitters in the road traffic flow

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ABSTRACT

NEMO (Noise and Emissions MOnitoring and Radical mitigation) is a research project aiming at developing an autonomous system to detected noise emitted and emissions from individual vehicles within the traffic flow. Müller-BBM (Germany), M+P (Netherlands) and SINTEF (Norway) are the three partners working on the noise emissions for road vehicles work package. The objective of this WP is to identify a high emitter from the normal traffic flow. A high emitter, is a vehicle that is either in a poor or modified condition (e.g. illegal or with an exhaust malfunction, etc.) or that is driven in a noisy way (fast acceleration, high engine speed in low gear, etc.). A vehicle that has been type approved, is well maintained, and is driven under normal conditions is never a high-emitter vehicle, even if it is subjectively perceived as annoying. A Noise Remote Sensing Device (N-RSD) is being developed. This device will process different data (vehicle speed, acceleration, engine speed and load, single-event noise levels, spectral characteristics, etc.) normalize these conditions to comparable driving conditions and feed it into a classification model. The classification model will then be able to identify the high emitters vehicles.

1. INTRODUCTION

Despite many efforts to reduce noise levels in Europe, environmental noise is still one of the major environmental pollution sources. According to the latest report from the European Environmental Agency [1] transportation noise is estimated to affect more than 20% of the EU. In particular, road

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traffic noise is estimated to affect 113 million people, followed by 22 million people affected by railway noise, 4 million people affected by aircraft noise and less than 1 million affected by noise caused by industries. Although these numbers are impressively high, it is believed that they probably underestimated the real problem and that the number of people suffering everyday due to any kind of transportation noise, and road traffic noise, is even higher. The impacts of noise exposure have been investigated since several decades now and environmental noise exposure causes cardiovascular diseases, is linked to cognitive impairment in children, causes sleep disturbances and high annoyance, resulting in physiological and psychological effects. Recent data [1] show the situation remains worrying as 12 000 premature deaths are every year caused by noise exposure. The number of people reporting to be highly annoyed by noise exposure reaches 22 million, while 6.5 million people suffer from high sleep disturbance due to the same problem. Although tackling noise issues is part of the European Union environmental policy and funding strategy, very often, a gap between research results (scientific community) and stakeholders' actions is found [2].

One of the issues is the fact that the EU Environmental Noise Directive (END), as well as almost all national noise regulations [3] are based on long-term average noise indicators, such as the L_{den} and L_{night}. Noise annoyance, however, is specifically strong for specific momentary events, such as noise peaks caused by a relatively few very noisy vehicles. For example, a recent Alpine study shows exposure-response functions for motorcycles show a shift of more than 30 dB in annoyance reaction compared to other road traffic noise [4]. For rail traffic, older wagons with cast iron brake blocks emit some 10 dB more noise, depending on local conditions, than new or retrofitted wagons with K- or LL-blocks. Such noise events are not well represented by long-term average indicators, nor by national noise emission limits. Reducing the impact of these high emitters requires a different approach.

In NEMO (Noise and Emissions MOnitoring and Radical mitigation) project we aim at developing an autonomous system to detected noise and air emissions from individual vehicles (road and rail) within the traffic flow, thus providing a tool to local stakeholders to take immediate action on infringing vehicles. This paper will describe the work done thus far to develop the N-RSD (Noise Remote Sensing Device) to identify high noise emitters in the road traffic flow (see also [5] and [6]). Developments within NEMO towards RSD's for rail noise and air emissions are also in progress but are not covered in this paper.

A "noisy" vehicle (or a "High Emitter" – HE) can be divided into two categories: a vehicle that is in a poor, or modified condition (such as exhaust malfunction, illegal silencer with no sound absorption, or rattling sound from goods on a trailer, chains etc.) or a vehicle driven in a "noisy" way (high acceleration, high engine speed in low gear, or revving up the engine while waiting for the green light). A vehicle which has been type-approved, well maintained and driven in a normal way is never a "noisy" vehicle. The N-RSD can be used to improve the acoustic situation at a local level, by limiting high emitter vehicle's access to certain areas, by informing the authorities and/or vehicle operators that the vehicle is noncompliant or by monitoring sound levels due to traffic flow and act immediately if certain pollution levels are reached. It is our expectation that it can contribute to bridge the gap between scientific community knowledge, European policy makers, national road and rail authorities and cities, to help the European population affected by noise.

