DELIVERABLE	**4.2.2**[1]	
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ACRONYM	**CITYHUSH**	
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Work Package 4	**Propagation attenuation of road traffic noise**	
4.2	**Air cooled tire hoods for passenger cars – Tire/road noise reduction by active and passive noise attenuation**	
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PU	Public	✓
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restrictec to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for the members of the consortium (including the Commission Services)	

Nature of Deliverable

R	Report	✓
P	Prototype	
D	Demonstrator	
O	Other	

SEVENTH FRAMEWORK PROGRAMME

1 see List of Deliverables, DoW – Annex I to the contract, p.32 (document 233655_CITYHUSH_AnnexI_DoW_2010-01-31_Corrections.pdf - available on the ftp-server)

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0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

WP 4.2.2 aims at evaluating the feasibility of active noise cancellation in combination with tire hoods. Previous studies (WP 4.2.1) have found tire hoods to be an effective method for tire/road noise reduction. In addition to the evaluation of the tire hoods, the introduction of active noise cancellation (ANC) of the tire/road noise on the surroundings of the vehicle is studied in WP 4.2.2 which is the topic of this deliverable.

0.2 DESCRIPTION OF THE WORK PERFORMED SINCE THE BEGINNING OF THE PROJECT

The performed evaluation of tire hoods in combination with active noise control (ANC) was carried out both in laboratory environment and using a CPX-trailer. A modifiable tire hood was developed in the earlier part of the project (WP 4.2.1) in order to perform measurements of different tire hood designs. Results from the tire hood evaluation were used as input in the process of evaluating active noise control (ANC). Early on, the decision to use a commercial ANC system and adapt it to the prerequisites of tire noise application was made.

0.3 FINAL RESULTS

0.3.1 ANC performance testing in laboratory

Performed measurements show approximately 3 dBA average sound level reduction with introduction of ANC technology (with extreme values of -5,7dBA and +0,6 dBA, dependent on measurement position). The performed lab-tests are a simplification of a real life situation (absence of background- and wind induced noise, tire directivity pattern, etc.) but the obtained results are still considered to be quite promising.

0.3.2 ANC performance testing on the CPX-trailer

Initial and simplified field tests were also performed within the project. Evaluation of the tire induced noise level reduction was performed with the CPX- method. The initial field tests show that it´s very difficult to attain high coherence between the reference and error microphone transfer functions, which is necessary for considerable noise reduction with the ANC-method. It´s assumed that the wind-induced noise at the microphones and background noise from other sources is the main reason for low grade of coherence. Initial measurements show very low improvement considering total A-weighted levels (approximately 1 dBA unit at the microphone mounted on the CPX-trailer), though 2-3 dB sound level reduction could be obtained in certain frequency bands at CPX-microphone position with introduction of ANC technology.

0.4 POTENTIAL IMPACT AND USE[2]

Traffic noise reduction has two major benefits. First, citizens experiencing traffic noise as a disturbance and potential health risk can be provided with a much quieter and healthier traffic environment with less residents disturbances.

Secondly, areas, which are not populated due to traffic noise pollution, may be reconsidered as an appropriate area to build residential buildings once traffic noise reduction has been achieved.

Active noise control is already being used for reducing mainly low-end drivetrain noise in certain production car cabins (manufacturers as Honda, Audi and others). However, it is not commercially used for reducing noise to the surroundings outside of the car. Introducing active noise control to the outside surroundings of a car is a new and unproven concept.

Previous investigation (WP 4.2.1) shows that tire hoods have the potential of reducing the tire/road noise in the range of 1 – 5 dBA-units. Superposing the effect of active noise control (ANC) to a car fitted with tire hoods, additional decrease of the tire/road noise could be expected.

0.5 PARTNERS INVOLVED AND THEIR CONTRIBUTION

This deliverable was produced by ACL and has involved:

- Development of a tire hood suitable for the CPX-trailer
- Developing or acquiring an active noise control system
- Performing laboratory and initial field measurements with subsequent evaluation

0.6 CONCLUSIONS

The peformed study shows that it´s very difficult to achive global sound level attenuation for tire/road induced noise with the chosen method and ANC-technology. The initial results performed in the laborathory conditions are though considered to be quite promising (app. 3 dBA noise reduction).

The implementation of active noise control on tire/road noise outside of the car cabin holds many complications, partly because of the theoretical restrictions of an active control system (ANC) and partly, because of practical problems, mainly:

- wind induced noise in microphones
- noise from other vehicles / noise sources
- vibration induced noise in microphones
- robust and weather proof loudspeaker construction needed

The initial problematic regarding the above mentioned issues needs to be solved prior to the implementation on real vehicles.

1 BACKGROUND

1.1 THE CITYHUSH PROJECT

Electric/hybrid vehicles have generally lower driveline noise than combustion engine vehicles; hence, the tire/road noise will be dominating at speeds as low as 20 km/h. This means that if the benefit from the low electric driving noise should be fully utilized, then tire/road noise must also be reduced by 5 -10 dBA units. The need for tire/road noise reduction for electric/hybrid vehicles is a substantial part of the CITYHUSH project.

This project aims at evaluating the feasibility of active noise cancellation technology in combination with tire hoods. Earlier performed CPX measurements (City Hush WP 4.2.1) have showed that a tire hood has the potential of reducing the tire/road noise in the range of 1 – 5 dBA-units (depending on the hood size). This project investigates the possibility of achieving an even greater noise reduction when the tire hood is combined with an ANC-system.

The main focus of this project has been to evaluate the concept and potential of noise reduction by ANC technology in a semi-anechoic lab environment. The concept was also evaluated by simplified field measurements with the single wheel trailer built for CPX (Close proximity) measurements.

