inter.noise
21-24 AUGUST
SCOTTISH EVENT CAMPUS
GLASGOW
2022

Advancements in autonomous detection of high noise emitters in road traffic

Nikolas Kirchhoff[1]
Müller-BBM GmbH
Helmut-A.-Müller-Straße 1-5
82152 Planegg

Manuel Männel[2]
Müller-BBM GmbH
Helmut-A.-Müller-Straße 1-5
82152 Planegg

Maximilian Ertsey-Bayer[3]
Müller-BBM GmbH
Helmut-A.-Müller-Straße 1-5
82152 Planegg

ABSTRACT

Noise pollution is an increasing problem in densely populated areas with high traffic flow. The NEMO project (Noise and Emissions Monitoring https://nemo-cities.eu/) is funded by the EU to develop a system that is capable of detecting high emitters in terms of noise and air pollutants to prosecute vehicle owners. To this end, a fully autonomous noise measurement system was developed and tested on several test locations, both unsupervised and supervised.

This paper describes the advancements in autonomous measuring of traffic noise and specifically addresses the problem of reliable noise source detection in dense traffic streams. While the correct localization of the source is of great importance, it is not yet enough to measure the correct sound pressure level. We therefore propose a method to estimate the influence of nearby noise sources, i.e. closely driving additional vehicles, that disturb the sound signal of the vehicle of interest and correct for it. This algorithm has been applied on several test locations. Using these insights, we will discuss the benefits and possibility of the integration of such a system in the near future.

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, where only road traffic noise is estimated to affect 113 million people.

---

[1] Nikolas.Kirchhoff@mbbm.com
[2] Manuel.Maennel@mbbm.com
[3] Maximilian.Ertsey-Bayer@mbbm.com

A further issue is the fact that the EU Environmental Noise Directive (END), as well as almost all national noise regulations [2] 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 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 [3]. 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 are developing an autonomous system to detected noise (and air) emissions from individual vehicles within the traffic flow, thus providing a tool for local stakeholders to take immediate action on infringing vehicles. This “Noise-Remote Sensing Device” (N-RSD) uses a microphone array to track vehicles passing by and measures the sound pressure level (SPL) the vehicle emits. 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 noise levels are reached.

Our experience from several test locations (Munich, Rotterdam, Barcelona) showed that a problem has to be addressed that has not been accounted for so far. In high density traffic situations vehicles drive closely behind one another. We already tackled the problem of separating the vehicle events in time [5]. However, nearby vehicles are the most dominant disturbing noise source when doing statistical pass-by (SPB) measurements in road traffic. Conventional SPB measurements (e.g. to characterize road surfaces) therefore have to be performed with highly level-dependent restrictions. Applying the same restrictions to the detection of high emitters is due to the generally high traffic flow, however, not feasible. We therefore propose an algorithm that corrects for the noise contributions of nearby vehicles to get a more accurate picture of the sound pressure level generated by a specific vehicle.

In the following, the autonomous measurement system will be explained and the methods for vehicle detection and peak level correction are described. The performance of the algorithms is qualitatively discussed with help of a data set from the test setup in Rotterdam. Finally, a conclusion is drawn with an outlook of the applicability of such a system in the near future.

2. SYSTEM DESCRIPTION

The goal of the NEMO N-RSD system is to identify highly pollutant vehicles driving inside or into urban areas. With the adjacent Infrastructure to Vehicle (I2V) communication, the vehicle owners could be informed if their vehicles exceed certain noise or gaseous emission limits, which can be a plain information, a fine or a ban 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).

The N-RSD system will be positioned at critical infrastructure positions, as e.g. roads with high traffic leading into the city. The autonomous measurement station is designed as either a gantry over the road which vehicles will drive through, or a pole-like structure on the side of the road. For multi-lane scenarios we developed a setup with top-down microphones which is described in [5]. The methods presented here will however focus on a single-lane scenario which merely requires a microphone array that can be mounted on a pole at the side of the road.

