REPORT

Simultaneous measurements of gaseous emissions, particulates and noise from individual vehicles in traffic

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Sammanfattning

För att kunna identifiera fordon och trafikplatser som har en negativ miljöpåverkan är det viktigt att mäta emissioner från individuella fordon i verklig trafik. I denna studie undersöktes möjligheterna att samtidigt mäta gaser, partiklar och buller som emitteras enskilda fordon i normal trafik. En s k FEAT utrustning, där NO, CO, HC och CO_2 mäts kombinerades med partikelinstrument, både för totalmängd och storleksfördelning, samt med utrustning för bullermätning. Partikelmätningarna gjordes via provtagning med en utsugningsutrustning vid vägbanan och en utspädningsutrustning. Bullermätningarna gjordes med två mikrofoner placerade intill vägbanan på olika höjd. Mätningarna visar att det är praktiskt möjligt att studera reglerade emissioner, partiklar och buller samtidigt från enskilda fordon i normal trafik.

Bullerdata samlades in från ca 200 fordon under mätkampanjen och en stor andel data analyserades vidare. Mätningarna övervakades och utvärderades i detta projekt manuellt. Erfarenheterna från projektet är goda och tyder på att det är möjligt att automatiskt generera stora mängder bullerdata genom att bygga på FEAT systemet med bullermätutrustning. För att detta skall bli möjligt krävs datoriserade rutiner för att välja bort oanvändbara data och beräkna bulleremissioner.

Vi erhöll partikelemissionsfaktorer för enskilda fordon genom att kombinera ett CO_2-instrument med partikelmätinstrument. Vi fastställde även att storleksfördelningar för partiklar från enskilda fordon kan fås om man använder ett tillräckligt snabbt instrument. Detta öppnar i princip för att kunna separera avgaspartiklar från resuspensionspartiklar och partiklar från slitage av hjul och bromsar. Mätningarna visar att partikelemissionerna varierar betydligt mellan olika fordonsindivider. En variation med två storleksordningar (mellan 8.5×10^{11} och 1.2×10^{14} partiklar per km och fordon) observerades.

FEAT-systemet kombinerades även med utrustning för att mäta hastighet och acceleration.

En generell slutsats är att uppställningen, efter en del vidare utveckling, bör kunna användas för en mer omfattande kartläggning av avgas- och bulleremissioner och att en stor mängd fordon kan kartläggas på relativt kort tid. Systemet kan även användas för att identifiera enskilda fordon som emitterar stora mängder avgaser och/eller buller.

Abstract

In order to identify vehicles and traffic situations that have a negative impact on the environment, it is important to be able to measure emissions from individual vehicles in traffic. In this study an attempt is made to measure gases, particles and noise emitted from single vehicles in normal traffic. An apparatus for Fuel Efficiency Automobile Test (FEAT), by which emissions of NO, CO, HC and CO_2 are measured, was combined with particle instruments for both total and size-distribution measurements, as well as noise measurements. The sampling of particles was done utilising a tube system for sampling on the road together with a dilution system. The noise measurements were done with two microphones at different heights. The measurements show that it is feasible to study regulated emissions, particle emissions and noise emissions from individual vehicles in normal traffic.

Noise data was collected from ca 200 individual vehicles during the measurement campaign and the emissions of some of the vehicles were evaluated. The measurements were manually supervised and the evaluations mainly made by hand. The experiences of this project are encouraging and show that it is possible to perform measurements of noise emissions from individual vehicles automatically. One way to achieve this would be by extending the FEAT system so that it also measures noise emission. Further it is important to perform sampling and evaluation automatically and to use computerized procedures for the evaluation.

By using CO_2 data together with the particle data, we were able to obtain PM emission factors for individual vehicles. We also showed that the particle size-distribution can be obtained from individual vehicles in traffic when using a fast instrument. This also, in principle, allows for the separation of particles emitted from the engine and particles from road and tyre wear. The results show that the emissions of particles vary significantly from vehicle to vehicle. A variation range of two orders of magnitude (between 8.5×10^{11} and 1.2×10^{14} part km^{-1} veh^{-1}) has been observed.

The FEAT systems together with a system for speed and acceleration monitoring, were able to record how the emissions of NO, HC, CO and CO_2 depend on speed and acceleration.

A general conclusion is that after some further improvement the setup should suitable for more systematic mapping of vehicle tailpipe and noise emissions. Further, the system may be used for identifying individual vehicles that can be considered large emitters.

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Acronyms and definitions

E_i, EF_i emission factor

C_i measured concentrations

Q_{vent} air flow through the tunnel

N_A Avogadro's number,

M_i the molecular mass of i

PM_{10} the mass of particles with an aerodynamic diameter < 10 μm

n_i moles of i

ppm parts per million

ρ density

Re Reynolds number

IR infrared

UV ultraviolet

LGV Light goods vehicle

HDV Heavy goods vehicle

FEAT Fuel Efficiency Automobile Test

CPC Condensation particle counter

ELPI Electric low pressure impactor

p sound pressure (Pa) –fluctuations caused by sound superimposed on the static air pressure

W sound power (W) – power of the sound emitted by an object

L_p sound pressure level (dB) – sound pressure presented using a logarithmic scale, thus imitating how human hearing perceives the strength of sound. Calculated as

$$L_p = 20 \cdot \log_{10}(p \,/\, p_0),$$

where $p_0 = 20$ μPa

L_W sound power level (dB) – sound power presented using a logarithmic scale. Calculated as

$$L_W = 10 \cdot \log_{10}(W \,/\, W_0)$$

where the reference sound power $W_0 = 10^{-12}$ Watt

L_{eq} equivalent sound pressure level (dB) is an energy mean value of the sound pressure over time. The indicator is denoted $L_{eq,T}$ when there is a need to explicitly write the averaging time T.

L_E (or SEL) sound exposure level (dB) – the time integrated noise dose during a complete pass-by.

L_{max} maximum sound pressure level (dB) is the highest sound pressure level during a time period. The measured maximum level is influenced by what time-weighting the sound level meter is using. In this project time-weighting F (fast, integration time 0.125 s) has been used and the corresponding maximum level is denoted L_{Fmax}.

A-weighting the most common frequency weighting is the A-weighting which is an approximate reproduction of the frequency response of the human ear at lower levels. The A-weighted sound pressure level is denoted L_{pA}, the A-weighted maximum sound pressure level measured with time-weighting F is denoted L_{AFmax} etc.

background noise sound caused by other sources than the one that is to be measured

1 Introduction

1.1 Environmental background

Gaseous emissions from individual cars have decreased substantially since the introduction of catalytic converters about twenty years ago. However, health and environmental problems associated to traffic remain a large issue, especially in urban areas. For example, trucks and off-road vehicles are only recently the subject of stringent regulations and, further, traffic is still increasing in most areas. Concerns about the health and environmental issues with emissions like carbon monoxide, nitrogen oxides and different hydrocarbons were the main driving force behind the introduction of catalytic converters. At present there is great concern especially with emissions of fine particles. Also health issues related to traffic noise have a great deal of attention. The recently enforced air-quality limits on NO_2 and PM_{10} put the focus even more on these matters [1].

It has been known for decades that air pollution episodes of extremely high aerosol particle concentration are associated with increased mortality. A well-known example is the “London Smog of 1952”. Mortality rates for the smog episode from December 1952 to February 1953 were 50-300 % higher than the previous year and it has been estimated that about 12 000 excess deaths occurred during this period [2]. Subsequently, as air quality improved over the following decades, it was widely believed that ambient aerosols no longer posed a serious threat to public health. The issue was revived with the publication of the “Six Cities Study” [3]. This study of various air pollutants in six American cities indicated that particulate matter was significantly associated with mortality. The epidemiological literature on the health effects of PM has been reviewed [4]. The results strengthen the evidence of adverse effects of PM after correcting for confounding effects of other pollutants and errors in the measurement of exposure. At present, the connection between aerosols and health effects is a very active field of research. Especially ultrafine particles (smaller than 100 nm) are respirable and have adverse effects in the respiratory tract, thus posing a severe health threat [5]. Road traffic constitutes a major source of both ultrafine and larger particles. Research on the characterisation of particle sources shows that the former ones are emitted by the combustion engines while the latter ones are a consequence of the wear of wheels, brakes and road surface.

Road traffic noise affects many people. In the year 2000, 1.46 million people in Sweden [6], corresponding to 16% of the population, were estimated to be exposed to equivalent continuous A-weighted sound pressure levels, L_{Aeq}, exceeding 55 dB in their immediate outdoor environment. In continental Europe the situation is even worse. There, more than 25% of the population is considered to be seriously annoyed by road traffic. According to the World Health Organization, [7], 55 dB yields serious annoyance during daytime and evening in an outdoor living area. In 1997 the Swedish parliament, [8], decided that it was not acceptable to exceed L_{Aeq} = 55 dB when building new dwellings or roads. The consequence of the above is not only that very many people are affected, but also that road traffic noise imposes severe restrictions on the building and planning of cities. Actually no house or road can be built without making sure that allowable noise limit values are not exceeded. In order to go through this procedure it is necessary to have access to reliable prediction methods correctly describing the noise emission of road vehicles and the propagation of sound. The noise emission of a road vehicle is a function of vehicle type, tyre type, speed, acceleration, road surface and air/road temperature, [9,10,11]. As examples, a change in temperature of 10^{o} or 4 mm in chipping size of the road pavement would change tyre/road noise by 1 dB. The difference between a very noisy and a very quiet road surface may be 10 dB.

1.2 Traffic noise assessments

Roughly speaking, noise emissions from road traffic are determined using measurements while the resulting immissions, with very few exceptions are calculated using standardized calculation methods (like Nord2000 Road and Harmonoise). These road traffic calculation methods basically consist of three parts:

- a source model that calculates the emission from the roads based on information such as number of vehicles per day, vehicle speed, vehicle type, road gradient, type of road surface etc.

- a propagation model that calculates the sound propagation over the terrain

- an integration part that sums up all sound contributions in the position where we want to know the immission

The source model is deduced from a noise emission database that ideally should contain emission measurements on all kinds of vehicles, operating under every imaginable situation. Building up such a road traffic noise emission database is very costly as the emission data is collected using manual measurements of single vehicles in real traffic situations. That is the reason why some vehicles and some conditions are not represented in the database and why the database is rarely updated. It is neither possible to take a short cut and build up a database from measurements made in other countries since the conditions there may be different. In Sweden we have studded tyres and a rougher road surface (to withstand the studded tyres), our light vehicles are bigger than in other countries and very few of them have a diesel engine whereas the diesel is very common in the rest of the EU.

The main problem with automatic measurements is to separate noise from the vehicle of interest from noise coming from other vehicles on the road. There are different ways to do this. One way is to use pattern recognition where the sound is analyzed with respect to its time history during pass-by and its frequency contents. The measured pattern is compared with a precalculated pattern and if the difference is between predefined limits the measurement is accepted. Another way is to use other sensors than the microphone to make sure that there are no other vehicles in the neighbourhood during the measurement. For large scale measurements pattern recognition has to be carried out by a computerized procedure.

1.3 Gaseous emission measurements in traffic

There are a few available methods for real-world emission measurements. A survey of four of these methods will be given here. The remote sensing and on-road methods are capable of measuring emissions from individual vehicles while tunnel- and roadside measurements are used to derive average emission factors from a large number of vehicles. A more detailed description of the methods can be found in [12].

Remote sensing methods are based on spectrometry and are useful to derive gaseous emissions from individual vehicles in real-traffic. The most common instruments used for remote sensing measurements on traffic are the FEAT (Fuel Efficiency Automobile Test) instruments developed by the University of Denver for measuring emissions from passenger cars. Detailed descriptions of the FEAT operational principles can be found in the literature [13,14,15].

Because the instantaneous emissions measured by the instrument depend on the rotational speed of the engine and its instantaneous power, it is not appropriate to compare emissions from individual vehicles. The utilisation of a camera for capturing the license plates of passing vehicles makes it possible to get information about, e.g., technology class (e.g., EURO 1, 2, 3) and then to derive an average emission factor for each group of vehicles [12].

Another method to measure emissions by individual vehicles is to perform on-road *chase experiments*. In this case, a mobile laboratory (usually aboard a van) equipped with gas-phase and/or particle instrumentation follows cars through everyday traffic in order to capture their exhaust plumes (see, e.g., [16]). These measurements thus provide data from real-world traffic under varying on-road traffic conditions, ranging from congestion and rush hour traffic over moderate speed city traffic to higher speed motorway traffic. Car chasing measurements are a useful tool for real-world emission measurements of individual vehicles. Emissions of selected cars under different driving conditions can be acquired. However, in order to obtain results from a representative automotive fleet, one has to follow a large number of cars.

Through *tunnel measurements* it is possible to attain a fleet average emission factor in grams per kilometre. The method is based on measurements of the increased concentrations of pollutants in the air within a tunnel compared to the concentration in the "clean" air outside. For measurements in single lane tunnels the average emission factor is calculated as shown in Equation 1, where E is the average emission factor, C_{cont} and C_{clean} are measured concentrations in contaminated and "clean" air, Q_{vent} is the air flow through the tunnel which can be measured by trace gas measurements, L_{tunnel} is the length of the tunnel and $f_{traffic}$ the traffic intensity through the tunnel.

$$E = \frac{(C_{cont} - C_{clean})Q_{vent}}{L_{tunnel}\, f_{traffic}} \quad (1)$$

By tunnel measurements it is possible to attain emission factors based on large numbers of vehicles. This makes the calculated factor insensitive to individual high emitting vehicles, and if the measuring spot is chosen to get a representative selection of the vehicle fleet, the factor may be representative as well. It is important to know that the result of a tunnel measurement is affected by the driving pattern in that tunnel. There have also been discussions about the constant tailwind in the tunnel, due to the vehicles, which may lead to lower emission factors [17].

Roadside measurements are in similarity to tunnel measurements based on measuring the difference in concentrations between polluted and "clean" air. By not measuring in a tunnel but in a "normal" traffic condition this method is more sensitive to meteorological conditions compared to tunnel measurements and a dispersion model is needed for calculating the spread of emissions from the road to the surroundings. These calculations are more complex than the calculations of emission factors from tunnel measurements and consequently errors are more easily introduced. Advantages compared to tunnel measurements are, e.g., the greater number of potential measuring spots.

1.4 Particle measurements in traffic

The approach to measure the particle content of the emission differs from ordinary trace gas measurements. The main difference is that particles are not uniform pollutants and that one has to decide which properties of the emitted particles are of interest, e.g., numbers, mass, size and light scattering of the particles. For in-situ measurements, the remote sensing methods can give part of this information but extractive methods are needed to achieve a good estimate on the emission factor of particles.

One piece of information that is vital in linking traffic and ambient PM concentrations, e.g., through model calculations, is the practical source strength and possible proxies for estimating particle emission from single vehicles. The particle emission from any combustion source can be derived from the emission ratio of the particle concentration to a co-emitted trace gas, e.g., CO_2 or NO_x. Knowing the emission factor of the chosen trace gas, this emission ratio can be converted to an emission factor for particles. Janhäll & Hallquist [18] used this method to derive average particle emission factors from a Swedish vehicle fleet.

There are few measurements on particle emissions by individual vehicles in real traffic today. In these few cases (e.g. Kittelson et al., [19]) the chase method (cf. above section) has been applied which limits the number of vehicles that can be measured during a day. Accordingly, this project now presents a novel method for particle emission measurements that can be used directly at the kerb side.

1.5 Purpose of this study

In a number of studies, emissions from individual cars in real traffic situations have been studied using the Fuel Efficiency Automobile Test (FEAT) method, where CO, CO_2, NO and HC have been measured. The present work is a feasibility study of how particle, gaseous and noise emissions can be measured simultaneously at the curb side for individual vehicles. The long-term aim is to develop systems that can automatically collect data from traffic regarding these parameters in order to collect indata for source models in calculation methods and also to determine if there are special types of vehicles or individuals that show large emissions. Further, the data may show possible connections between the measured parameters.

For noise measurements very large amounts of data have to be collected in order to be able to make a correct description of the noise emission from a specified type of vehicle on a specified road under specified operating conditions. The cost of such measurements has so far been very high and accordingly it has not been possible to collect reliable data for cases other than the most common ones. The main aim with the noise measurements is to investigate the possibilities for an automatic procedure to collect these data and if that is successful, the cost for future measurements will drop drastically. If we succeed in integrating automatic measurement of noise from individual vehicles with the FEAT measurements, we would get the tool since long needed for collecting data for a national road noise emission database. The costs for measurement campaigns would be reduced and at the same time the improved quality of the database would make it possible to improve the quality of immission calculations as well.

Another objective of the work presented in the present report is to find methods to measure actual particle emissions from vehicles in general, every-day traffic.

2 Methods

2.1 Measurement site

The measurements were performed during the period August 29 - September 1, 2006 at Delsjövägen in Göteborg, Sweden. It is a single lane road with counter flow and a speed limit of 50 km h^{-1}. The weather conditions during the measurements were mostly partly clouded, with weak winds and a temperature around 20°C. Near the measurement site there were a crossroad and a light-regulated pedestrian crossing (see Figure 1). This means that relatively large shares of the passing vehicles were accelerating while passing the measurement site.

