

CRANFIELD UNIVERSITY

I ZISSIMOS

DESIGN AND CONSTRUCTION  
OF AN ACOUSTIC MEASURING DEVICE  
TO INVESTIGATE AUTOMOTIVE TYRE NOISE

SCHOOL OF ENGINEERING  
DEPARTMENT OF AEROSPACE SCIENCE

PhD - PART TIME

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of an acoustic measuring device  
to investigate automotive tyre noise

Supervisor: Professor D. Drikakis

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for the degree of Doctor of Philosophy

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## **ABSTRACT**

Tyre noise measuring procedures are used worldwide and covered by appropriate International Standards, but from the literature search and the author's 30 years' expertise in acoustics, it became clear that there are still problems to overcome.

The objective of this project is to design and construct a prototype stationary acoustic device that can produce and measure the noise emitted by the grooves and treads of automotive tyres and develop a new acoustic tyre measuring procedure.

Through this new procedure, the noise measurement can be performed in a controlled laboratory environment, no expensive measuring platforms are needed, the cost of the tyre developers will be kept to a minimum, different models or a portion of the tyres can be used (even before tyre production starts), the tyres can be "noise classified" by public authorities, and the procedure will be isolated from the varying surfaces, e.g. roughness and porosity of the road pavement.

The constructed apparatus / device is an open platform, and by using this procedure and methodology, research and many investigations can be performed in the future, to suit each investigator's objectives, both in tyre design and in pavement design.

In the second stage of the thesis, it was necessary to compare the measured noise from the developed device with an actual rolling tyre, measured according to standard procedures. So a towed one wheel trailer, installed with microphones, has been constructed and tested. Validation of the trailer's noise data has been established conducting a further literature search and has proven satisfactory.

In the third stage of the thesis, the main platform of the device was used to investigate further, more tyre related acoustic phenomena.

Keywords:

Tyre, road, acoustics, noise, measurement, spectral analysis, sound level meter, CPX trailer, pass-by, pavement interaction, porosity, texture, roughness, horn effect, noise regeneration.

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# **1 RESEARCH OBJECTIVES**

## **1.1 Motivation**

The author is a Mechanical Engineer and consultant in industrial Acoustics with over 30 years' experience and it was concluded (from his previous relevant projects) that the noise from a pass-by car at velocities over 60-70km/h is predominant in the mid-high frequency range, with level and spectrum depending strongly on the road surface texture.

Later on, and by investigating the relevant literature, it was clear that most papers conclude that a major contributing factor is the aerodynamic noise, produced by the revolving tyre, forcing air either through the pores of the pavement or squeezed out through the grooves and treads of the tyre.

In the author's country (Hellas), the aggregates used for asphalt road pavements are "soft" (mostly limestone) since they are from local quarries in contrast with northern Europe where "hard" aggregates are used (granite or similar).

In Hellas, it is common that a lot of newly paved roads become quickly smoothed and glazed by the tyre's abrasion.

So the author was subconsciously familiar with the excessive "hissing" noise produced on such smooth road surfaces, but he always had a question in his mind, "why are newly paved asphalt roads quieter?".

Considering that all tyres, regardless of manufacturer, are not very different in material hardness (for tyres with the same velocity and load classification) and are not very different in diameter or width (for typical automotive tyres), the noise from different tyres (even from the same manufacturer) on the same roads, may differ significantly.

So besides the pavement texture, it was obvious that the shape and design of the grooves and treads of the tyre may also be responsible for the excess noise.

All the above was the author's motivation for this project, and the factors were examined thoroughly to understand the problem in the best possible way in order to design and construct a prototype noise measuring device, hoping to help tyre designers to improve their design, pavers to improve the pavement mix, and to investigate a portion of a complex noise generating problem.

## 1.2 The “Why not?” Question

A question that may arise from an opposing point of view is that noise is produced by the “tyre/pavement interaction” under static and dynamic conditions as well, so investigating only the noise produced under static conditions as a small part of a complex noise problem may be utopian since it cannot be found in real life situations.

This is true but is also the basis for further research and further development.



**Fig. 1-1.** Example of anechoic chamber



With exactly the same question in mind, all machinery manufacturers should not measure the noise from their equipment in “anechoic conditions”, in expensive anechoic chambers (closed high volume insulated rooms, with all six surfaces treated with lining of considerable thickness that absorb the sound reflections), since anechoic conditions do not exist in real life or in a typical urban environment.

But all these anechoic measurements are proven to be the basis and are very useful for further estimations, modelizations, simulations, calculations, validations, etc, because they provide a commonly approved measuring method, not influenced by other factors, such as the acoustic reflections of surrounding structures or walls.

So the seemingly unorthodox anechoic chambers are very useful and are used widely worldwide.

So “Why not?” design and construct a device or apparatus that could produce and measure a portion of the tyre’s noise, not taking into account the dynamic interaction of the system, and to be used for further tyre noise development and even for classification purposes, as a new tyre /pavement measuring procedure.

### **1.3 Aim and objectives**

The aim of this Phd Thesis is to investigate the noise produced by the groove and tread pattern of typical automotive tyres from a new approach.

The objective is, by investigating the existing measuring procedures and their dependency on pavement textures, to propose an enhanced method to obtain better comparable results, regardless of the measuring institute or the different testing tracks.

The author believes that tyres can be ranked relatively for road noise, by measuring the aerodynamic noise, generated by air flow, through the grooves and tread at the pavement contact patch, for a non rotating tyre.

A second, but main, objective is to design and construct a small, inexpensive, stationary device, capable of producing tyre noise and then

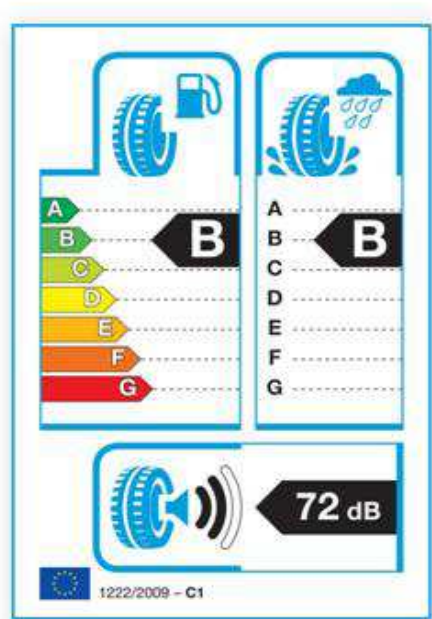
measure it under stationary conditions, using a real tyre, only a portion of the tyre, or even a small physical model of a tyre.

- The noise producing mechanism of the device should be capable to be regulated and adjusted by the user, easily.
- The noise data collection should be as easy as possible.
- The measuring procedure should be as fast as possible.
- The noise measurements should be able to be repeated as many times as required, and the same noise results should be obtained.
- The device should be inexpensive both as a construction and as measuring procedure, in order to be used as an acoustic research platform.
- The device should be able to perform noise measurements not only using an existing tyre, but also tyre models, or parts of tyres.
- The device should be able to alter its contact surface in order to study acoustically different surface/pavement textures and porosities.
- It should be able to be used under dry or wet pavement conditions.
- It should be able to alter, with minimum effort, the tyre/pavement contact load.
- It should be used inside a protected environment in order to make measurements regardless of environmental conditions.
- In order to obtain reliable noise data, the measuring instrumentation should be of reference “type I” SPL & FFT meters.
- The obtained spectral noise data should be able to be adjusted from 1/1 octave to any desired octave band, in order to help engineers design low noise tyres or low noise pavements.
- In order to conduct any further experimentation, it should be allowed to use part of the device or it should allow for easy structural alterations.

As can be seen in the Conclusion chapter, all the above objectives have been fulfilled with success.

## 1.4 Research overview

The European Union has issued a new legislation stating that noise classification is mandatory to be stated on all new automotive tyres on a reference label [132].



**Fig. 1-2.** EU tyre labelling

On this label information data for fuel consumption, wet grip and noise are mentioned, that are supposed to help the consumer to select the best tyre for him.

As seen from the literature search, a major problem with the noise classifications that are performed today is that they depend on pavement texture, even if the pavement is considered to be a “reference” pavement, since all pavements age depending on their use and environmental conditions.

So it is the author’s believe that a difference of 1 or 2 dB per tyre, written on the above label may be in the region of a statistical deviation error, depending on the testing track and even worst a 1 or 2 dB difference is very difficult to be detected by a person.

It has to be mentioned that in all acoustic books, worldwide, it is stated that a person can safely detect level differences more or equal than 3dB.

Therefore a tyre with a label of 71dBA may not be perceived as louder than a tyre with a 70dBA rating, so this kind of labelling is believed to be more ‘market” oriented than absolute and the author’s view on this, is explained in later chapters.

### **1.4.1 First research stage**

The idea to construct a small stationary measuring device is the main objective, but in order to obtain real and accurate noise data, all other existing noise measuring methods are evaluated through a comprehensive literature search.

The author, with his own funds, started to design and construct a prototype device in order to produce noise from the squeezing of air at the leading edge of the tyre, passing it through the grooves and treads, and then perform acoustic measurements at the trailing edge of the tyre.

The device will be stationary with no revolving parts, relatively small in dimensions and will be capable of accepting any kind of automotive tyre, by changing “air flow adaptors” according to the width of each examined tyre.

One of the advantages of the device will be that the tyre to be used could not be a pre-existing tyre, but only a portion of a tyre, a hand grooved semi-tyre, a plaster model, or a tyre under development.

The noise measurements will be performed using reference and calibrated digital “type I” Sound Level Meters from the author’s own acoustical laboratory and, for even better results, a spectral analysis FFT meter is used, with adjustable spectral width, from 1/1 or 1/3 or even near band spectral data and stored on a hard disk.

Through this procedure, the noise measurement per tyre can be performed in a controlled laboratory environment, no car “pass-by” or expensive measuring platforms are needed, the cost of the tyre developers will be kept to a minimum, different models or portion of the tyres can be used (even before tyre production starts), the tyres can be “noise classified” by public authorities, and the procedure is isolated from the uncontrolled or varying surfaces, roughness or porosity, of the road pavement.

The different pavement surfaces for tyre testing used up to today are a significant factor to obtain good, medium or bad noise results per tyre, and a “reference” test surface is standardized worldwide.

But as it is obvious, no surface is exactly the same as another one. They are “aging” [66] depending on use, and repetitive measurements and statistical results are needed with today’s conventional methods in order to have an acceptable result.

The apparatus under development is an open research platform and by using this procedure and testing methodology, many future investigations can be performed with minimum costs, on a reference non-aging surface.

#### **1.4.2 Second research stage**

The second research stage was to design and construct a comparison or safety device for validating the acoustic data of the main measuring device, and Reverse Engineering was considered [75].

The Reverse Engineering methodology is widely used when the result or the end object is known but the construction methodology or data under investigation is either fuzzy, or cannot be comprehended, or understood at the early stages of the project, so the research methodology is reversed, starting from the end.

For the above reason, a towed trailer has been constructed and actual tyre/pavement noise data is collected via a SPL (Sound Pressure Level) meter and analyzed with real time spectral analysis software that was installed in a laptop.

For safety reasons, the trailer had to be transported with a crane truck in a closed-to-traffic area and the old Athens Airport was selected. The “taxi” runway, and not the main landing runway, was used, since its structure and roughness are similar to a typical road surface [41, 50].

The reason that the trailer was constructed in order to obtain noise data, and not just a search of the literature for similar data (since a lot of trailers have been tested by official road authorities), is that by searching it became clear that:

- a) There is a distinct spectral signature depending on tyre type.
- b) There is a considerable spectral shift depending on road surface.
- c) Aggregates used for road construction in northern European countries, are mostly from granite, basalt and other hard aggregates, in the USA there are a lot of concrete roads [19, 57], and in Greece a softer kind of aggregate is used (asbestolithic).
- d) The author decided that it would be best to compare the exact same tyres rather than “similar” ones and undertook this construction time and cost as well.

For the above reasons, an extensive measuring set was performed both with the trailer and with the device under development, using the exact same tyres so the measured noise data cannot be questioned and be valid.

### **1.4.3 Third research stage**

The third research stage is to use the device and conduct further acoustic investigations, regarding

- a) the coincidence peak at around 1000Hz that is common in all tyre/pavement published data, by different authors and projects and not explained to the best satisfaction of the author and
- b) The so called by others “horn effect” and its contribution to the emitted acoustic energy, since the author believes that during the effort to explain a difficult to explain phenomenon some points are either miss explained or misunderstood and the author would like to offer his optical view to the future researcher.

## **2 INTRODUCTION – EXISTING WORK**

Noise pollution is a growing problem worldwide and a major noise source is traffic noise [32, 33, 28, 51, 96] Traffic noise can be separated into two major categories: traffic noise in an urban environment, produced mostly by slow moving or idling car engines, and traffic noise produced by fast moving cars on highways or open urban roads [13].

The noise produced by fast moving cars is investigated in this thesis, and since the major contributing factor is the noise produced from the tyre / pavement interaction, a literature search was performed to investigate the existing noise measuring procedures.

It was found that all had some inherent problems either concerning the cost involved per measurement, or the obtained results are influenced by other factors, or influenced by environmental conditions, and this produced a need to investigate the problem further.

As explained in later chapters, the two major methodologies used by the industry and the research today are the CPX method (Close ProXimity) [152] and the Pass-By method [151].

The first measures the noise produced by the tyre/pavement interaction at a very close distance from the rolling tyre, using a specially constructed trailer with microphones, towed by a car [55, 18], and the second measures noise at a greater distance using a test field of significant dimensions where a car is travelling at a predetermined speed [27].

It is understood that a noise producing mechanism is never simple and never dependent on a single factor. Usually a combination of factors

produces several distinct sounds of a different spectrum, amplitude, phase, directivity, etc., and all of them combined are perceived as “noise” or noise source [1, 7, 9, 15, 49].

