Monitoring the environmental impact of individual vehicles in a traffic flow

Truls BERGE1; Herold OLSEN2; Audun SOLVANG3
SINTEF ICT, Dept. of Acoustics, Norway

ABSTRACT
In the project MOVE, SINTEF has tested different methods to measure the environmental impact of individual vehicles in a traffic flow. One of the methods to measure the noise levels is to use a microphone array. An array with up to 8 microphones has been tested, together with a special algorithm for processing of the microphone signals. A simulation, based on measured pass-by sounds of vehicles, showed that it was feasible to acoustically separate two cars with a separation time of less than 1 second, at a speed around 70 km/h, using only 4 microphones.

A commercial available traffic registration system has been used, to measure the speed of the vehicles, lane position and a classification up to 8 different vehicle categories. During the test program, the pass-by noise level of more than 9000 vehicles has been measured. The tests showed that the monitor system could identify some vehicles with very high noise levels; more than 100 dB at speeds around 60-80 km/h. In addition to monitoring of the noise levels, a new laser gas detection device has been tested, which showed that it was feasible to measure abnormal CO levels of random passing vehicles.

Keywords: Noise, Traffic, Monitoring

1-INCE Classification of Subjects Number(s): 13.2

1. INTRODUCTION
Road traffic noise is by far the most important source of noise annoyance in an urban environment. Many investigations have shown that the most efficient measure in a cost/benefit-perspective is to reduce the noise at the source itself. This is done by controlling the noise emitted by the individual road vehicle. The noise emitted by the vehicle is normally dominating by two independent dependent noise sources; power-train related sources and tyre/road related sources.

A wide range of parameters influences these sources; related to the construction of the vehicle either itself or the use of the vehicle and maintenance. The most important parameters are:
- Type of engine
- Engine and vehicle speed
- Power-to-mass ratio
- Type of gear (automat/manual) and gear used
- Tyre type
- Road surface (tyre/road interaction)
- Driving style (aggressive, economic, etc.)
- Traffic conditions
- Weather conditions (temperature, surface wetness, etc.)

Several parameters interact with each other, such as the traffic condition obviously influences the speed of the vehicle, gear selected and acceleration/deceleration levels. The gear selected and engine speed is related to the power-to-mass ratio of the vehicle.

To summarize, the noise emitted by vehicles can be regulated by:
1) International noise regulations for vehicles and tyres
2) Local measures, like the traffic composition, posted speed, road surfaces, ITS systems, user

1 truls.berge@sintef.no
2 herold.olsen@sintef.no
3 audun.solvang@sintef.no
incentives/restrictions, etc.

3) Driver influence/maintenance of vehicle/tyres

1.1 Vehicle and Tyre Regulations – Effect on Traffic Noise Levels

The noise emitted by a new vehicle is regulated by the noise regulative, such as the UN ECE Reg.51-03 for M and N category and UN ECE Reg.41-04 for L category (motorcycles/mopeds). Reg.51-03 is in line with the EU directive EU/540/2014. From July 1st 2016, new noise limits are introduced. The first phase is more or less comparable to the previous limits, but is linked to a new type approval procedure (ISO 362-1 and 2). More stringent limits (phase 2) will be introduced from July 2020 for new vehicles and from July 2022 for new registrations. A phase 3 is defined (2024/26), but a cost/benefit analysis is required before phase 3 is applied.

Tyres are regulated by UN ECE Reg.117 and new noise limits were introduced in the EU/EEA from 2012 (Regulation (EC) No.661/2009). All these regulations and limits are related to type approval of new vehicles/tyres in perfect condition.

The new testing methods (M/N/L) have been developed to be more consistent with how the vehicles are normally used in urban traffic conditions, than previous methods. The clear goal of updating the methods and limits is to gain a real reduction of traffic noise when these vehicles and tyres dominated the vehicle fleet. Several institutes (1, 2) have calculated the effect of introducing the new regulations.

Calculations using the TRANECAM model (2) have indicated the effect of the new vehicle and tyre regulations on the L_den-levels, depending on the type of road. The reference year is 2025. In general, the expected reduction is less than 2 dB (range from 1.6 to 1.8 dB).