2. RESEARCH GOALS

2.1. Classification of high noise emitters

The main goal for the N-RSD is to identify vehicles that make significantly more noise than they should, compared to a 'normal' vehicle or to some (inter)national or local limit value. Vehicles can be noisy because there is something wrong with the vehicle itself, for example a malfunctioning driveline or illegal exhaust system, or because the vehicle is driven in a noisy way: aggressive acceleration, high engine speed, or revving up the engine while waiting for a traffic light. The highest emitters may very well be a combination of both: a noisy vehicle driven in a noisy way. Appropriate measures may include enforcement of proper vehicle state, access restrictions, raising driver/owner awareness or changing the road lay-out. To allow application of appropriate measures, we want to distinguish between noisy vehicles and noisy driving behavior.

For each vehicle pass-by, the N-RSD measures the maximum noise level (L_{Amax}) and frequency spectrum, as well as the driving conditions (speed, acceleration and engine speed). The classification model that will identify high noise emitters is built up of two parts:

- a *pre-processing model* that normalizes the measured L_{Amax} to reference driving conditions: How high is the noise level compared to an average vehicle of the same type, at this particular speed, acceleration and engine speed? The pre-processing model will also correct for situational aspects, e.g. pavement type and temperature;
- the *classification model* that decides if the normalized noise level is above a particular threshold. This threshold may be defined as an absolute level at defined driving conditions, e.g. 75 dB(A) at 50 km/h and 3,200 rpm, or as a 'never-to-exceed' limit value: no more than 80 dB(A) on this location regardless of driving conditions. It may also be defined as a relative level, e.g. 10 dB(A) more than the pre-processing reference.

The pre-processing model describes the L_{Amax} as a function of speed v, acceleration a and engine speed n:

$$L_{Amax} = c_0 + c_v \cdot v + c_a \cdot a + c_n \cdot n \qquad (1)$$

This form uses a linear increase with speed and acceleration, as was proposed for instance in the IMAGINE method to describe propulsion noise [7]. The engine speed is added to this model to account for gear shifting behavior, but as the engine speed detection is under development (see below) this has not yet been implemented. The c coefficients then need to be found for different vehicle categories (cars, medium/heavy trucks, powered two-wheelers) and may be differentiated further using power-to-mass ratio, vehicle age, etc. Results after first testing are explained in section 5 below. During the project other or additional noise indicators, such as for low frequency noise ($L_C - L_A$) or tonal components, will also be tested.

2.2. Engine speed detection

An algorithm for detection of the engine speed (RPM) has been developed. Together with the measured acceleration, this can be a tool to classify the noise level for either of the two categories. The RPM algorithm is based on the knowledge of the number of cylinders. A detailed description of the principle of the algorithm is described in [8]. Preliminary tests on selected vehicles show that the research goals of this task have been met so far, but further testing and development of the algorithm are planned throughout the project.

2.3. Vehicle separation and microphone positions

Noise exposure is especially critical in urban areas, where the population as well as the road traffic is dense. The NEMO research project is aiming at not only detecting high emitters, but also creating a possibility to act on such violations by, e.g., distributing fines or restricting the access to dedicated low noise areas. To this end the single vehicles causing high noise have to be separated from the other noise sources contributing to the total measured sound level. Only then can the perturbator be identified.

A microphone array will be used to locate the most apparent noise source in a stream of traffic. Two microphones located on the road side and separated horizontally by a distance of approx. 20 cm are sufficient to estimate the angle of the impinging sound wave, thus the horizontal direction of the sound source. Since the sound field is not homogenous, additional microphones can be used to measure the sound level at different positions around the road, e.g. from above. A test setup of a N-RSD

will be used to find the optimal number and positions of microphones to achieve the detection and identification of high emitters.
In a dense traffic situation, the sound of multiple sources adds up to a total noise level. Next to the localization of the loudest source, the actual sound level of this one source has to be estimated. It has to be separated from the overall measured noise level. If the loudest source is at least 6 dB higher than the sound level created by all remaining sources, the influence of the latter can be neglected [9]. However, this is – especially within dense traffic – often not the case. An important goal of this project is thus to estimate the sound level of a high emitter accurately, even if it does not exceed the overall noise level by 6 dB.