The same applies in this case and noise from a tyre depends on several factors, such as air pressure distribution around a travelling tyre [2], air turbulence around and across the tyre [8], noise resonance inside a tyre [53], roughness [58], softness [17], temperature [20], porosity [60] and aging [45], of the pavement, tread [12], groove [68], sipe design [135], contact pressure [52] of a tyre, travelling speed [23] and other more distinct factors such as Helmholtz resonance [30], horn effect [31], dynamic factors [39], air pumping [61], belt resonances [105] etc.

This thesis investigates only the factor, “noise produced by the tread, groove and sipe design”, and in so doing, the other factors are isolated and not measured.

In order to isolate the other dynamic factors and be able to measure only the groove, tread and sipe noise, the author designed, manufactured and tested a prototype measuring platform, hoping to motivate researchers to use such a device or noise measuring methodology, due to the good results it produced and due to the easy, simplified and inexpensive test procedure needed.

To diffuse the knowledge gathered during this project, a detailed construction program is documented and explained.

By performing several test measurements with all the constructed equipment, another aspect also emerged. It is believed that tyre noise classification with the methods used today can be enhanced, if the author’s suggestion is accepted and better, comparable noise data can be produced, as explained in later chapters.

It has to be noted that the term “pavement” is used throughout this thesis, instead of “road surface” mostly because the base surface used with the under development device is small in dimensions and can not be considered as “road”.



## **2.1 Literature search – Similar devices**

From the literature search undertaken, noise conferences, market reviews, existing legislation, patents and standard searches, it has been confirmed, to the best of the author's knowledge, that a tyre noise measuring device as the author has conceived it, does not exist in the world.

Other devices and measuring platforms do exist, but they either use major and expensive laboratory equipment and machinery, or they use large "reference" testing tracks.

This means that the investigated tyre must be an existing one, which must be a production tyre that has all its development and construction costs absorbed.

All the above are methods that no third party, such as an independent engineer or small firm, can use easily or fast or inexpensively enough in order to investigate the noise production mechanism, or even investigate a portion of the noise mechanism, or to establish the tyre's noise classification.

So the existing devices can be used only by large research centers or public authorities that can afford the large measuring costs.

## **2.2 Existing problems**

As was concluded from the literature search, there are problems, both in the scientific area (how to measure) [43, 54] as well as in the market area (how to develop a quieter tyre) [85], with the methods that are used today for tyre noise measurement.

All research papers, tyre manufacturers, public authorities, EU joint research projects, [124, 125] agree that noise from tyre/pavement interaction is mainly produced by the "pumping action" of the trapped air in the tyre's grooves and treads that tries to exit through the pavement's porous structure [14], (other factors are also present).

The produced noise is radiated to the environment, thus creating traffic noise pollution, a modern problem to all communities next to urban roads that are seeking passive methods to be protected such as the erection of road noise barriers [38].

Most public noise authorities are not able to perform noise measurements (due to the complexity and cost of the existing methodology) in order to produce a scientifically approved noise classification per tyre.

All noise data is subject to serious deviation due to the road/pavement surface and texture, which is never the same in different measurement facilities, even if the “standard” construction method for test pavements is implemented [174, 175, 176, 177].

In order to conduct the measurements, the tyre has to be manufactured, so production costs for the industry are high (tyre design, die construction, trial production, final production of a new tyre, etc.).

From the author’s viewpoint, the measuring device under development will become a major research tool for fast, accurate and inexpensive tyre noise measurements in their first developing stages.

The literature search has shown that such a proposed apparatus, device or methodology are non-existent or not used.

No mention of the above methodology was found in any book, scientific paper, conference proceedings, research committees, patents, or university theses.

Therefore, for the moment, this thesis project seems to be a promising “blue sky research” project.

## 2.3 Existing work and apparatus

As described by BS - ISO standards and international bibliographies, the most common methodology used today is the following:

- **Controlled Pass-By method (CPB)** [151]
- **Trailer method – Close ProXimity method (CPX)** [152]
- **Revolving drum** [83, 90]
- **Revolving tyre** [83]
- **Computer simulations** [4, 5, 6, 16, 24]

And some small scale apparatus that produce vibration excitations in order to study the structural behaviour of the tyre and inner belt resonances [62].

Note that it is estimated that all may have “unsatisfactory” results due to the road pavement flatness, porosity, open or closed pores, micro and macro texture, roughness, surface aging, surface wear, surface clogging by dust, etc., so general “statistical” methods are used either for the pavement classification, or tyre classification, or for the measured noise data, in general [59].

### 2.3.1 Controlled Pass-By method (CPB)

The synopsis of the method is that:

A car with the 4 investigated tyres accelerates in a straight path till it reaches the start line of the measuring path at a designated speed, and switches the engine off during the “passing by” over the measuring track. At that time, stationary measuring microphones placed at a fixed distance and height from the ground gather and store the acquired noise data.

The surface of the acceleration path should not be of dirt, sand or gravel, in order to keep the main measuring area clean from debris which could alter the measurement accuracy.

The main measuring area should be a level, reflective and clean surface.

One of the reference standards is:

- **BS ISO 10844/94** *“Specification of test tracks for the purpose of measuring noise emitted by road vehicles”* [153]  
(according to the latest literature search, the same Standard is improved in the 2011 & 2014 version, but the main scope of the Standard is the same)

As seen in the following graph (taken from the above-mentioned new ISO), a large facility is needed with low background environmental noise, with no reflecting barriers or nearby buildings and a significant runway before and after the test track, in order to allow the car to obtain a specific speed.

It has to be noted that the background noise level must be or must be kept as low as possible to obtain accurate noise data not influenced by environmental noises.

Besides the large physical dimensions of the facility, another important factor is its texture, that has to be within specific limits and requirements in order to be not so rough or not so smooth, or not aged or clogged by dust, otherwise the noise generation from the interaction between tyre/pavement will be affected.

The following parameters (mentioned only by name) are taken from the same ISO - 2011 version - only for the reader to understand the construction precision needed for the test track / pavement and all the factors that could go wrong or deteriorate as time passes.

“sound absorption coefficient of test track” – “texture profile” – “longitudinal irregularity” – “transversal irregularity” – “straightedge” – “megatexture” – “microtexture” – “gradient slope” – “cross fall” – “propagation area” – “properties of drive lane” – “stiffness” – “dense asphalt concrete” – “mean profile depth” – “stability with time and maintenance”

For most of the above, a separate validation method is proposed according to other ISO standards [156, 157, 158, 159, 160, 161, 162, 163], in order to obtain an acceptable test track.



between them (for example, the multiple uncontrolled reflection when the noise wave is passing under the car is a questionable factor for this procedure).

In acoustics, it is a widely known fact that different and spaced apart sound sources (the 4 tyres) are interacting between them and they produce a spectral summarized noise [116, 117].

Since the term “summarized” used above may be confusing, it has to be noted that the noise from the 4 tyres can either be added, or subtracted, per frequency band (in some frequencies it will be added, in some frequencies it will be subtracted, and in some frequencies it will be cancelled out).

From the author’s point of view, this method is a simplistic approach and no noise measuring per tyre can be performed, but in the early years it was a simple and quite logical approach for engineering purposes, although with the passing of time, a lot of influencing factors are better evaluated than in the first edition of the Standard.

In any circumstances, why do we need a 58 page standard in order to cover and explain the method’s problems, and just not re-evaluate the tyre measuring approach in general?

Another major reference standard is:

- **BS EN ISO 11819-1/2001** “*Measurement of the influence of road surfaces on traffic noise – Part 1. Statistical Pass-By Method*” [151]

This part of the Standard describes a method of comparing traffic noise (not tyre noise) on different road surfaces for various compositions of road traffic for the purpose of evaluating different road surface types. The method is applicable to traffic travelling at a constant speed of 50km/h and upwards.

This Standard categorizes the speed conditions of the passing vehicles into 3 categories: a) “Low”, b) “medium”, and c) “high”.

“Low” road speed category refers to traffic conditions at an average speed of 45 – 64km/h, usually associated with urban traffic.

“Medium” road speed category refers to traffic conditions at an average speed of 65 – 99km/h, usually associated with suburban traffic.

“High” road speed category refers to traffic conditions at an average speed of 100km/h or more, usually associated with motorway traffic.

It also classifies noise from passenger cars, light trucks and heavy trucks.

The method uses an equation (not further elaborated here) in order to determine the “Statistical Pass-By Index (SPBI) according to travelling speed, type of vehicles and some weighting factors, so noise measurements are not absolute and depend on several factors.

The equation for the “statistical Pass-By index” is:

$$\text{SPBI} = 10\lg[W1 \times 10^{(L1/10)} + W2a(v1/v2a) \times 10^{(L2a/10)} + W2b(v1/v2b) \times 10^{(L2b/10)}] \text{ in dB}$$

So, one can see that there are 9 factors that could go wrong (the factors are not analyzed here).

In the same ISO, it is mentioned that <typical values for the weighting factors may vary considerably from place to place, country to country and with time of day and night>.

So it is confirmed that noise data collected from the <pass-by methods> cannot be directly or safely compared to each other.

### **2.3.2 Trailer method - Close Proximity method (CPX)**

Although this measuring method has been widely used for a long period of time in several countries, there was no standard available up until January 2013.

- **DRAFT BS ISO 11819-2** “Acoustics – Method for measuring the influence of road surfaces on traffic noise – Part 2: Close Proximity Method” - 03 Jan-2013 [152]

As stated in paragraph 1 “scope” of this Standard <as explained in the introduction, the Statistical Pass-By (SPB) method specified in part 1 of ISO 11819, has a number of limitations. The Close-Proximity (CPX) method proposed in this part (2) of ISO 11819 has the main objective as the SPB method but is intended to be used specifically in applications that are complementary to it, such as:

- Noise characterization of road surfaces at almost any arbitrary site, with the main purpose of checking compliance with a surface specification; for example, for conformity of production as suggested in paragraph 1.
- Checking the acoustic effect of maintenance and condition, e.g. wear of and damage to surfaces, as well as clogging and the effect of cleaning of porous surfaces
- Checking the longitudinal and lateral homogeneity of a road section
- Development of quieter road surfaces and tyres.>

Measurements with the CPX method are faster and more practical than with the SPB method.

The main setup is the investigated tyre mounted on a specific trailer, pulled by a car and noise is measured by a microphone array mounted inside the trailer but very close to the tyre and the pavement surface.

It has to be noted that when the measuring procedure is used, not to investigate the tyre itself but the noise produced from a specific pavement, reference tyres should be used [35].

The trailer’s travelling speed, stated in this draft standard, are 40, 50, 80 & 100km/h) but during the performance of the measurements in this thesis, this standard was not available and the speeds from other worldwide performed tests were used (50, 80 & 110km/h).





**Fig. 2-2.** NCAT CPX trailer

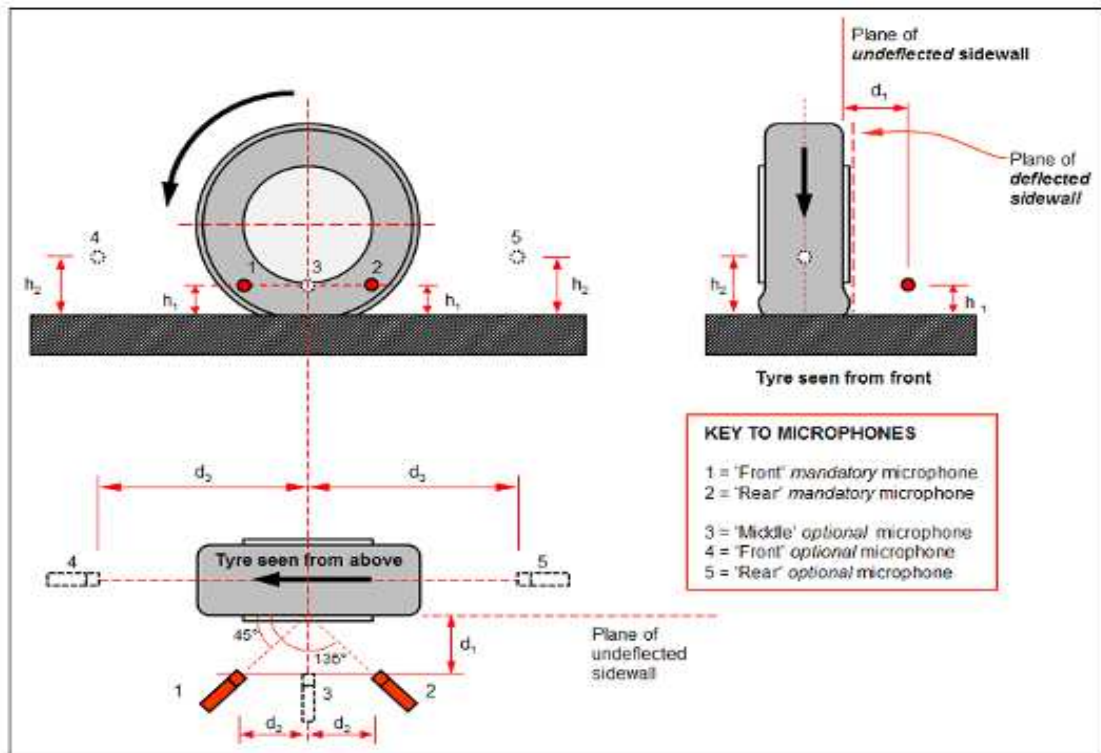
As seen in the picture (taken from the NCAT project), a specially constructed trailer (with one or two wheels – depending on the trailer’s manufacturer) with a long connecting tie bar, to reduce the car noise, is used [104].

Note that the trailer has a closed protection cover in order to protect the microphones from environmental conditions, but mostly due to its internal sound absorptive lining that is “muffling” environmental noise and reducing the air stream passing in front of the microphones, thus reducing aerodynamic noise.

All CPX trailers, regardless if they have one or two wheels, use the same methodology for noise measurements.

The following figure (from this Standard) is common in all trailers and the recorded data is either dB or dBA but a spectral recording and analysis instrument is always preferred.

Modern instruments are capable of measuring not only 1/1 or 1/3 octave spectrum but also 1/12 or 1/96 or even in user defined band width.