These results depend of course on the speed of replacement of old vehicles with new vehicles, which can vary from country to country. Replacement of old tyres with new is expected to be much faster than for vehicles.

These calculations do not take into account a growing fleet of electric vehicles (EV), or plug-in hybrids (PHEV) in some parts of the world. In Norway, approximately every fourth new car is EV or PHEV (Statistics, February 2016). These vehicles have a potential to be much more silent than ICE cars at low speeds (below 20 km/h), a speed area frequently used in residential areas or in dense traffic situations.

1.2 Vehicles-in-use

In addition to the effect of introducing more stringent noise regulations for new vehicles (and tyres), it is important to also consider the noise levels when vehicles are in-use. This is normally not regulated, with the exception that some countries have some sort of roadside checks of vehicles in-use. Annual (or bi-annual) technical inspection of vehicles may also be a tool to prevent non-legal noise levels in the traffic. However, such inspections of for example motorcycles with non-legal replacement silencers are rarely implemented.

2. SCOPE OF THE MOVE PROJECT

As shown in the introduction, the main focus has been on new and more stringent noise limits when vehicles and tyres are type approved. Less focus has been the noise levels of vehicles in-use.

Since only "theoretical" calculations of the effect of new vehicle and tyre regulations have been presented, it is important to include monitoring of the individual noise levels of vehicles in-use. In addition to monitor the effect of international regulations, such a monitoring can also identify vehicles with abnormal high noise levels. Such levels can be caused by illegal muffler systems or modified powertrain, combined with poor maintenance of the vehicle itself. Such lack of maintenance can also influence the exhaust emissions of a vehicle.

In the MOVE project, the main scope has been to test and develop methods and systems to monitor the environmental impact of individual vehicles in a traffic flow. Even if monitoring of the noise levels has been the main topic, a test of a laser gas device set up to measure the CO level of passing vehicles in a traffic flow, has been included in the project (3).
3. BASIC PRINCIPLE OF THE MONITORING SYSTEM

The monitoring system consisted of 3 independent devices:
1) Traffic registration system
2) Meteorological system
3) Noise measuring system

3.1 Traffic Registration System

The system chosen for this project is the, TOPO.bigbox, from the German company RTB GmbH & Co.KG.

TOPO.bigbox is a radar-based system that measures the speed of the car in two driving directions (approaching and receding lane). In addition, the vehicles are categorized into 8+1 different classes, according to a German standard for classification of vehicles (TLS 2002):

1) Passenger car (2 axles)
2) Passenger car + trailer, delivery van, delivery van + trailer (2-4 axles)
3) Truck (2-4 axles)
4) Truck + trailer (3-8 axles)
5) Road tractor (semitrailer), Road tractor + trailer (3-6 axles)
6) Bus (2-5 axles)
7) Motorcycle
8) Bike
9) Not classified

The measurement of vehicle length and number of axles defines the classes.

Figure 1 show the TOPO.bigbox mounted on a mast for measurements.

Figure 1 – TOPO.bigbox mounted by the road side (photo left: Torgeir Vaa, SVV, right: RTB)

Measured data is transferred to a server in Germany by a GSM line, where the data (both raw and processed) can be downloaded on request.

In addition to the radar itself, the TOPO.bigbox has an electret microphone facing the road (see figure 1). The intention with this microphone was to investigate the possibility to detect noisy motorcycles (primarily). However, this feature was not utilized in the MOVE project.

3.2 Meteorological System

The meteorological system measured the following indicators:
- Air temperature
- Wind speed and direction
These parameters were logged every second, and thus can be allocated to a single pass-by of a vehicle. Figure 2 shows the position of the met station.

### 3.3 Noise Measuring System

For the test program, a simplified noise measurement system was implemented, mainly for practical reasons. The system was based on a laptop with several microphone input channels. A program in LabVIEW has been made for the calibration procedure and to measure the noise from 2 or 3 microphone positions simultaneously.