3. N-RSD SYSTEM DESCRIPTION

The Noise Remote Sensing Device (N-RSD) is a measurement station located at critical infrastructure positions in urban areas, such as roads leading towards downtown areas. It consists of several microphones, a radar system and a weather station. The N-RSD will be part of the overall measurement station, whereas the exhaust gas emission sensing device and a license plate camera will complete the set.
The microphones are used to localize the vehicles and measure their sound level within the constant traffic flow. Details are described in the following chapter. The sound levels need to be set in relation with the vehicle speed and acceleration, that will be measured with the radar system, as well as with the vehicle type, whereas the license plate camera will provide the technical data from the vehicle, assuming the service is available in the specific country.
The technical vehicle data is needed to assess if the vehicle is a high emitter, as the expected or allowed noise level, and also the relation between noise level and driving conditions, depend on the vehicle details (category, power-to-mass ratio, fuel type, etc.). As the goal of this research project is not to look into enforcement or investigation of legal possibilities, we are not interested in who owns the vehicle. Nevertheless, for privacy reasons, camera images are taken only for the purpose of reading the license plates and are not stored. Also, the plate number converted to a unique hashed key, to be able to detect if a vehicle has been measured before; the key is however no longer recognizable as a license plate number and therefore privacy-safe.
The noise and exhaust emission reports will be synchronized and an individual report will be generated in the integrator, the NAUTILUS platform. With the adjacent Infrastructure to Vehicle (I2V) communication, the vehicle owners will be informed if their vehicles exceed certain noise or gaseous emission limits, which can be a plain information, a fine or a permit of entering certain low emission zones. Additionally, the road manager (e.g. the municipal civil engineering office) will be provided with some statistical information on the traffic composition that passes the measurement site (Infrastructure to Infrastructure communication).

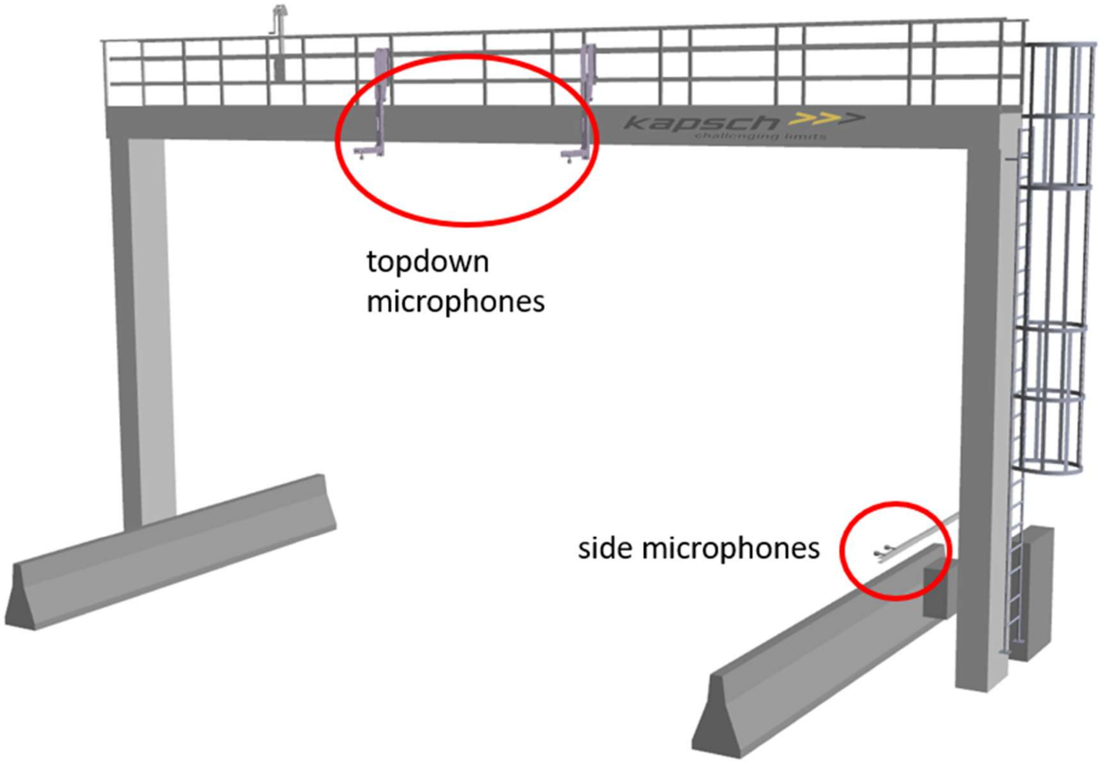

Figure 1:3D-model of the N-RSD measurement setup (*image provided by Kapsch TrafficCom AG*)

4. MICROPHONE POSITIONS AND VEHICLE SEPARATION

The microphone array consists of two side-microphones and one topdown-microphone per lane. The side-microphones are mainly used to determine the localization of the vehicles.