**Fig. 2-3.** Microphone Positions from BS ISO 11819-2

In the above figure, the tyre rotation is shown (determining the leading and trailing edge of the tyre) and the suggested positions to place the microphones.

### 2.3.3 Revolving drum

Not covered by any ISO standard.

The investigated tyre is mounted on the external (or internal – depending on type of drum and apparatus used) perimeter of a revolving drum and noise is measured by a stationary microphone array mounted very close to the tyre. – the drum's surface can be covered by different precast materials with specific porosity and roughness [89].

As seen, the cost for such a measuring procedure must be very high since it includes costs for:

- the construction of the device itself,
- the occupied laboratory,
- acoustic treatment of the hall,
- precast surfaces of different types,
- expert handling by trained personnel, etc.



**Fig. 2-4.** Revolving Drum Facility PFF at the BAST Institute, Germany

### 2.3.4 Revolving tyre

The same as above but the investigated tyre is revolving on the perimeter of a stationary and non-revolving drum of 3,7m diameter and noise is measured by a microphone array mounted on the tyre's supporting structure – the drum's surface can be covered by different precast materials with specific porosity and roughness and speeds up to 50km/h can be implemented [115].

The surface materials are usually precasted in specific concave metallic molds, and let to dry to obtain their maximum strength, and only then they are mounted on the machines drum.

It is supposed that the measurement cost may be less than the “revolving drum” method, due to smaller dimensions and occupied room, but it is still estimated to be a high cost installation.



**Fig. 2-5.** Revolving Tyre at SQDH Purdue Univ. Indiana USA

### 2.3.5 Computer simulations

Using different software, the tyre / pavement noise is estimated.

As it is known, the software models can be very accurate, provided they are fed with the right data each time and use the right algorithms. But, input data and cross reference data must be obtained from measurements.

At the moment, only “general” noise data is provided from the “general” procedures described above, and little specific data is available, such as noise generation in tread type “a” or “b”, or under different loads, or under specific textured pavement.

### 2.3.6 Vibration apparatus

A number of small scale apparatus that produce vibration excitations exist and can be constructed easily and cost effectively.

They are used in order to study the structural behaviour and structure borne noise generation of the tyre and its resonances, when an exciting force or impulse is induced on the tyre.

Results are mostly taken by accelerometers placed in different positions on the tyre, or by close proximity microphones.



**Fig. 2-6** Vibration setup from RATIN project of ISVR Research Center



## 2.4 Existing CPX Trailers

Most CPX trailers are towed by a car or light van and have 2 wheels since they are easier to construct.

The following photographs are taken from several measuring projects worldwide that are trying to gather noise data from different tyres, or are evaluating the noise behaviour of road surfaces, or are private trailers used for noise research.

More data can be found on each site, as mentioned beneath each photo.



**Fig. 2-7.** *The TRITON CPX measurement vehicle*

<http://www.highways.gov.uk/aboutus/10895.htm>



**Fig. 2-8.** *TRL noise test trailer*

[http://international.fhwa.dot.gov/quiet\\_pav/chapter\\_two\\_d.cfm](http://international.fhwa.dot.gov/quiet_pav/chapter_two_d.cfm)



**Fig. 2-9.** *CEDEX CPX trailer*

[http://www.cedex.es/ingles/presentacion/datos/instalaciones/cet\\_re.html](http://www.cedex.es/ingles/presentacion/datos/instalaciones/cet_re.html)



**Fig. 2-10.** *M&P Consulting Engineers' CPX trailer*

<http://www.mp.nl/leaflets/leaflets.php?langID=2&page=CPX>



**Fig. 2-11.** *SILENT Roads Project*

<http://www.silentroads.nl/index.php?section=research&subject=robustcpx>



**Fig. 2-12.** *SILENT Roads Project*

[http://www.silentroads.nl/index.php?section=research&subject=cpx\\_validation&page=cpxval\\_participants](http://www.silentroads.nl/index.php?section=research&subject=cpx_validation&page=cpxval_participants)





**Fig. 2-13.** *SILENT Roads Project*

[http://www.silentroads.nl/index.php?section=research&subject=cpx\\_validation&page=cpxval\\_participants](http://www.silentroads.nl/index.php?section=research&subject=cpx_validation&page=cpxval_participants)



**Fig. 2-14.** *SILENT Roads Project*

[http://www.silentroads.nl/index.php?section=research&subject=cpx\\_validation&page=cpxval\\_participants](http://www.silentroads.nl/index.php?section=research&subject=cpx_validation&page=cpxval_participants)



**Fig. 2-15.** SILENT Roads Project

[http://www.silentroads.nl/index.php?section=research&subject=cpx\\_validation&page=cpxval\\_participants](http://www.silentroads.nl/index.php?section=research&subject=cpx_validation&page=cpxval_participants)



**Fig. 2-16.** Ulf Sandberg's trailer

<http://www.highfrictionroads.com/index.php?q=node/18>



**Fig. 2-17.** ADOT Quiet Pavements Program

<http://enr.construction.com/news/transportation/archives/040202b.asp>



**Fig. 2-18.** FHWA project

<http://www.fhwa.dot.gov/publications/publicroads/10julaug/01.cfm>

## 2.5 Tyre parts

With the exception of slick racing tyres or other specially designed tyres, all car tyres have tread, grooves and sipes incorporated in the circumference, mostly to be used as water drainage on rainy days and minimize the aquaplaning effect [95] that makes a car uncontrollable.

Aquaplaning happens when an amount of water is trapped and cannot escape, or escapes slower than it should, between the tyre and the pavement and the tyre loses contact and steering because the trapped water acts as a lubricant.

Each manufacturer promotes a tread, groove, and sipe design claiming to have better grip or better behaviour on a wet or dry surface, or lasts longer, or consumes less fuel, or be quieter, etc.

The common factor, regardless of other reasons, is that in dry conditions the surrounding tyre air is compressed and driven into those narrow passages and, by doing so, noise is produced. The same air during its abrupt release to the environment produces more noise, so a combined noise is radiated when a tyre is rolling, especially at high speeds.

The constant compression and decompression of air passing through those channels is of major significance since it is a contributing factor to noise generation.

An uncontrolled factor in noise production and noise dissipation is the roughness, texture and porosity of the pavement that, in all today's measuring procedures, is the "beast" to be defeated.



**Fig. 2-19.** Tyre parts

The reader is believed to have a perception of different noises produced when travelling in his car on different surfaces or with different tyres (after a tyre change), such as tonal noises at a specific frequency, deep low frequency noises or hissing noises, all of them depending mostly on the tyre/pavement interaction.

Rubber hardness or belt/liner materials or other aspects of a tyre structure will not be examined in this thesis, since they do not contribute to the aerodynamic noise that is produced from the tread, groove and sipe design of the tyre.

The main parts of a typical automotive tyre are as follows:

Data from: (<http://tireguides.com/TireTips/TireDocument>).

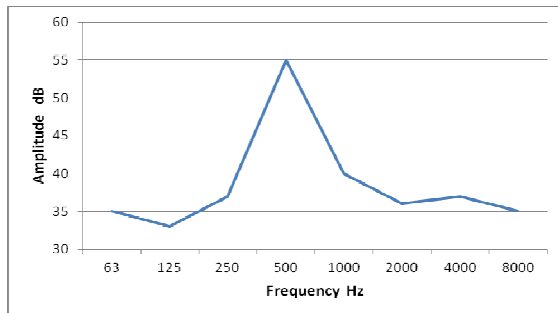
1. Grooves: Channels for water evacuation between tread and road surface.
2. Ribs: Circumferential bands of tread rubber between grooves for continuous road contact and traction may be enhanced with sipes.
3. Tread: Contact area with road surface using various compound strategies, like maximizing grip or mileage.
4. Shoulder: Transition element between tread and sidewall for traction during cornering and manoeuvring.
5. Belts: Woven steel cord mesh for rigidity of tread rubber to reduce tread squirm and increase tread life.
6. Undertread: Compounded for high heat resistance to increase high-speed durability and sometimes fuel economy.
7. Inner Liner: Special rubber compound highly impervious to air migration for maintaining air pressure without leaking.
8. Body Plies: Either fabric cord (passenger and light truck tyres) or steel cord (mainly truck tyres) for structural strength of air chamber.
9. Bead Cable: Rigid cable serving as an anchor around which body plies are wrapped and which secures tyre to rim flange area.
10. Bead Apex/Filler: Special hard rubber compound extending up into sidewall to increase flexing around bead cable and enhance stiffness of lower sidewall for improved handling.
11. Bead Chafer: Layer of fabric material protecting bead area from rim chafing and mounting damage.

## 2.6 Noise perception

Noise from the tyre / pavement interaction when a tyre is rolling on a smooth surface may be tonal or broadband [25, 56].

Tonal noise occurs when a listener perceives it as a distinct sound in a specific frequency range. The exact frequency is irrelevant but the frequency span is always narrow. In a typical frequency/amplitude graph, a distinct spike is observed..

A lot of effort has been undertaken by all tyre manufacturers to reduce the tonal noise some tyres produce, one of which is to incorporate, the different axial spacing between transverse sipes or treads into the tyre's design, to avoid producing repetitive pulses that are interpreted as tonal noises.



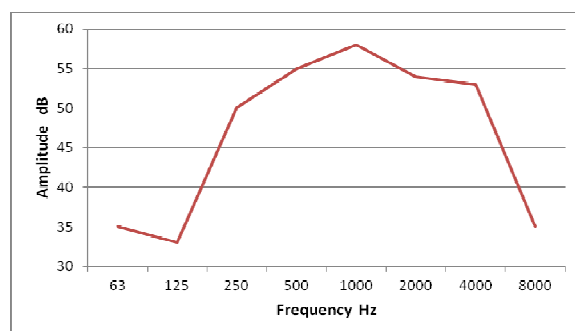
**Fig. 2-20.** Typical Tonal noise

Tonal noise of specific frequency is produced by any revolving item (such as tyre, fan, propeller, compressor, etc.) when it is revolving at a specific rotational speed and is periodically hitting or interrupted by a static object or groove or hole or barrier. Note that this is the typical noise producing mechanism of a mechanical (not electronic) alarm siren.

Broadband noise is one that is perceived as a general complex noise without tonal spikes and has a span distribution over a wider frequency range.

Broadband noise is the most common noise spectrum in nature and can be dominant in the low, mid or high frequency area but should not have specific spikes in its spectrum.

Some examples of nature's broadband noises are the waves on a beach, wind blowing through tree leaves, or rain drops falling.



**Fig. 2-21.** Typical Broadband noise



### 2.6.1 Contact area

The theoretic contact area between a flat surface and a hard cylinder is always a narrow line.

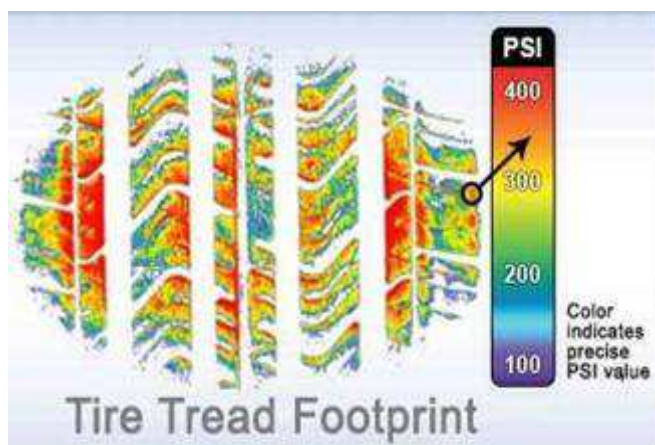
But the tyre/pavement contact, due to the softness of the tyre and the car's load, produces an elliptical area as a "footprint" that, in turn, does not cover the tyre's overall width but only a large section of it, due to the shoulder curvature that is incorporated in all commercially available tyres.



**Fig. 2-22.** Shoulders of a tyre

As seen in the figure below, the tyre/pavement contact area is not orthogonal but has curvature at both the left and right shoulders, with a radius depending on tyre width and tyre specification.

On the other axis, the axial cross section of the tyre produces a contact area of some length (depending mostly on the tyre's diameter and inflation pressure).



**Fig. 2-23.** Footprint of a stationary tyre

*Figure from [www.sensorprod.com](http://www.sensorprod.com)*

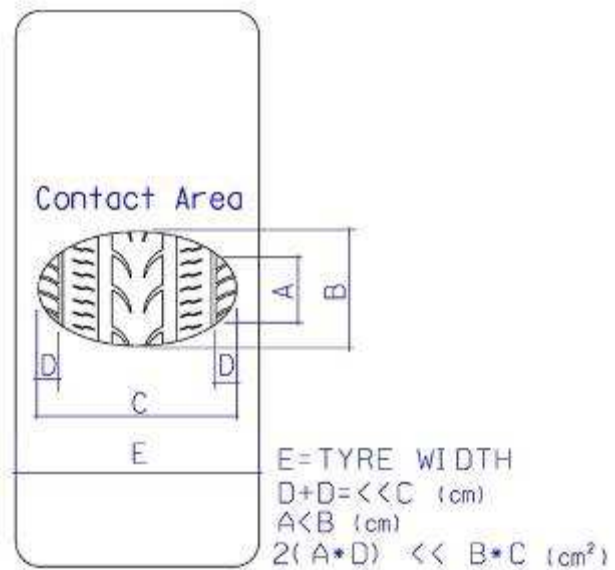
Deformation of the contact area occurs due to the softness of the tyre under the load of the car.

Even with the appropriate inflation pressure, the tyre produces a contact area with the pavement that could be considered to be bevelled orthogonal or elliptically shaped.

### 2.6.2 Sipe tonal noise

Tyre manufactures have put in a great deal of effort to reduce the noise produced from the lateral sipes of the tyre [97].

In the tyre/pavement contact area (if seen from below a hypothetical glass pavement), one can see the longitudinal deep grooves, different tread patterns and the lateral shoulder sipes, that are claimed, by manufacturers, to produce tonal noise.