Figure 1 The measurement site with the FEAT instruments in the cabinet. The reflector is on the right side of the road (not seen).The particle instruments are on the table. The particles are sampled with the black tubing that ends in the middle of the lane. The other tubes are for measurements of speed and acceleration. The noise measurement equipment is located behind the photographer (not seen).

The FEAT-equipment was set up with transmitter and receiver on the north side of the road and a reflector on the south. A system for measuring speed and acceleration and for approximating the instantaneous power of the vehicles was also used. The particle instruments were set up at the same location and the sampling was done with a rubber tube on the road (cf. details in Section 2.3). For the noise measurements, the horizontal distance (*d*) between the microphones and the centre line of the nearest lane was 7.5 m and the heights of the microphones were 1.2 m and 3 m, respectively. In order to avoid reflection/screening from the FEAT cabinet the microphone stand was put 12 m from the cabinet, further down the road. As sound was registered somewhat later than gases and particles the correlation between them may have been affected. Further, there is also a certain delay for the particle measurement in relation to the gas measurements due to the tubing used as probe.

The measurements were performed, monitoring the traffic on one of the two lanes. Cars passing the site, but driving on the other lane into the opposite direction might have given rise to the detection of additional pollutant peaks that could not be assigned to the cars logged by the observation equipment. This applies especially for northerly and/or westerly wind directions.

2.2 Technique for automated noise measurements

The noise measurements in this project were made with a multi-channel real-time analyzer (01dB Harmonie). Two channels were continuously recording L_{pFmax} and $L_{eq,60ms}$, A-weighted as well as in one-third octave bands (see further Appendix 1).

Figure 2. The noise measurement equipment.

Depending on the location there could be lots of disturbing sounds that need to be screened out, most likely originating from other vehicles. In order to be sure not to approve a pass-by that is coloured by noise from other sources, a computerized procedure has to be very restrictive. Still, even if an automatic algorithm only will be able to measure as few as 5% of the passing vehicles it will be a large step forward compared to the manual methods of today as it will be relatively cheap and thus will provide much more data for the same money spent. Accordingly this is also a way to improve the quality that our road noise calculation method provides since it would be possible to have access to newer data that also covers more variants of vehicles and driving behaviour.

2.2.1 Test site requirements

There are some general requirements that the test site needs to meet in order to be appropriate for pass-by measurements of noise from vehicles when the purpose is to get input data for prediction methods.

Reflecting or screening objects must not affect the measurements. Unfortunately the cabinet containing the FEAT equipment is both reflecting and screening, making it virtually impossible to measure sound in exactly the same position as the other emissions. In order to decrease the influence from this screening/reflection the microphones were moved away from the FEAT station but instead the sound measurement is no longer synchronous with the other measurements.

The road section should be level and straight and the road surface in good condition. In this case the measurements were made close to a crossing and a lot of the vehicles passing made a left-turn into the measured road, meaning that they were not driving on a straight line but making a 90° turn. If we cannot avoid making measurements close to crossings we need a method to detect vehicles turning.

During the pass-by of a measured vehicle background noise should be of negligible order. This means that there should be no sounds present from other road vehicles, aircrafts, trains, machines, people, birds etc. From the measuring equipment itself we have two noise sources to deal with: the sound from the tubes when a vehicle passes over them and the noise from the pumps belonging to the particle measurement.

For the measurement of sound exposure level of one single vehicle the road section (i. e., the undisturbed pass-by) should preferably extend $\pm 5d$ from the position of the microphones (d = perpendicular measurement distance to the road). If a reduced accuracy is accepted this distance could be decreased to $\pm 2d$ for vehicles shorter than 10 m and minimum $\pm 3d$ for longer vehicles [20].

2.2.2 Algorithm to check pass-by noise against quality criteria

A straightforward method to verify the quality of the measured time history is outlined in Figures 3-5. In Figure 3 an idea of a complete algorithm is outlined. None of the discussed algorithms have been implemented and tested, they are just ideas. It would be interesting to investigate if more sophisticated methods like neural networks [21] or Kalman filtering are feasible as well.

The envelopes in the following examples are produced by calculating a point source moving over hard ground. This is a simplification but can easily be refined to include directivity and several sources, such as the different axles of a vehicle. In the simulations the receiver is positioned approximately 10 m from a long, straight and level road and the speed of the vehicles are around 50 km/h.

Based on information of speed, acceleration, vehicle type, road surface temperature etc, calculation of an ideal envelope is made using a state-of-the-art road traffic prediction model. From this ideal time history an upper and a lower envelope limit is calculated. Limits $\pm 5d$ and $\pm 2d$ for the length of the undisturbed pass-by are also calculated using the information of the speed of the vehicle. If the tested envelope is within the limits it has passed the envelope test, like in Figure 3.

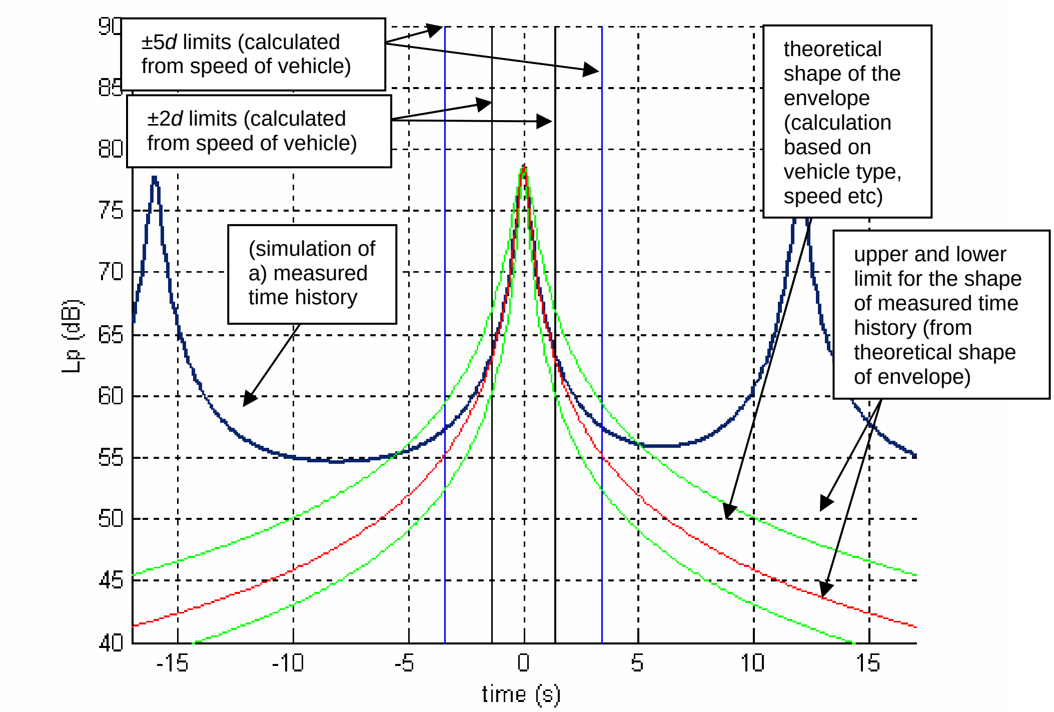

Figure 3 Lines for ±5*d* and ±2*d* limits as well as for the shape of the envelope calculated and applied together with the recording. Since the measured time history is between upper and lower limits for the envelope shape not only between the ±2*d* limit lines but also between the ±5*d* limit this step in the quality test is passed without deterioration of the accuracy.

If we have disturbances from other noise sources the time history will not look as expected (or as predicted) and will fall outside the limits. This is what has happened in Figure 4 where a loud noise source makes it hard to measure noise coming from the vehicles. In such a case we might still be able to extract some information about the vehicle from the L_{pFmax} measurement.

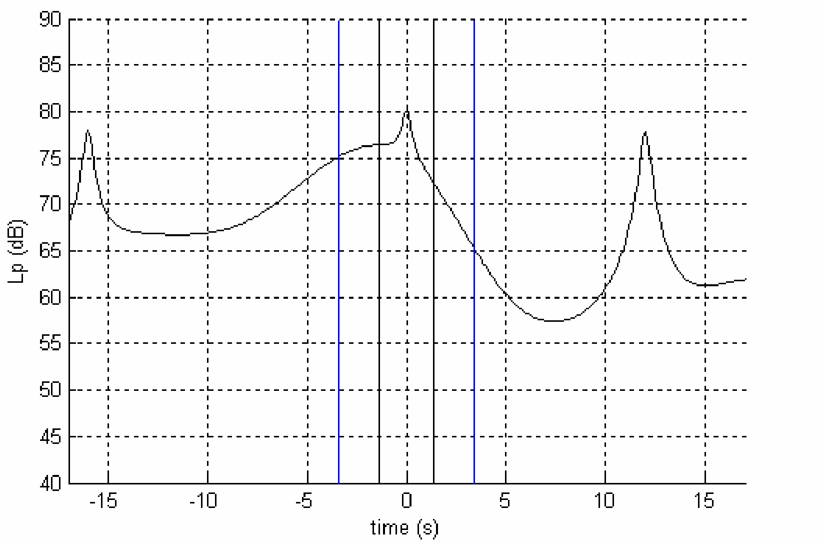

Figure 4 Same vehicles as in Figure 3 but now with an unidentified noise added. Lines for ±5*d* and ±2*d* limits are included. As only an L_{pFmax} value of the pass-by noise is possible to evaluate, the measurement accuracy of this passage is reduced.

Finally we have an example of what is very common in traffic and that is vehicles driving close after each other. In Figure 5 such a simulation is presented. The individual vehicles can only be measured by means of L_{pFmax} (from which we can estimate L_E). However, if they all belong to the same vehicle class we can get an improved accuracy of L_E by measuring them as a group.

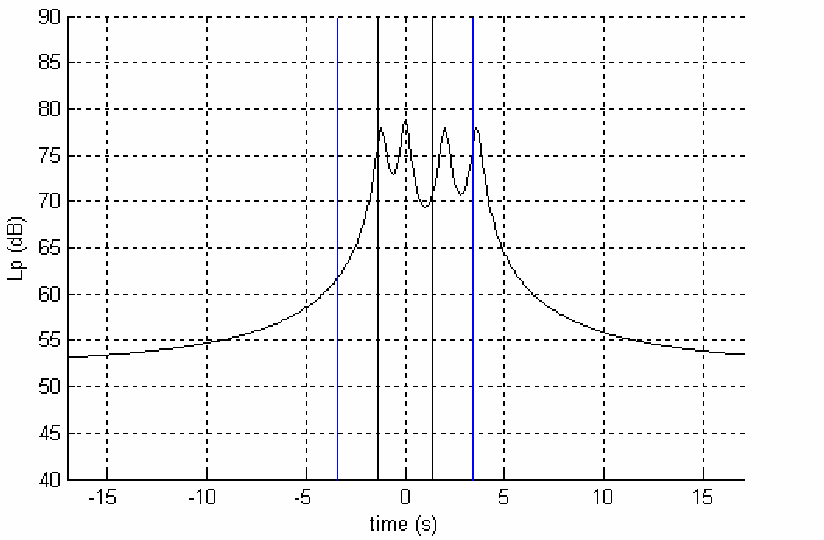

Figure 5 Four vehicles driving in a row rather close to each other. Lines for ±5*d* and ±2*d* limits are included. Evaluation of the individual vehicles could only be achieved by means of L_{pFmax} resulting in reduced accuracy. If all four vehicles belong to the same category L_E could be calculated for them grouped together.

A proposal for a complete algorithm according to this uncomplicated approach is presented in the flowchart in Figure 6.

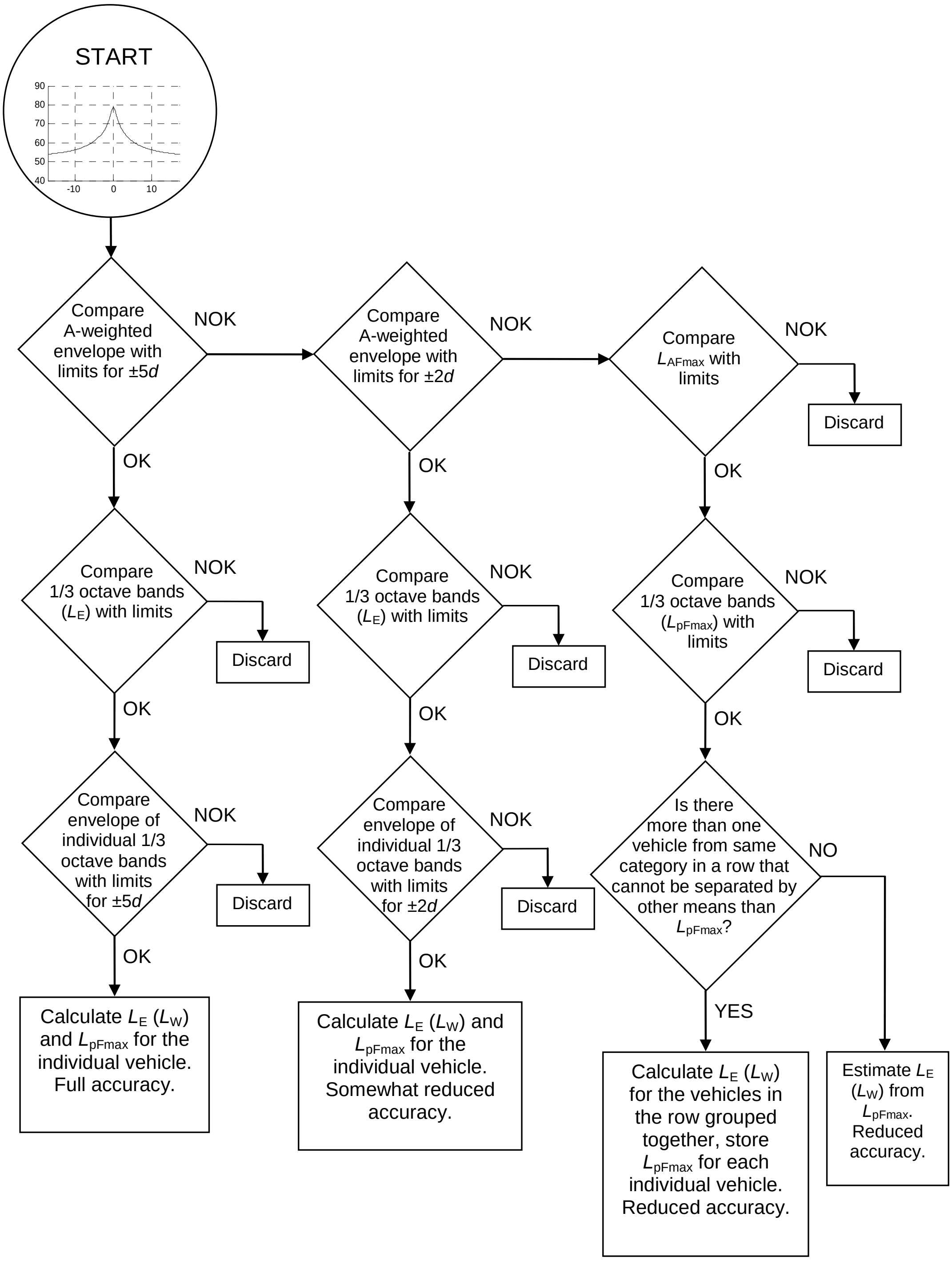

Figure 6 Quality check of pass-by noise – outline

2.2.3 Vehicle categorization

In state of-the-art road noise calculation methods of today (Nord2000 Road and Harmonoise) vehicles are separated into different classes. All vehicles that fall into the same class use the same source geometry and coefficients when calculating the emission. In Table 1 the categorization of Harmonoise is presented. It is a necessity that an automatic measurement procedure is capable of sorting all measured vehicles into these categories. At present only the main categories are used but for future data collection it is desirable to include also the different sub categories.

Table 1 Vehicle categorization according to the Harmonoise engineering model [22].