Two microphones are positioned on the same height with a distance of approx. 20 cm in driving direction. Using a beamforming algorithm, the main sound source can be detected as function of an input angle, that resembles a rotated tangent curve when a vehicle is passing by. The sound levels will also be measured preliminary through the side-microphones.

Figure 2 gives an exemplary situation of a cluster of vehicles passing by. The incidence angle (upper diagram) is set up at -90°, when the main noise source is located left of the microphones (vehicles approaching the station). For each passing vehicle, the incidence angle rises, passing the 0° line as the vehicle passes and going up to +90° (vehicle descending). As the incidence angle always detects the most dominant noise source, the pointer jumps towards the negative as soon as the following vehicle becomes louder. These jumping points (marked with arrows in the graph) are in line with the local minima of the overall sound level (lower diagram).

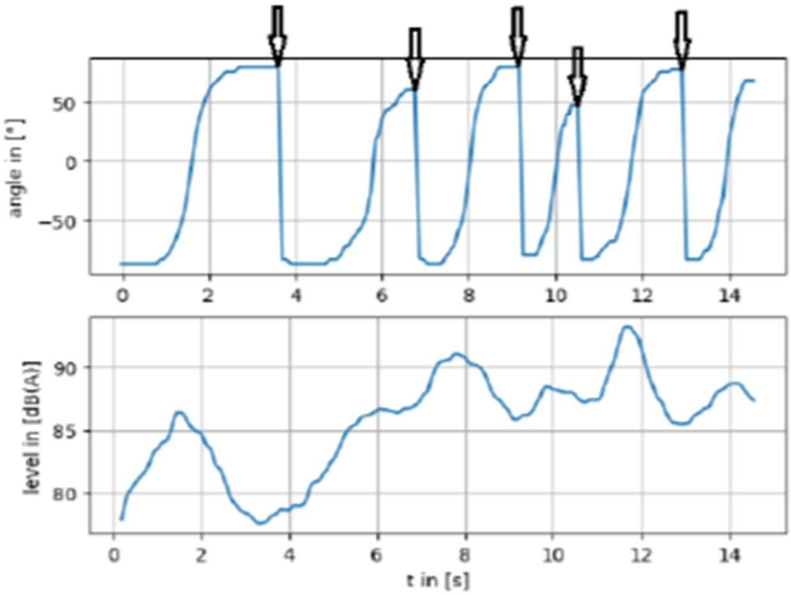

Figure 2: Diagram of a cluster of vehicles passing by. Upper diagram: Trajectory of the main noise source as function of the incidence angle. Lower diagram: sound pressure level of the passby

Additionally, there will be one microphone located above each lane. This so-called topdown-microphone shall be used to measure the sound levels of the individual vehicles in complex situations. A typical situation would be two vehicles passing the measurement site on both lanes simultaneously, where the side-microphones are not capable to measure the sound levels on the second lane, as they are shaded from the vehicles on the first lane. Furthermore, the topdown-microphones have the advantage that they detect the overall vehicle noise in a different composition: the tyre/road-noise that typically radiates to the side are less prominent on the topdown microphone position than the engine and exhaust noise. As the engine and exhaust noise components are the typical causer of high-emitter vehicles, it is an advantage for the detection algorithm to have these sound sources filtered to be more prominent than the uncritical tyre/road-noise.

The main challenge of the N-RSD is to measure the maximum sound pressure levels of single vehicles out of a constant traffic flow. This will be achieved by iteratively estimating the contribution of each vehicle towards the overall sound level that has been measured.
The algorithm (which has been presented in [10]) assumes that two vehicles need to be separated. For multiple vehicles, the steps can be repeated iteratively. The procedure works as follows:

- The position where both vehicles contribute the same sound pressure level towards the overall level needs to be detected. This is the point where the incidence angle falls towards -90°.
- The real contribution of both vehicles will be 3 dB less than the measured level on this position
- The trajectory of the single pass-by curve is then estimated as a linear curve that is fitted between the measured peak value and the estimated intersection point (red dashed line).
- The contribution of the second vehicle is hence estimated as the value of the linear fit at the peak position of the pass-by of interest (red circle).
- This contribution is subtracted from the peak value to obtain an estimate of the single pass-by maximum sound level (red x).