2 METHOD

2.1 ANC SYSTEM USED AND BACKGROUND

Active noise cancellation technology (ANC) as a concept is not new. The basic idea of the concept is reduction of unwanted noise by addition of a phase inverted copy of the original noise signal to the sound field. The noise level is reduced according to the superposition principle. ANC technology has been used with successful results primarily for low frequency noise reduction in fan ducts, car- and airplane interiors. For the purposes of this deliverable, a basic tire-hood mockup was built and set up in the lab. The mock-up was equipped with a commercially available, DSP based ANC-system (S-Cube™ Development Kit from Silentium). The ANC-kit contains a controller card with built in speaker and microphone amplifiers, two microphones, one 3" speaker and USB-drivers and PC- software for the ANC-controller.

Figure 2.1
ANC-kit.

2.1.1 Basic principles of the ANC-technology

The building blocks of the ANC-technology chosen for this project are outlined in the schematic presentation of the system if figure below. The used ANC system is of a feed-forward control type, so the unwanted noise signal is picked up before it propagates to the noise-cancelling source (loudspeaker).

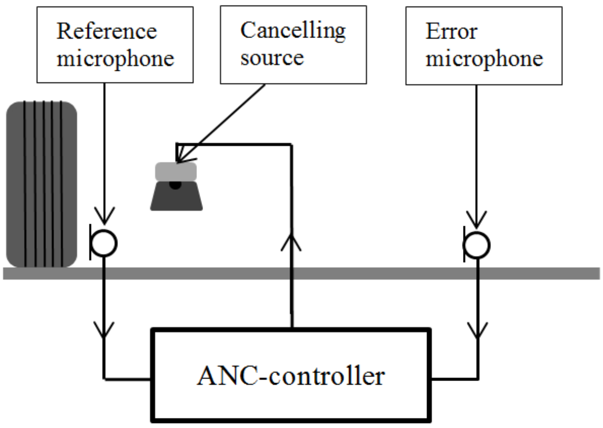

Figure 2.2
Principles of ANC-technology.

The reference microphone is used for feeding the ANC controller with the noise signal from the tire. The phase inverted signal being fed to the cancelling source (speaker) is optimised by an adaptive algorithm that uses the control data from the error microphone. The goal of the adapting algorithm (filtered-X LMS) is to minimise the energy of the total signal (noise source + cancelling source) at the error microphone.

The propagation path between the reference microphone and the error microphone as well as the propagation path between the cancelling source and the error microphone can be described by measured acoustic transfer functions (MTF and STF). The transfer functions can be stored in the ANC-controller and subtracted from the error signal.

The concept with the transfer functions makes it possible to remove the error microphone after the MTF and the STF have been measured and stored inside of the ANC-controller.

The feedback problem between the cancellation source and the reference microphone can be solved in a similar way by measuring the transfer function between the cancelling source and the reference microphone. The measured transfer function is then used for an echo cancellation filter.

Following transfer functions are measured and stored inside of the ANC-controller:

- MTF – Transfer function between the reference microphone and error microphone
- STF – Trasnfer function between the speaker and the error microphone
- EC – (Echo cancelling) Transfer function between the cancelling speaker input and the reference microphone
- PF – prediction filter used to predict future sampling data from the reference microphone (it´s usually much easier to attenuate harmonic signals compared to wide-band random noise)

Coherence

The similarity between the noise source signal collected at the reference microphone and error microphone are essential in order to obtain high noise reduction at the control point. The degree of similarity between the signals can be checked by coherence calculations. The power spectrums of the reference microphone signal and the MTF-filtered control microphone signal are compared in the frequency range of interest and coherence is calculated. High grade of coherence indicates high phase relation and therefore high correlation between the signals. Under perfect circumstances (no background noise, low phase delay) it´s easier to obtain high grade of coherence at lower frequencies (longer periods and therefore lower phase difference between two points separated in time and space).

Some of the man factors that can be a cause of low coherence are summarised below:

- Wind and other kinds of background noise – it´s not possible for the system to separate pressure fluctuations caused by the wind from the source signal, these fluctuations are highly nonlinear between the two measurement points and are impossible to predict
- Near and far fields – sound sources that are not perfect point sources (infinitely small) produce sound fields with different characteristics in close proximity to the source and at some distance from the source. The reference microphone is often positioned in the near field of the source and the error microphone in the far field of the source
- Nonlinear transfer path – physical obstacles in the acoustic path between the reference and error microphones gives rise to acoustic diffraction effects and therefore low coherence
- Nonlinear distortion (valid for STF and EC) – most loudspeakers are nonlinear sound sources, nonlinear distortion usually rises with higher output level
- Reflections (valid for EC) – acoustic reflections between the loudspeaker and the reference microphone add to the measured transfer function

Global sound attenuation

The aim of the ANC in this case is to be able to achieve tire/road-noise reduction not only at one point in space but preferably everywhere outside the car – global sound attenuation. In order to be able to achieve that aim the cancelling source should be able to create a "perfect" phase inverted copy of the original sound source. In that case the acoustic flow from both sources will not be able to produce any acoustic pressure – which means no energy flow to the acoustic environment.

The limit of the amount of sound attenuation is governed by several factors. The main ones are summarised below:

- Distance and arrangement between the noise source and cancelling source – sets an upper limit for how much global attenuation can be achieved. The cancelling source should be acoustically near to the noise source, preferably 1/10 (36° phase miss match) of the wavelength of interest or closer. The cancelling source should have similar directivity pattern in the frequency region of interest
- Control/Error microphone placement - controls how much attenuation can be achieved compared to the upper limit set by the cancelling source arrangement
- Coherence – limits the electronic/controller part of the system; high coherence between the reference signal and error signal is essential for high attenuation
- Hardware and software ANC controller performance – governs how much cancellation can be achieved at the error microphone position within the constraints set by the coherence