Main type	m	Example of vehicle types	Notes
Light vehicles	1a	Cars (incl MPV:s up to 7 seats)	2 axles, max 4 wheels
	1b	Vans, SUV, pickup trucks, RV, car+trailer or car+caravan(1), MPVs with 8-9 seats	2-4 axles*, max 2 wheels per axle
	1c	Electric vehicles	
	1d	Hybrid vehicles	
Medium heavy vehicles	2a	Buses	2 axles (6 wheels)
	2b	Light trucks and heavy vans	2 axles (6 wheels)(2)
	2c	Medium heavy trucks	2 axles (6 wheels)(2)
	2d	Trolley buses	2 axles (6 wheels)(2)
	2e	Low noise design	2 axles (6 wheels)(2)
Heavy vehicles	3a	Buses	3-4 axles
	3b	Heavy trucks	3 axles
	3c	Heavy trucks	4-5 axles
	3d	Heavy trucks	≥6 axles
	3e	Low noise design	≥3 axles
Other heavy vehicles	4a	Construction trucks (partly off-road use)	
	4b	Agr. tractors, machines, dumper trucks, tanks	
Two-wheelers	5a	Mopeds, scooters	Include also 3-wheel motorcycles
	5b	Motorcycles	

2.3 Particulate measurements

To measure particulate emissions from on-road vehicles it is necessary to make extractive sampling since there is no reliable method of detecting small particles (diameter d < 0.1 µm) *in situ*. A set-up illustrated by Figure 7 was used in the present study. The sample was continuously drawn through a cord-reinforced flexible rubber tube (length 3 m, i.d. 10 mm, o.d. 17 mm), the inlet end of which was fixed to the road surface at the centre of the lane of interest. To minimise particle loss through electrostatic mechanisms, the tube was electrically conducting and provided with good earth connection. The compression and blockage, typically during 10 ms or less, of the tube by the tyres of passing vehicles had no serious effect on sampling. No remaining deformation of the tube could be seen after several days of measurements.

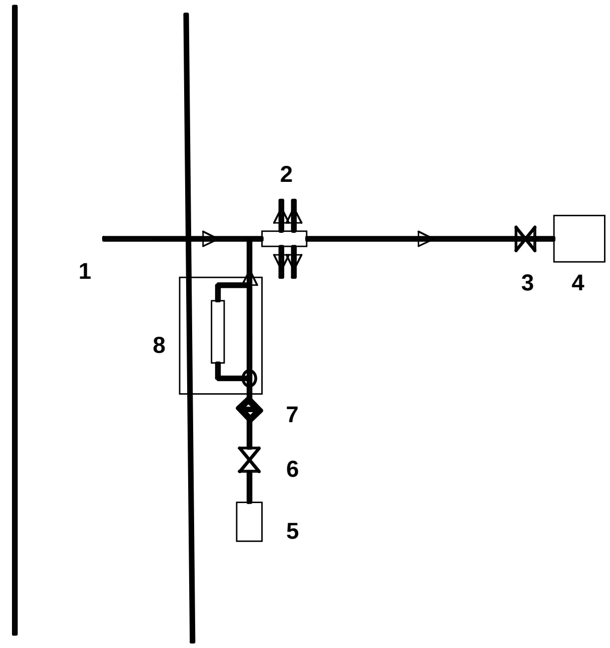

Figure 7 The particle/CO_2 measurement set-up (not to scale). 1/ sampling tube inlet located in the centre of lane and secured to the road surface by clamp and nail, 2/ mixing volume with connectors for CO_2 analyser, CPC, Grimm aerosol spectrometer and ELPI, 3/ valve for sampling flow regulation, 4/ pump, 5/ compressor for dilution air, 6/ valve for regulation of dilution flow, 7/ high efficiency particle filter, 8/ optional CO_2-scrubber, not in use during the measurements

The sample pump flow rate was set to 30 l/min giving a linear velocity in the sampling tube of between 6.4 m/s (without dilution) and 2.1 m/s (when diluted 2:1). This gives turbulent flow for the undiluted case (Re ≈ 4350) and laminar flow (Re ≈ 1400) in the diluted case, from the inlet end to the point of dilution. Turbulent flow is expected to induce greater losses of particles in the tube but to improve time resolution, compared to laminar flow. Particles between 0.01 and 10 µm are expected to pass the tube without significant loss at laminar flow conditions. If accurate measurements are desired it is necessary to quantify the losses, e.g. by simultaneous measurements of number-size distributions at the inlet end and at one sampling port (cf. Fig. 1).

The exhaust cloud behind a passing car would normally be diluted and dispersed to reach the inlet end of the tube in less than 200 ms. Ideally, the sample gas should then be moved through the tube up to the measurement instruments. The plug of "information-containing" gas would pass the instrumentation slightly delayed but with duration of the same time scale as the car passage, typically a few seconds. The instruments should give accurate response to CO_2 concentration and any other desired quantity. This requires instruments with good response time, ability to deliver data at around 10 Hz and having a considerable dynamic range. No such instruments were available at the present feasibility study. Instead, a TSI condensation particle counter (CPC) model 3010 with a maximum concentration range of $1x10^4$ cm^{-3} and a rise time of about 3 s (90% of full value) was used to measure total particulate concentration with d > 0.01 µm. The background concentration at the site varied typically between $2x10^3$ and $4x10^3$ cm^{-3}. A CO_2 analyser (PP Systems model WMA-4) with a range of 1000 ppm was employed to measure CO_2,. This device delivers data at 1 Hz and has a rise time of the same magnitude. The background concentration at the site was around 400 ppm, leaving 600 ppm as the dynamic range for the measurements. The Grimm aerosol spectrometer measures particle size distributions by light scattering in the range from 0.3 µm to > 2 µm at 1 Hz. The DEKATI Electrical Low Pressure Impactor (ELPI) quantifies particles in 12 size bins from 30 nm - 10 µm by measuring the electrical charges carried by particles separated at the different impactor stages. Data were collected from the CPC and CO_2 instruments by a logger operating at 1 Hz. The ELPI has an update interval of 5 sec.

Two measures were taken to counteract the lack of time resolution and dynamic range of the instruments. One was to introduce a "damping" volume of 1.1 l from which the instruments took their gas samples (cf. Fig. 1). A short, high concentration gas pulse representing a vehicle passage, entering the well mixed volume, would mix with background gas thus lowering the concentrations and extending the available time for the instruments to sample the gas. Applying this technique relieved the problems to some extent but particle concentrations still exceed the CPC upper concentration limit with annoying regularity. A second measure was then to add dilution air before the mixing volume. This air was filtered to remove background aerosol and the particle concentration could in principle be lowered to any limit desired by allowing the dilution flow rate to approach the pumping rate of the sample pump. The detection of the CO_2 peaks then becomes a challenge since these peaks are reduced at a similar rate as the particles but are superimposed on the background of ca 400 ppm and thus difficult to quantify. It is feasible to remove also CO_2 from the dilution air to allow the use of a more sensitive measurement range of the CO_2 instrument. This option is indicated in Figure 1 but was never tried in practice. The price for adding the extra "damping" volume is loss of time resolution. When the mixing volume is introduced, peaks are extended in time and the separation of passing vehicles needs to be 5 s or more in favourable cases, much longer than required by the FEAT-measurements. Removing the damping volume would improve the time resolution considerably.

2.4 Measurements of gaseous emissions

Measurements of CO, HC, NO and CO_2 were carried out by means of an AccuScan RSD 3000 instrument from Environmental System Products Inc., Tucson, Arizona, which is based on the remote sensing methodology originally developed by the University of Denver. This FEAT arrangement is well suited for measuring pollutions from light goods vehicles (LGV). Because some of the heavy goods vehicles (HGV) have the exhaust pipes placed on different heights compared to LGV's the light beam may hit the outer limits of the exhaust plume or in much diluted exhaust. Because of the built-in quality system, the instrument discards the measured value if a sample in some ways seems suspect. Some of the HGV's even have their exhaust pipe placed at such height that the exhaust never reaches the instrument. A share of the passing HGV's will therefore not be measured.

The instruments generate and monitor a co-linear beam of IR- and UV-light emitted and reflected approximately 30 centimetres above a single lane road. When a car passes, the absorption in the exhaust plume at some specific wavelengths is measured. Because the path length within the plume is not known, Lambert Beer's Law will not give the absolute concentration of pollutants in the exhaust plume. However the concentrations of CO, HC and NO relative to the CO_2 concentration can be determined. These quotas are then recalculated and the instrument provides emission data as volume% (or ppm by volume) in the undiluted exhaust. These calculations are based on the assumption that oxygen is stoichiometrically provided, but since this is not the case with diesel engines this emission data cannot be used for such vehicles. This is easily solved by converting the emission data given from the instrument to fuel-specific emission factors as shown in Appendix 2.

2.5 Vehicle data

Besides the FEAT instrument, a system developed by VTI for measuring speed and acceleration and for approximating the instantaneous power of the vehicles was used. A description of this system can be found in the literature [23]. The system consists, among other things, of three tubes lying across the road. When a car passes a pulse of air is generated in the tubing and this is recognized by the system as a vehicle passing. The speed between the first and second and also between the second and third tubing is calculated. From this data the acceleration and the space between the wheel axes are calculated. The instantaneous power of the car can be approximated [24] by using a relation between the axis space and the total mass of the vehicle, as shown in Appendix 3.

Facts on individual vehicles can be obtained from the Swedish vehicle registry since the licence number is available from the video camera. This was used to obtain technology class, make-year and weight.

3 Results

3.1 Noise

Here we present results from the acoustic measurements in the form of measured sound pressure levels at the two microphones. The measurements were performed during two days, August 29 and August 31, 2006. The sound pressure levels at the microphones were recorded during approximately 5 hours each day with a time resolution of 60 ms.

The number of passages that could be used for noise evaluation out of the total number of passing vehicles was quite low, below 10%. However, about 44% of pass-bys with acceptable particle and gaseous emission measurements were also acceptable for noise measurements. In an automatic system for simultaneous measurement of noise, particles and gases, long term measurements will give a lot of passages and there will be a sufficient number of acceptable passages to provide reliable statistical data.

3.1.1 An ideal pass-by

From an acoustical perspective the ideal situation for the measurements is when there is a relatively sparse and even distribution of the traffic. Each pass-by should be separated with no other cars too close influencing the measurement. Figure 8 shows an example of what could be considered as an ideal case. Four vehicles pass by the measurement site with a long enough distance separation so that each individual vehicle can be measured. The separation between the cars is sufficient to use the complete pass-by to determine the sound emission level and hence the sound power level. At the same time the background noise is relatively low which gives a high accuracy for the measurement.

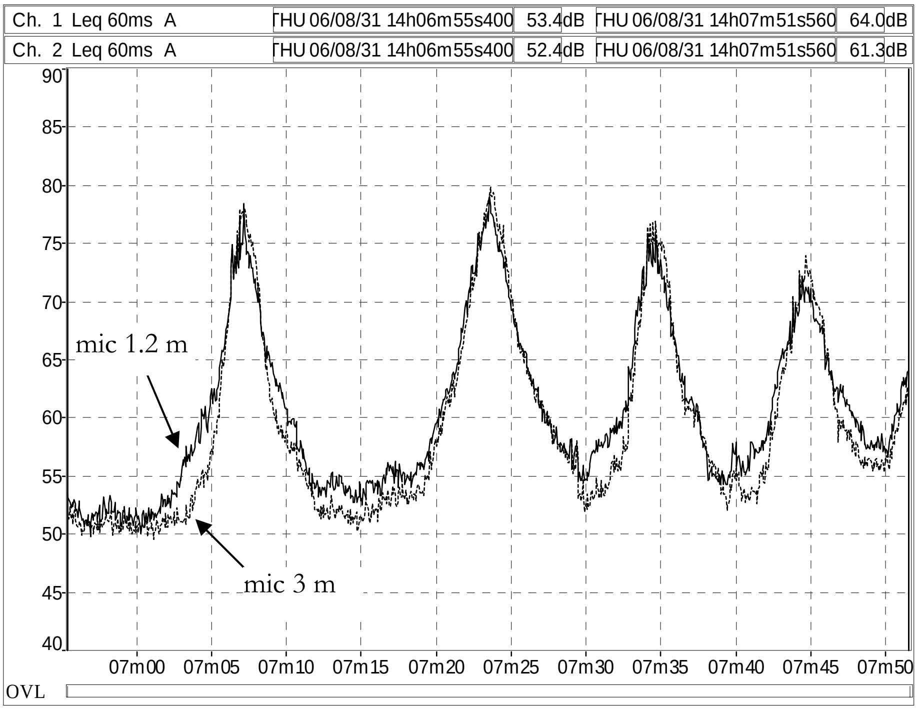

Figure 8 Time record of the sound pressure levels at the two microphone-positions for four vehicles passing by the measurement site. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

The figure contains the measured sound pressure levels $L_{A,\mathrm{eq,60ms}}$ at the two microphone positions as function of time. At this measurement site the highest microphone position (3 m) gives the highest noise level during the passage of a vehicle, but at the same time the lowest level of background noise. This is not always the case, and further, the directivity of the vehicle, both vertical and horizontal, influences the measured result at different heights which explains some of the variations between the microphones.

3.1.2 Disturbed pass-by

Figure 9 shows the measured sound pressure levels in a typical situation when there is not enough separation between two vehicles to have a full pass-by for the evaluation. When there is a car either too close in the same lane or in the opposite lane, the measured sound pressure level will be disturbed. In these cases, either the passage has to be rejected or in some cases the angle of integration can be reduced or the maximum sound pressure level during the passage can be used, see Section 2.2. However, this reduces the accuracy of the measurement.

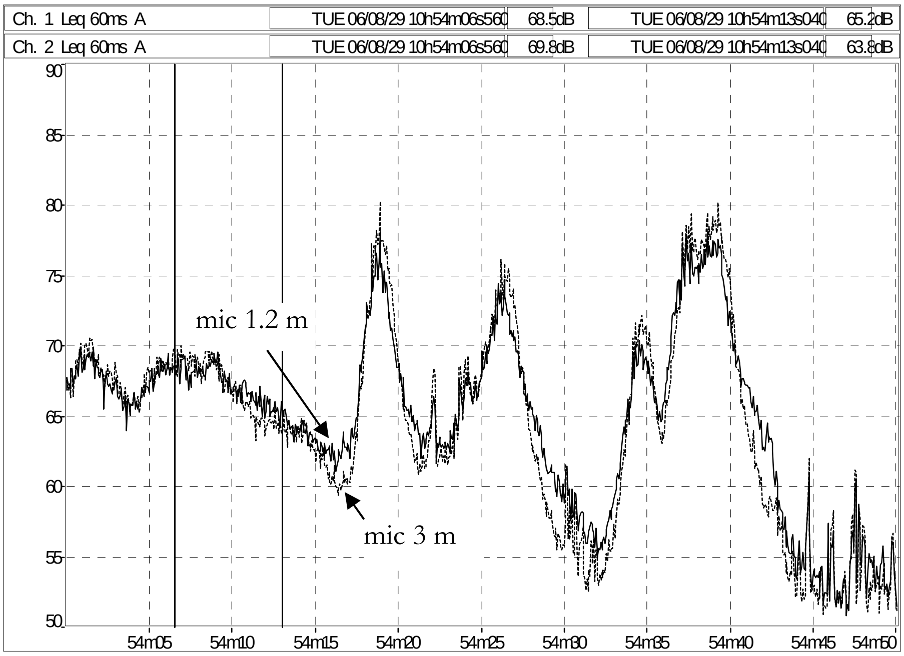

Figure 9 Sound pressure level in a situation where the vehicles are too close. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

In this project three tubes on the road were used to measure speed and acceleration of the vehicles. They also provide information on the weight and the distance between the axles of the car. This information is vital for the processing of the data. However, each time a vehicle passes over the tubes a kind of impact sound is generated, which influences the measurement (Fig. 10). On the one hand the tubes should be placed as close as possible to the microphone position in order to estimate the speed and acceleration of the vehicle as accurate as possible at the microphones but on the other hand, the closer the tubes are placed, the more disturbances on the measured sound pressures they will give. Additionally, not all vehicles were influenced significantly by the tubes, but were able to cross them rather silently.

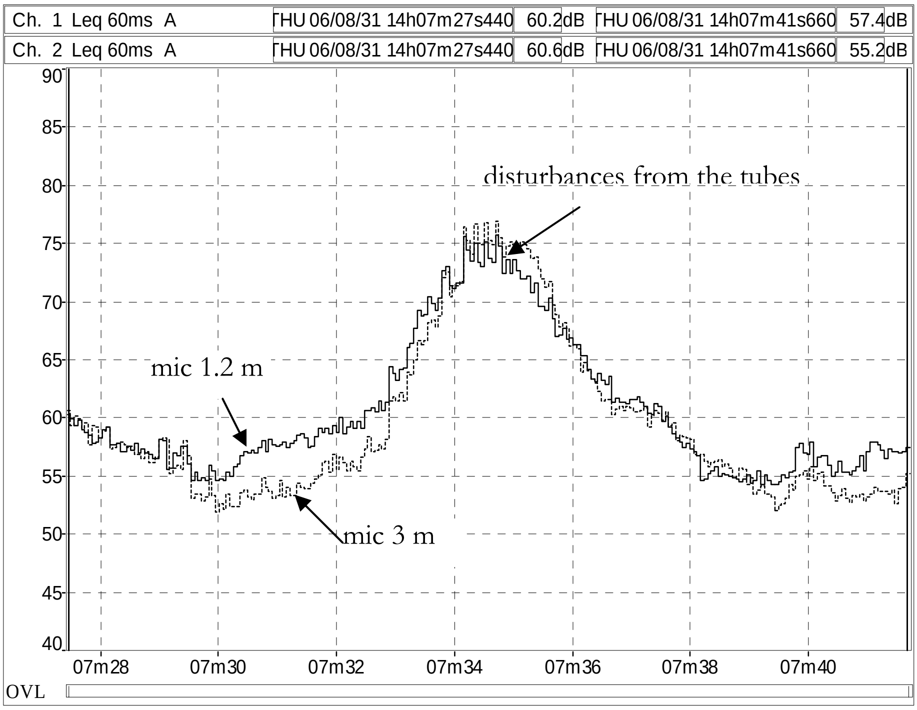

Figure 10 Sound pressure levels when noise from the tubes influences the measurement. The impacts can be seen at the top of the peak in the pass-by. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

Figure 11 shows a measurement when a car passes by on the opposite lane. In the middle of the figure a passenger car runs on the opposite side and to the left and right two cars pass by closely at the nearest lane. The two closest passages are disturbed by the noise generated when passing over the tubes, which can not be seen in the sound pressure level from the opposite car. The noise from the car passing the opposite lane is a little bit lower in amplitude compared to the noise from the closest lane. This can be because of the larger distance from the microphones to the farthest lane or because the car on the opposite side has a lower noise emission. It can also be a combination of both.