**Fig. 2-24.** Bottom view of tyre

a) if the overall tyre width is considered to be “E”, the width of the contact area “C” is smaller than “E” due to the tyre’s shoulder curvature.

b) it can be considered that “B” is the maximum contact length, due to the elliptically shaped contact area.

c) the lateral sipes are incorporated on the lateral shoulder curvature of the tyre (in some tyres both left and right) so the contact length “A” is much smaller than “B”.

d) the contact width of the sipes “D”, even if doubled (left & right =2D), is considerably smaller than the contact width “C”.

e) therefore, the contact area of both left and right sipes is only a small portion of the complete contact area of the tyre.

So, due to the much smaller contact area of the shoulder sipes with the pavement, their noise producing capability seems to be overestimated by tyre manufacturers.

As proven under the CPX trailer measurements no sipe tonal noise was dominant.



### 2.6.3 Air turbulence

The noise producing effects of the tyre are greatly based on aerodynamic behaviour of the tyre / pavement interaction and not only as a single tyre or object passing through high speed air stream [29].

Although there are several projects and simulations that have studied tyre acoustic and pressure behaviour in wind tunnels, in this thesis these phenomena are isolated and not measured since they are considered unconstructive to the project [2].

If the surrounding air during the travel of a vehicle is considered to be still, when the tyre is rolling, two main aerodynamic phenomena are created [11]:

- a) Major air turbulence, considering the tyre as one rigid body (shown in the left figure)
- b) Smaller air turbulence considering the tyre grooves as air orifices (shown in the right figure)



**Fig. 2-25.** Schematic of air turbulence

When the tyre is rolling on a smooth closed pore surface, the non-grooved rubber part of the tyre that is essential for better traction (see “1” in the above enlarged drawing) is forcing air to deflect either outside the tyre’s perimeter, or into the main grooves (2) of the tyre. It has to be mentioned that all summer tyres have grooves and treads mainly for water drainage and not for better traction, as it is believed. Winter tyres are of a different design and believed to be noisier in some cases.

In many tyres, smaller and narrower longitudinal grooves are carved at the left or right or even on both sides of the tyre (3) and are usually connected to the lateral shoulder sipes of the tyre (4) (seen in green in the above drawing).

It is clear that the grooves, either the deep and wide ones (2) and the smaller and narrow ones (3), are accelerating the air stream and when the air is exiting to the environment, an orifice effect is taking place and more violent turbulence is created, thus more noise.

The air stream is, therefore, of major interest for this project and will be exploited from the prototype noise measuring device construction.

## **3 LITERATURE OVERVIEW**

### **3.1 Subjective classification of tyre/pavement noise**

Subjective classification of sound is very difficult even between trained musicians, and one may hear expressions such as “deep sound”, “brilliant”, “robust”, “full”, “empty”, “heavy”, “stringy” and many more. As a result a commonly accepted term to describe the perception of sound exactly, is still a utopia.

The exact same problem exists when trying to make noise qualifications with a linguistic approach.

Noise from a tyre, when travelling at medium-high speeds over a road surface is subjectively distinguished by the author at least as :

“hissing” noise

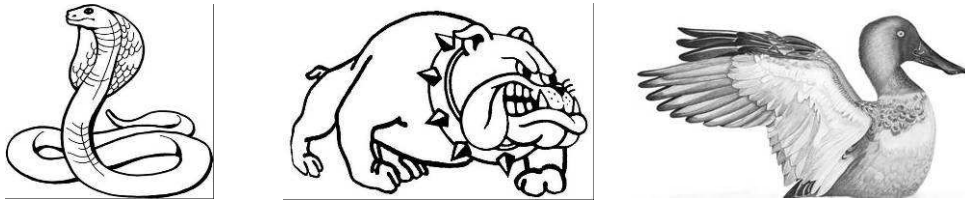
“growling” noise

“flapping” noise

Hissing noise (term widely used in acoustics) is rich in high and very high frequency energy (above 2000Hz) and is encountered mostly when a tyre is travelling over a smooth, level and closed pore road surface. It is called hissing since its acoustic stimulus is perceived as a continuous “Hisssssssss”

Growling noise is rich in medium and low frequency energy (below 800Hz) and is encountered mostly when a tyre is travelling over a rough but level road surface. It is called growling since its acoustic stimulus is perceived as a continuous “Grrrrrrrrr”

Flapping noise is rich in low-medium frequency energy (around 1000Hz or lower) and is encountered mostly when a tyre is travelling over a road gap or over a pavement discontinuity or over a stone road at significant velocity. It may be called flapping, since its acoustic stimulus is perceived as a bird flapping its wings “Flap-Flap”.



**Fig. 3-1** subjective noise classification – Hissing / Growling / Flapping

Hissing noise is believed to be developed mostly from the air jet that is exiting at high speed via the tyre's groove as the perimetric groove (one or more per tyre) is acting as air orifice or short length pipe when in contact with a smooth, level and closed pore road surface.

All car drivers have experienced the above noise stimulus especially when driving over a wet (but not flooded) road surface since the thin water film is filling completely the pores of the surface, thus making the road surface reflective instead of partially sound absorbing.



**Fig. 3-2** Smooth -closed pore road

Additionally the entrapped under the tyre air has more difficulty escaping through the wet closed road pores and all the air supply is forced to exit via the tyre grooves, thus increasing the air jet phenomenon.

Growling noise is believed to be developed mostly from the continuous hammering of a revolving tyre at high speed over the projected or jagged aggregates of road surface.

All car drivers have experienced the above noise stimulus especially when driving over a rough but level road surface.

Additionally the entrapped under the tyre air, is much easier to escape not through the tyre grooves but in any possible direction since the rubber part of the tyre is never in complete contact with the road surface.



**Fig. 3-3** Level and Rough road

In his study von Blokland, *et al.* (2014), states that irregularities in the contact area between rolling tyre and road surface excite the tyre

structure, causing it to vibrate and radiate sound into the environment. This is often referred to as texture induced vibration.

Both above phenomena are produced and rely absolutely on the continuous but progressive approach of the tyre's curved surface to the road surface.

Flapping noise on the other hand is believed to be developed mostly from the sudden hitting of a significant tyre area at high speed at the opposite ridge of a road gap (when the tyre is passing over a road gap or road discontinuity). This sudden contact (in respect to the progressive ones mentioned above) is not obeying any of the above mentioned noise producing mechanisms and a completely different noise is produced.

Wong *et al.*(2013) in his study concerning the noise behaviour of mechanical joints in several bridges, concludes that when a car is travelling at 70km/h over such a joint, it needs 0,2 to 0,35 sec to pass over the joint, meaning that a time factor is also a variable that correlates with the produced noise and spectra.

All car drivers have experienced the above noise stimulus, especially when driving over a stone road surface or over a deteriorated road segment, at high speed, since at low travelling speeds there is not such a sudden tyre/road contact.



**Fig. 3-4** Deteriorated road segment

At high speeds, the entrapped under tyre air, is more difficult to escape via the grooves but is forced to escape instantaneously at any possible direction.

Additionally the sudden hitting/flapping is producing flexural stress of the tyre's carcass increasing even further the radiating vibration of the tyre's walls.

In contrast of all the above, if the road surface is smooth, open pore, level, without gaps or discontinuities (as a newly paved asphalt road) the tyre/ pavement interaction noise could be considered by some, even as pleasing, since it is less noisy and of steady state.

It has to be clear that all the above mentioned noises may be heard by a listener when the very same tyre is used, but over different pavements. So, one can conclude well in advance, that the pavement is playing a significant if not the most significant part, in the noise producing mechanism.

## 3.2 Literature comments

### 3.2.1 Hammering.

During the literature review the term “hammering” was encountered, Ponnaiach (2010), was referring to the sudden impact of a rubber block of a rotating tyre tread over a pavement surface.



**Fig. 3-5** Rubber blocks  
– Wrong design

All treads are implemented to the tyre design in order to expel water under the rotating tyre when in contact with the pavement in order to avoid aquaplaning.

So the treads are designed to expel water but simultaneously they have to do it progressively and smoothly in order to avoid the sudden and forced water extraction, which in terms would produce vibrations to the tyre rotation, unbalancing, driving discomfort and safety issues.

In theory this phenomenon may exist but to the best of the author’s knowledge there is no tyre tread design that allows this phenomenon to happen and rubber block deformation (mentioned in several thesis and presentations) is overestimated. It is never implemented in a tyre as shown in the left design (perpendicular to the rotation and as isolated rubber blocks).



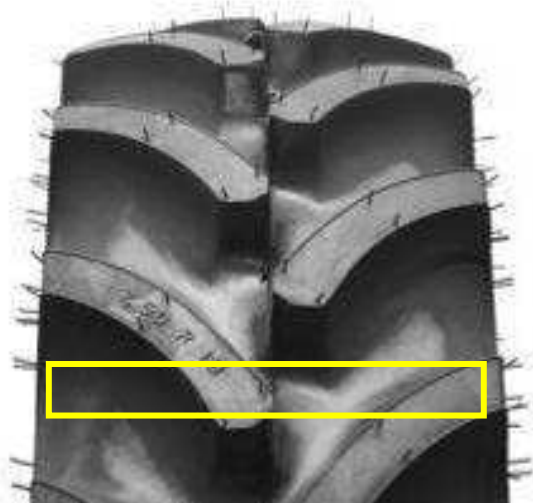
**Fig. 3-6** Rubber blocks  
– Actual design (progressive)

The tyre manufacturers need the most tyre/pavement contact area for traction purposes so most lateral treads are displaced by several millimetres to each other in order to obtain the needed larger rubber contact area at all times. So when one tread is detaching from the road the next one is already in contact with the road.



A good and very obvious example is seen in the large wheels of earth moving tractors. They have extensive and deep treads to guarantee the best traction in muddy fields. Simultaneously the large rubber blocks provide a constant contact area when the tyre is rolling on a road, thus a smooth ride of the vehicle without bumps is obtained.

It could be said that at the leading edge of a rotating tyre, each rubber block is progressively touching the road surface instead of hammering it and at the trailing edge it is progressively peeling from the road surface instead of an instant detach.



**Fig. 3-7** Rubber blocks

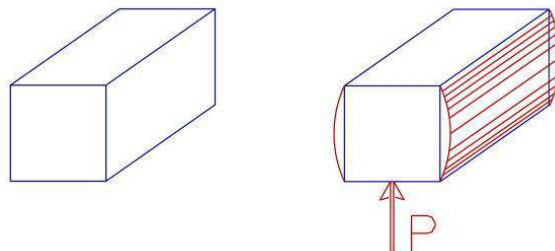
Constant contact with pavement

In any case it has to be considered that a slight rubber compression of the part of the rubber that is about to get in contact with the road will be obtained, since the rubber part that is already in contact with the road surface is already slightly deformed.

The above term “slightly deformed” is used not to describe the large tyre deformation at the road contact area (due to vehicle’s load), but is describing the deformation of the rubber material it self, when loaded.

It is known that rubber is used as an anti vibration material and is widely used in industrial acoustic projects to support vibrating machinery in order to reduce the vibration transmissibility to the ground.

This good antivibration behaviour of rubber is obtained from its mass deformation when loaded, depending of the rubber hardness/softness (described by the SHORE “A” measuring scale)



So when the rubber of a tyre is in contact with the road surface there are two deformations of different nature.

**Fig. 3-8** Rubber deformation under load

- deformation of the pneumatic tyre under load, that increases the contact area and
- deformation of the rubber material itself.

Going a step further the small treads of the tyre, that help water drainage, also permit the slight lateral expansion of the rubber material, when it is loaded, enabling a better progressive rubber vertical compression and horizontal expansion and as a result provide a smoother vehicle ride.

So the hammering effect is tried by the manufacturers to be kept as low as possible even in winter tyres, and in summer and all weather tyres (that are smoother in design) it may not be present at all.

From the above it is understood that the hammering effect will not be measured by the developed device since a) it is a dynamic phenomenon and the author's static device can not produce nor measure noise from dynamic behaviour and b) it is considered to be of low importance.

### 3.2.2 Helmholtz

The term "Helmholtz resonator" is mentioned in several papers but is separated in two categories.

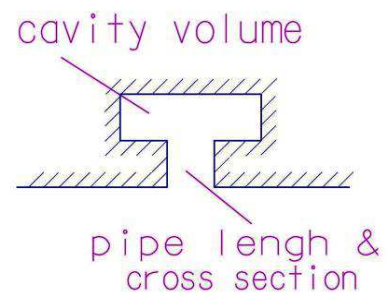
- A) the sound absorption provided by the Helmholtz resonator inside the tyre cavity, Periyathamby (2004), and
- B) the sound absorption due to the behaviour of the tyre treads as Helmholtz resonators, Jiasheng (2013).

The insertion of an absorption mechanism or absorbing material inside tyre's air cavity on the perimeter of the rim, is considered to be working well and reduces the air cavity noise resonance by 8 dB.

But Helmholtz absorption due to the tread design of the tyre is rather difficult to be produced, due to physical restrictions and due to the mechanism that this phenomenon occurs.

The phenomenon occurs when a confined air space of specific volume and hard walls is in contact with the surrounding air space via a hole of specific length and cross section, which interconnects both of the above volumes / areas (inner and outer).

This system acts as an air spring system and when acoustic waves are in front of the



**Fig. 3-9** Helmholtz cross section



opening hole, a specific frequency is absorbed due to air resonance at this frequency.

On the other hand if a wind jet is passing in front of the same hole it sets the air in the hole and the cavity in motion, and produces noise at a specific frequency band.

So the same configuration may act as a sound absorber or sound generator depending on the external air velocity.

Generally Helmholtz resonators are widely used in acoustics as low or very low frequency absorbers due to their geometry, since typical sound absorbing material are capable of absorbing sound only in the mid-high frequency area, proportionally depended on their thickness.

A treaded tyre has no large confined spaces behind its grooves or treads, so Helmholtz resonance cannot take place as a sound absorbing nor as a noise generating mechanism.

Even if this phenomenon was present, due to small tread depths the resonance frequency of the system would be placed in the very high frequency area, thus unimportant for the overall noise level contribution.

In his study Lesniewicz (2014), concludes that there is a lack of information about the flow structures inside tyre grooves due to the difficulties of the existing measuring equipment.