2.2 ANC TESTING – LABORATORY MEASUREMENTS

2.2.1 Laboratory setup

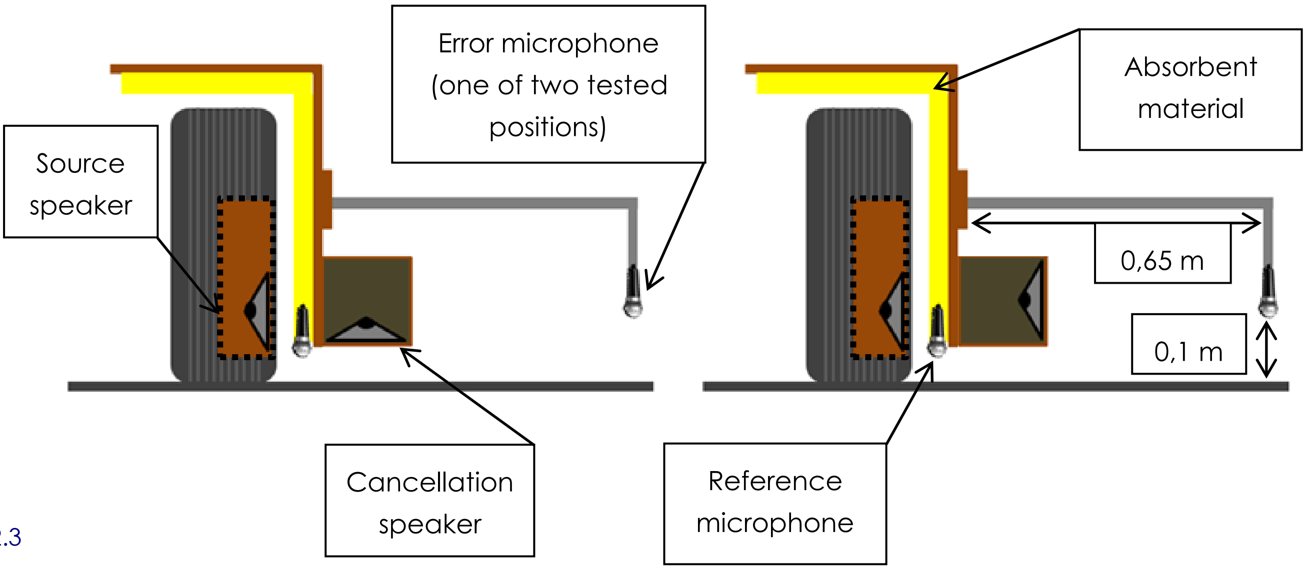

Figure 2.3

ANC testing setup in semi-anechoic chamber. Both tested orientation positions of the cancelling speaker.

In order to evaluate the prospect of noise reduction of tire noise by implementing an ANC-system, initial testing was performed in ACLs semi-anechoic chamber. A mock-up model of a tire hood, made of 16 mm MDF board was built and fitted with a noise cancelling sound-source (see figure 2.3 and 2.4). A loudspeaker emitting near-field pre-recorded tire road noise signal was fitted inside the tire hood and used for simulation of road/tire noise. The hood was fitted with sound absorbent material (40 mm glass wool) on the inside.

The distance between the bottom edge of the tire hood and the floor was fixed at 5 cm, which is consistent with the lowest setting used for the tire hood measurement setup used in WP 4.2.1. Two different positions were tried for the error microphone.

The loudspeaker used as a cancelling source was a 6,5" high quality speaker (PX17-LTS) fitted in a sealed box. The cancelling loud-speaker was placed as close to the tire/road surface contact point as possible (within practical limitations) approx. 0,2 meters to the speaker centrum from the tire edge.

The ANC-system was tuned in accordance with the specifications of the manufacturer. Two different orientation positions of the cancelling noise speaker, were tried. See figure 2.3. The resulting noise level difference was measured in 20 (10 positions at 1 m above the floor level and 10 positions at 2 m above the floor level) positions in a 90° radius, figure 2.6.

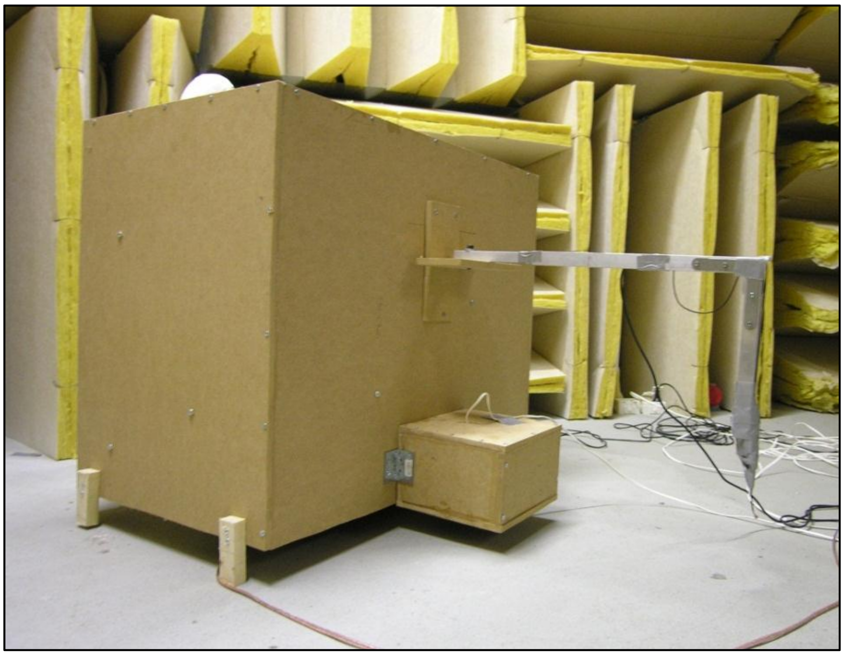

Figure 2.4

Mock-up model of tire hood for testing in semi-anechoic chamber.