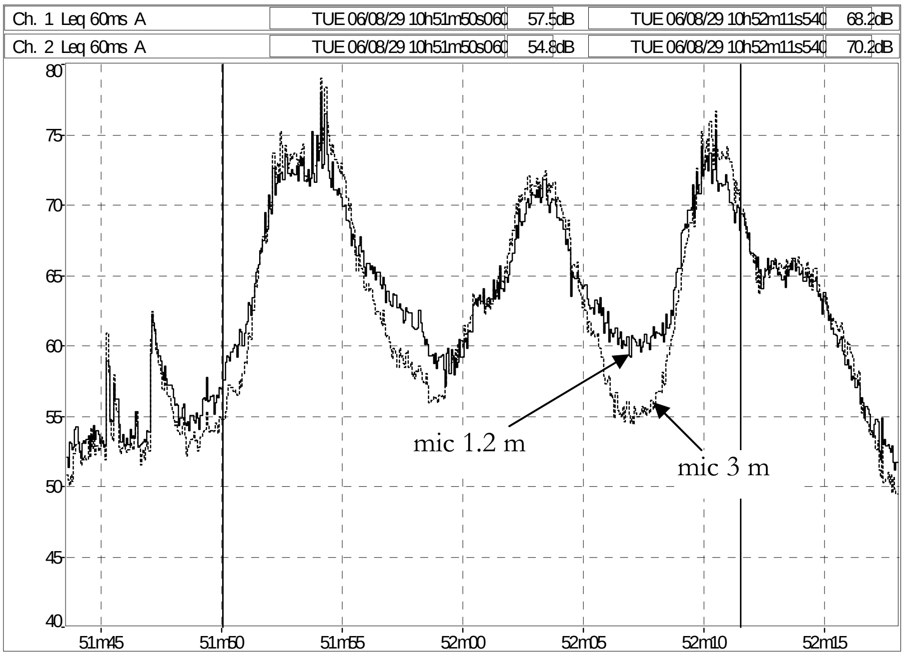

Figure 11 Measured sound pressure levels for two cars passing by at the closest lane and a car in the middle at the opposite lane. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

Figure 12 shows an example of recording where the background noise disturbs the measurements. In this case the background noise originates from a nearby tram stop. The background noise is not stationary but varies over time. This noise is very difficult to compensate for and normally the only option is to reject the measurement. In some cases the maximum level can be used if the level is greater than the background level in all frequency bands of interest.

Figure 12 Measurement signal with a relatively high background noise. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

3.1.3 Calculation of sound power levels

Figure 13 shows the normalized sound exposure levels for four selected passages (see further Section 3.4). For each passage the highest sound exposure level of the two microphones in each third octave band is chosen in accordance with [10]. In these measurements an angle corresponding to ±3*d* was used for the sound exposure during the pass-by, but normalized to ±5*d*. For an explanation of the angle of integration see Section 2.2. In an ideal case an angle of ±5*d* should be used. Because of limitations at the measurement site smaller angles can be chosen with reduced accuracy.

It can be seen in the measurements that the three passenger cars that were selected, are quite similar in sound emission. The frequency characteristics are similar except at very low frequencies below 80 Hz where large differences are expected. Passage four, a light truck, is clearly louder than the other 3 vehicles at high frequencies above 1000 Hz. This can be due to the acceleration of this vehicle.

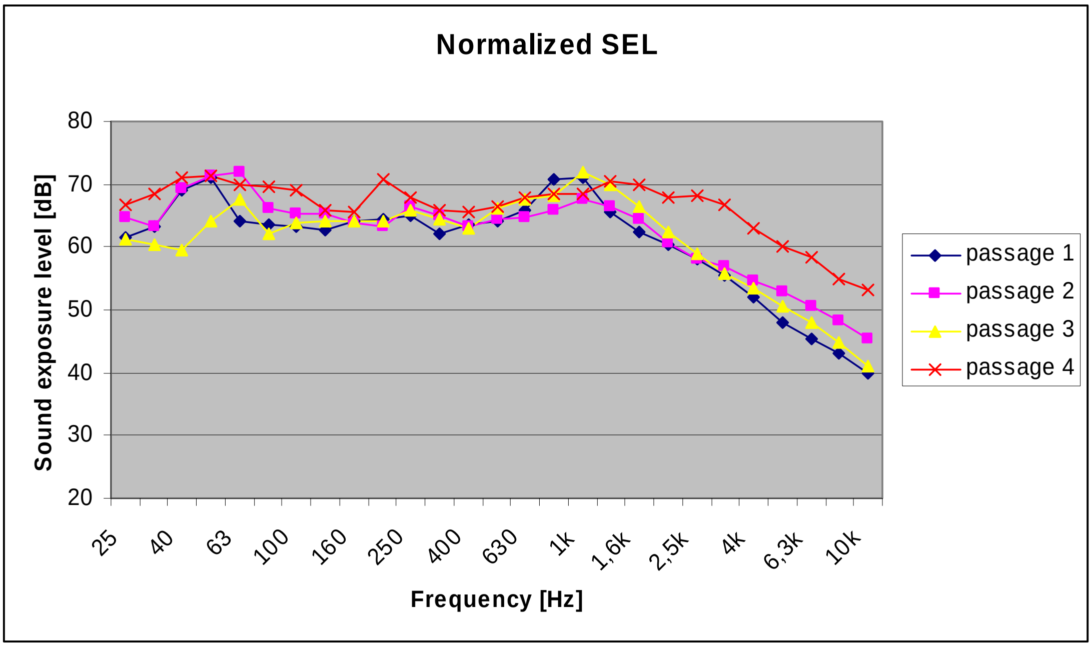

Figure 13 Normalized sound exposure level.

Beside the normalized sound exposure level, the maximum levels were also recorded during the measurements. From the maximum levels, the L_E can be estimated using an empirical, theoretical or semi-empirical model. The difference between L_E estimated from the maximum level and the measured L_E is shown in Figure 14. In this case, a semi-empirical method developped in the European Harmonoise project was used. The estimate of L_E from the measured maximum levels overestimates the levels in this case. One reason for this could be the disturbances caused by the impulses from the tubes. Although the difference between A-weighted sound exposure levels is acceptable (it is less than 0.5 dB), it is still desirable to improve the algorithms used for the individual frequency bands.

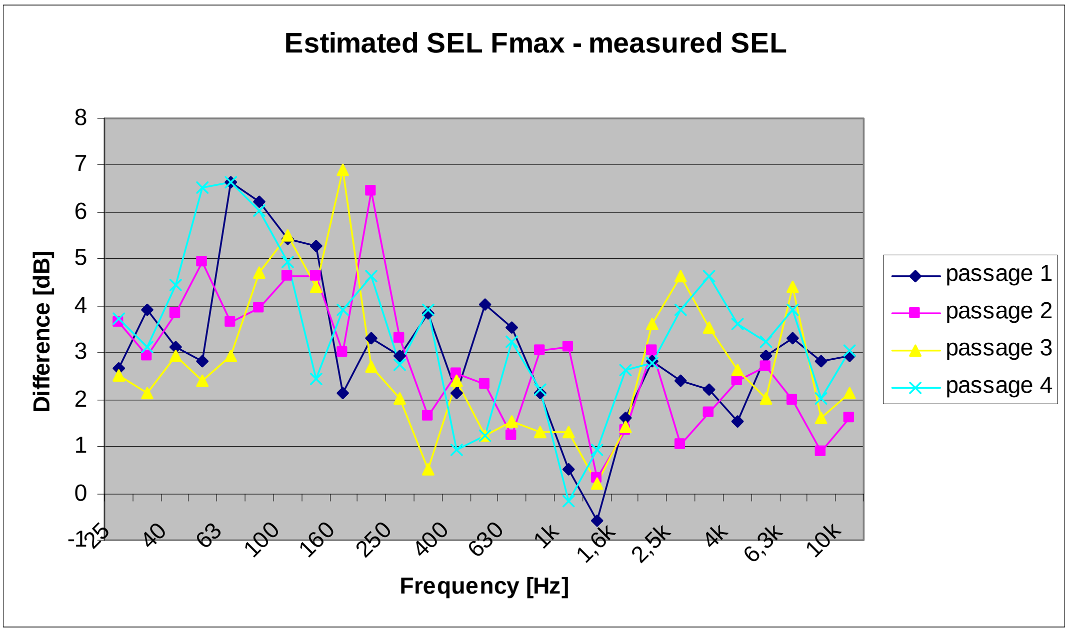

Figure 14 Difference between normalized sound exposure levels estimated from the L_{Fmax} and the measured L_E.

More data from the noise measurements can be found in Appendices 4 and 5.

3.2 Particles

Before deployment, the measurement system was set up in a parking lot and tested by repeatedly driving a new, well-kept car past the sampling inlet. Low velocities and atypical driving had to be used for safety reasons. Under these conditions the system operated flawlessly without dilution. However, at the actual measurement site, an initial data set without dilution had all CPC particle measurements out of range. Therefore, all data afterwards was collected using the dilution system. After one and a half day the ELPI was added. A few hours into the second day, the CO_2-instrument and later its back-up unit failed. It was, however shown that both the Grimm spectrometer and the ELPI worked well in the system and could have produced useful data, had the CO_2 analyser been operational. Table 2 summarises the operating time of the measurement equipment.

Table 2: Availability of measurement instruments (✓: instrument was in operation, ×: instrument was not running).

	Tue. 29 Aug.	Thu. 31 Aug.	Fri. 1 Sept.
CPC (> 10 nm)	✓	✓	✓
CO_2	✓	×	×
ELPI (0.02 – 6.2 µm)	×	✓	✓
Grimm (0.3 – 2.0 µm)	✓	✓	✓

Simultaneous CO_2 and particle enhancement peaks were quantified to derive particle emission factors (EF) for the passing vehicles. Due to the aforementioned problem of plume particle concentrations exceeding the upper concentration limit of the particle counter used, analytical integration of the excess concentrations was rarely applicable. Instead, the areas of the near-Gaussian-shaped peaks were assessed using a geometrical method. By fitting triangles to the peaks even the areas of saturated peaks could be approximated. For consistency reasons, the same method was applied to quantify the CO_2 peaks. Considering non-saturated peaks, the comparison to the analytically calculated area under the curve yielded a very good correlation for both CO_2 (see Fig. 15 left) and particle peaks (Fig. 15 right). Because of the good agreement, especially for the smoother particle peaks (r = 0.99), the geometrically derived peak areas were used for further examination.

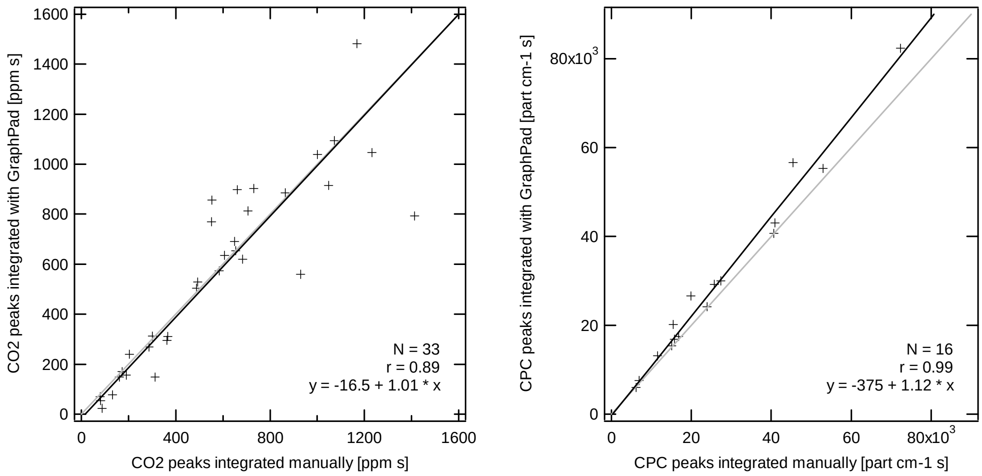

Figure 15 Scatter plots of analytically versus geometrically integrated (left) CO_2 and (right) particle peak areas (measurements of 29 August 2006). The results of an orthogonal linear regression analysis are given within the figures.

For the determination of particle emission factors of passing vehicles on the first measurement day, a CO_2 emission of 164 g km^{-1} veh^{-1} was assumed (value for petrol-fuelled Volvo S40 [25]). Values between 100 and 250 g km^{-1} veh^{-1} are usual for petrol-driven vehicles; diesel-driven vehicles emit somewhat lower CO_2 amounts. Particle emission factors of the order 2 x 10^{13} part km^{-1} veh^{-1} were derived from 33 coincidences on 29 August 2006 using Equation 2:

$$EF_{part} = EF_{CO2} \cdot \frac{N_A}{M_{CO2}} \cdot \frac{\Delta[part]}{\Delta[CO2]} \qquad (2)$$

where EF_{part} is the particle emission factor, EF_{CO2} is the carbon dioxide emission factor, N_A is Avogadro's number, M_{CO2} is the molecular mass of CO_2, and $\Delta[part]$, $\Delta[CO_2]$ are the excess particle number density and CO_2 mixing ratio within the plumes towards the background, respectively. Figure 16 shows emission factors for PM emissions from these 33 vehicles. A relatively large spread in the emissions can be observed.

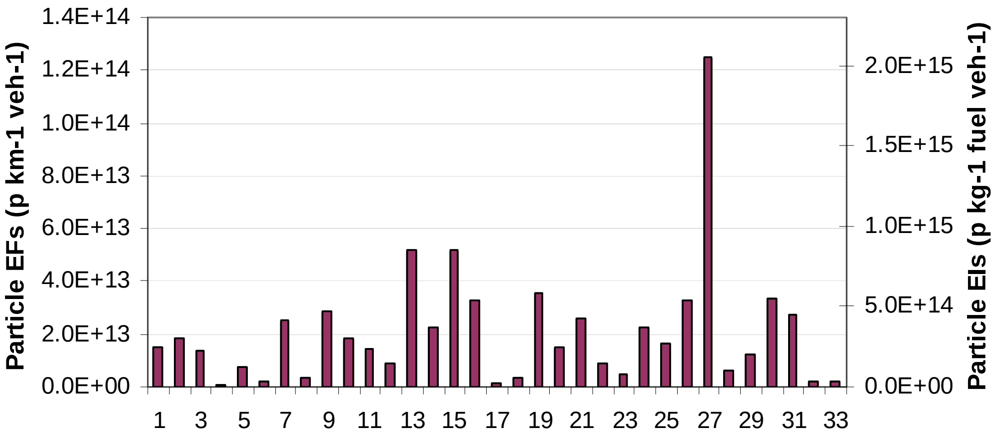

Figure 16. Emission factors for particle emissions from 33 different vehicles.

The value for EF_{part} agrees well with those published in the literature for petrol-driven vehicles, which constitute more than 90% of the Swedish fleet (The proportion of diesel cars in Sweden is low compared to the EU average, where it amounts to 30% [26]): For petrol-fuelled cars, particle number EFs are reported to be between 1.7 x 10^{13} and 4.5 x 10^{13} part km^{-1} veh^{-1}; for diesel fuelled vehicles they are one order of magnitude larger [27, 28].

Given the obtained results, the measurement setup proved appropriate to quantify particle emission factors from road traffic. The characterisation of particle size distributions within vehicle emission plumes using ELPI data revealed three different classes of size distributions (Fig. 17): One showed a maximum particle fraction at sizes ≤ 0.02 µm (the smallest particle size measured with the ELPI), another one peaked at 0.04 µm. The third class had a broad maximum between 0.04 and 0.07 µm. The size distributions shown in Fig. 17 are normalised to the overall measured particle concentration. Unfortunately, there was no overlap between CO_2 and ELPI measurements (cp Table 2). Less than 10% of the particles detected in vehicle emission plumes had sizes > 0.3 µm.