The localization task will be performed by a pair of microphones that are separated horizontally by approx. 17 cm to 30 cm. This sensor pair is performing a localization restricted to the horizontal plane. A second microphone pair separated vertically by approx. 2 m or more will be used to estimate the distance of the vehicle to the array. A fourth microphone can be deployed next to the top microphone, creating a third microphone pair which can perform the horizontal localization from a different height. This might be useful in certain situations, where e.g. road barriers influence the sound field of the lower horizontal microphone pair. Additional to the acoustic sensors, a speed radar as well as a weather station is deployed. The speed radar is outputting approx. 70 values per second, which are used to estimate the acceleration of the vehicle. The speed/acceleration and the meteorological data is used in the classification model which categorizes the vehicles into high, medium, and low emitters and which is described in [5]. A three-microphone-setup can be seen in Figure 1. A setup with four microphones (bottom and top horizontal pair) is depicted in Figure 2, where a concrete road barrier is blocking the sound field especially for the lower microphone pair.

Figure 1: Microphone array mounted on a pole, left: vertical microphone pair and speed radar (below), right: horizontal microphone pair. Test setup in Barcelona, Spain, April 2022.

Figure 2: Microphone array with a four-sensor-configuration, horizontal microphone pairs marked in red circles. Note the concrete road barrier that will influence the sound field especially for the lower microphone pair. Test setup in Teesdorf, Austria, April 2022.

3. METHODS AND DISCUSSION

In the following chapter we will describe the general principle of the localization and focus more specifically on the peak level correction of disturbed sound pressure level measurements.

3.1. Localization Algorithm

The localization algorithm has been first presented in [4]. The localization of a passing vehicle is performed with a set of two microphones. They are positioned on the same height with a distance of approx. 17 cm to 30 cm in driving direction. A beamforming algorithm is used to detect the main sound source as a function of the input angle, i.e. the angle between the road lane and the line of sight between vehicle and sensor array. We are able to accurately estimate the vehicle position with merely two microphones because many of the remaining geometrical parameters are fixed, since the vehicle has to be on a geometrical curve defined by the road. The estimated input angle plotted over time has the shape of the *arctan()* function with a range of *(-90°,90°)*, where an angle of *0°* indicates the position directly in front of the array and *-90°* and *90°* correspond to the vehicle being infinitely far away. This characteristic curve is used to determine whether a peak in sound pressure level corresponds to a vehicle passing by or possibly background noise and is called the “pass-by trajectory” or “localization trajectory”. It also helps to find pass-bys with a low SPL that do not generate a distinct peak in the level-time-curve.

Figure 3 shows an example of a train of vehicles driving closely behind one another. The upper graph depicts the sound pressure level in dB(A) over time with the peak values marked in circles, the lower graph shows the corresponding estimated input angle with the positions of the peak values marked with dashed lines. The beamforming algorithm can be thought of a “listening beam” in a certain direction. The beam always focuses on the most dominant sound source. This is why there is abrupt jumps from positive to negative angles between the *arctan*() curves of adjacent vehicles at the points in time when the sound of the following vehicle becomes more dominant. We notice, that the peak level value of the pass-by is not necessarily at the *0°*-position, which implies that the maximum sound pressure level of the vehicle can be shortly before or after it has passed the array. We further notice that some of the peaks in the upper graph are barely exceeding the high noise floor generated by the surrounding vehicles. The vehicle position, however, can clearly be distinguished by the pass-by trajectory (see second pass-by in Figure 3). Pass-bys like this are likely to be disturbed by the noise of nearby vehicles, which is why a SPL correction is necessary.