The maximum A-weighted noise level of a passing vehicle is synchronized (in time) with the data from TOPO.bigbox, for the analysis. A time limit of 3 s was applied to be able to acoustically separate vehicles in a traffic flow. This means that within this time window, only one vehicle was allowed to pass the microphones. Experience from tests, showed that this time window probably should have been increased during rush hour at the test site, as the vehicle speed in that period was considerably reduced (to below 30-40 km/h).

Figure 2 shows the monitor at the test site with 3 microphones.

![Figure 2 – Test site with the monitor, including microphone array and 3 microphones](image)

Microphone 2 and 3 was located 7.5 m from the centre line of each of the two lanes and at a height of 1.2 m. This is in accordance with the requirements in ISO 11819-1(SP). Microphone 3 was at the same distance from lane 1 (closest lane) as mic.2, but at 3 m height. If such a monitoring system shall measure unattended over a longer period, it would be necessary to use a height of 3 m, to prevent any unwanted damage, thefts or unwanted sounds e.g. made by humans.

Figure 2 shows the position of the microphone array and chapter 6 describes the test program of this array.

Acoustic One/Norsonic has developed the Precision Sound & Vibration Analyser Nor150 as part of...
the MOVE project. This unit is planned to be the central control unit with communication to the other censors as well as the acoustical sensor in a future monitor system for measuring the noise of road traffic and other environmental noise sources.

4. TEST PROGRAM AND RESULTS

During the test period, 26 138 vehicles were detected by the TOPO.bigbox radar system and transferred to the computer through the serial port. Of these, the acoustical system approved 9283 pass-by noise levels of individual vehicles, which is 35.5 % of the total number. Table 1 shows the number of approved vehicles for the 8+1 categories.

Table 1 – Total number of vehicles per vehicle class

<table>
<thead>
<tr>
<th>No</th>
<th>Vehicle class/category</th>
<th>Number of measured vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Class 7 Cars</td>
<td>7033</td>
</tr>
<tr>
<td>2</td>
<td>Class 2 Cars and delivery vans + Trailer</td>
<td>183</td>
</tr>
<tr>
<td>3</td>
<td>Class 11 Delivery vans</td>
<td>729</td>
</tr>
<tr>
<td>4</td>
<td>Class 3 Trucks</td>
<td>318</td>
</tr>
<tr>
<td>5</td>
<td>Class 5 Bus</td>
<td>70</td>
</tr>
<tr>
<td>6</td>
<td>Class 8 Truck + Trailer</td>
<td>260</td>
</tr>
<tr>
<td>7</td>
<td>Class 9 Road tractor + Trailer</td>
<td>391</td>
</tr>
<tr>
<td>8</td>
<td>Class 10 Motorcycles</td>
<td>18</td>
</tr>
<tr>
<td>9</td>
<td>Class 6 Unidentified/hidden vehicles</td>
<td>281</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>9283</strong></td>
</tr>
</tbody>
</table>

For all pass-by registrations in lane 1 with the microphone at a distance of 7.5 m and in 1.2 m height (mic 2 in figure 2), an analysis have been made of the average levels for each of the classes. All measured data has been normalized to a reference speed of 70 km/h, using a speed correction of 30*\log(v/v_{ref}) for categories 1,2,3 and 8 in table 1, and 25*\log(v/v_{ref}) for the other categories. Only vehicles with a speed above 40 km/h are included and measured on a dry surface.

Table 2 and figure 3 show the results of this analysis. In figure 3, the 95 % confidence interval is included.

Table 2 – Measured average A-weighted noise level (dB) for 8 classes of vehicles, $v_{ref} = 70$ km/h