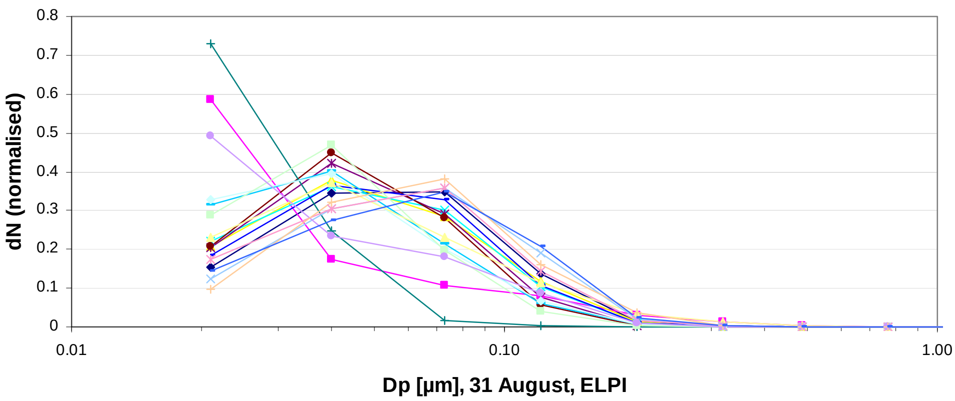

Figure17 Particle size distributions in vehicle emission plumes obtained by the ELPI on 31 August 2006. Three different classes of size distributions were identified, peaking at ≤ 0.02 µm, 0.04 µm and between 0.04 and 0.07 µm.

These observations were similar on both days (31 August and 1 September), however due to the limited number of peaks on both days (17 and 16, respectively) and the uncertainty attributing the plumes to particular car passages, no clear conclusion can be drawn regarding the connection between particle size distribution and, e.g., used fuel type or age of the car.

3.3 FEAT

An example of data is shown in Table 3. The first six columns show parameters determined with the vehicle detection tubing system. The total weight is approximated from the measured distance between the wheel axles (see Appendix 3), this distance is also used to determine type of vehicle, i.e., personal car or truck. The information about fuel type, make year and technology class is taken from the Swedish national vehicle register. The three last columns show emission factors for CO, NO and HC in g (kg fuel burnt)$^{-1}$. Some of the emission factors are negative. This is an issue related to the uncertainty in the measurements. Negative values can be considered as very low levels of emissions. At least one high emitter of CO and HC can be identified in the table. This vehicle emits about 621 g of CO and 19 g of HC per kg fuel burnt. Because this high emission can't be traced to a high instantaneous power for this vehicle, it is reasonable to suspect that this vehicle has some problem with the engine and needs service. The ability to detect such high emitters is undoubtedly one of the biggest advantages with the FEAT instrument compared to other methods for measuring road emissions.

Table 3. Data from the FEAT and tube measurements.

Vehicle Type	Speed (km h^{-1})	Acc. (m s^{-2})	Total weight (kg)	Instan-taneous Power (kW)	Nr. of axis	Type of fuel	Make year	Technol-ogy Class	CO (g kg^{-1} burnt)	NO (g kg^{-1} fuel burnt)	HC (g kg^{-1} fuel burnt)
PB	34.27	0.02	1429	2.4	2	Petrol	1999	Euro2	-2.6	1.8	6.4
PB	59.72	-0.29	1753	-3.1	2	Petrol	2005	Euro4	-1.3	0.0	0.0
PB	44.97	-0.12	2720	1.4	2	Petrol	2005	Euro4	-5.3	-1.8	2.4
PB	31.45	1.59	2711	45.2	2	Diesel	2005	Euro3	1.3	3.9	3.0
PB	54.64	-0.32	1810	-4.2	2	Petrol	2002	Euro3	57.6	37.5	12.1
PB	23.48	0.51	1566	7.3	2	Petrol	1998	Euro2	72.9	8.5	11.5
PB	22.77	0.49	2162	9.3	2	BI-Fuel (petrol/CNG)	2002	Euro4	4.0	4.1	-6.2
PB	27.66	0.7	2005	14.2	2	Petrol	2002	Euro3	13.2	0.1	0.6
PB	27.73	0.73	2086	15.3	2	Diesel	2003	Euro3	7.9	8.9	11.4
PB	24.23	1.03	2190	18.8	2	Petrol	2002	Euro3	0.0	5.8	-0.3
PB	36.27	0.19	2172	8.2	2	Petrol	2002	Euro3	-9.3	3.1	-3.7
PB	28.92	1.25	2011	24.6	2	Petrol	1997	Euro2	2.6	2.8	9.9
PB	36.64	1.77	1617	34.7	2	Petrol	2004	Euro4	-1.3	0.3	-0.2
PB	24.21	0.92	2163	16.8	2	Petrol	1994	Euro2	620.6	1.8	18.5
PB	24.38	0.8	2791	19.5	2	Petrol	2004	Euro4	5.3	-1.1	0.0
PB	32.73	0.26	1490	6	2	Petrol	2002	Euro3	14.5	-2.1	7.7
PB	41.99	0.64	1615	16.6	2	Petrol	2004	Euro3	-6.6	14.0	2.8
PB	29.07	0.64	2055	14.2	2	Diesel	1999	Euro2	0.0	11.4	3.0
PB	24.21	0.66	1807	10.6	2	Petrol	2000	Euro2	-1.3	0.6	0.7
PB	32.98	1.84	2207	44	2	Petrol	2006	Euro4	39.6	-0.5	1.2
PB	32.3	0.45	1714	10	2	Diesel	1999	Euro2	-5.3	6.8	1.0
PB	37.01	0.09	1969	5.3	2	Petrol	1995	Euro1	-6.7	3.1	-2.7
PB	28	1.2	2036	23.3	2	Petrol	2004	Euro4	32.8	11.2	10.4
PB	31.72	1.39	1857	27.5	2	Petrol	2003	Euro4	2.7	3.7	0.3

3.4 Simultaneous measurements

In this project only a few passages were obtained where simultaneous measurements of emissions from noise, particles and gases could be evaluated. The chosen passages consisted of three passenger cars and one light pickup truck. The speeds of the passenger cars were between 30 and 50 km/h. For the light truck the speed was approximately 20 km/h at the point of speed measurement. However, the acceleration was rather high for that vehicle. In the following, the first three passages correspond to the passenger cars and passage four corresponds to the passage of the light truck.

The noise classification of the three passenger cars is 1a and 1b for the pickup truck according to the categories in Table 1. The classification of the vehicles was made from the data from the licence plates. The acoustic analysis was made manually for these four passages. However, in an automatic system these calculations could be programmed in a computer. In this case there was a time delay in the noise measurements compared to the other measured data because of the distance between the tubes and the microphone position, which was compensated for.

The recorded noise data can be used for a number of purposes. Considering the collection of data to the source model for road traffic noise the main result should be to update coefficients for the sound power level L_W of the vehicles. What normally is measured at the two microphones is the sound pressure level L_p as functions of time. The measured sound pressure levels are integrated over an angle of sight to obtain the total energy during a single passage. In this way the sound exposure level L_E is obtained. The L_E is then normalized to a specific measurement distance and a specific angle of integration in order to be able to compare measurements carried out at different distances and with different angles of integration. Finally, there is a relationship between the sound exposure level and the sound power level depending on the speed of the vehicle. A procedure to determine the sound power level is described in Appendix 5.

Figure 18 shows the spectrum in third octave bands of the total sound power level from the individual passages. This is the sum of the sound power from both the tyre/road noise source and the engine noise source in the model. All passages are quite similar except for the light truck at high frequencies above 1000 Hz.

In the context of the FEAT measurement, relationships of particle emissions and characteristics of trace gas emissions of registered vehicles were studied. A positive relation between NO and particle emission was found as well as weak negative relations between particle and HC and CO, respectively. However, since the cars often come in groups, the measured particle peaks cannot unambiguously be associated with the individual passing vehicles. Nevertheless, a clear positive relation between driving speed and particle emission was found. The results are promising and may be strengthened by further measurements using improved particle equipment.

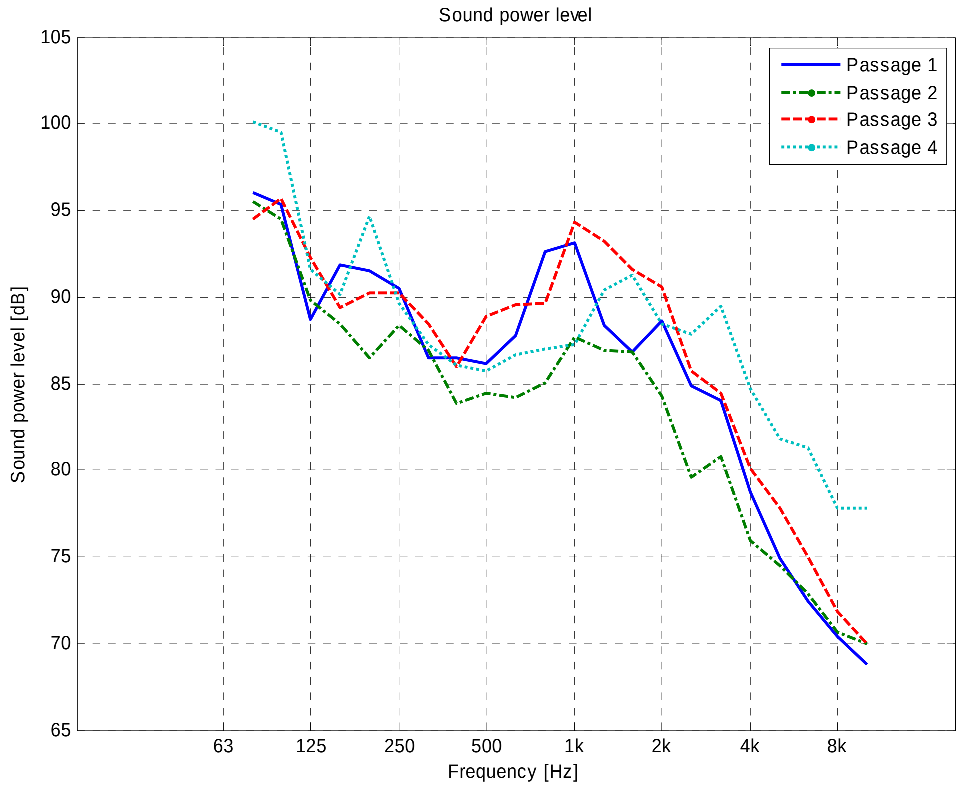

Figure 18 Total sound power level of the vehicles

From the first day's measurement data, particle emission factors for vehicles were derived as outlined in Section 2.3. Since the cars came in groups and the time resolution of the particle measurement equipment was not ideal, it was not always possible to assign the obtained particle emission to a specific individual vehicle. For this reason, in Figure 19, the calculated particle emission factors are plotted versus the trace gas emission quantities of all cars coming into question (maximal 3). Considering the speed of the vehicles and according to the observations, it is reasonable to confine the selection of cars to those passing within a time frame of 10-15 s before the peak appears in the particle data. As long as the time resolution of the particle measurements is not improved, it will be hard to distinguish vehicles which pass the measurement site as a group with narrow distances (which translate to a time interval of just 1-2 s) from each other. Despite the limited data set and the uncertainty assigning emissions to a vehicle, relations between particle and trace gas emissions could be identified (cp. Fig. 19). A positive relation to NO_x emissions is visible, whereas the relationship to carbon monoxide and hydrocarbons is negative. More evident results are expected from longer-term observations of traffic emissions.

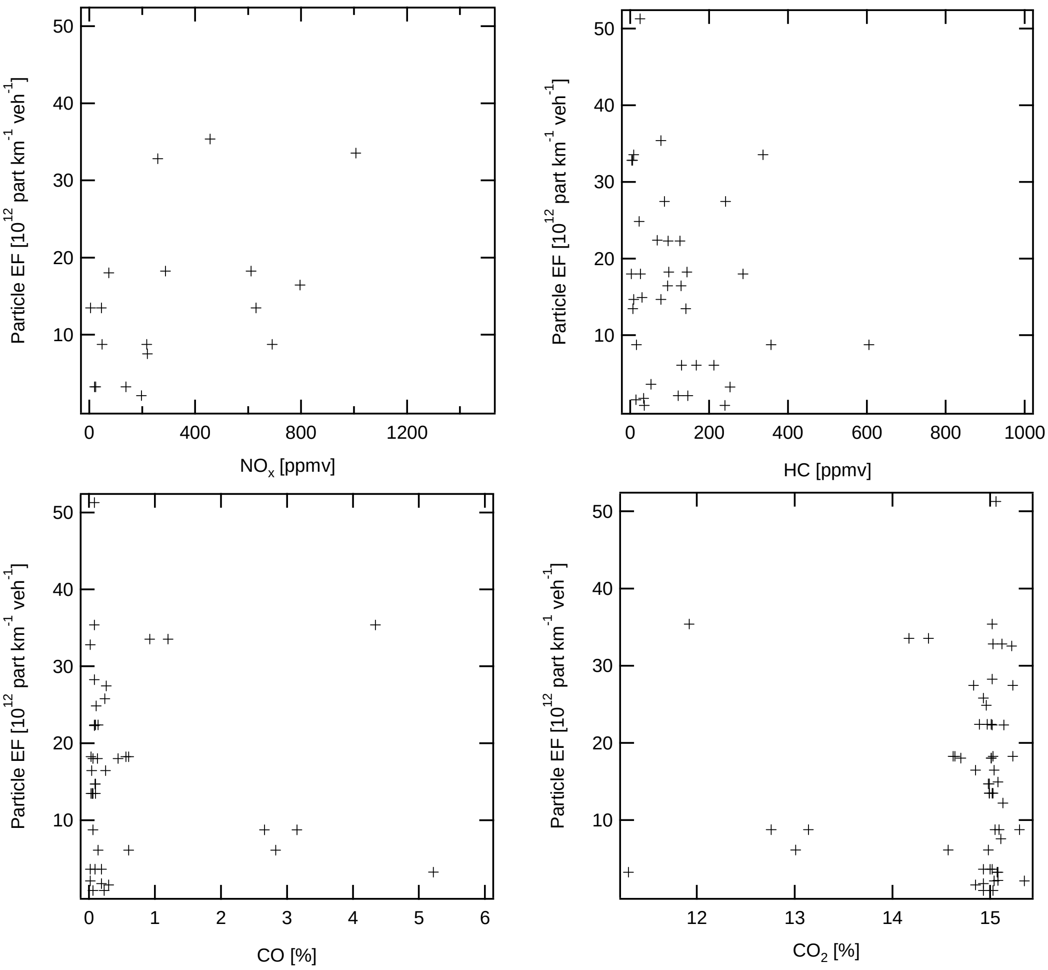

Figure 19: Relationships between particle emissions and trace gas emissions obtained from simultaneous measurements with the particle setup (cp. Sec. 2.3) and the FEAT system. Particle emission factors (EF) are plotted versus the fractions of NO_x, hydrocarbons, CO and CO_2, respectively, in the exhaust plumes of passing vehicles. See text for details.

Table 4 summarises the available data for four chosen vehicles in order to show the potential of the combined measurements presented in this work.

Table 4 Measured emissions from individual vehicles.

Date	Time	L_{EA}	L_{AFmax}	L_{WA}	CO g/kg fuel burnt	NO g/kg fuel burnt	HC g/kg fuel burnt	Particles 10^{13} /km
29082006	14:06:57	75.5	73.7	99.1				2.8
29082006	14:07:37	74.1	70.6	95.4	58.1		0.24	1.8
29082006	15:20:28	76.7	75.3	100.8	-25.4		-1.89	1.2
31082006	13:36:30	78.5	74.6	99.5	14.5	9.98	3.8	

4 Discussion

In order to be able to identify vehicles and traffic situations that have a negative impact on the environment, it is important to be able to measure emissions from individual vehicles in traffic. The measurements show that it is feasible to study regulated emissions, particle emissions and noise emissions from individual vehicles.

Noise data was collected from ca 200 individual vehicles during the measurement campaign and the emissions of some of the vehicles were evaluated. The measurements were manually supervised and the evaluations mainly made by hand. The experiences of this project are encouraging and lead to the conclusion that it should be possible to perform measurements of noise emission from individual vehicles automatically. One way to achieve this would be by extending the FEAT system so that it also measures sound emission. To make it work it is essential that screening of bad data and calculation of sound emission is made using a computerized procedure. A draft of such an algorithm that has been designed within this project is presented in Section 2.2.

By using a CO_2 instrument together with the particle instruments, we were able to obtain PM emission factors for individual vehicles. However, due to the lack of time resolution of the used instruments (cp. Sec. 2.3), it was not always possible to explicitly identify the vehicle causing the emission peak when a group of cars passed the measurement site. We also showed that the particle size-distribution can be obtained from individual vehicles in traffic when using a fast instrument. This also, in principle, allows for the separation of particles emitted from the engine and particles from road and tyre wear. The results show that the emissions of particles vary significantly from vehicle to vehicle (cp. Figure 16). A variation range of two orders of magnitude (between 8.5×10^{11} and 1.2×10^{14} part km^{-1} veh^{-1}) has been observed. Instruments for similar measurement of particle concentrations are often limited by rise times in the 2 - 5 s range. The instrument used in this investigation can be operated to give a rise time of around 1 s by increasing the flow rate through the instrument. It is necessary to dilute the sampled exhaust to handle the high particle concentrations. The time separation needed between vehicles becomes longer than for standard FEAT measurements but should still be possible to make. It is estimated that a separation of 5-7 s should give useful data.