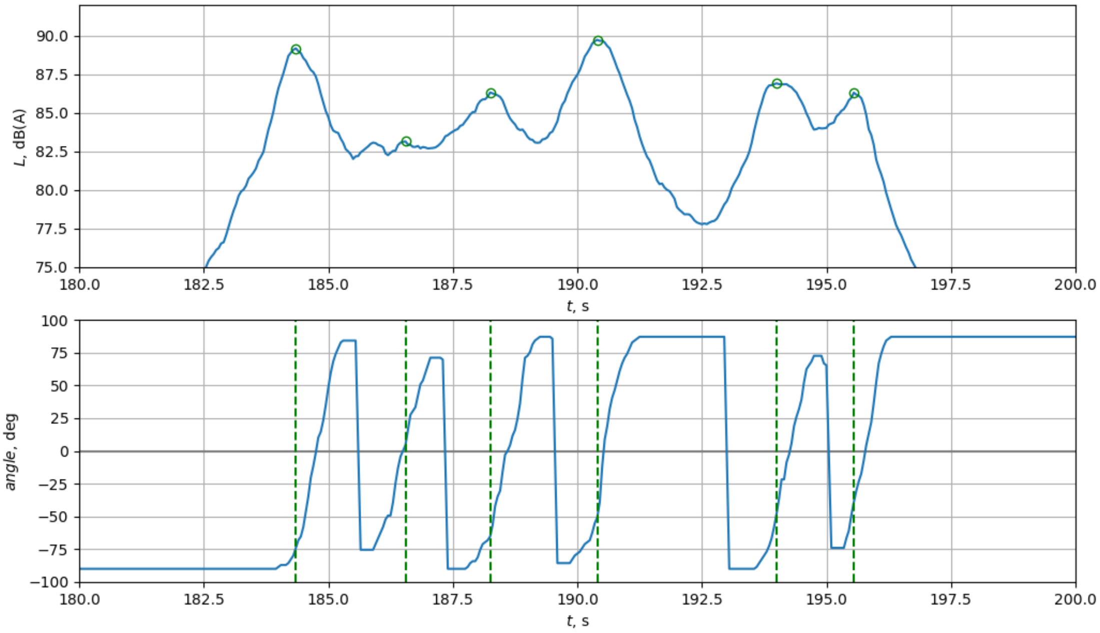

Figure 3: Sound pressure level (upper graph) and pass-by trajectory (lower graph) of a train of vehicles driving closely behind one another. Circles mark the peak level values, dashed lines indicate the vehicle position relative to the array at the peak level value. Data retrieved from the test setup in Rotterdam, The Netherlands, November 2021.

3.2. Peak Level Correction

Using the localization trajectory we can reliably separate the vehicle events in time. However, closely driving vehicles are influencing the absolute sound pressure level of one another. A nearby vehicle is generally the most dominant background noise source in statistical pass-by (SPB) measurements. For SPB measurements that are performed to characterize acoustic properties of road surfaces, the decrease in SPL for adjacent vehicles must be at least 6 dB, since then it can be assumed that the contribution of the disturbing vehicle is more than 10 dB lower [6]. For the purpose of detecting high emitters, however, the restriction of a peak value exceeding at least 6 dB over the surrounding SPL valleys is too strict. If the measured SPL of a vehicle is influenced by the noise of another vehicle it has to be prevented to classify the vehicle as a high emitter only based on this measured SPL, since the actual SPL generated by the vehicle would be less and the classification might give a different result. Therefore, a peak level correction method is needed.