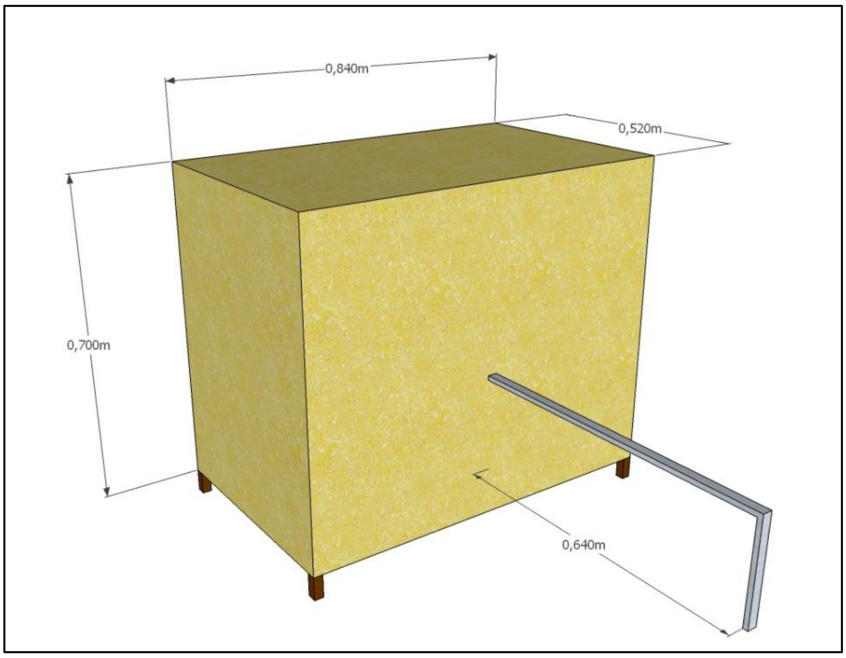

Figure 2.5

Mock-up model of tire hood, dimensions.

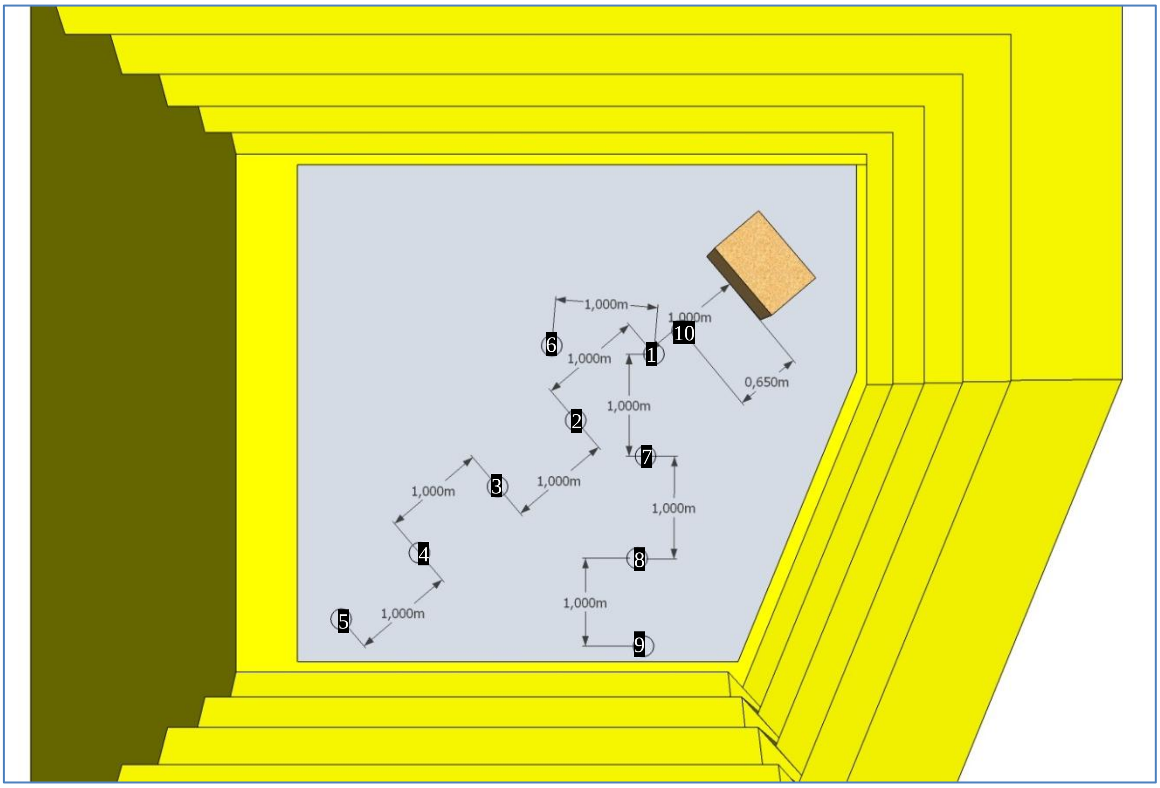

Figure 2.6

Measurement positions in laboratory. Positions 11-20 have same planar coordinates as positions 1-10 but with vertical placement of 2 m above the floor level

2.3 ANC TESTING – FIELD MEASUREMENTS

2.3.1 CPX setup

Initial and simplified field tests were performed within the scope of the project. Evaluation of the tire induced noise level reduction was performed with the CPX-method. The tire-hood and the ANC equipment were mounted on a CPX-trailer. All tests were performed at a speed of 50 km/h on a straight road segment with the same type of the road surface, (ABS11). The surface was slightly humid during the test. The speed chosen was due to overcoming background noise levels. The distance between the lower hood edge and the road surface was set to 5 cm which is consistent with the lowest tire hood setting used in WP 4.2.1. Following results from laboratory testing, the orientation of the cancelling loudspeaker was chosen to be pointing downwards.

2.3.2 CPX measurement

2.3.3 Microphone positioning

The microphone positions stated in the provisional standard CPX-method (*ISO CD 11819-2*) had to be rearranged in order to evaluate the effect of the tire hood and ANC, see Figure 2.3, since the mandatory microphone positions are located too close to the tire. Only one microphone position was used. The microphone position was selected with respect to the fixed pass by microphone position according to ISO 362-1:2007. The position of the microphone is 0.8 m from the tire edge, which was as far as possible due to traffic safety regulations since measurements were carried out on a public street. The height of the error microphone above ground was 10 cm. Hence, the placement of the error microphone during field measurements was consistent with the laboratory measurements. The source microphone and the error microphones were equipped with 9,5 cm wind shields during all the field-tests.