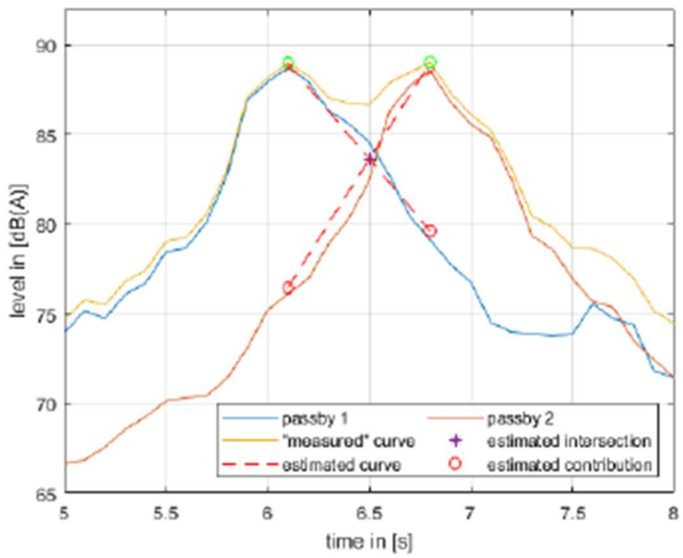

Figure 3: approach to estimate the contribution of every vehicle within the overall noise level.

5. CLASSIFICATION MODEL

5.1. Test measurements

To develop a first version of the pre-processing and classification model, a series of supervised test measurements were done during three days in November 2020. Measurements were done on accelerating vehicles, on 15 and 30 meters after a roundabout in a 70 km/h road. The measurements were performed using an SPB setup [9], with additional equipment to measure the vehicle acceleration and to capture the license plate. The acceleration was measured with a speed radar, taking multiple speed readings in a ± 1 s interval around the L_{Amax} occurrence time and calculating the average speed increase from a linear regression. The license plate was used to retrieve technical information about each vehicle: vehicle (sub)category, weight, age, fuel type, etc. Each of approximately 550 vehicles was measured at two microphones, providing some 1000 data points. The analysis focuses on data for light motor vehicles only, which were about 800 points.

5.2. Classification

The classification model starts by finding a best fit for the pre-processing model, see section 2.1. The goal of the pre-processing model is to predict from the driving conditions and technical vehicle information a reference L_{Amax} level for similar vehicles in similar conditions. Several statistical methods have been applied while adding more and more technical information about the vehicle, to find out how an accurate reference L_{Amax} value can be predicted. Several conclusions were found from this analysis:

- Robust linear modelling techniques that limit the influence of outliers, such as RANSAC or weighted least squares, help to describe better the influence of driving conditions for ‘normal’ vehicles than ordinary least squares methods. After all, we want to limit the influence of the high emitters themselves when trying to fit a model that describes the reference L_{Amax}.
- Separating the ‘light motor vehicles’ class into subcategories for M1 (passenger cars) and N1 (light duty vehicles, small vans) significantly improves predictions. M1 and N1 vehicles show differences in their average noise level as well as in the speed and acceleration coefficients. For the future N-RSD system, this implies that license plate information will be needed to accurately describe the relation between driving conditions and noise level.
- Differentiating further by adding the fuel type and power-to-mass ratio to the model only leads to small improvements to the prediction accuracy. Following Occam’s razor, these parameters can be left out. However, this may also be caused by the relatively low amount of data points: further separation means less points per category. When large volumes of data from the autonomous measurements become available, we will reconsider this.

Figure 4 below shows the improvement of the model resulting from these points. The L_{Amax} values predicted by the pre-processing model, calculated from the speed and acceleration registered for each pass-by, is plotted against the measured L_{Amax} level for that same vehicle. A perfect prediction model would imply that all points would be on the dashed 45° line (prediction = measurement). It is clear that the model in the right graph, based on robust linear regression and with additional model parameters providing information on vehicle category and fuel, is able to explain more of the observed variation in L_{Amax} levels than an ordinary least squares regression without vehicle info as shown in the left graph.