The proposed correction algorithm is based on a data approach. A test setup of the autonomous measurement station was running in Rotterdam continuously from October 2021 until March 2022 at a fixed location. We were able to collect data of many thousand vehicles per day, most of which where driving in a train behind one another. Due to the large amount of data, however, we captured several thousand single pass-bys as well, which are not disturbed by noise of surrounding vehicles. Using different criteria on the localization trajectory, the weather conditions and the level-time-curve, we selected pass-bys that are exclusively single and generated a characteristic mean level-time-curve for different speed categories. The speed categories are crucial, since the shape of the level-time-curve of a passing vehicle is highly dependent on the velocity, showing a broader peak for lower speeds and a narrower peak for higher velocities. Such an algorithm needs to be trained to specific test sites to take into account specific acoustic characteristics of sites such as the road surface, topography, reflecting objects etc. The model curves are shown in Figure 5 for different speed categories. Table 1 shows the amount of single pass-by level-time-curves that have been used to generate the mean model curve in the corresponding speed category, Figure 4 shows the corresponding distribution as a bar plot. It can be seen that the most data curves come from the speed category of 55 km/h – which is close to the overall mean velocity at this site – and that the distribution is approx. normal distributed. Inspecting the model curves in Figure 5 for the different speed categories we notice that the smoothness of the curve is affected only little by the number of used sample curves. In fact, the curves are mainly affected in the border regions that due to the high level difference to the peak of more than 10 dB will not affect the correction performance. This indicates that a smaller set of sample curves, i.e. only 100 to 200, would be sufficient, which dramatically decreases the "training phase" of the measurement system, making it practically applicable.

Table 1: Speed categories and available sample curves of single pass-bys to generate the mean model curve.

Velocity from – to in km/h	Number of sample curves used
32.5 – 37.5	108
37.5 – 42.5	324
42.5 – 47.5	904
47.5 – 52.5	1754
52.5 – 57.5	2140
57.5 – 62.5	1664
62.5 – 67.5	985
67.5 – 72.5	346
72.5 – 77.5	87

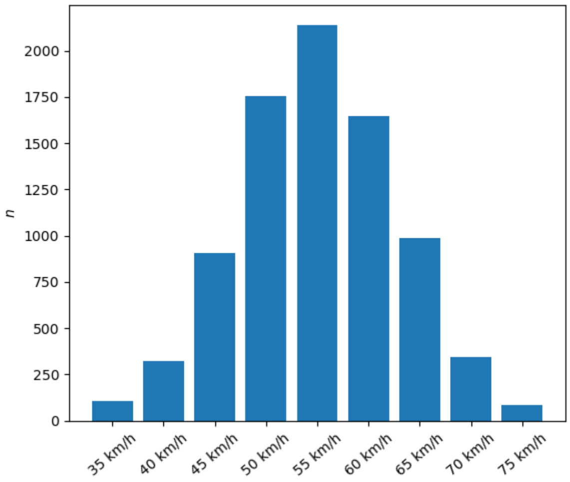

Figure 4: Distribution of the number of used level-time-curves for the different speed categories.