The FEAT system together with the system for speed and acceleration monitoring, were able to record emissions of NO, HC, CO and CO_2 as well as acceleration and speed.

During the measurement campaign there were few times when all systems were available at the same time. However, we showed that we were able to measure particles, noise and other emissions from individual vehicles in a few cases. A general problem is to identify the contribution from individual vehicles when cars come in groups.

The approach taken here has proven to be useful. In a separate project the FEAT data is used to inform the driver of the status of the vehicle. This is done via a sign using a colour code with a red signal for high emissions. In principle this type of information could be expanded to inform drivers also about particle emissions and noise levels.

Over the past years, FEAT measurement of individual vehicles has been proven to be a tool that can be used to find high-emitters. These are usually either older cars without catalytic converters or where the catalytic converter is deactivated. These cars may contribute to a very high degree to the pollutant-levels in cities and are important to identify. In the same way the present approach can be used to find vehicles that emit large amounts of particulate matter. This can be the case if the engine is worn or not properly adjusted. In the same way noisy cars can be identified.

The type of data collected in this study is further very useful for input in databases. By measuring the emissions and at the same time, obtaining facts about the vehicles, a number of emission factors with great details regarding, e.g., type of vehicle and make-year, can be obtained. However, in order for this to be effective a more automatic system would be required, where data can be collected and attributed to different types of vehicles. This would also open up for studying different traffic situations by placing the equipment at different sites.

The main goal for the noise measurements is to produce input data for a national road noise source database but a spin-off from the measurements is that we can give the drivers feedback of how loud their vehicle is. The normalized L_{AFmax} is a suitable measure for this and the value is best presented in a way as simple as possible – say as green, yellow or red light depending on if it is under, close to or above a certain noise limit. This gives also a possibility to influence the driving style to reduce the noise level in traffic and to inform drivers if there are any problems with the vehicle. The maximum level is least influenced by background noise (except for noise from the tubes). It correlates also to the sound power level of the vehicle if the speed and size of the vehicle is taken into account. The normalization procedure makes it possible to compare results from different sites and to give reliable information. A microphone height of 3 m or more is recommended to reduce influence of differences in excess ground attenuation at different measurement sites.

The FEAT system collects most of the information that is needed for the noise measurements but a few supplements are needed. Since the emissions vary with the temperature of the road surface this must be recorded. It would also be good to know if the surface is wet. Furthermore we need to know if there are vehicles driving on the other side of the road and their approximate position. If a vehicle on the opposite side of the road passes the microphones at the same time as a vehicle is passing on the nearest side we would measure a too high sound pressure level. As it would be very hard to detect the presence of the other vehicle just by analyzing the recorded sound some kind of (noiseless) sensor is needed.

The problem with the sound from the vehicle detection system needs to be taken care of. It will probably be possible to find a signal processing algorithm that can filter out the noise good enough that it would not affect the calculated L_E. (It might be harder to make it work perfect for L_{pFmax} though.) One way to do this is simply to remove those samples from the measurements that include sound from the tubes and use the rest of the data from the pass-by to evaluate the sound emission. This is possible if the time resolution used is sufficiently short. However, some data will be removed from the measurements resulting in reduced accuracy. A different approach could be to fit a polynomial to the measured envelope to decrease the unevenness of the curve. In this process the peaks when the vehicle passes the tubes can be removed. The polynomial is then used to evaluate the sound emission level and the sound power level.

One could also think about having a different way to measure the speed and acceleration. A radar or laser measurement system placed at the measurement site would remove the acoustical influence of the tubes on the measurements. However, such a system might be more expensive.

It would also be interesting to include a way to determine if the vehicles are using winter or summer tyres. The noise measurements could give a possibility to identify studded tyres in some cases due to the typical frequency characteristics they produce. This would give the possibility to study noise and particle emissions from studded tyres in more detail.

5 Future work

The promising results in this study should be followed up in two ways. First the methods need to be further improved and secondly, the equipment can be used to generate large amounts of data.

The FEAT equipment has been used in several studies and generated large amounts of data. It would be useful to extend the measurement capacity to include NO_2 and maybe N_2O and NH_3. Further, a system to extract the information from the video automatically would be very useful, especially if it is possible to connect to a vehicle database.

This feasibility study shows that a particle measurement system could be added to the FEAT setup. The particle measurement setup could be arranged either corresponding to an acceptable level of technology or to an advanced level, depending on the resources available.

The acceptable level includes a CO_2-analyser and a condensation particle counter of similar performance characteristics as the ones used here. By diluting with particle- and CO_2-scrubbed air it would be possible to stay within the dynamic range of these instruments and obtain useful particle/CO_2 data in many cases. The mixing volume would still be necessary due to the limited time resolution of the instruments. Coarse particle size distributions could be added to the measured parameters by adding, e.g., a Grimm aerosol spectrometer to the setup. Fine particle size distributions could be measured by the addition of an electrical low pressure impactor (ELPI). The latter instrument needs the mixing volume due to its comparatively slow response. It also requires the presence of a skilled operator. The estimated costs for adding a CO_2-analyser, a CPC and the Grimm spectrometer to the FEAT-system are less than, but not far from, 400 000 SEK. A sound-proof housing for the pumps should be included to facilitate the noise measurements. It would also be of interest to arrange automatic synchronisation of data from the aerosol/CO_2 measurements with the data from the FEAT system.

The advanced level involves a faster CO_2-analyser, a faster, possibly custom-built, particle counter and removal of the mixing volume to improve time resolution. Turbulent flow conditions combined with experimentally measured, size-resolved loss factors in the tubing should be considered. It is believed that the particle measurement system then would approach but not quite match the time resolution offered by the FEAT system. Here it should be remembered that a fraction of the FEAT-data is lost already today due to unclear conditions during passage of some vehicles. Increasing total measurement time could compensate a slightly larger fraction of data lost. A Grimm spectrometer may be added also to this system as long as its shortcomings in time resolution are acknowledged. ELPI-data valid for single vehicles would be scarce and it is unlikely that investment in such a device would pay off.

For the noise measurements the natural next step would be to implement quality check and sound power level calculation in software routines. The draft algorithm presented in Section 2.2 could serve as a starting point for such a development but it would probably be necessary to also include further research about pattern recognition methods. It would also be desirable to improve the algorithms for conversion of maximum sound pressure levels to sound exposure levels.

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Appendices

A1. Some acoustic background information

A1.1 Emission versus immission

We talk about noise *emission* when we want to describe the sound radiating from an object (the sound source) while we use the word *immission* for the sound that is reaching and exposing people. *Example*: An idling truck has a noise emission, expressed in A-weighted sound power level, of L_{WA} = 90 dB. At the balcony of a nearby house, this truck is causing a noise immission of L_{AFmax}= 55 dB (A-weighted sound pressure level).

A1.2 Emission measurements

Traditionally noise emission measurements on cars are carried out during pass-by at a distance of 7.5 m from the centre axis of the vehicle and at a microphone height of 1.2 m, [i, ii]. In the past the maximum sound pressure level was always measured but in recent years it has become more common to measure the sound exposure level and to introduce additional microphone heights, [iii,iv]. The sound exposure level (L_E) which is the time integrated noise dose during a complete pass-by has the advantage of being better related to what we want to predict, L_{eq}, than is the L_{max}. However, L_{max} is easier to measure as it is not influenced by noise contributions coming from longer distances. Thus it is less sensitive to background noise.

The traditional microphone height of 1.2 m has the serious disadvantage of being very sensitive to changes in the propagation path between vehicle and microphone. This means that changes in measured levels from one site to another do not only depend on differences in the tyre/road noise generation but also on differences in excess sound attenuation along the propagation path. As the excess attenuation is higher at low heights than at high heights it is preferable to use a higher height. In [iv] the height 3 m is recommended.

A1.3 Sound power level versus sound pressure level

The final result we are trying to get out of the measurements in this project is input data to the source models used in the calculation methods for road traffic noise. To be more specific: we want to determine the sound *power* level (L_W) of each one of the point sources used to model the vehicles.

The sound power level is a measure that tells us how much sound power an object emits. The sound *pressure* level (L_p) on the other hand tells us something about how the sound is perceived in a certain point. For example a lawn mower emits approximately the same sound power level as long as it is operating but the magnitude of the sound pressure level depends on how far from the machine we are. When standing close to it the sound pressure level is very high and we would have to scream if we need to talk to someone. But the farther we stand from it the lower the sound pressure level gets. At 100 m distance there would normally be no problem at all to have a discussion in a low voice.

The emitted sound *power* level does basically *not* depend on the surroundings, or better, *propagation* (that is distance, reflections, screening etc) but only on the physics of the emitting object. If we look at a vehicle this means that the emitted sound power level is a function of the construction of the vehicle, how fast it is driving, how much power the engine is developing for the moment, which tyres are used, if the silencer is working properly, if car audio system is turned up loud and so on. The sound *pressure* level on the other hand depends both on the emitted sound power level and on the sound propagation from the vehicle to the assessed position.

The measurements in this project give the sound pressure level at the microphone which is a result of two things: the sound power level emitted from the vehicle and the attenuation we get from the propagation of the sound to the microphone. Thus we have to subtract the propagation part from our measurement results in order to get the sound power level of the point sources that model the vehicle. We actually do this by using the calculation method backwards.

A1.4 Source separation

When compared to the human hearing sound measurement systems are inferior in one specific respect – they cannot separate different sounds from each other. If there were two or more sound sources simultaneously active when the measurement was made the result is the total sound pressure level from all sources and you cannot afterwards find the contribution from each source (except for some very rare cases when the sources have very special and, between themselves, different characteristics). Instead we have to be very careful to make sure that the contributions from other sources than the one to be measured are small enough not to contribute to the measured level.

For example, when making outdoor measurements of noise emitted from a specific industry building, we have to watch carefully so that disturbing sounds are not included in the result. There could be people talking, birds singing, wind blowing, cars passing etc and every time this happens we have to stop the recording. Depending on how noisy the environment is we will have to spend more or less time to collect a certain amount of data. It might very well take several hours of intense work to collect 20 minutes of the noise from the industry in question.

The measurement of individual vehicles is similar to the industry building example. We cannot just record everything continuously and afterwards use a fantastic filter that sorts out only the contribution from the vehicles we want to measure. But we can try to find an algorithm that automatically verifies the quality of the measurement per vehicle passage and disregards those pass-bys that does not fulfil a predefined criterion. A draft algorithm has been designed within this project and is presented in Section 2.2.

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[i] ISO 362:98, Measurement of noise emitted by accelerating road vehicles - Engineering method
[ii] SS-ISO 11819-1:97, Acoustics-Method for measuring the influence of road surfaces on traffic noise. Part 1: Statistical pass-by method
[iii] NT ACOU 109 :2001, Vehicles: Determination of immission relevant noise emission
[iv] H.G. Jonasson, Test method for the whole vehicle, HAR11TR-020301-SP10

A2. FEAT calculations

Example for calculating NO emission factor, this calculation is based on three assumptions:

- The exhaust plume is well mixed
- All carbon atoms in the exhaust gases derive from the fuel
- The C/H quota for the fuel is known ($\approx$2H per C)

The raw data from the FEAT consists of the following quotas:

n_{CO}/n_{CO2} n_{HC}/n_{CO2} n_{NO}/n_{CO2} (3)

where n are the moles of pure substance. By expressing hydrocarbons as hexane equivalents the total content of carbon in the path length, n_{Ctot}, is calculated by:

$n_{Ctot}=(n_{CO2}+n_{CO}+6n_{HC})$ (4)

The carbon atoms correspond to a certain volume of fuel, V_{fuel}:

$$V_{fuel} = \frac{M_{CH2} n_{Ctot}}{\rho_{fuel}} \tag{5}$$

where M_{CH2} is an approximated molecular mass of the fuel. The mass of the NO molecules in the path length m_{NO} is:

$m_{NO}=n_{NO}M_{NO}$ (6)

The NO emission per volume of fuel is then calculated as:

$$m_{NO}/V_{fuel} = \frac{\rho_{fuel}}{M_{CH2}} M_{NO} \frac{n_{NO}}{n_{CO2} + n_{CO} + 6n_{HC}} \tag{7}$$

By dividing (7) with n_{CO2} the emission is expressed in terms of the measured relations shown in (3):

$$m_{NO}/V_{fuel} = \frac{\rho_{fuel}}{M_{CH2}} M_{NO} \frac{n_{NO}/n_{CO2}}{n_{CO2}/n_{CO2} + n_{CO}/n_{CO2} + 6n_{HC}/n_{CO2}} \tag{8}$$

The emission data from the FEAT-instrument was then recalculated as emission factors in g (kg fuel)$^{-1}$.

A3. Vehicle power calculation

Besides the RSD instrument a system developed by VTI for measuring speed and acceleration and for approximating the instantaneous power of the vehicles was used. A description of this system can be found in literature [i]. The system consists - among other things - of three tubes lying across the road. When a car passes a pulse of air is generated in the tubing and this is recognized by the system as a vehicle passing. The speed between the first and second and also between the second and third tubing is calculated. From this data the acceleration and the space between the wheel axes are calculated. By using a relation between the axis space and the total mass of the vehicle the instantaneous power of the car can be approximated (9):

$$P = mva(1+\varepsilon_i) + mvg\alpha + mvgC_R + \frac{1}{2}\rho_A \frac{C_D A}{m}(v + v_w)^2 v \tag{9}$$

Where:

m: vehicle mass

v: vehicle speed

a: vehicle acceleration

ε_i: ”Mass factor”, which is the equivalent translational mass of the rotating components (wheels, gears, shafts, etc.) of the powertrain. The suffix i indicates that ε_i is gear-dependent.

α: vertical rise/slope length

g: acceleration of gravity

C_R: coefficient of rolling resistance

C_D: drag coefficient

A: frontal area of the vehicle

ρ_a: ambient air density

v_w: headwind into the vehicle

[i] Sörensen, G., 1996. System för bestämning av fordonskoder. Statens väg- och transportforskningsinstitut. VTI meddelande 762

A4. Additional noise data

A4.1 Different vehicle categories

Figure 20 shows the measured sound pressure level of a small passenger car and Figure 21 shows a large passenger car (category 1a according to the Harmonoise classing system) passing by the measurement site both at approximately 50 km/h. Comparing the two figures reveals that the smaller car has in this case somewhat lower noise level and a narrower peak. From experience this is explained by larger cars normally having wider tyres resulting in higher levels of tyre/road noise.

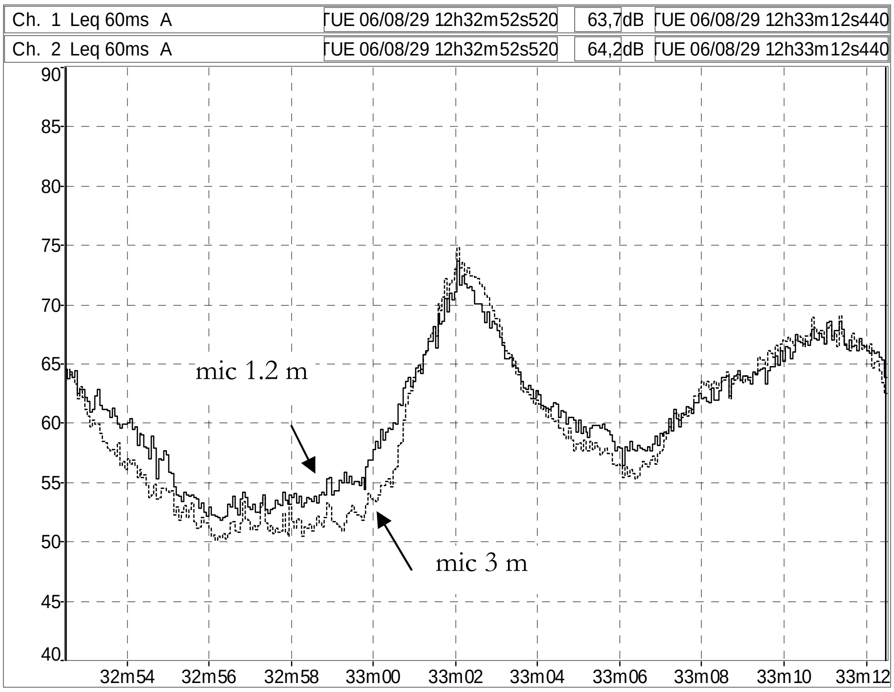


Figure 20 Pass-by of a small passenger car. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

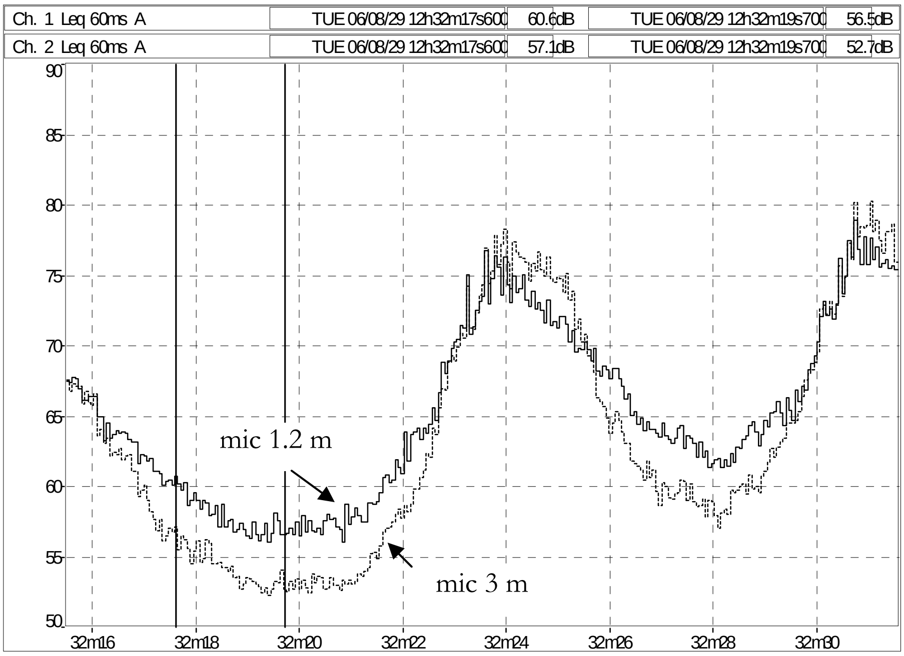


Figure 21 Pass-by of a large passenger car. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

Figure 22 shows an example of a pass-by of a 2-axle truck. The number of trucks at the chosen measurement site was quite low and no heavy trucks with more than three axles were recorded during the measurement days. To obtain reliable statistical data for all types of vehicles the measurement site has to be selected with care. More than one site might be necessary to obtain a full set of data.