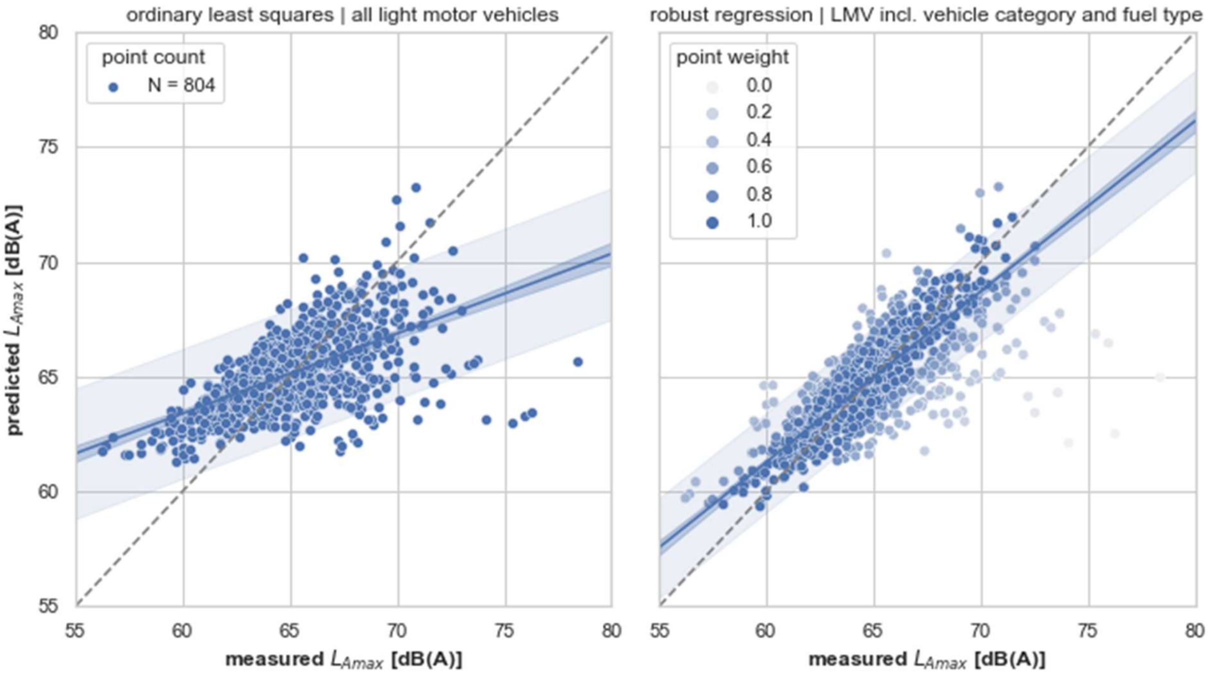

Figure 4: Predicted vs. measured L_{Amax} levels for light motor vehicles using different pre-processing models; <u>left</u>: ordinary least squares without vehicle info, <u>right</u>: robust regression with lower weights for outliers, with vehicle subcategory (M1/N1) and fuel type information. The blue line shows the linear regression through the points, with 95% confidence and prediction intervals

Figure 5 shows the influence of the pre-processing model. The left top graph shows the difference between the measured L_{Amax} and the reference value calculated for each vehicle by the pre-processing model. Some vehicles clearly stick out with noise levels more than 6 dB higher than the reference, in other words: making significantly more noise than ‘normal’. Green circles indicate the same vehicle measured by both microphones, at different speed/acceleration values. The right top graph shows the results without pre-processing, so no correction for driving conditions. On the bottom, the statistical distributions of both approaches are shown. It is clear that the pre-processing model significantly reduces the effect of driving conditions, leading to lower 95 and 99 percentiles, making high emitters more clearly distinguishable.