The developed by the author device could measure such acoustic behaviour if in the future, tyres with external Helmholtz resonators would be manufactured, but for the moment it seems to have only theoretical value.

### **3.2.3 Frequency peak at 1000Hz**

Hanson *et al.* (2005) concluded that during measurements on different road surfaces treated as diamond ground or longitudinally tined or transverse tinned or dense graded stone mastic or open grade etc has shown that a consistent spectral peak at around 1000Hz was always present.

Sandberg (2003) concludes that, despite a wide range of tyre types, it is amazing how similar the spectral shapes are and how the sound concentrates around a peak at 800-1000 Hz. The chosen road surface should emphasise tyre differences, but still the spectra per measurement are similarly shaped.

Blokland *et al.* (2014), has studied the aging effect of different pavements in Scandinavia and found that even the ones manufactured with low noise technique, have the same spectral peak at 1000Hz regardless of the elapsed time from construction.

If one notices the test results in this thesis, it is clear that the spectral data agree with the above observations, and a strong point for the developed device is that it behaves similarly to the above, even if dynamic factors or rotating tyres or typical road pavements were not present.

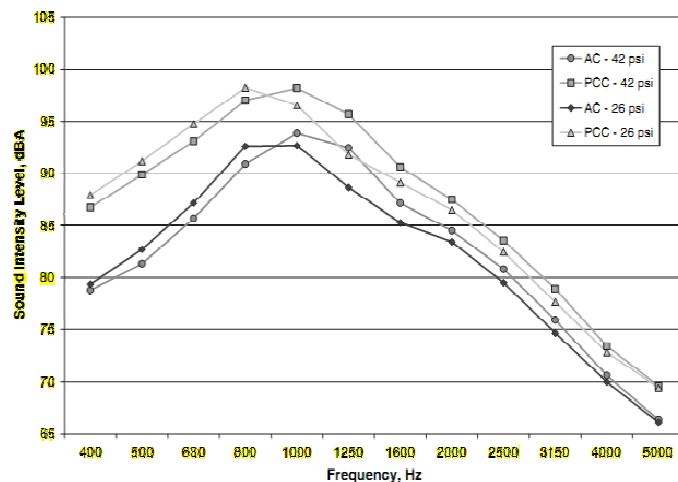
This has to guide our thinking that it is not the road surface, nor the tread design that produces such “tonal” noise spectra at 1000Hz.

Since pavements in the performed tests are different between them and since tyres are different as well, the only thing the tested tyres have in common between them in all measuring situations is the incorporated perimeteric grooves, so further attention of the groove’s acoustic behaviour should be paid by researchers.

### 3.2.4 Inflation pressure

In his project Donovan (2009), states that as tyre inflation pressure increases, 1/3 octave band levels below 1,000 Hz decrease and levels above 1,000 Hz increase, resulting in small overall changes to the sound intensity level (0 to 0.5 dB increase per 10 psi increase) as shown in the relevant Figure

These changes are within the baseline variability. However, the frequency shifts are notable; a 2.4 dB increase per 10 psi increase was indicated in the 1250 Hz band for both pavements; shifts in the other frequency bands were smaller.



The above results are **Fig. 3-10** tyre response to inflation pressure verified by the author, using the developed static device, when a mistake in inflation pressure occurred during measurements and the results were similar to the above but nevertheless puzzling, since they deviated from the expected results and thus required more investigation.

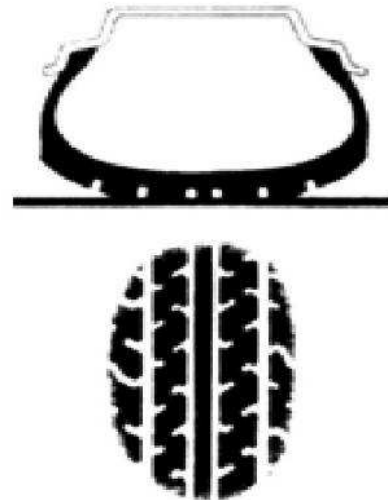
Although Donovan (2009), did not provide more information for the reason this happens, it was found out during the author's tests that at low inflation pressures a small void area between the road surface and the middle of the tyre was emerging, altering the air distribution through the grooves and the treads of the tyre and thus altering the radiated noise spectra.

It is common knowledge to all drivers that when over or under inflating a tyre it is unevenly damaged, Reithmaier (2003).

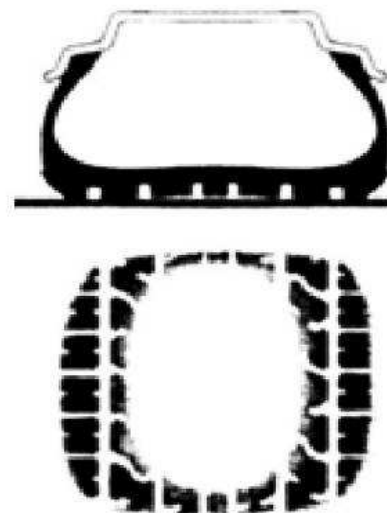
The damage is pronounced in the middle of the tyre when it is over inflated (which means that the middle part of the tyre is getting all the road friction and wear) and besides the increased wear, breaking distance increases, cornering stability is reduced and riding comfort degrades.

When the tyre is under inflated mostly the left and right edge of the tyre are in contact with the road (which means that both edges of the tyre are getting all the road friction and wear) subsequently due to the increased flexion effort of the tyre, it suffers from severe heating and it heightens the risk of unseating off of the rim and in consequence a void area in the middle of the tyre is created.

During the author's measurements, this same phenomenon of under inflation was observed, since it produced large amounts of very low frequency noise, that were not consistent at all with the typical noise spectra of a correctly inflated tyre and its peak was much lower than 1000Hz.



**Fig. 3-11** Over inflated tyre



**Fig. 3-12** Under inflated tyre

### 3.2.5 Stick and Slip

In his study Jiasheng (2013), refers to a Stick and Slip phenomenon that is part of the noise producing mechanism. Acoustic engineers understand that tonal noise is produced when an oscillation occurs and if this oscillation implements small body displacements then the noise is of high pitch (high frequency) perceived as squeaky sound.

When larger body displacements occur then a lower pitch sound is perceived. For example a high pitched sound may be heard when turning the steering wheel of a non moving car over an epoxy layed garage floor or during high speed “drift” races where the tyre is spinning.

A lower pitched sound may be heard when inserting new brake pads that are still not in good contact with the old brake disk and it vibrates. Although in all rotating tyres a degree of slippage when in contact with the pavement is expected (and thus tyre wear occurs) the rate of tyre deterioration is very small and takes place during several years from the time a new tyre was first used. Due to this very slow deterioration one may be sure that the slip phenomenon is not related to tyre noise.

In the same study another phenomenon is mentioned, described as “Stick”, meaning that when the tyre tread is gradually detaching itself from the pavement, at the tyre’s trailing edge, due to cohesion between rubber and pavement a sudden “unsticking” or “popping” noise is produced.

From an acoustic point of view this may be the case, especially when this happens during a very short time window. But in order to happen there must be an accelerated stream of air that is trying to fill the void produced from the abrupt rubber detachment from the road surface.

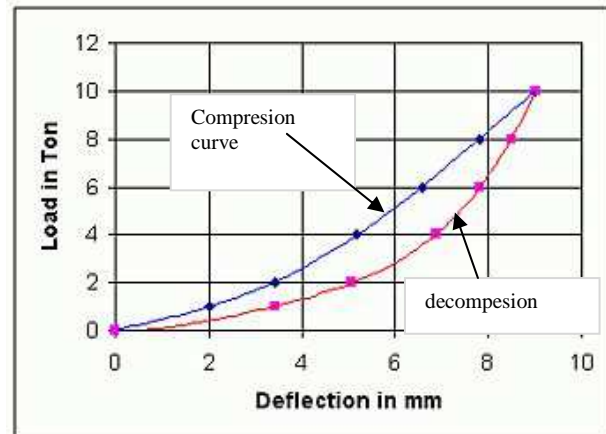
But due to the porosity of the pavement even in very smooth pavements, air pockets are always present in the pavement’s micro voids, thus the abrupt external air stream is not expected to be as fast or as sudden as is needed to create the popping noise.

Nevertheless the author has explained in earlier chapters that at the trailing edge the detachment of the rubber blocks from the surface is progressive (even at high speeds) and simulates a continuous progressive “peeling” effect since no rubber block is free standing, but interconnected with its previous or side one.

In their study Morgan *et al.* (2003), for the same slip effect use the term “micro-movement” effect and claim the same noise behaviour and for the “stick” term they used the term “snap-out”.

What should raise questions in these projects, is that they consider the rubber block as a material that will gain its original (expanded) dimensions, when relived from its load, after it is detached from the pavement, instantly.

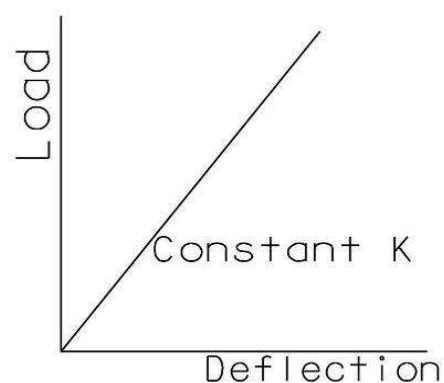
But it is known that rubber is a viscous material and instant deflection (when compressed) or instant expansion (when load is removed) is impossible due to its inherent viscoelastic characteristics, not matching the behaviour of a metal spring (that could be compressed or expanded instantly).



**Fig. 3-13** Rubber typical deflection curve

Depending on the rubber compound and its softness, it is not unusual that a rubber material deforms differently when loaded and differently when unloaded. In any case the typical deflection curve or rubber per load is never a straight line but is in the shape of the relevant figure due to internal particle friction, so instant decompression is rather impossible. The compression and decompression rate of a rubber material can be altered if the ingredient mix is altered, if it is casted in a specific shape, if the compression length is altered, etc

In contrast a metallic helical spring has a higher service life without altering its performance with time and its compression and decompression curve is a straight line (if it is working within its design limits). The angle gradient of the curve is depending on its K constant, which depends on the design characteristics of the spring. (K constant describes the deflection of the spring e.g. mm per Kg)



**Fig. 3-14** Spring deflection curve

So the developed device does not have to produce nor measure the above stick & slip phenomena, since they are thought not to influence the measured noise.

### 3.2.6 Temperature

In his study Mogrovejo Carrasco (2012), on specific type of pavements, concluded that the increase of pavement temperature (from environmental reasons) is affecting the noise results measured with the CPX trailer method by  $-0,05\text{dB per }^{\circ}\text{F}$ , and suggests that correction should be made according to the temperature variations for measurements taken during different seasons.

In the same study he concludes that no correction is needed if air temperature is altering, since it is not contributing in the noise measurement procedure as much as the pavement temperature.

Buchlmann *et al.* (2013), states that during his CPX measurement over a temperature range  $5^{\circ}$  to  $30^{\circ}$  has measured noise level differences up to  $2,5\text{dBA}$  and he agrees that temperature correction is needed. He concluded that the overall Noise-Temperature slope is  $-0,10\text{dB(A)/}^{\circ}\text{C}$

Bearing the above in mind, the author proposes that if the temperature gradient of the pavement needs to be studied with the developed static device, it is rather easy to implement a controlled heating element under the contact surface, with the appropriate control and safety circuits, in order to heat each contact surface to a desired degree.

Going a step further, one could incorporate a cooling circuit, such as copper pipes connected to a freezer compressor and a thermostat, under the contact surface, if measurements with a cold or even frozen surface should be performed.

### 3.2.7 Damping

Schumacher *et al.* (2003), during the modelling of tyre noise propagations, states that in order to model the acoustic environment, a boundary element mesh of the complete tyre was made and the hard ground is taken into account as an infinite rigid plane located  $0,05\text{m}$  below the tyre.

The above statement that the tyre is  $5\text{cm}$  away from the pavement gave thought to the author and a question has risen. What is the acoustic influence of the tyre/pavement contact area, seen from the perspective of sound damping and if such influence exists.

In Acoustics one way to reduce the vibration of an oscillating structure such as a car's metal floor or its metal door, is to incorporate a damping material, that is nothing else than a rather soft material in contact with the vibrating metal sheet, that is able to absorb kinetic energy and dissipate it as heat.

Depending on the viscous properties of this material, its area and its thickness compared to the area and thickness of the metal sheet a moderate, medium or excellent damping can be achieved.

Damping can reduce the noise radiation of any lightweight structure considerably and thus is used widely in acoustics and in car manufacturing.

Perhaps the deformation of a tyre when under load, is a factor that should be studied, as a damping factor, since the author has not encountered such a statement or conclusion in none of the reviewed technical articles or papers.

With the developed device and with a small adaptation to the air inducing orifice this phenomenon could be investigated as well.

### **3.2.8 Air pumping**

Morgan *et al.* (2003), in his chapter about aerodynamic sources, investigates the “movement” of air inside the tread pattern as being most commonly cited to as “air pumping”.

The air pumping process involves the sudden outflow of air trapped in the grooves of the tread pattern or road surface texture when the tyre comes in contact with the road surface. Those air pressure modulations cause significant levels of noise, particularly on smooth pavement surfaces.

If the pavement is porous some of this energy is dissipated through the pavement’s porosity, thus less noise is radiated to the surroundings. Air resonance inside the grooves is possibly affecting the noise generation mechanism as well, but his claim is not supported by measured data.

Eisenblaetter *et al.* (2003) states that air pumping is believed to be present at the leading edge of the tyre/pavement contact area.

Other measurements show that there is a sudden increase of pressure just in front of the leading contact edge, Lesniewicz *et al.* (2014), but in the author’s point of view, this hardly qualifies as “air pumping” related to the tyre grooves or tread design.

It seems that air pumping is present due to the rotating direction of the tyre body that is trying to compress the air, as a rotating cylinder getting in contact with the pavement. One has to bear in mind that this

is the primary function of industrial screw air compressors that squeeze and compress the air in a continuous rotating motion.