Initial testing was performed with the error microphone fitted on an extension arm in the same way as measurements were performed in WP 4.2.1. Since unsatisfactory coherence between the reference and error microphone transfer functions was measured during the initial testing, the test rig was fitted with additional wind shield as seen in figure 2.7. The coherence increased slightly when using added wind protection. The Sound Pressure Level (SPL) with and without ANC was measured at the error microphone position.

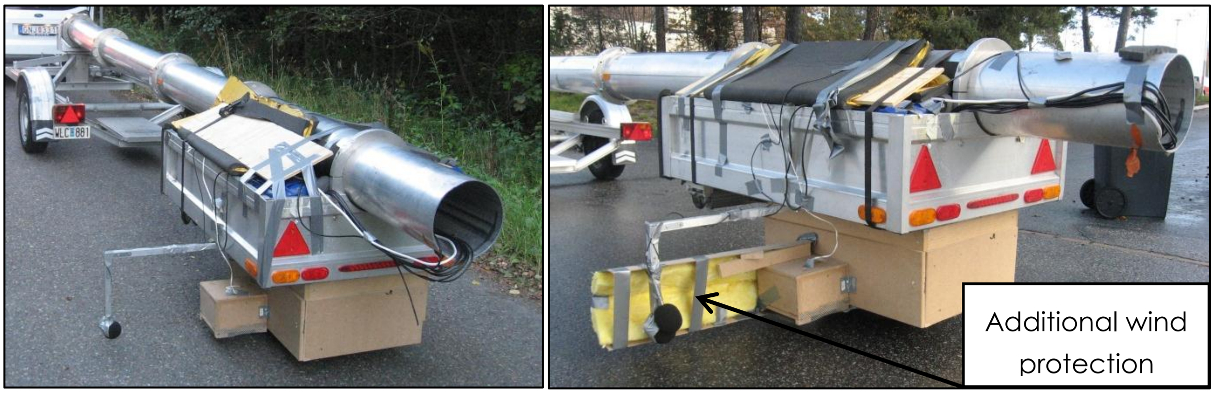

Figure 2.7

CPX-trailer with error microphone arm. Left picture shows the error microphone fitted with only a standard windshield while on the right picture, additional wind protection has been added.

2.3.4 Driving conditions and measurement location

The measurements were carried out in the countryside north of Stockholm in October of 2012. The test segment was straight and no large sound reflecting objects where located near the road. The road surface contained a rough texture with a maximum stone size of 11 mm. The measurement equipage is seen in Figure 2.8.

Sound pressure levels were measured six times with ANC activated and six times without ANC for the same road segment. The vehicle speed and external noise interferences were monitored making it possible to exclude eventual disturbances.

Figure 2.8

The CPX-trailer with mounted tire hood, ANC-system and additional wind protection.

3 RESULTS

3.1 ANC TESTING – LABORATORY MEASUREMENTS

The performance of the ANC system was tested in a semi-anechoic chamber. Two different orientation positions for the cancelling source were evaluated. See figure 2.1. The resulting noise level difference was measured in 20 positions in a 90° radius centred on the tire.

Table 3.1 shows the room-averaged single value results of the different measurement setups. Figures 3.1 through 3.4 show the spectral characteristics of each of the measured setups (at the Error microphone position). Sound level difference (with and without ANC) is presented for each measurement position in tables 3.2-3.4.

Table 3.1 Tire hood modification scheme.

Test scenario	Cancelling speaker	Error microphone position	Arithmetic average sound pressure level reduction [dBA]
1	Pointing downwards	Approx. 3 m from the tire hood, at normal ear level (1,7 m above floor)	1,1
2	Pointing downwards	0,65 m perpendicular to tire hood	2,7
3	Pointing out from the tire hood	0,65 m perpendicular to tire hood	-0,5 (amplification)