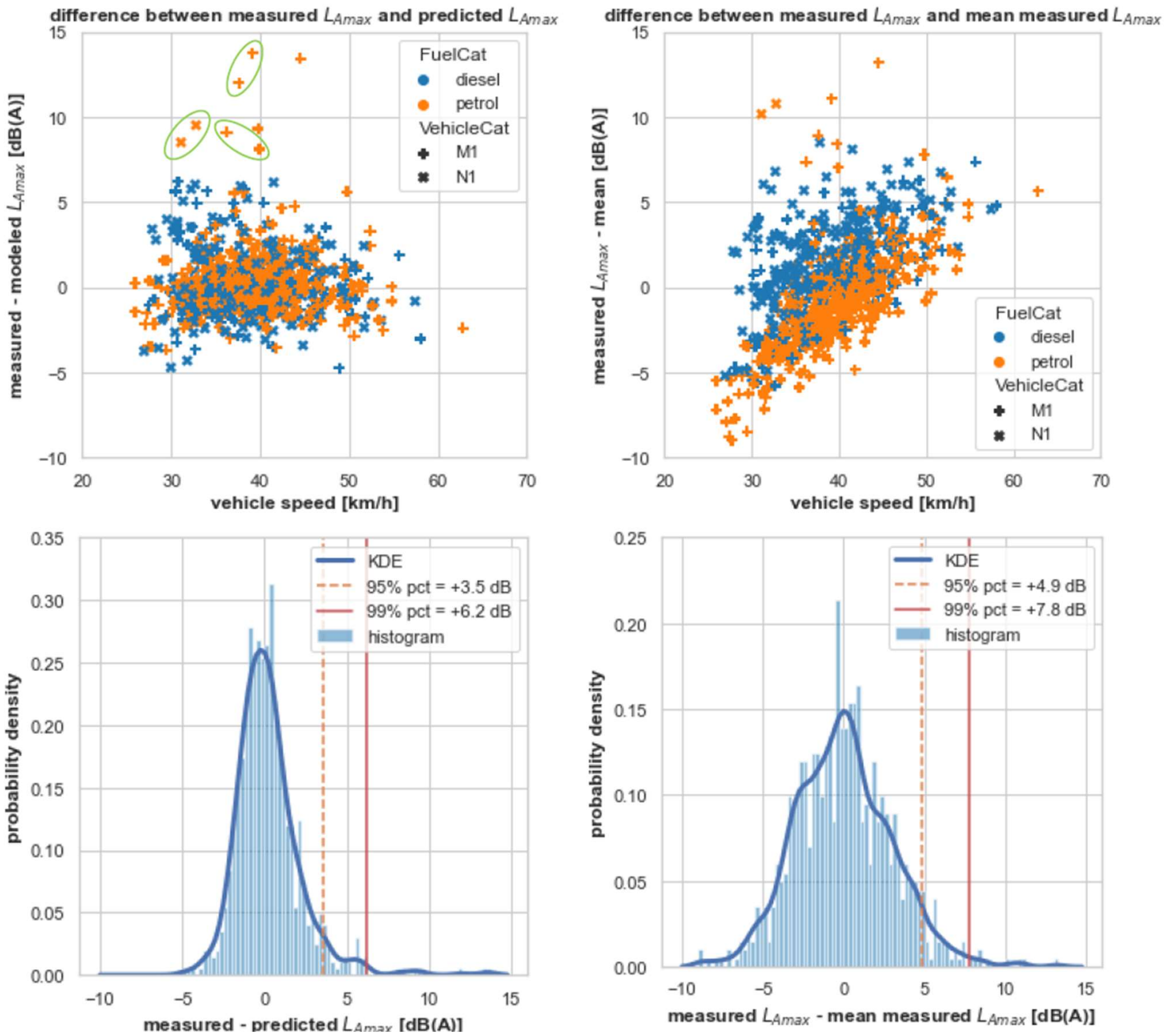

Figure 5: Distribution of L_{Amax} levels; left: measured minus predicted L_{Amax}, right: measured minus mean measured L_{Amax} (no pre-processing). Top graphs: difference values vs. speed, Bottom: distribution of differences as histogram and kernel density estimate (KDE).

The purpose of the pre-processing model is not to approve the fact that aggressive drivers make more noise, but just to separate noisy drivers from noisy vehicles (or both). Figure 6 shows the top-10 most noisy vehicles, ranked in two ways: by ranking the measured, uncorrected L_{Amax} ('ranking measured') and by ranking the difference between the measured L_{Amax} and the reference ('ranking model 2'). The left table shows the top-10 ranked by measured L_{Amax}, the right table shows the top-10 ranked by the pre-processed values. It is clear that the five or six highest emitters (marked red) are the same in both tables: these are noisy vehicles driven by noisy drivers. The yellow marked events have high measured L_{Amax} levels but rank much lower after correcting for driving conditions; these vehicles are noisy because of the driving style. The blue marked events did not rank high when regarding only the measured L_{Amax}, but they pop up in the top-10 after correcting for the (modest) behavior. These are noisy due to the vehicle itself.