In the same paper Eisenblaetter mentions that at the trailing edge, there is an air induction effect and air is sucked in vigorously. Again the author believes that the above phenomenon (although true) is not dependent on the tread or groove design of the tyre but on the tyre's behaviour as a rotating cylinder.

One has to notice the water distribution of a rotating tyre on a wet day when the tyre's leading edge is creating a pressure wave, pushing water to the front and at the trailing edge as it is sucking water in, but not due to the tyre's tread design but due to the tyre's behaviour as a rotating cylinder.



**Fig. 3-15** Water mist at trailing edge

Simultaneously the water mist behind the trailing edge is partially created due to the rubber/water cohesion that is suddenly interrupted by centrifugal forces.

Therefore it is suggested that air pumping is not depended on the tread and groove design.

It seems that it became a common ground in several publications but is based on the tyre's behaviour as a cylinder (in some cases as an infinite cylinder).

The developed device cannot measure such phenomena since no dynamic measurements can be performed with it.

### **3.2.9 Pavement aging**

One of the aspects that interferes most with the noise producing mechanism is the type of the pavement on which the tyre is rolling. In studies performed in Europe concerning the acoustic behaviour of road pavements, Gibs (2005), has concluded that the aging of the pavement surface and the progressive clogging of the pavement's pores contribute to the problem.

Regeneration of the road surface and cleaning of the clogged pores has been tried in several countries with good results but only for a limited duration. It has been found that some pavement mixes behave better



than others but all have the tendency to alter their acoustic emission by passing time, even though some are more durable than others.

Porous pavements may have a life expectancy more than 10 years but at the same time these pavements tend to suffer more in clogging than thin laid smoother asphalt pavements, so in general, porous pavements are no longer implemented in several European countries.

In the same paper another problem of the porous pavement was observed, that is related to the higher and faster heat radiation of a porous pavement, compared to a thin layer asphalt mix, due to its increased radiating area thus in winter conditions freezes faster and at lower temperatures, thus providing a hazardous pavement.

Ponniah *et al.* (2010) mentions that the permeability measurement, using the outflow meter based on ASTM E2380 test procedure provided a good indicator of the porosity of the pavement test sections. So since an accepted measuring technique exists on how to measure the porosity of a pavement, it could be used to measure a reference surface that could be manufactured and used with the developed device to simulate any kind of pavement porosity.

As mentioned in other chapters, the proposition of this thesis to make tyre measurements on smooth and closed pore surfaces is not a prejudice that has to be broken but a fact imposed by measurements for making better and accurate measurements.

In the study of surface friction characteristics Karol Kowalski (2010), concluded that the influence of the traffic volume, implements changes in the frictional properties of the pavements and the friction values of a new pavement initially increases, most likely due to wearing-off of the binder film from the surface of the aggregate particles.

After this initial increase, the friction values decrease and then stabilize at a lower level (terminal level). Once the terminal level is reached, no further traffic-associated changes due to friction are observed.

This gradual aging of the surface is also a major contributing factor in noise generation, and the older the pavement is, the higher noise level it produces. It has to be clear than when the term pavement aging is used it is not referred to the physical age of the aggregates or the mix used, but to the condition of the surface that is being polished as time passes and is traffic dependent.

Also a lot of typical debris are present and enhance the clogging of the surface, such as environmental dust, rubber deposits, brake material deposits, dirt etc. Polishing may be referred to a polished and glazed

surface (with low friction coefficient) or as polished aggregates that tend to be smoothed over time depending on their initial hardness.

As known to all drivers and stated in the above project as well, is that for many pavement sections, the left and right wheelpaths had lower friction than the center of the lane. Most likely, this phenomenon is related to the unequal exposure of these areas to the tyres of the passing vehicles.

If one considers that the same phenomenon may be present during tyre noise measurements with the existing measuring techniques (CPX trailer technique or the Pass By technique) that are used widely today, a question mark may be risen on the conformity of the procedures and results used for noise classification and labeling of the tyres.

Trevino (2006), has studied the pavements in Texas USA that are in general constructed as concrete pavements instead of asphalt and agrees that after 3 years they become noisier due to aging.

However in a later chapter he states that

It is generally accepted that as a pavement surface ages it becomes louder, but this general perception is not necessarily true. The common hypothesis supporting this premise is that, with time, the pavement air voids become clogged with dust and other debris, and when the voids are filled with material, they can no longer absorb sound, making the surface louder.

This is true in many cases, and the desirable acoustic properties can be restored with cleaning of the porous surface. However, the usefulness of cleaning procedures is the subject of debate. An instance in which an aging pavement does not become louder with time is when a non-porous riding surface (e.g., a concrete pavement) gets polished with use and loses its texture, making it smoother and hence, quieter.

This statement may be confusing to a reader but one has to consider the concrete pavement manufacturing and pouring method, that allows some stone aggregates to be risen from the pavement, thus they are able to induce vibrations to the rolling tyres, and when those aggregates are deteriorated with time, then the ride is smoother and becomes quieter.

A strong point that a smooth and closed pore pavement is louder than a smooth open pore one is emphasized in this thesis during the preliminary measurements using our CPX trailer over both surfaces where an increase of more than 10dB was measured in the high frequency area over the closed pore surface.

The FEHRL Final report on Tyre Road noise Vol1 (2005), examines the properties of the road pavement and compares the acoustic behaviour of a prototype road surface constructed with the ISO 10844 guidance and several typical SMA and HRA road surfaces.

SMA stands for Stone Mastic Asphalt and HRA stands for Hot Rolled Asphalt, all with different stone aggregate size.

Hot rolled asphalt (HRA) is a dense asphalt concrete with 20mm stones rolled into the top of the surface and may be considered as a rough textured surface.

The report concluded that for 1dBA noise reduction on the ISO surface, an average reduction of 0,65dBA on SMA with small aggregate size 8-11mm was measured. For the rougher surfaces such as HRA or SMA with larger aggregates the corresponding reduction was less than 0,29dBA.

The report agrees that the ISO surface is constructed in such a way as to correlate to real driving conditions, but as the same report states, different roads produce different noise.

The above intensifies the author's point of view that tyre noise measurements should not be performed on ISO surfaces and a new type of smooth closed pore road surface must be implemented, guarantying better comparative tyre noise measurements.

### 3.2.10 Horn Effect

In his analytical and BEM models, Ledee *et al.* (2000) takes into account the assumption that the tyre is considered as a rigid cylinder of infinite length for the horn effect to be valid.

In Acoustics it is common practice to calculate the noise enhancement due to reverberation in rooms with “normal” dimensions, in order to be allowed to use the Sabine or Eyring equation (that require “normal” room dimensions).

In all cases where the room is of abnormal dimensions (such as a long corridor) the calculations suffer considerably and should be used with caution. So from the author’s point of view, all models that use abnormal dimensions (such as the above mentioned infinite cylinder) although they may produce the requested results, should be used with caution as well. A better approach would be to use a solid ring, since aerodynamic behaviour of a ring is different of a cylinder.

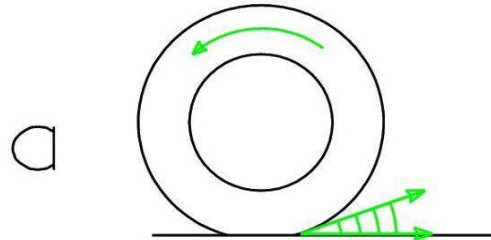
In his study Iwao *et al.* (1996) refer to the horn effect in a experiment using a small loudspeaker imbedded at the tyre’s circumference and concludes that there is an enhancement of radiated noise when the loudspeaker is at the  $10^0$  position (just in front of the road contact area) and several millimetres over the road surface. In this way a mirror sound center is created and reflection can take place.

The above result seems to be true since the reflection of the road surface is used and as known each acoustic reflection on a non porous and stiff surface increases the sound pressure by 3dB per reflection. He also states that due to multiple reflections in the horn there is a sound pressure amplification.

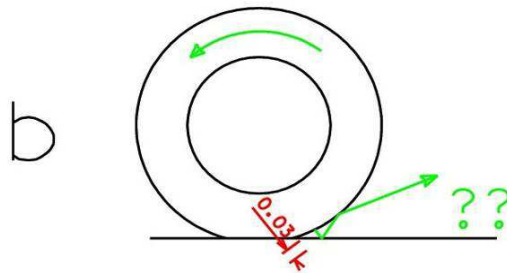
The only problem the author has with the above approach is that due to the shape of the horn (one flat surface and one curved) there is a slim possibility for building up considerable sound reflections especially if it is understood that the noise generating acoustic center is at grazing incidence with the flat road surface and not in the middle of the throat of the horn.

### 3.2.11 Reflection behaviour of the Horn

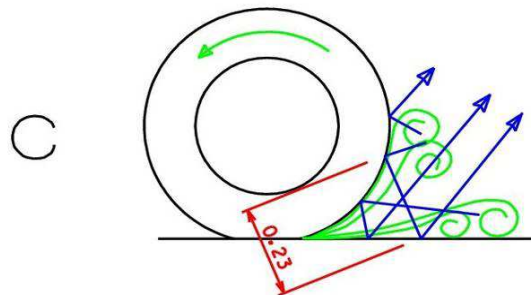
In figure “a” the only possible way for the noise signal produced in the tyre/road trailing edge to be radiated outwards is in a straight line since the noise source is at contact with the road surface and no acoustic reflections can be created.



In figure “b” and with two assumptions, a reflection could be developed.



1<sup>st</sup> assumption: the acoustic wave is never a straight line but a developing wave. (in the texts the propagation direction is usually drawn as a line, but all understand that it means “wave” and is only drawn as a line for clearer drawings.) So since it is expanding as a wave, a part of the wave could be reflected on the tyre or on the road.



2<sup>nd</sup> assumption: since the tyre’s groove is about 7-10mm deep it may allow the new allocation of the sound source a few millimetres above the road surface, and reflections could be generated.

**Fig. 3-16** Noise radiation and reflections at trailing edge

It has to be mentioned however that under these circumstances the largest distance a reflection could be generated is around 3cm that is equal to 0,03m of wave length “λ” and in term is translated into 11.500Hz !! from the following equation.

$$f = c / \lambda \rightarrow f = (20,05 * \sqrt{T}) / \lambda$$

where

f= frequency in Herz

c= speed of sound at 20°C (m/sec)

T = deg Kelvin plus temperature of environment in deg. Celsius

λ = Wave length in meters

From the above frequency calculation it is clear that even if the above reflection could be build, it is of no importance at all to the sound receiver since it is of an extra high pitch and is possibly hidden under other noises of higher amplitude.

In figure “c” however a different phenomenon is presented that could be misunderstood as horn effect but it is not. The air turbulence that is created by the rotating tyre (either by its groove design or as a rotating body) is actually a multiple sound source since each large eddy is a sound source by itself.

If one takes into account the distance from the road surface, each large eddy may be fully developed, then we may have a significant agent that can implement reflections to the system.

As the figure shows a distance of 0,23m could be evolved (or even larger distances) and with the same equation used above we may get a frequency in the area of 1500Hz. This frequency seems more promising to be heard by a listener and seems closer to the noise pattern the tyres are emitting.

The author strongly believes that the term “horn effect” should be replaced or at least reconsidered since it subconsciously implies to acoustic horn (wind) instruments that by itself is a misleading approach.



**Fig. 3-17** Straight design horn

It has to be mentioned that the straight cones do indeed generate reflections by design since they don't have an exponential bellmouth but are straight through in design. They also do not handle air flow but only sound waves, so excessive air turbulence inside the straight design horn is not generated.

Meaning that the typical straight cones can produce reflections and sound level enhancement and further on they can guide the amplified sound to a straight through direction, making the noise source a highly “directional” one.

In all bellmouth designs, were air flow is present the phenomenon of turbulence and large eddy generation is always present and in some cases it is requested by the user.

One has to notice all the different bellmouth designs in pneumatic instruments that in general use the same acoustic pipe principal,

produce the same frequencies but can be clearly distinguished and recognized from their different tone / hue.



**Fig. 3-18** Fishtail pipe

Another well known factor not in the scientific community but in the bikers' world, is that when a fish tail pipe is added to the gas exhaust of a motorcycle the produced noise is getting a little higher in amplitude but mostly it alters significantly its pitch (it is getting lower in frequency) and is no more of steady state but rather more abrupt.

This can be explained a) due to the induced turbulence explained above and b) do to the destruction of the circular end pipe reflection phenomenon.

Selamet (2000) describes this end pipe reflection phenomenon both for circular and orthogonal pipes, that is a significant factor in the sound absorption mechanism of ducts as they exit to the environment and they interact with an infinite wall that the environment represents, that reflects some energy back to the duct opening.

In Acoustics it is known (and described in detail in the ASHRAE and SMACNA duct design manual) that the progressive growth of a pipe or duct cross section should be kept under 7% slope in order to obtain the smoothest air travel in the pipe or duct and not regenerate turbulence dependent noise.

The specific design of fish tails is using this very abrupt expansion in order to generate turbulence and destroy the steady state flow of exhaust gases. On the other hand the end pipe reflection is used in exhaust gas manufacturing and in duct grilles design in order to increase the absorption of acoustic energy as the fluid (air) exits to the environment via a hole of specific dimensions.

In our case the curved tyre rubber surface may be considered to be a "fishtail" so one should expect the creation of excessive turbulence and increased noise level.

Khavaran *et al.* (2012) in his research on dual stream air jet mixing noise, issued a figure that describes the 4 mixing regions that a primary

and a secondary air jet undergoes when exiting to the environment.