<table>
<thead>
<tr>
<th>Class</th>
<th>Cars</th>
<th>Cars/deliv. +Trailer</th>
<th>Deliv. vans</th>
<th>Bus</th>
<th>Truck</th>
<th>Truck + Trailer</th>
<th>Road truck +Trailer</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>3335</td>
<td>103</td>
<td>335</td>
<td>64</td>
<td>176</td>
<td>84</td>
<td>174</td>
<td>9</td>
</tr>
<tr>
<td>L_{A,mean}, dB</td>
<td>81,2</td>
<td>83,3</td>
<td>82,1</td>
<td>83,9</td>
<td>84,9</td>
<td>87,7</td>
<td>87,8</td>
<td>83,5</td>
</tr>
<tr>
<td>St.dev, dB</td>
<td>2,1</td>
<td>2,0</td>
<td>1,7</td>
<td>1,2</td>
<td>1,9</td>
<td>1,5</td>
<td>1,5</td>
<td>3,2</td>
</tr>
</tbody>
</table>
These results show that there is a strong link between the measured noise levels and the number of axles. Class 2 (cars and delivery vans with a trailer) has 3 or more axles. The same is the case for classes 8 and 9, compared to classes 3 and 5 (table 1). Figure 3 also shows that class 3 (delivery vans) in average has a pass-by noise level approximately 1 dB higher than class 7 (cars). This may reflect the previous noise regulation (UN ECE Reg.51-01), where this category (N1) was allowed 2 dB higher noise levels during type approval. In the present regulation (UN ECE Reg.51-03/EU 540(2014)) both these vehicle classes have the same noise limit; 72 dB(A).

In figure 4, the maximum A-weighted pass-by noise levels (both lanes) is shown for all vehicles in class 7 (cars), as a function of vehicle speed. The analysis have been made for dry surface condition only and no temperature correction has been made (the temperature during the measurements were in the range of -1 to +12 °C, with an average around +5 °C).

This figure shows that there are some cars detected with abnormal high noise levels of 100 -107 dB(A), at speeds around 60-80 km/h. These cars could represent a high contribution to the noise annoyance from road traffic, and there should be some ways to eliminate such vehicles from the traffic, e.g. like roadside control.

Figure 3 – Measured average A-weighted noise level (dB) for 8 classes of vehicles, \( v_{\text{ref}} = 70 \text{ km/h} \)

![Figure 3](image)

Figure 4 – Measured A-weighted noise levels (dB) of cars (class 7) as a function of vehicle speed. Number of vehicles = 6585

![Figure 4](image)
5. MEASUREMENT OF CO

In addition to measuring the noise of passing vehicles, a test was performed with a new laser gas detection device, LaserGas iQ2, developed by the Norwegian company, NEO. This device is primarily designed for industrial applications. In the MOVE project, the device was tuned to measure CO (could also be tuned to other gases, like NO). A test was performed on random passing vehicles. The mirror reflecting the laser beam was placed at the other side of the road, in a height similar to the location of most exhaust tail pipes of cars see figure 5. A total of 554 vehicles were measured (classes cars, delivery vans, bus, truck, truck with trailer and mc). Of these, 14 vehicles (2.5 %) were found to have a CO level above the background level, as shown in figure 6.

![Figure 5 – Set-up with LaserGas iQ2 with reflector](image)

![Figure 6 – Measurement of CO levels of passing vehicles. Red curve is average background level](image)

Especially one truck had a very high CO level (286.70 ppm*meter). The reason for the higher levels of CO for these cars is of course unknown. However, the main purpose of this test was to see if it was feasible to detect a level of CO from passing vehicles. The test shows that it should also be feasible to measure the NOx level from passing vehicles, which is currently a big concern related to diesel cars in urban traffic (especially on cold winter days).
6. MICROPHONE ARRAY

As shown in chapter 4, using a time window (3 seconds in this test) to separate acoustically vehicles in a traffic flow, means that about 2/3rd of the passing the vehicles cannot be measured (on this test site). They are too close to each other, either in the same lane or in the opposite lane. Especially, when a car is too close to a heavy truck, it is not possible to measure the noise from each vehicle separately. However, there are other projects using a microphone array (4), indicating that it should be feasible to separate vehicles acoustically for such conditions, with a suitable algorithm for the signal processing and using more than four microphones.

In the MOVE project, a test with an array up to 8 microphones was used, as shown in figure 7.