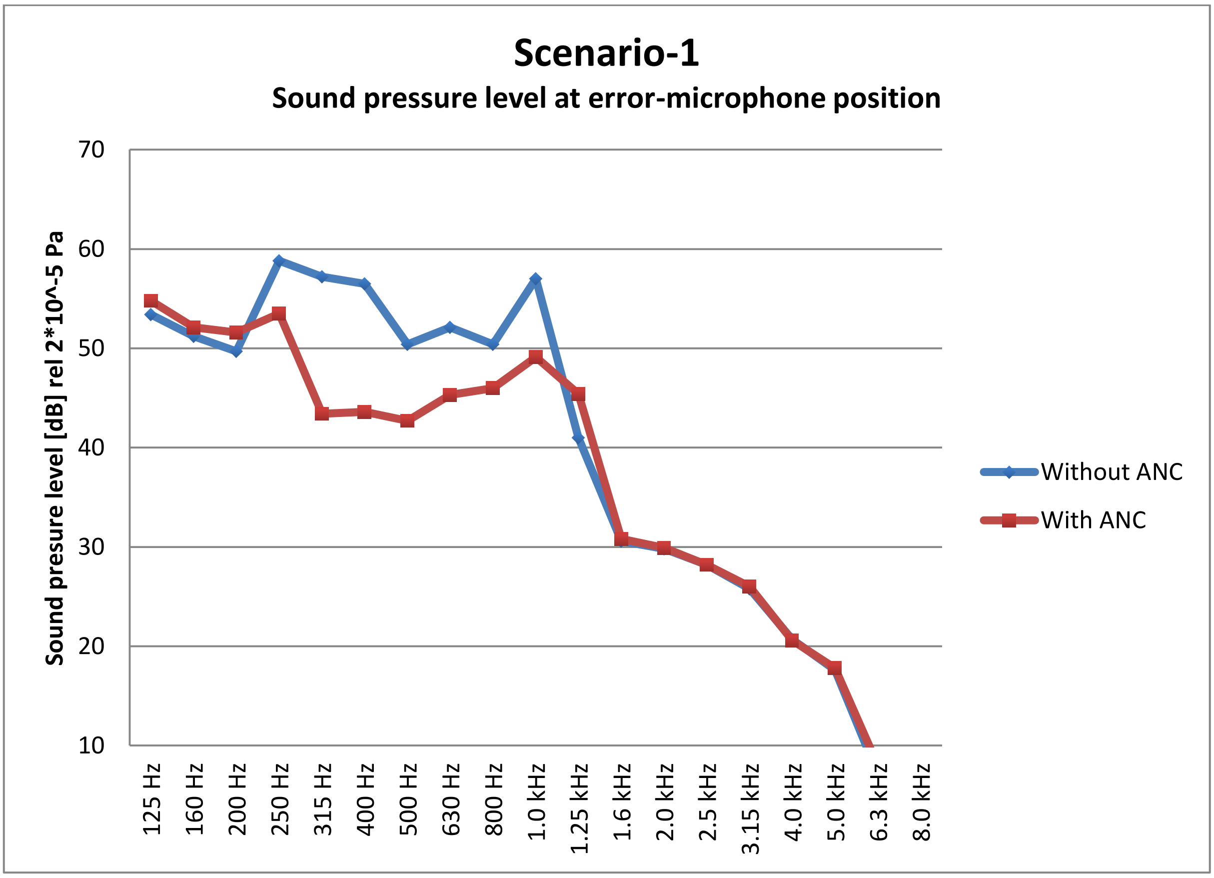

Figure 3.1 Laboratory test, sound pressure level measured at error-microphone position with and without ANC

Table 3.2 Laboratory test, sound pressure level, dBA measured at error-microphone position with and without ANC.

Position	Height above floor level [m]	Sound level difference [dBA]
1	1	-5,2
2	1	-6,8
3	1	-6,4
4	1	-6
5	1	-4,8
6	1	0,7
7	1	-0,2
8	1	2
9	1	1,6
10	1	-0,7
11	2	-4
12	2	-5,4
13	2	-5,3
14	2	-5,6
15	2	1,8
16	2	1
17	2	1
18	2	2,4

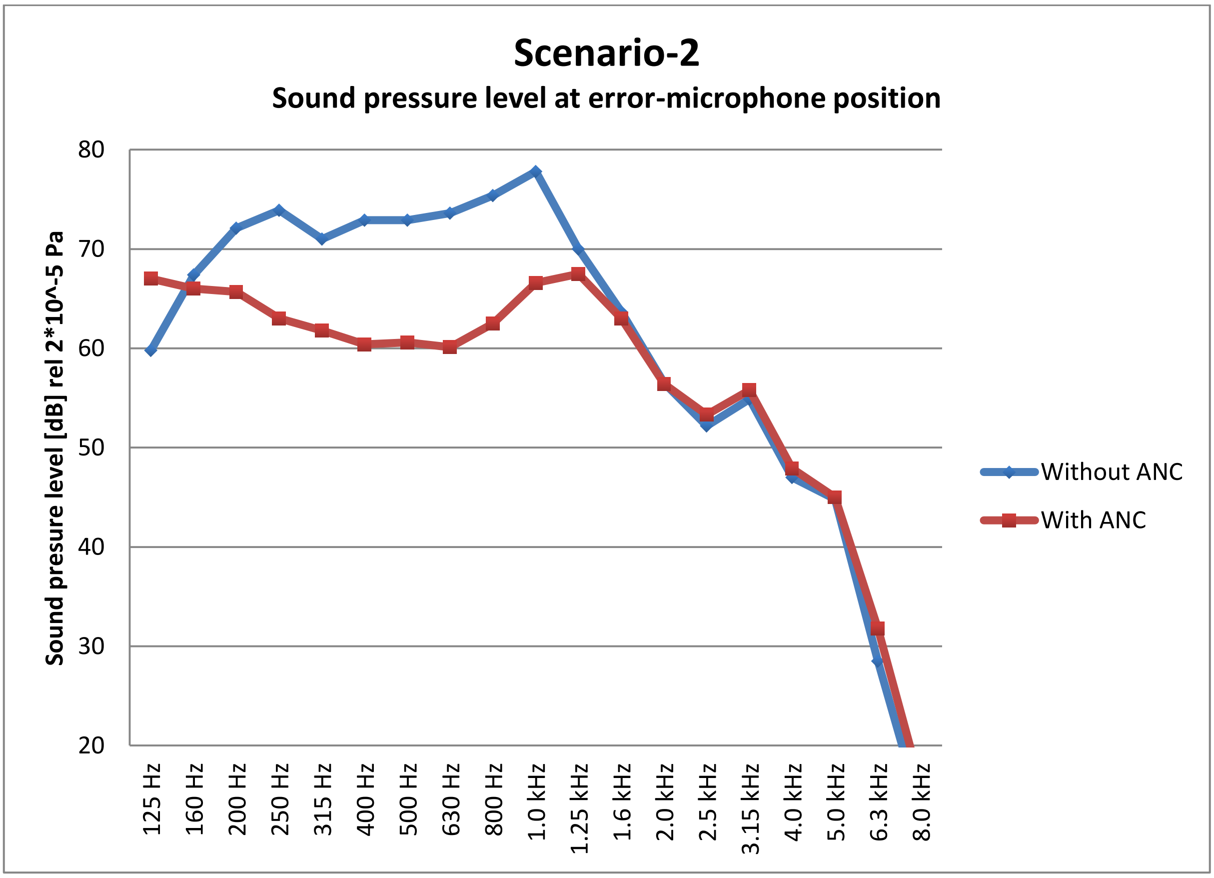

Figure 3.2 Laboratory test, sound pressure level measured at error-microphone position with and without ANC

Table 3.3 Laboratory test, sound pressure level, dBA measured at error-microphone position with and without ANC.