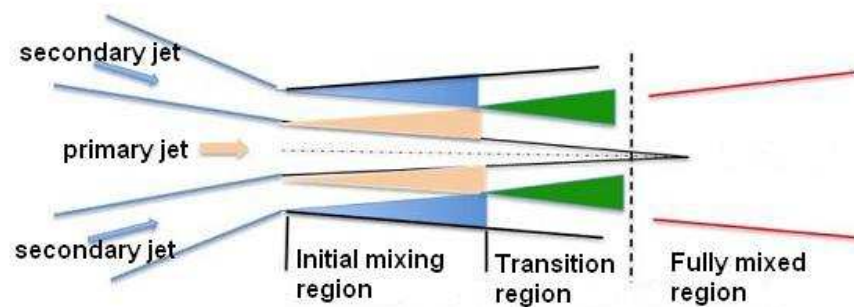
1<sup>st</sup> region : distinct primary and secondary air jet (air jets are still inside pipes or nozzles)

2<sup>nd</sup> region : Initial mixing region (just outside the pipe or nozzle)

3<sup>rd</sup> region : both air jets undergo a transition region and

4<sup>th</sup> region : both air jets are fully mixed

During his measurements he concludes that the noise level in the transition region has a higher amplitude and in the fully mixed region is of lower amplitude as a function of the velocity ratio.



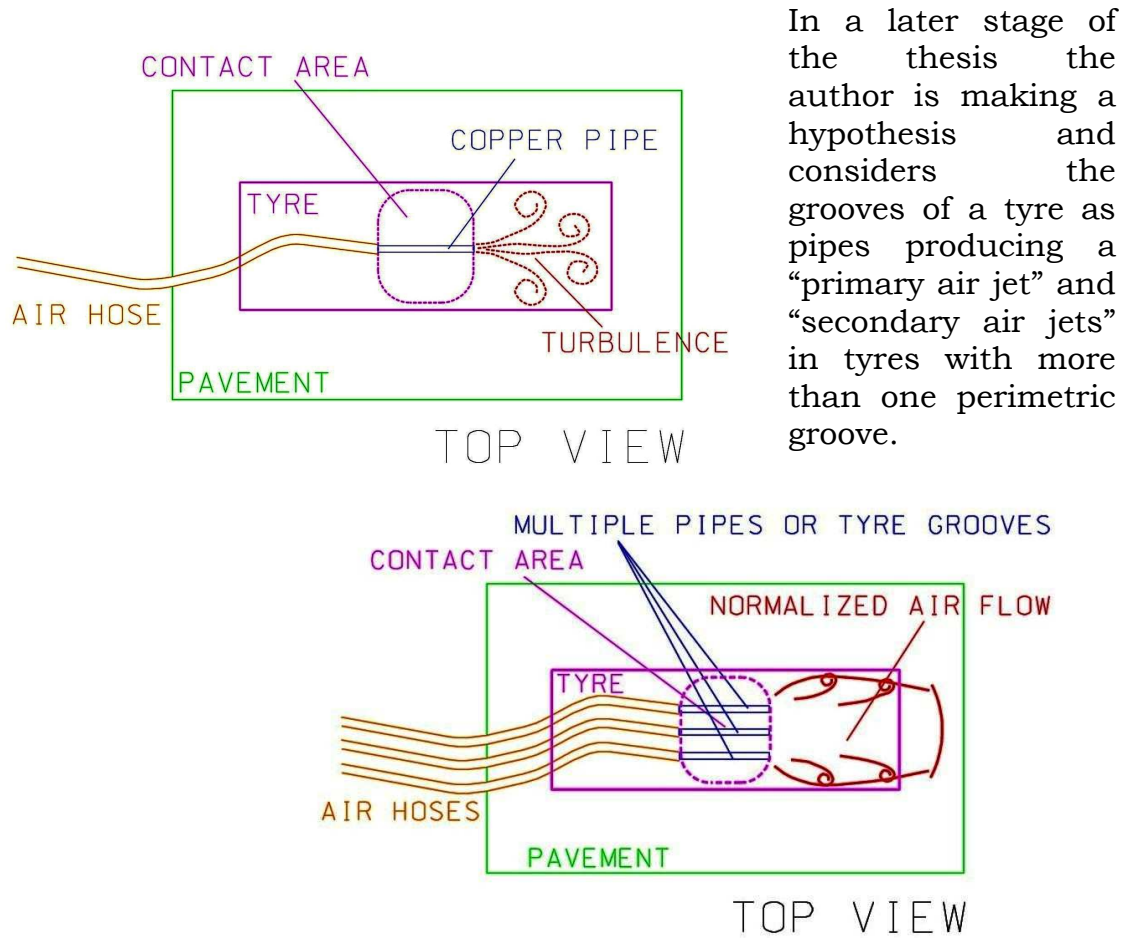
**Fig. 3-19** dual stream air jet - A. Khavaran et al (2012)

Henderson *et al*, (2008), in experiments conducted in the NASA Langley wind tunnel, concluded that broadband shock noise reductions of up to 8 dB are achieved in a single stream jet with injection of a second air stream with mass flow rates of 1.2% of the core mass flow.

Most researchers have investigated the need to reduce noise dissipation from aircraft engines and have introduced the dual air stream jet in the exhaust of aircraft engines. The author is familiar with the good results of dual air stream noise reduction from the former use of air nozzles of such design, in industrial noise insulation projects where the introduction of such double nozzles has reduced significantly the noise amplitude in pneumatic lines.

It seems that the secondary air jet is contributing to the overall noise reduction of a single primary air jet by producing a steadier mixed flow with less large eddies so a further investigation on this specific topic should be undertaken by tyre manufacturers and researchers.





**Fig. 3-20** air flow with one or multiple grooves

As proven during the tests performed with the CPX trailer and with the Device, with tyres with one, two and three grooves, there is a logical claim that each tyre groove could be considered as an air jet, and be subjected to air jet behaviour. (explained further in other chapter)



## **4 ACOUSTICS**

### **4.1 Near Field measurements**

In all types of acoustic measurements, the result is influenced by the acoustic field the measurement is performed in, meaning if big obstacles or reflecting facades are near the measuring area, they contribute to some extent to the actual measurement [116].

The same problem, but even worse, is present when the measurements are performed in a closed room or surrounding structure, as reverberation may significantly alter the acquired noise data.

One way to overcome the above problems is to make the measurements in an anechoic field (where no reverberation is produced) or treat the interior of the room accordingly with sound absorbing materials in order to absorb the reflections.

It has to be noted (but not analyzed here) that reverberation is a frequency dependent phenomenon, so data may be altered in a different magnitude according to its acoustic frequency propagation.

Another way to reject the reverberation influence to a great extent, such that the actual measurement is not affected by it, is by conducting the measurement in the acoustic “near field”.

Near field and far field measurements are strongly dependent on the emitted acoustic frequency or wavelength, so if a measurement is performed very close to the sound source that has small physical dimensions, and if the propagated wavelength is of similar length compared to the distance between source and instrument, then the data is not strongly influenced by the surrounding background noise or the reverberations from nearby obstacles.

## 4.2 Direct sound in closed rooms

“Direct sound” is the sound that travels directly from the sound source to the receiver (or to the measuring instrument) where no audible sound reflection is involved, and the room reverberation is of no importance.

So the measured sound level is not affected by the acoustic characteristics (reverberation) of the room. Therefore, the level of the “direct” sound ( $L_{\text{direct}}$ ) has the same value at a given distance as it would have in an open area, away from any reflective surfaces or in an anechoic chamber.

At some point after a specific distance (called critical distance, depending on the dimensions of the closed space), the reflected sound waves start to affect the measured values, so the closer the instrument is placed to the noise source, it can be certain to make “anechoic” (without reflections) measurements even in closed, non-treated rooms. This area is called “near field”.

This “near field” phenomenon is used in this project in order to place the SPL measuring instruments at a distance from the noise source no further than 10cm and is the best way to obtain valid noise data.

## 4.3 Wavelength

The wavelength, symbolized internationally by the Greek letter  $\lambda$ , is associated with frequency  $f$  (Hz) and the speed of sound (in m/s or ft/s) in the simple equation

$$c = f * \lambda$$

where

$c$  = sound velocity (m/sec)

$f$  = frequency (cycles per sec or Hz)

$\lambda$  = wavelength (m)

for the propagation of sound through air  $c = 20,05 * \sqrt{T}$

where  $T$  = degrees Kelvin (273,2) + degrees Celsius of the environment

The speed of sound in air when the temperature is 21,2°C =

$$c = 20,05 * \sqrt{T} = 20,05 * \sqrt{273,2 + 21,2} = 344m / sec$$

The wavelength, depending on the system of units, is expressed in metres or feet. In most noise problems, the wavelength is a very important parameter and must always be mentioned when making reference to audio frequencies or spectral analysis, in order to perceive or understand the correspondence between wavelength and frequency.

Since the main acoustic data in this experiment is mostly in the spectral area of 800-4000Hz , then

$$\mathbf{c = f * \lambda \rightarrow \lambda = c / f = 344 / 800 = 0,43m}$$

$$\mathbf{c = f * \lambda \rightarrow \lambda = c / f = 344 / 4000 = 0,086m}$$

Using the above information, if the positioning distance of the SPL meters is kept at about 10cm from the noise source (the tyre), it can be assumed that they are in the “near field” for most of the required spectral band.

As seen in a later chapter, the CPX trailer data lies between the above frequency limits ~800 – 4000 Hz, so all the measurements are in the mid-high frequency range and well under the influence of the acoustic “near field”.

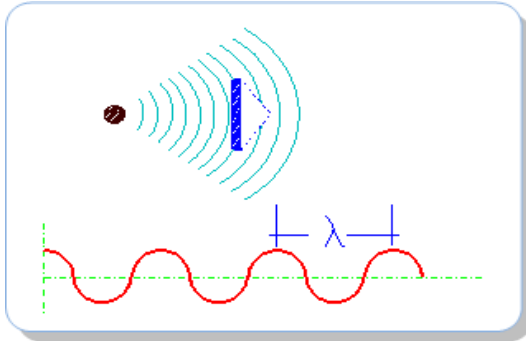
The physical dimensions of a compact obstacle may act as an excellent, moderate or bad barrier to the rectilinear propagation of the sound wave, and the expected noise reduction depends always upon the wavelength of the sound wave.

In the following graphs a schematic analysis is sketched.

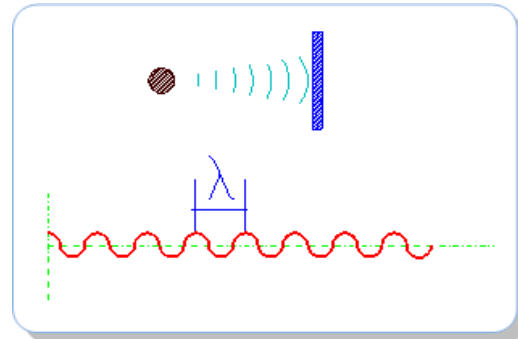
If the same rigid closed pore barrier of specific physical dimensions is used in both examples, two phenomena will be observed.

- a) If the emitted noise has a smaller wave length ( $\lambda$ ) than the barrier’s physical dimensions, it will be blocked by the barrier

- b) If the emitted noise has a bigger wave length ( $\lambda$ ) than the barrier's dimensions, the barrier will be ignored



**Fig. 4-1.** Big  $\lambda$



**Fig. 4-2.** Small  $\lambda$

With the above example the significance of the wave number is better understood.

## 4.4 Decibel

The span of sound pressure (in units Pa or Nt/m<sup>2</sup>) found in acoustics is so wide that it is more convenient to use the sound pressure level (in decibels - dB) resulting from logarithmically calculated pressures.

Identification: Level (in dB) is the logarithm of the ratio of a measured quantity to a predetermined reference quantity of the same species. The base of the logarithm, the reference quantity and the kind of level must be listed.

The «Level»  $L$ , in response to each sound «pressure»  $p$ , defined as decibel, is

$$L_p = 10 \log_{10} (p / p_0)^2 \text{ dB} \quad \text{or} \quad L_p = 20 \log_{10} (p / p_0) \text{ dB}$$

where

$p_0$  is the reference value and always constant and equal to  $2 \cdot 10^{-5} \text{ Nt/m}^2$

The above value is taken as a reference because it is approaching the minimum sound pressure that can be heard by a normal, young adult ear in the frequency range in which the ear is most sensitive.

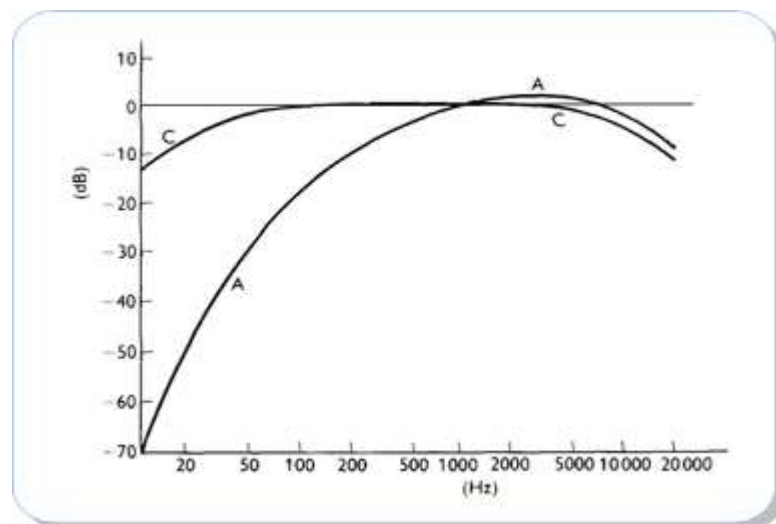
Weighted sound level is the level obtained from a sound level meter which is filtered with a reference filter. (the calculation is done using internationally accepted standard weighting curves).

It is known the human ear is not sensitive to the same extent to all audio frequencies and is level dependent as well.

For this reason, although the sound level of two different sounds may be the same, the first sound may be considered stronger than the second if the first sound power is concentrated in a frequency range where the human ear is most sensitive.

To obtain a more representative indication of the SPL meters, closer to the sensitivity of the human ear, the so-called «frequency-weighting networks» are introduced, which are electronic weighting circuits integrated into all SPL meters and most FFT software.

These are electronic filters that modify the value of the actual sound pressures on the sound level meter, per frequency, so that the instrument is less sensitive to frequencies where the human ear is less sensitive [117].