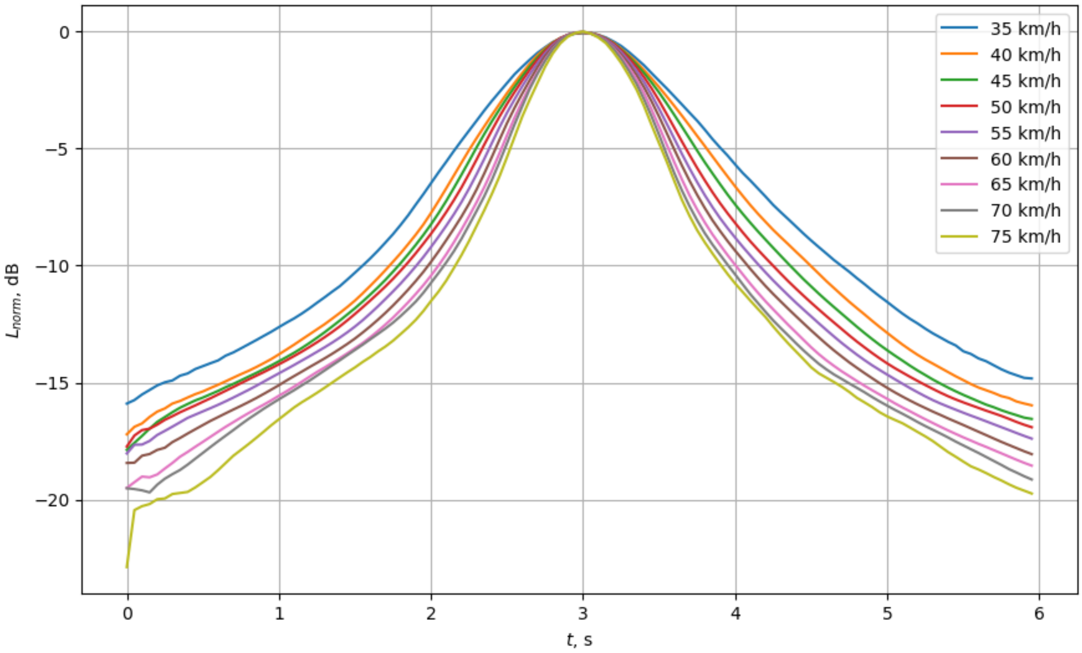

Figure 5: Normalized model curves of single pass-bys for different speed categories. Model curves are generated from data retrieved from the test setup in Rotterdam, The Netherlands, between October 2021 and February 2022.

The model curves are used to estimate the contribution of nearby vehicles as follows:

- For each level peak check if the SPL is decreasing by at least 6 dB towards any surrounding peak.
- If the 6 dB criterion is satisfied, the contribution of nearby vehicles is small enough that a correction is not necessary. Continue with the next peak.
- If the 6 dB criterion is not satisfied, overlay the neighboring peak with the model curve for the specific vehicle speed. There might be several surrounding peaks contributing to the disturbance of the peak of interest.
- Find the contribution of the model curve at the level peak of interest and subtract it energetically from the peak value. Do this for all surrounding peaks that contribute to the disturbance.
- The corrected peak sound pressure level has been found. Continue with the next peak.

Figure 6 shows a visualization of an exemplary result of this algorithm for the same level-time-curve seen in Figure 3. The original peak values are marked with green circles and the corrected values are marked with red crosses. The model curves are plotted in different colors for the different speed categories. We notice that especially lower peaks that lie next to higher peaks will be corrected, since the contribution of the disturbing noise source is here most prominent, see e.g. the third peak or the last peak from the left in Figure 6. For the mentioned peaks, the corrected level is up to 0.5 dB lower, which is a significant difference. To visualize the reliability of this algorithm, the energetic summation of the model curves is plotted as a dashed line. It can be seen that the dashed line correlates well with the actual measured level-time-curve plotted in blue.