Position	Height above floor level [m]	Sound level difference [dBA]
1	1	-5,1
2	1	-5,5
3	1	-5,7
4	1	-5,4
5	1	-5
6	1	-3,4
7	1	-4
8	1	-3,1
9	1	-2,8
10	1	-2,4
11	2	-3,8
12	2	-4,8
13	2	-4,8
14	2	-5,2
15	2	-2,1
16	2	-2,1
17	2	-2,7
18	2	-2,4
19	2	0,6
20	2	-1,9

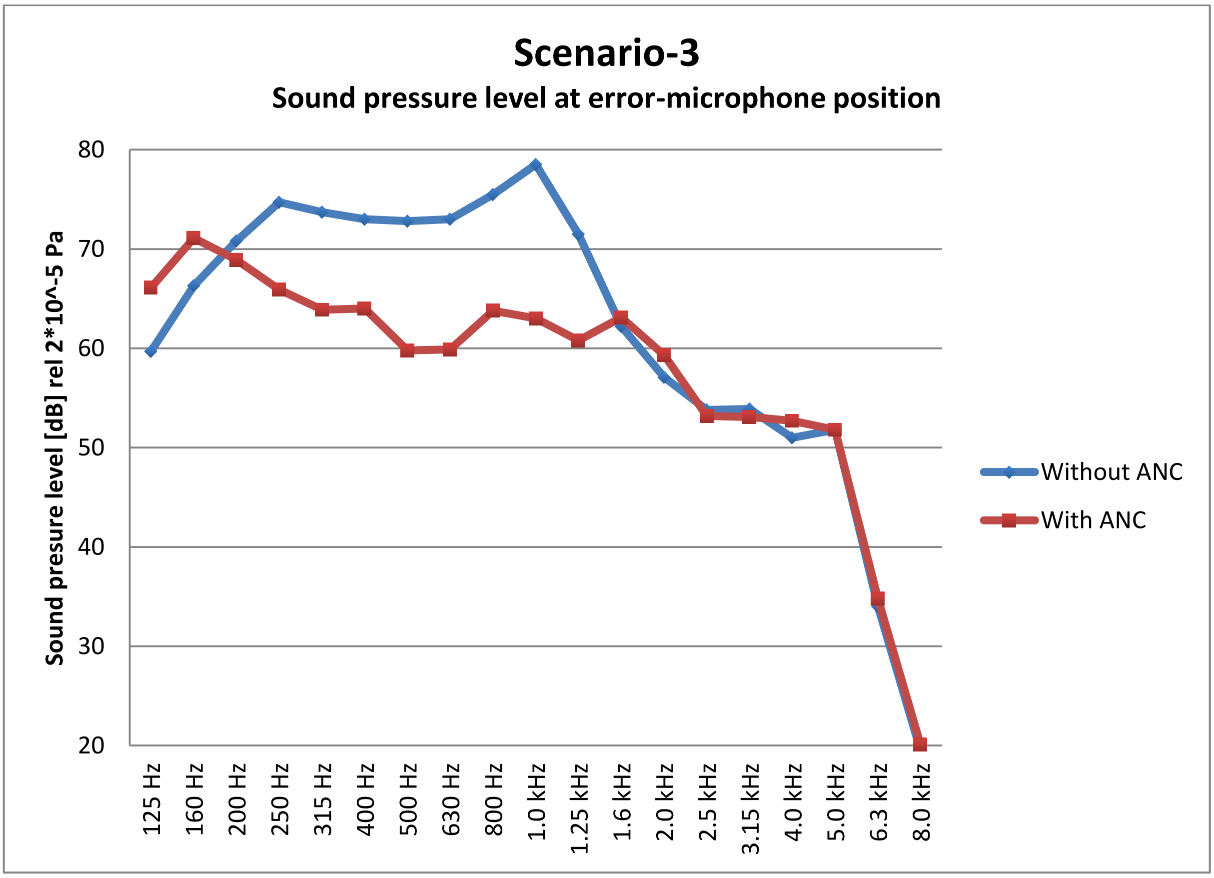

Figure 3.3 Laboratory test, sound pressure level measured at error-microphone position with and without ANC

Table 3.4 Laboratory test, sound pressure level, dBA measured at error-microphone position with and without ANC.

Position	Height above floor level [m]	Sound level difference [dBA]
1	1	-0,6
2	1	-4,5
3	1	-5,1
4	1	-5,6
5	1	-5,1
6	1	0
7	1	0
8	1	-3,4
9	1	-4,5
10	1	2,3
11	2	1
12	2	-1,7
13	2	-3,8
14	2	-4,5
15	2	1,6
16	2	1
17	2	0,8
18	2	-1,4
19	2	1,5
20	2	2,7

3.1.1 Comments on laboratory measurements

The combined sound field from the noise- and cancelling sources has angle dependent sound energy distribution and distance dependent directivity; obtained sound level reduction/increase is therefore angle- and distance dependent, which is reflected by obtained measurement results, table 3.2-3.4.

The largest attenuation effects are noted in the 200 Hz -1000 Hz region, which is also a frequency region with degree of high coherence (ca. 98%). Attenuation at higher frequencies is limited by the distance between the noise source and the cancelling source (several wavelengths) as well as transfer function estimation algorithms for the noise signal (low coherence). The limited attenuation at lower it frequencies is assumed to depend on near field characteristics of the noise source. It is also noted that the thread pattern generated noise is high in the frequency range of 200Hz -1000Hz. Thread pattern generated noise is coherent for a spinning tyre while the road road texture excited noise is less coherent due to the random distribution of the stones. Due to this, there is a bigger chance to be successful with the ANC in this frequency range and on smooth road surfaces.

The performed tests show that it is difficult to obtain substantial global sound level attenuation even in controlled laboratory conditions. The best results were obtained with the error microphone at CPX-position and with the cancelling loudspeaker oriented towards the floor surface. The sound level difference was measured in a limited number of points, mostly in the frontal direction from the tire hood (because of the size limitations of the lab), the degree of sound level attenuation in all directions from the sound source is there for not known. The possibility of higher sound levels (amplification) behind the tyre hood can therefore not be ruled out.