![Test with microphone array](image1)

A. Solvang and G. Taraldsen (SINTEF) have developed an algorithm based on a beamforming technique and a new approach called "Correlation fitting method" and the test of the array used this method. A visiting student from France, Lucas Ciret, was engaged to do a simulation of the estimation of the trajectory of passing vehicles (sound power level vs time and position) under different configurations. Based on measured signals from passing vehicles, a simulation program in MATLAB was developed. In this program, different number of microphones in the array could be varied, different locations of the vehicles (different distances between vehicles), and at different vehicle speeds. Figure 8 shows an example of the estimation of a trajectory.

![Estimated and true trajectory](image2)

Figure 8 – Estimated (red) and true (white) trajectory of a single pass-by: car at 72 km/h
The first results showed that the accuracy of estimation of the trajectory of the sound power could be improved by using the real vehicle speed signal from the radar. The study also revealed that the estimation could be improved by changing the fixed distance $y_R$ from the source to the array. Initially, this distance was 7.5 m. By varying this distance for all the single pass-by recorded, an optimum distance for the value of the sound power was found. This distance was on average close to 5.9 m, which correlates well with the actual distance between the array and the tyres on the right side of a vehicle in the closest lane. It then demonstrated that the most important sound source for passing vehicles at this test location is the tyre/road noise source.

Only a minor number of simulations (based on actual measurements), could be made within the time available for the project. However, these simulations showed that it was feasible to separate acoustically two cars in the same lane with a distance of each other of 17 m at a speed of 72 km/h, using only 4 microphones in the array. A distance of 17 m at this speed means that the vehicles pass the microphones with a time difference of 0.9 of a second, which in practice is a very unsafe distance. Using only 4 microphones showed that there were some problematic configurations, like a truck following a car too closely. In addition, vehicles cars too close to each other in opposite lanes is also difficult to separate acoustically. It is recommended to do further investigations and optimizations of the array configuration and algorithm.

7. OTHER INVESTIGATIONS WITHIN THE PROJECT

To monitor the effect of more stringent noise limits for new vehicles, it would be more efficient if the identity of the passing vehicles could be revealed, and not only the class of vehicle (as done in this project). To identify what type of vehicle regulations (noise, exhaust emission) the measured vehicle has been certified for, one should be able to read the license plate and link this information to the general national vehicle database (in Norway: AUTOSYS). In Norway, a system called Automatic Number Plate Recognition (ANPR) has been developed and is currently in-use to check if the vehicle owner has paid annual fees and insurance. This technology can be applied in a monitoring concept as tested in the MOVE project. The procedure to implement ANPR and AUTOSYS has been outlined in the project.

One of the scopes of the project was also to present a possible layout for a public available web site for a monitor. An example of a web site for a "public user" and an "expert user" has been developed and can be accessed at: http://biamove.cloudapp.net/

8. FUTURE WORK

Within the period of the MOVE project, only a minor roadside test of the system was possible. The test of the microphone array was also limited and further testing and development of the signal-processing algorithm should be encouraged.

Implementation of ANPR was also not feasible within this project.

The following recommendations for further work are given:

* Implementation of ANPR
* Tests of an integrated system with Nor150
* Further development of a public access system, using internet
* Further development of the microphone array technology
* Develop procedures for processing and presentation of large amount of data ("big data")
* Further testing of the laser gas equipment, including measurements of NOx
* Investigations of the connection between measured noise emission levels and traffic noise calculation methods (e.g. reference values for different categories of vehicles)
* Include algorithm/system to detect studded tyres

9. CONCLUSIONS

In the MOVE project, we have demonstrated the feasibility to monitor the individual noise emission levels of vehicles in a traffic flow. Especially the use of a microphone array could increase
the number of registrations, as it can acoustically separate vehicles close to each other. Normally this is not possible using a single microphone, unless there is a 6 dB drop in the maximum noise level between the two vehicles, as required in the Statistical Pass-by Method (ISO 11819-1).

By measuring the individual noise emission level of vehicles, it has been demonstrated that it is feasible to identify some vehicles with abnormal high noise levels (above 100 dB(A)).

It has been demonstrated that it is feasible to measure the CO level of a passing vehicle. The system used for this test, could easily be tuned to other gases, like NOx. Within the period of the MOVE project, only a minor roadside test of the system was possible. The test of the microphone array was also limited and further testing and development of the signal-processing algorithm should be encouraged.

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