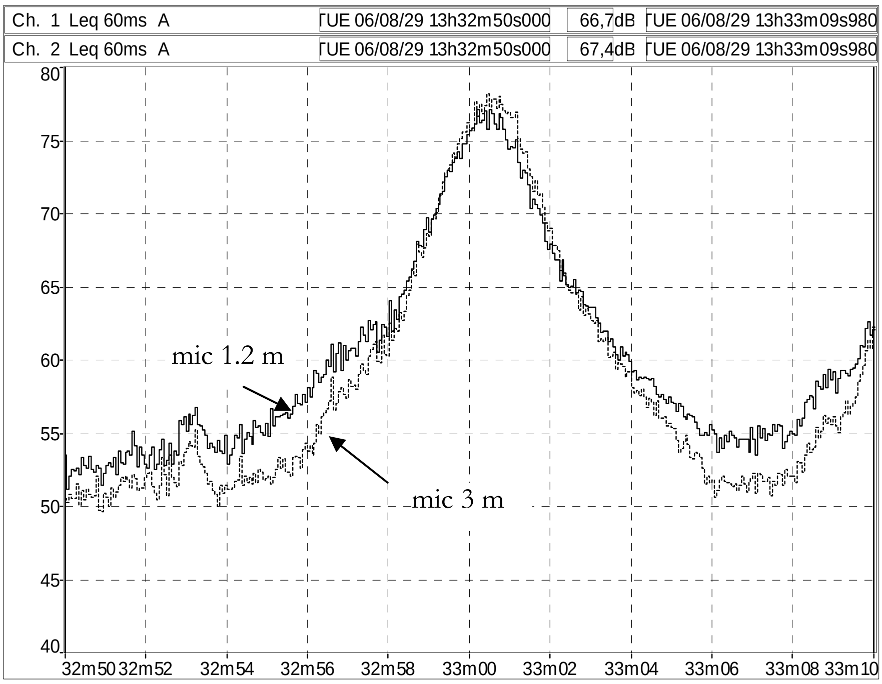


Figure 22 Pass-by of a 2 axle truck. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

A4.2 Problems in the measurements

Figure 23 shows the recorded sound pressure level as a function of time for an accelerating car. It shows that the noise signal from the passage is not perfectly symmetric. The sound pressure level increases with speed and hence the noise level is higher when the vehicle has passed the centre of the measurement site compared to before the centre and the result is a non symmetric signal from the passage. Additionally, the directivity of the source influences the results. Different sources have different speed dependences. One can also see that there is a larger difference between the two microphone heights on the leading and the trailing side of the passage. Normally this type of pass-by would be rejected in this case.

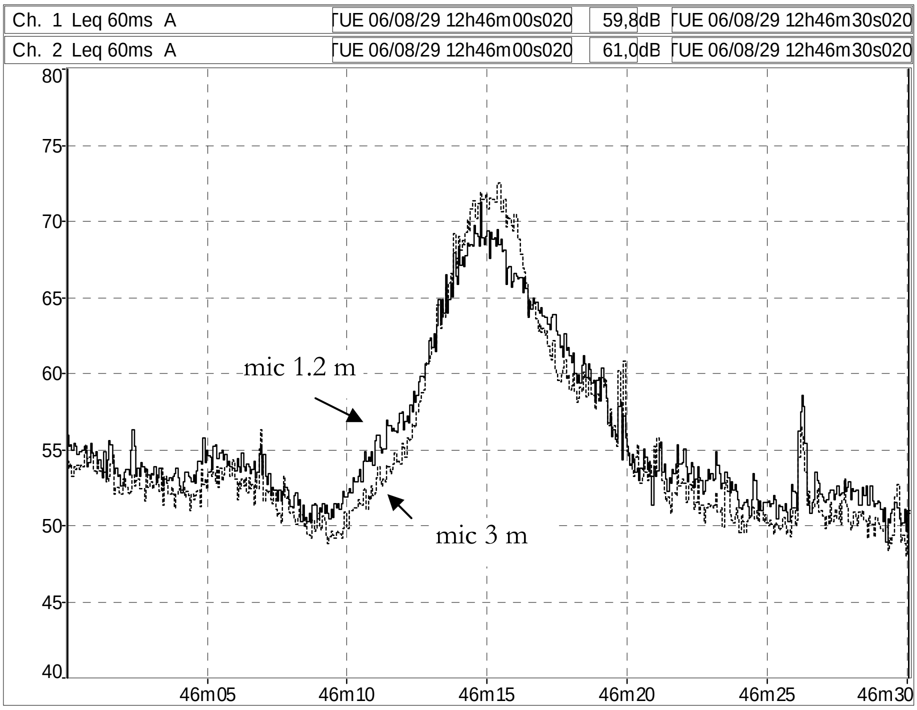


Figure 23 Example of measurement of an accelerating car. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

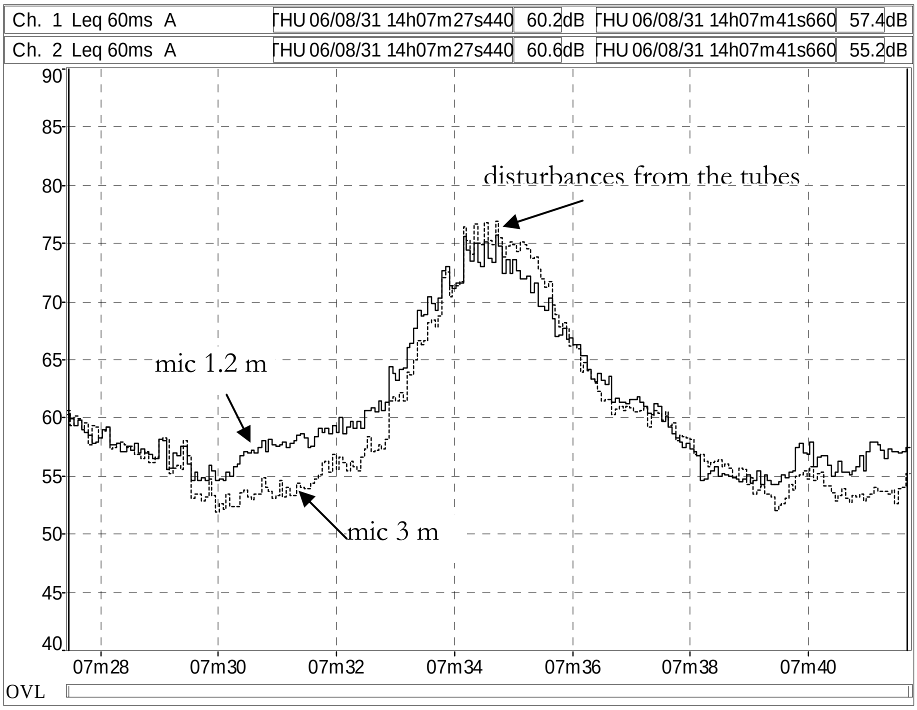


Figure 24 Sound pressure levels when noise from the tubes influences the measurement. The four impacts can be seen at the top of the peak in the pass-by. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

In this project three tubes on the road were used to measure speed and acceleration of the vehicles. They also provide information on the weight and the distance between the axles of the car. This information is vital for the processing of the data. However, each time a vehicle passes over the tubes a kind of impact sound is generated, which influences the measurement (Fig. 24). On the one hand the tubes should be placed as close as possible to the microphone position in order to estimate the speed and acceleration of the vehicle as accurate as possible at the microphones but on the other hand, the closer the tubes are placed, the more disturbances on the measured sound pressures they will give. Additionally, not all vehicles were influenced much by the tubes, but were able to cross them rather silently.

Figure 25 shows a measurement when a car passes by on the opposite lane. In the middle of the figure a passenger car runs on the opposite side and to the left and right two cars pass by closely at the nearest lane. The two closest passages are disturbed by the noise generated when passing over the tubes, which can not be seen in the sound pressure level from the opposite car. The noise from the car passing the opposite lane is a little bit lower in amplitude compared to the noise from the closest lane. This can be because of the larger distance from the microphones to the farthest lane or because the car on the opposite side has a lower noise emission. It can also be a combination of both.

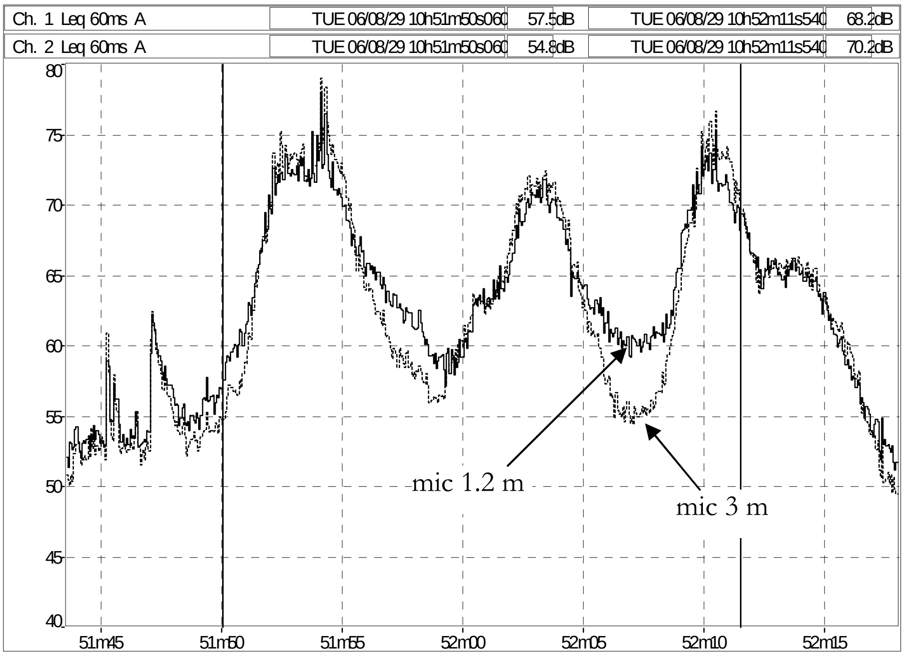


Figure 25 Measured sound pressure levels for two cars passing by at the closest lane and a car in the middle at the opposite lane. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

Figure 26 shows an example of recording where the background noise disturbs the measurements. In this case the background noise originates from a nearby tram stop, the background noise is not stationary but varies over time. This noise is very difficult to compensate for and normally the only option is to reject the measurement. In some cases the maximum level can be used if the level is greater than the background level in all frequency bands of interest.

Figure 26 Measurement signal with a relatively high background noise. On the axes: x-axis time [s], y-axis sound pressure level [dB re 20 μPa].

These problems make it hard only to use the recorded sound to verify the quality of the measurements and are normally solved by using information from the FEAT system. However, some additional information regarding cars on the opposite side of the road is often necessary.

A5. Calculation of sound power levels

Figure 27 shows the normalized sound exposure levels for the four selected passages in the project. For each passage the highest sound exposure level of the two microphones in each third octave band is chosen in accordance with [i] . In these measurements an angle corresponding to $\pm 3d$ was used for the sound exposure during the pass-by, but normalized to $\pm 5d$. For an explanation of the angle of integration see section 2.3. In an ideal case an angle of $\pm 5d$ should be used. Because of limitations at the measurement site smaller angles can be chosen with reduced accuracy. It can be seen in the measurements that all three passenger cars are quite similar in sound emission. The frequency characteristics are similar except at very low frequencies below 80 Hz where large differences are expected. Passage 4, the light truck, is clearly louder than the other three vehicles at high frequencies above 1000 Hz. This can be due to the acceleration of this vehicle.

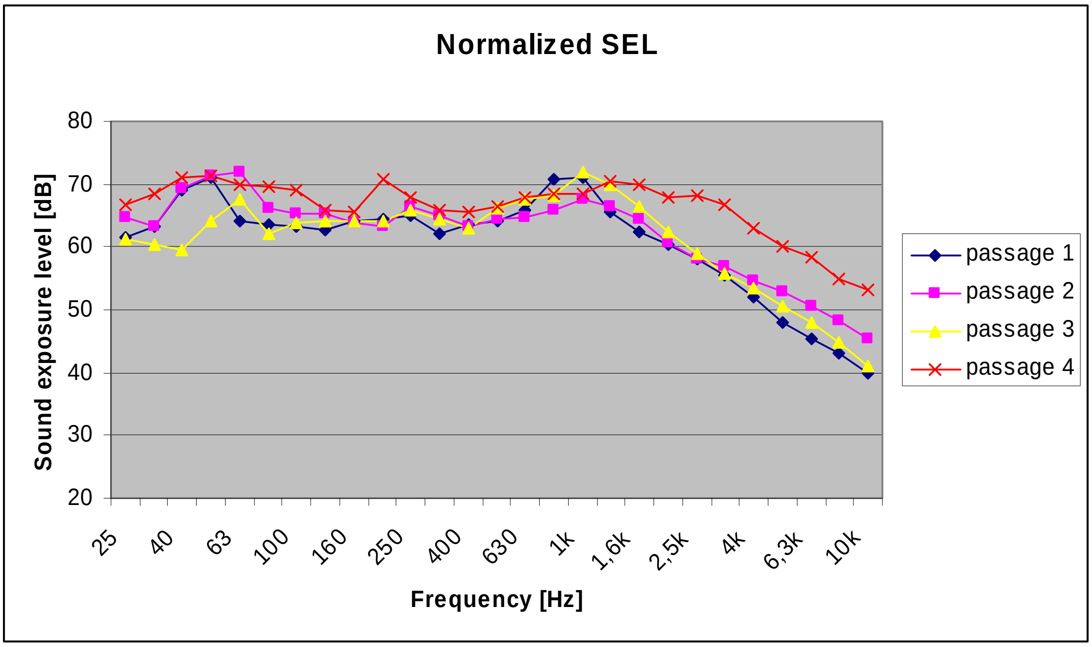


Figure 27 Normalized sound exposure level.

A5.1 Estimation of the sound exposure level from the maximum levels

Beside the normalized sound exposure level also the maximum levels were recorded during the measurements. Also for the maximum levels normalization is made and the results are shown in Figure 28. The same distance, 7.5 m, is used for the normalization of the maximum levels as for the sound exposure levels.