It should also be noted that, for the laboratory tests, the sound directivity of the noise source (tire/road) were approximated by a loudspeaker and not modelled correctly. This approximation is believed to be valid since the sound source is “screened” by the tyre hood. The visible sound source from the outside have properties similar to a line source in the gap between the road surface and the tyre hood.

3.2 ANC TESTING – FIELD MEASUREMENTS

The performance of the ANC-system was tested in field conditions with the CPX-method, the results of the measurements are presented in Figure 3.4. The presented results are mean values of six different measurements for each measurement condition (w. and w.o. ANC)

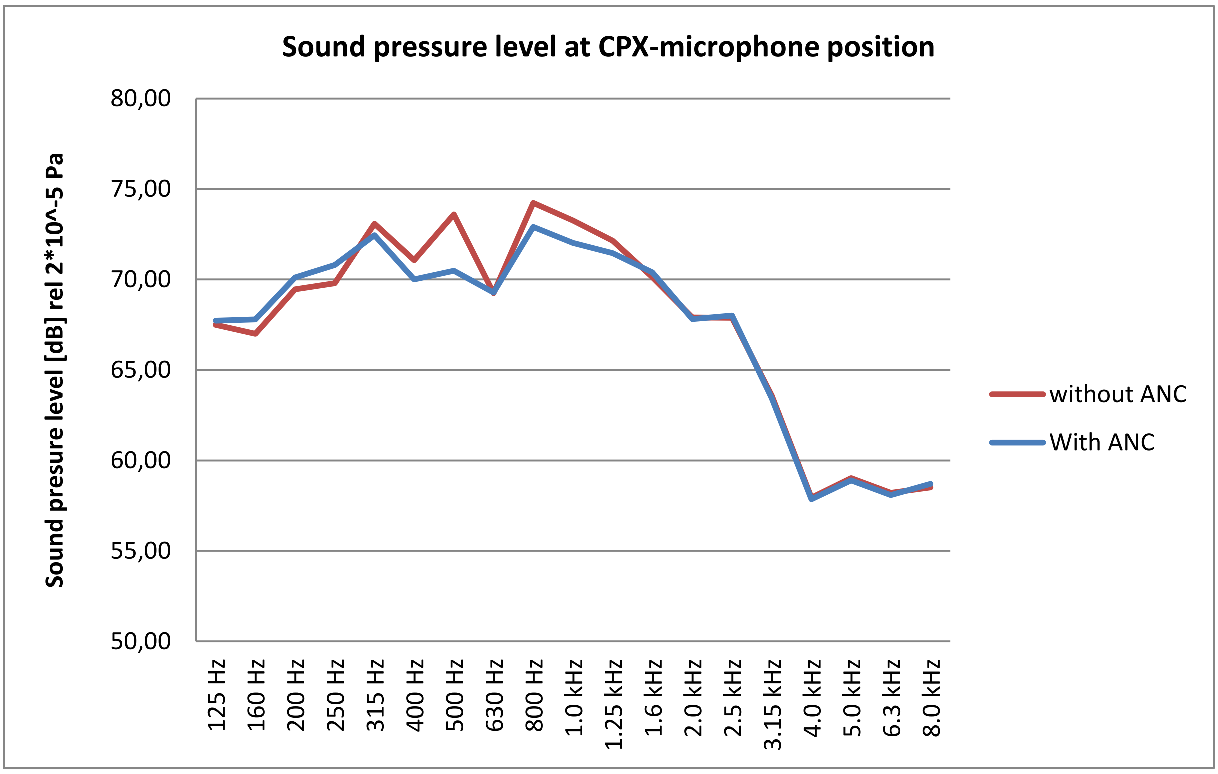

Figure 3.4 Results from initial field measurements of ANC of tire/road noise from CPX trailer.

3.2.1 Comments on field measurements

The Initial measurements show very low improvement considering total A-weighted levels (approximately 1 dBA unit), though 2-3 dB sound level reduction could be obtained in certain frequency bands at CPX-microphone position with introduction of ANC technology.

The main reason for the low attenuation at the CPX-position is assumed to be low coherence grade between the reference- and error microphone positions. The coherence was calculated to approx. 30 % without additional wind protection and approx. 45 % with additional wind protection, (See figure 2.5) which is considered as low. It´s assumed that the wind-induced noise at the microphones is the main reason for low grade of coherence. Literature[2] points out noise levels in the range of 60 to 70 dB at 1000 Hz due to the resulting wind velocities corresponding to 50 km/h.

[2] Frede Skröde, Windscreening of Outdoor Microphones,

4 GENERAL DISCUSSION

The peformed measurements show that it´s achivieng global sound level attenuation for tire/road induced noise with the chosen method and ANC-technology is not straight-forward. The initial results performed in the laborathory conditions are though considered to be quite promising (app. 3 dBA noise reduction).

Several obstacles need to be overcome before field use of an ANC system for tire/road noise for the surrounding environment can be practically feasible. Higher correlation of the transfer function between the error and reference microphones is an important issue to be examined in further studies. If the correlation can be raised closer to the level corresponding with the laboratory measurement increased noise reduction levels can be expected. The main focus should be put on reduction of wind induced noise, and other background noise sources.

Other speaker- and error microphone configurations can result in better sound level attenuation over a wider frequency range.

The performed tests were somewhat limited by the control software that came with the chosen commercial ANC-kit, more functional signal analysis tools, filtering capabilities and few other tuning options could result in somewhat better sound level attenuation.

A factor worth considering is that an ANC system may potentially increase noise levels in the interior of the car vehicle. This could however be solved through for example, the use of an ANC-system inside the car cabin.

5 REFERENCES

1 – Skröde, F. (1986), Windscreening of Outdoor Microphones - Technical Review, Brüel & Kjær

2 – Silentium S-cube™ Development kit users manual.

3 – Snyder, S.D., (2000), Active Noise Control Primer.