ID	category	fuel	measured L_{Amax} [dB(A)]	speed [km/h]	acceleration [m/s²]	ranking measured	ranking model 1	ranking model 2
630	M1	petrol	78.38	44.50	0.11	1	2	1
401	N1	petrol / LPG	75.96	32.79	0.44	2	1	3
755	M1	petrol	74.10	37.62	-0.36	3	3	2
485	N1	diesel	73.28	41.53	0.46	4	4	5
129	M1	diesel	72.54	55.63	1.32	5	76	41
421	M1	petrol	72.21	39.90	0.61	6	5	4
209	N1	diesel	71.94	51.66	0.62	7	22	30
121	M1	petrol	71.64	52.37	0.76	8	40	18
525	N1	diesel	71.21	46.01	1.11	9	25	43
203	N1	diesel	71.17	47.35	0.64	10	20	29

both

driving behaviour

ID	category	fuel	measured L_{Amax} [dB(A)]	speed [km/h]	acceleration [m/s²]	ranking measured	ranking model 1	ranking model 2
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485	N1	diesel	73.28	41.53	0.46	4	4	5
213	M1	diesel	69.85	40.40	0.30	20	11	6
105	M1	diesel	68.32	32.85	0.57	51	12	7
459	M1	diesel	69.05	37.07	0.36	35	13	8
922	M1	petrol	69.51	43.92	0.11	25	17	9
519	M1	diesel	68.50	37.05	0.50	44	15	10

vehicle

Figure 6: Top-10 ranking of high emitters; left: ranked by measured L_{Amax}, right: ranked by highest difference between measured L_{Amax} and calculated reference (pre-processing model 2)

6. CONCLUSIONS

The main conclusions regarding the development of the N-RSD system are the following:

- The two-step classification approach for the classification model enables us to detect high noise emitters more accurately. Because the measured noise levels are normalized towards reference driving conditions, it helps to separate between noisy vehicles and noisy driving, and allows noisy vehicles to be identified even in a modest driving style.
- We have identified a set of disturbances that make up the total uncertainty of the N-RSD measurements and, consequently, the classification. Values for each uncertainty contribution will be investigated.
- A method that detects engine speed from the noise signals was developed. Results are very accurate for signals with distinct engine noise, but less reliable when the engine noise is relatively low and also when the engine speed is low. However, these may also be the circumstances in which a vehicle is less likely to be a high emitter. Engine speed values will be added to the classification model when in-traffic measurement data become available later this year.
- Regarding microphone positions, besides the 'main' microphone position at 7.5 m / 1.2 m height, an additional microphone is needed for localization in the driving direction. To determine on which lane the vehicle is driving, we may use a top-down microphone, or a third additional roadside microphone to allow lateral localization. Results showed that the top-down microphone and/or an extra 'exhaust' microphone at low height improves the detectability of driveline noise (rather than tyre/road noise).
- An algorithm to detect if the pass-by contains a single vehicle has been tested and works accurately. A method to estimate the individual sound levels from two vehicles closely after each other is being developed; the results are promising, but with a certain inaccuracy.
- A first application of the pre-processing and classification model has been done on supervised test measurements. Classification of high emitters is possible by comparing the measured L_{Amax} level to a reference value calculated from speed, acceleration, and vehicle information.
- The classification for light motor vehicles is largely improved by separating passenger cars (M1) from light goods vehicles (N1). That implies that the N-RSD cannot run without license plate recognition, as it is not currently possible to get this information otherwise. Fuel type information does not significantly improve the model, at least not for the current, limited dataset.

We identified the following future work items, some of which are already in progress:

- integration of the developed N-RSD components into a full system: multiple microphones, engine speed detection, acceleration measurements and license plate detection;
- installation on test locations and gathering of a new, larger dataset (ca. 10.000 pass-bys).
- expansion of the pre-processing and classification model to other vehicle categories (medium and heavy vehicles and powered two-wheelers);

- further improvements and fine-tuning of the engine speed detection and vehicle separation algorithms;
- quantification of the uncertainty, possible by specific measurement campaigns for some individual parameters;
- consider adding other noise parameters, such as tonality and low-frequency indicators in the classification model.

7. ACKNOWLEDGEMENTS

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