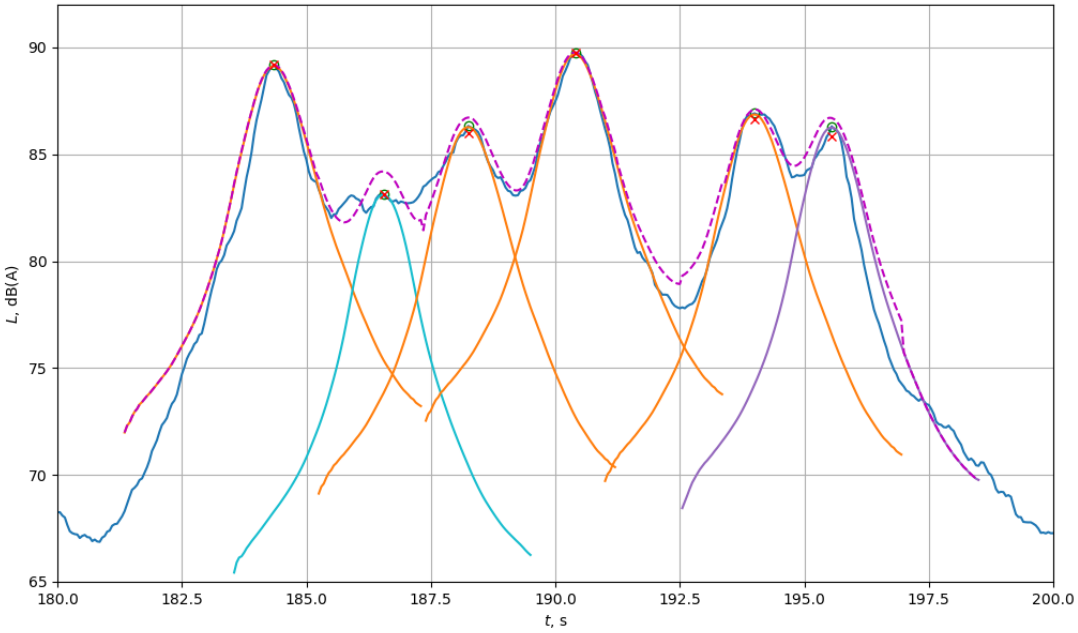

Figure 6: Level-time-curve of a train of vehicles driving closely behind one another (blue), original peak level points (green circles), model curves for different speed categories (orange: 40 km/h, purple: 45 km/h, cyan: 50 km/h), corrected peak values (red crosses), and estimated level-time-curve due to the model curves (dashed). Data retrieved from the test setup in Rotterdam, The Netherlands, November 2021.

4. CONCLUSION

The detection of high noise vehicles in urban areas is gaining more and more attention. The welfare of citizens living close to high-traffic infrastructure is a growing concern of municipalities. Identifying high emitters and taking actions like sending fines of restricting access to problematic areas is an important step as a remedy to high noise exposure, which we are eager to achieve within the NEMO project. We pointed out the importance of a reliable mapping between the vehicle and the measured sound pressure level. The fact that the pass-by can be disturbed by noise of other nearby vehicles thus has to be accounted for.

To this end, we propose a peak level correction algorithm that uses model curves generated from collected data to subtract the noise contribution of nearby vehicles. Such an algorithm needs to be trained to specific test sites to account for specific acoustic characteristics of sites such as the road surface, topography, reflecting objects etc. We found that a relatively small set of measured sample curves (100 to 200) is sufficient to achieve satisfactory results for the model curves. This means that it is feasible to install the autonomous measurement system with a relatively small amount of "training time" of a few days/weeks depending on the traffic situation. In turn, this implies that the system is movable within relatively short time frames, which increases the reach and thus the impact of the system, also because commuters won't get to know any fixed position of the measurement station. Furthermore, the mapping of the model curves onto the measured level-time-curve results in a good match between the measured and the predicted SPL curve. The corrected SPL peak values in the shown example are, depending on the situation, up to 0.5 dB below the measured SPL peak value, which is a significant difference.

Using this correction algorithm is an important step towards an accurate N-RSD to substantiate stakeholders' actions – like fining or restricting access to urban areas – taken on high noise emitting vehicles.

5. ACKNOWLEDGEMENTS

The NEMO project is funded by the European Commission under the Horizon2020 program, under grant agreement No. 860441. More information about the project can be found on https://nemo-cities.eu/.

6. REFERENCES

1. European Environment Agency, Environmental noise in Europe – 2020, *EEA Report No. 22/2019* (2020).
2. Peeters B., Nusselder R., Overview of critical noise values in the European Region, *report M+P.BAFU.18.01.1, prepared for EPA Network Interest Group on Noise Abatement (IGNA)*, October 2019.
3. Lechner C. et al., Effects of Motorcycle Noise on Annoyance – A Cross-Sectional Study in the Alps, *Int. J. Environ. Res. Public Health, vol. 17 pp. 1580* (2020).
4. Ertsey M., Männel M., Fastl H. – *Zur autonomen Messung von Vorbeifahrgeräuschen (towards the autonomous measurements of passby-noises)*, Fortschritte der Akustik, Aachen 2016.
5. Ertsey-Bayer M., et al., NEMO project: developing a N-RSD (Noise Remote Sensing Device) to identify high noise emitters in the road traffic flow, *Internoise 2021 proceedings*, 2021
6. ISO 11819-1:1997, Acoustics – Measurement of the influence of road surfaces on traffic noise – Part 1: Statistical Pass-By method