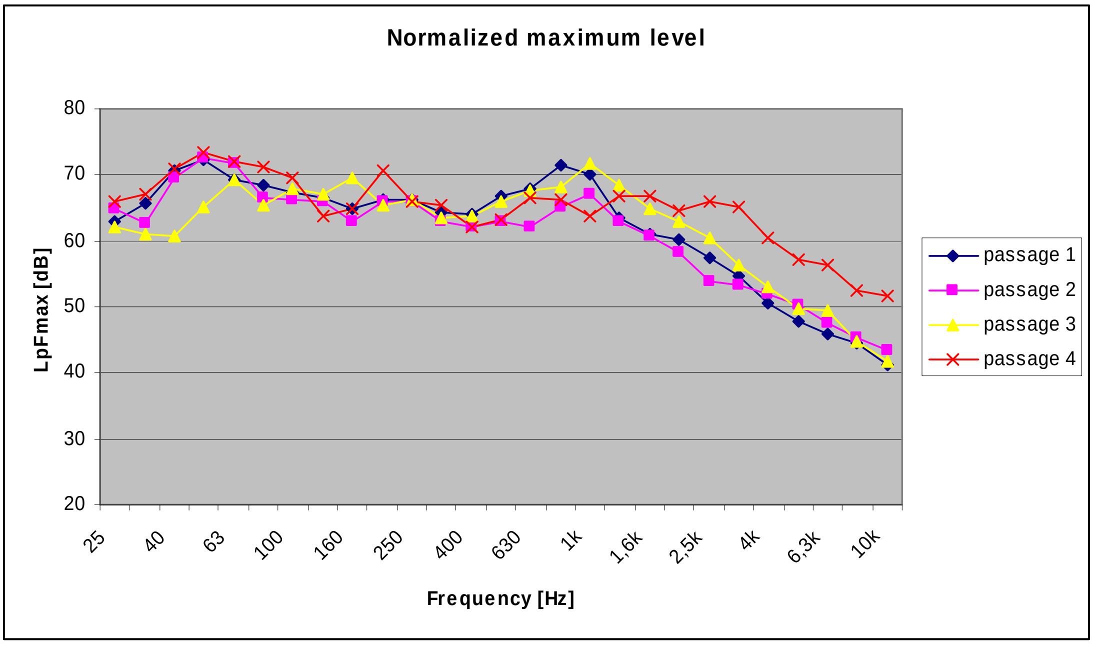


Figure 28 Normalized maximum levels for the vehicle.

From the maximum levels the L_E can be estimated and is shown in Figure 29. The difference between L_E estimated from the maximum level and the measured L_E is shown in Figure 30. The estimate of L_E from the measured maximum levels overestimates the levels in this case. One reason for this could be the disturbances caused by the impulses from the tubes. However, the difference between A-weighted sound exposure levels is less than 0.5 dB.

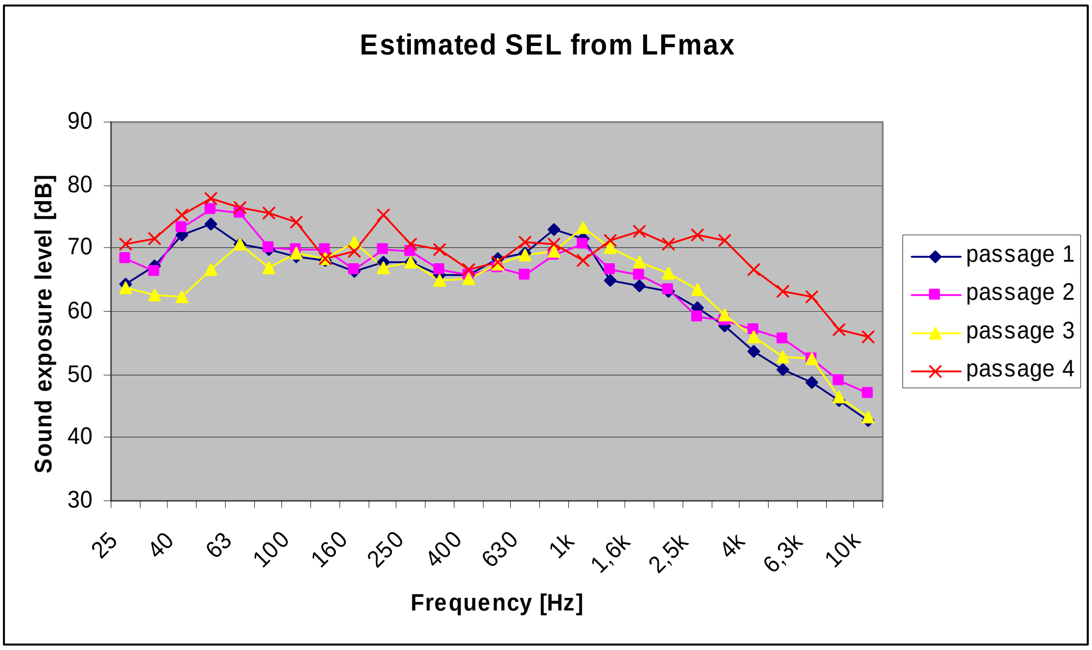


Figure 29 Sound exposure level estimated from the maximum levels of the passages.

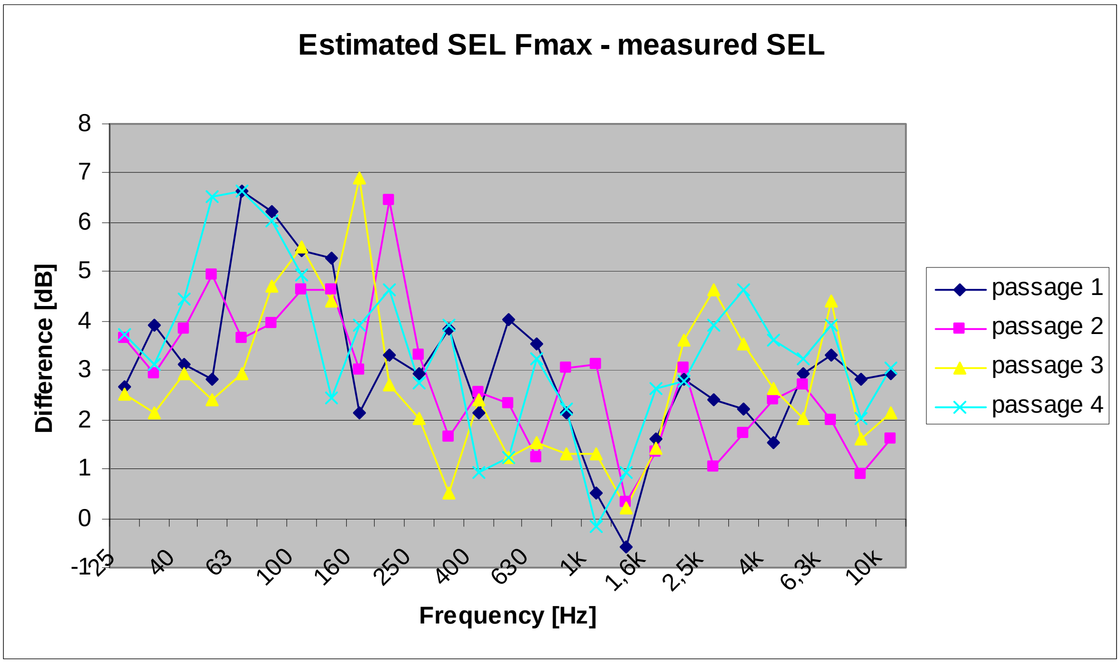


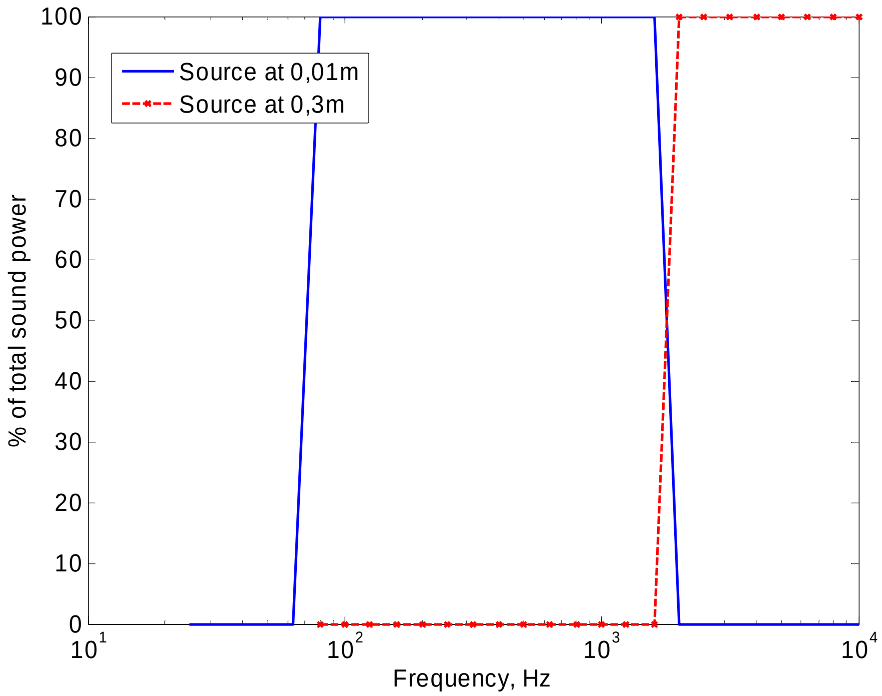
Figure 30 Difference between normalized sound exposure level estimated from the L_{Fmax} and the measured.

A5.2 Calculation of the sound power level

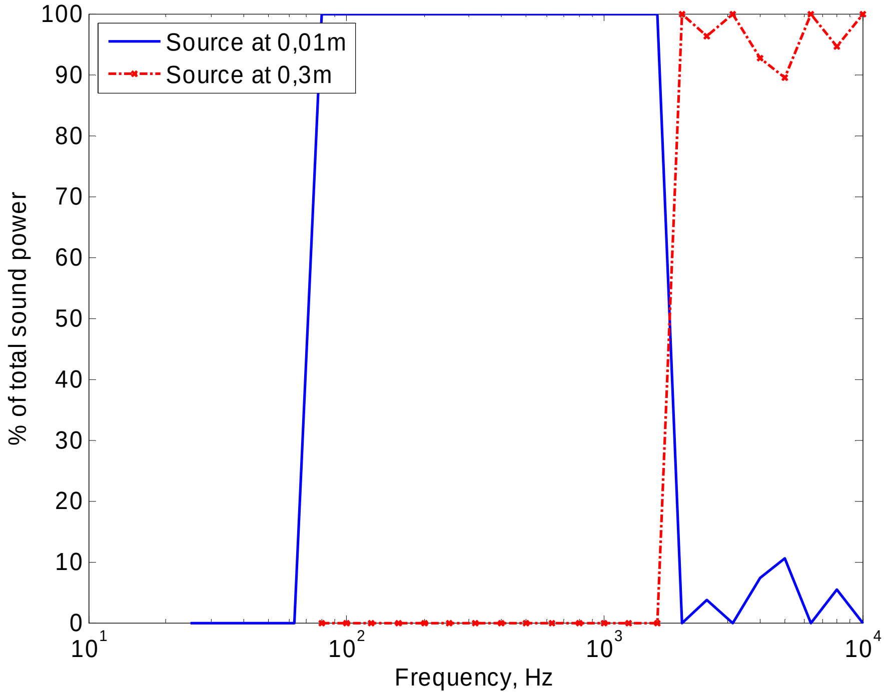
Determining the sound power level of the individual vehicles is done by compensating the measured sound exposure levels at the microphone positions for the excess attenuation from the source to the receiver. When the transfer functions between the source and the microphones are known it is possible to do a backward calculation to obtain the source strength from measured sound pressure levels. However, this requires a source model where the positions of the sources are well defined. In this case the source model describes the vehicles as two point sources for most vehicles but three point sources may be used for heavy trucks with a high exhaust pipe. In this project only two point sources were considered, because of the composition of the traffic at the measurement site. The lowest point source is located at 0.01 m height and the higher one at 0.3 m for light vehicles and at 0.75 m for heavy vehicles. The sound power is distributed between these two sources. A thorough description of the source model can be found in [ii].

Moreover, two types of sound generation are considered in the model; rolling noise and propulsion noise. The rolling noise is mainly generated at the interface between the tyre and the road and the propulsion noise originates mainly from the engine, exhaust pipe and air intake. In the source model we assume that 80% of the sound power of rolling noise is attributed to the lowest source and 20% to the highest. For propulsion noise it is the other way around 20% to the lowest source and 80% to the highest.

Since the transfer functions between the source positions and the microphone positions are known we can calculate the distribution of sound power between the two sources. In the calculation also the speed of the vehicles is taken into account since the measured sound exposure level depends on the measurement time, which in turn depends on the vehicle speed.



100
90
80
70
60
50
40
30
20
10
0
% of total sound power
Source at 0,01m
Source at 0,3m
10^1
10^2
10^3
10^4
Frequency, Hz



100
90
80
70
60
50
40
30
20
10
0
% of total sound power
Source at 0,01m
Source at 0,3m
10^1
10^2
10^3
10^4
Frequency, Hz

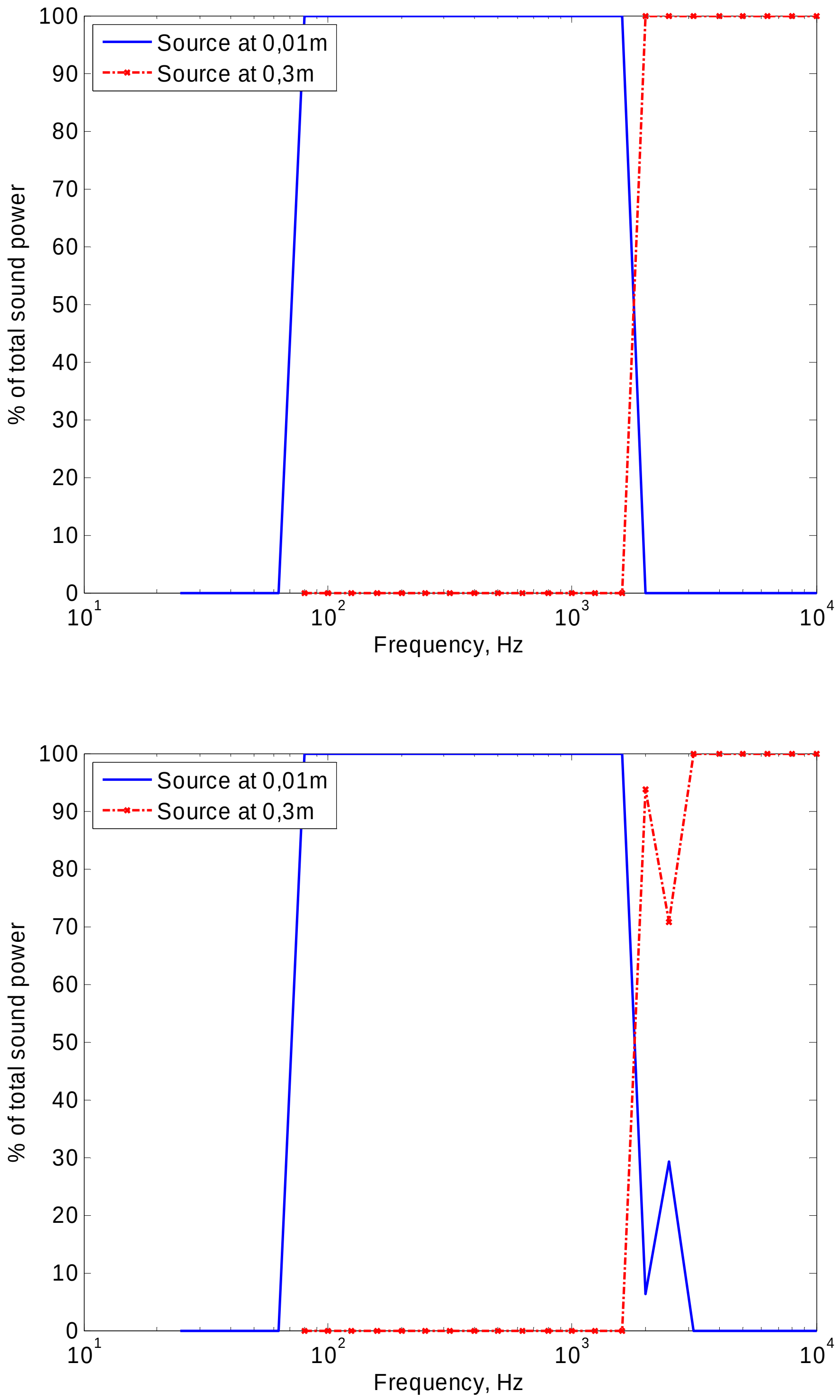


Figure 31 Distribution of sound power between the sources in the source model.

Figure 31 shows the calculated distribution of sound power between the two sources in the source model. At low frequencies, below 80 Hz, the distance between the sources is too low to distinguish the sound power from each of them. The wavelength of the sound waves in air is much larger than the distance between the sources. However, from experience it is clear that the propulsion noise from engine and exhaust system dominates at low frequencies. At medium frequencies it is the lower source at 1 cm height that dominates the sound generation. In this frequency range the tyre/road noise is dominating which explains this. At high frequencies the situation is more complex and in some cases the higher source dominates while in other cases both sources contribute to the total sound power.

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[i] Ulf Sandberg & Jerzy A. Ejsmont, Tyre/road noise reference book, Informex, SE-59040 Kisa, 2002
[ii] Uppskattning av antalet exponerade för vägtrafikbuller överstigande 55 dB(A), Naturvårdsverket, kontrakt nr 215 0009