The sound levels are **Fig. 4-3.** A and C weighted values measured with SPL meters that have integrated at least one or two weighting networks, usually the “A” and “C”, and some have also the “unweighted” or “Z” value.

The unweighted or “Z” values are not passed from any weighting filter and show the actual sound pressure at the specific point in space but are generally used for research purposes and not as a value that is affecting human perception of sound.

Regardless of the weighting circuit used, the main unit is always the decibel (dB), and it is a common practice in acoustics to attach the appropriate letter in parentheses after the unit symbol as a reminder of the circuit used, e.g. dB (A).

The A-weighting units are widely used in noise control work, because they resemble the specific behaviour of the human ear at levels from 30dB up to 85-90dB.

## 4.5 Using FFT software

The Fourier Transform is a mathematical tool developed and named after Jean Baptiste Fourier (1768 - 1830) and is commonly used to convert a signal from the time domain (amplitude-vs-time) to the frequency domain (amplitude-vs-frequency). A frequency domain plot is also known as a spectra plot.

The Fast Fourier Transform (FFT) is a computationally efficient implementation of the Fourier Transform developed by J.W. Cooley and J.W. Tukey in 1965. The Fast Fourier Transform is limited to block sizes which are even powers of 2.

For example, if a FFT is performed on a pure sinusoidal signal, the resulting spectra would be single peak (line). Real world signals are a composite of many sinusoidal signals; examining the signal's spectra closely shows the frequency tones which are present.

*The following is from the acoustic software developed by PioneerHill Software.*

In the real-time mode, the program acquires an FFT sized block of digitized sound data directly from the sound card, computes the spectrum and displays the results. The program will continuously acquire new data, average it with previous data, and display the results until it is stopped.

By default, the last 60 seconds of digitized audio data is stored in a temporary buffer. Switching to the Recording or Post Processing modes



will allow conversion of this buffer into a WAV file for further processing.

Often it is useful to run the analyzer in the “real-time” mode while making preliminary measurements and then switching over to the “Recorder” mode before making the final measurements.

The Averaging settings of the program control how the measured spectral data is averaged. There are the Free Run and the SLM settings.

#### **4.5.1 Free Run (blocks) setting**

This is the default mode and updates the analyzer each time a new FFT block of data is computed. In this mode, the average block size directly determines how many spectra blocks are averaged together to compute a moving average. For instance, if the averaging block size is set to 4, the spectrum currently displayed is a moving average of the previous 4 traces.

If the measured signal is rapidly changing in frequency, a low averaging block size should be used. One can use a high block size to "dig" out a steady state signal buried in a noisy background.

#### **4.5.2 Sound Level Meter (SLM) setting**

This mode of the program sets the averaging algorithm to match that of a standard Sound Level Meter (SLM). The average speed controls the spectral averaging period and decay time as follows:

- Off - no averaging is performed.
- Fast - computes a running average with a decay rate of 32dB/sec.
- Medium - computes a running average with a decay rate of 20dB/s.
- Slow - computes a running average with a decay rate of 4dB/sec.
- Forever - accumulates the data for as long as the analyzer is running.

Exponential averaging should be used when the Sound Level Meter mode is selected.

### 4.5.3 Averaging Type

**Exponential** - this method produces an average where the most recently acquired spectra have more influence on the average than older ones. If one was to suddenly shut off the input signal, the decay rate will follow an exponential curve. Exponential averaging should be used when the Sound Level Meter mode is selected.

**Linear** - this method is a straight linear average of the spectra over time. Each spectra block contributes equally to the average. This type of averaging is also known as "stable averaging".

**Vector** - this method performs a complex (vector) average of successive spectra over time. Because vector averaging includes the phase component in the computation, triggering must be employed if meaningful results are to be expected. This type of averaging is also known as "synchronous averaging".

Exponential averaging is the default as it is more computationally efficient and was used for the purpose of this project.

## 4.6 Glossary

*From: <http://www.vibrationandshock.com/glossary.htm>*

**Acoustics.** The science of sound. The nature, cause and phenomena of the vibrations of elastic bodies; and the vibration creates compression waves or wave fronts which are transmitted through various media, such as air, water, wood, steel, etc.

**A/D Converter.** A device that changes an analog signal, such as voltage or current, into a digital signal (consists of discrete data values).

**A-weighting.** Emphasis given by filtering sound measurements, with the goal of compensating for the non-flat frequency response of human hearing, in order to get numbers approximating human response.

**Background noise.** The level, from all sources that interfere in a measurement, independent of the presence of a data signal.

**Bandwidth.** The frequency range (usually stated in hertz or Hz) within which a measuring system can accurately measure a quantity.

**Broadband.** Acoustic signals of a full spectrum that are unfiltered. Signals at all frequencies contribute to the measured value.

**Calibration.** An orderly procedure for determining sensitivity as a function of frequency, and level.

**decibel.** Ratios of identical quantities are expressed in decibel or deciBel or dB units. The number of dB is a ratio against some standard or reference value in terms of the base 10 logarithm of that ratio.

**Dynamic Range.** The ratio of a specified maximum level of a parameter, such as power, current, voltage, or frequency, to the minimum detectable value of that parameter.

**FFT or Fast Fourier Transform.** A popular computer method of shifting data from the time domain to the frequency domain.

**Frequency.** The reciprocal of the period  $T$  in seconds (of a periodic function) ( $1/T$ ). Usually given in hertz (Hz), meaning cycles per second (cps).

**Level.** The (usually base 10) logarithm of the ratio between a quantity and a reference quantity. For acoustic measurements the reference quantity is 20 micropascals.

**Logarithmic scale.** A method of displaying data (in powers of ten) to yield maximum range while keeping resolution at the low end of the scales.

**Microphone.** An instrument which converts a relatively small dynamic pressure change into an electrical signal.

**Noise Floor.** The minimum discernible signal that can be detected by a receiver.

**Octave.** The interval between two frequencies differing by exactly 2:1.

**Peak.** Extreme value of a varying quantity, measured from the zero or mean value. Also, a maximum spectral value.

**Precision.** The smallest distinguishable increment (almost the same meaning as *resolution*); deals with a measurement system's possible or design performance.

**Repeatability.** (1) The maximum deviation from the mean of corresponding data points taken under identical conditions. (2) The maximum difference in output for identically-repeated stimuli (no change in other test conditions).

**Resolution.** The smallest change in input that will produce a detectable change in an instrument's output. Differs from precision in that human capabilities are involved.

**RMS or Root-Mean-Square value.** The square root of the time-averaged squares of a series of measurements. In the exclusive case of a sine wave, the RMS value is 0.707 the peak value.

**Sound.** (1) An oscillation in pressure, capable of evoking the sensation of hearing. (2) The sensation of hearing.

**Sound level.** The quantity in dB measured by a standardized Sound Level Meter. The reading is  $20 \log_{10}$  of the ratio between a given sound pressure and 20 micropascals.

**Spectrum analyzer.** An instrument which displays the frequency spectrum of an input signal, usually amplitude vertical vs. frequency horizontal.

**Threshold.** The smallest change in a measured variable that gives a measurable change in output signal.

**Weighting.** Emphasis or attenuation applied to sound measurements at certain frequencies. C weighting is essentially flat. A weighting attempts to compensate for the non-constant sensitivity of human hearing at certain frequencies.

## 4.7 Instrumentation used

The 2 SPL meters used in this project are:

Calibrated digital "Type 1" instruments, made by Delta\_Ohm

1<sup>st</sup> SPL meter  
Code HD2010 –  
Serial No 09052941900 &

2<sup>nd</sup> SPL meter  
Code HD2010UC -  
Serial No 10032342190



**Fig. 4-4.** Sound Level Meter (SPL)

**Table 4-1.** SPL Meter Technical Characteristics

Standards	Class 1 group X according to IEC 61672:2002 and class 1 according to IEC 60651:2001 and IEC 60804:2000 Class 0 according to IEC 61260:1995 Type 1 according to ANSI S1.4-1983 and S1.43-1997 Class 1-D, order 3, Extended range according to ANSI S1.11-1986
½ inch Microphones	MK221 condenser microphone prepolarized (200V), for free field, high stability, type WS2F according to IEC 61094-4.
Dynamic Range	21 dBA ÷ 143 dB Peak
Linear Field	80 dB
Acoustic Parameters	Spl, Leq, SEL, LEP,d, Lmax, Lmin, Lpk, Dose, Ln
Frequency Weighting	Simultaneous A, C, Z (only C and Z for Lpk)
Temporal Weighting	Simultaneous FAST, SLOW, IMPULSE
Integration	From 1s to 99 hours with Back-Erase function
Spectrum Analysis	Parallel filters in real time complying with class 1 specifications according to IEC61260 Octave bands from 16 Hz to 16 kHz Third octave bands from 16 Hz to 20 kHz Average spectrum (AVR) mode
Statistical Analysis	It displays up to 3 percentile levels for, L1 to L99 “Advanced Analyzer” Probability distribution and percentile level calculation from L1 to L99 Parameter: A, C or Z weighted, LFp, Leq, Lpk (only C or Z for Lpk) - Sampling frequency: 8 samples/second Classification: Classes of 0.5dB
Reverberation Time	Reverberation time measurement using sound source interruption or impulse response integration
Profile Data Logging	1 profile with programmable sampling from 1/8 s to 1 hour and 3 profiles with 2 samples/second
Spectrum Data Logging	Programmable sampling from 1 second to 1 hour (AVR mode)
Display	Backlit graphic display 128x64 3 parameters in numeric format Profile LAFp with 8 samples/second Octave band spectrum from 16 Hz to 16 kHz Third octave band spectrum from 16 Hz to 20 kHz “Advanced Analyzer” option Graph probability distribution of sound level Graph of percentile levels from L1 to L99
Memory	Internal, equal to 4 MB (4 profiles for 23 hours or over 23 days recording 3 parameters + spectra per minute) Expandable to 8 MB External, via the HD2110MC memory card interface, using MMC or SD cards up to 2 GB
Input/Output	RS232 serial and USB interfaces AC output (LINE) - DC output
PC Programs	DeltaLog5: PC interface for download, setup and sound level meter

	management (supplied with the instrument) DL5 Noise Studio: Analysis modular program
Operating conditions	Working temperature -10÷50°C, 25÷90%RH (without condensation), 65÷108kPa. Protection degree: IP64
Power	4 alkaline or rechargeable NiMH type AA batteries or external 9÷12Vdc 300mA
Dimension and weight	445x100x50mm with preamplifier, 740 g (with batteries)

The laptop sound card is a typical commercial digital item, by Realtek High Definition Audio issue 5.10.0.5413, installed in the laptop with Intel Core2 Duo CPU T7250@2GHz, 2Gb Ram with a two channel spectral analysis program, as mentioned above, that runs in real time. The software has the capability to run both channels (left & right) synchronized, when input data from the two SPL meters are used.

Both SPL meters and Laptop's soundcard are calibrated using a "type 1" acoustic calibrator made by Delta Ohm, code HD2010 S/N 08004660.

The SPL meter and calibrator have calibration & verification reports that are valid and up to date (reissued every year from the Italian SIT metrological institute).

## 4.8 Measurement accuracy

As stated earlier, in order to make the noise measurements, two different sets of instruments (SPL meters and DSP laptop board) are used both for the CPX trailer noise measurements and the researched device noise measurements, and their interaction could under some situations be problematic.

One possible problem could be the frequency range of all the instruments involved. For example, one instrument could be measuring in a different frequency range to the other one, so the collected data could be affected. This was not the case in this project, since all instruments were calibrated to measure within the same frequency range.

Another typical problem is the dynamic range of each instrument, and in order to avoid over- or under-loading of the measuring chain, since the SPL meters have a preset linear dynamic range of 80dB, the DSP board on the laptop was set to 16 bit sampling precision so a 96dB

dynamic range was obtained safely overlapping the SPL meter's dynamic range.

Another problem when using DSP boards is that the microphone input on some sound cards utilizes Automatic Gain Control (AGC).

If this is the case, calibration with a reference signal will be impossible since the card's gain is constantly changing according to the measured level and calibration of the amplitude axis will be impossible.

So AGC was not selected for this project and the input level was kept constant.

#### **4.8.1 Frequency accuracy**

The frequency accuracy depends directly on the accuracy of the sampling clock on the sound card. This is typically a fraction of a Hertz (Hz). Older 1<sup>st</sup> generation sound cards had some inherent problems but new design DSP boards (even the very cheap ones) and the much faster new computers are no longer problematic.

#### **4.8.2 Amplitude accuracy**

By default, the analyzer is calibrated to show the relative power levels where 0dB is the strongest possible bit signal. It is possible to calibrate the amplitude axis by equating a known reference signal level with a measured sampling level; however, the frequency response of the sound card still comes into play (the frequency response of the sound card ultimately determines the accuracy of the measurement).

It is possible to use the microphone compensation feature to compensate for the frequency response of the sound card.

By measuring the response of a known reference signal (e.g. from a typical class 1 acoustic calibrator, or even from a white noise generator or swept sine measurement), one can determine the frequency response of the input circuitry of the DSP board and this was kept constant in this thesis also.

### 4.8.3 Octave Scaling accuracy

Historically, spectrum analyzers have utilized analog filters for each band and standards, such as ANSI S1.11-1986, have been developed which specify the performance of these filters.

SpectraPLUS (the program used) uses a Fast Fourier Transform (FFT) to compute the spectral data and then derives the octave data. This algorithm uses the same ISO center frequencies and bandwidths as analogue instruments; however, the FFT filtering method produces much steeper "shoulders". These digital filters meet or exceed the performance of traditional analogue filters.

### 4.8.4 Dynamic range

The theoretical dynamic range of the system is as follows:

- 8 bit sampling precision = 48dB
- 16 bit sampling precision = 96dB (selected)
- 24 bit sampling precision = 144dB

## 4.9 Calibration procedure of instruments

Since a measuring chain of different instruments was used, they had to be calibrated with a reference signal produced by a reference acoustic calibrator with a valid calibration report from a recognized metrological institute.

### Step 1:

The calibrator was inserted into the SPL meter's microphone and placed on a horizontal level surface without vibration or excessive environmental noise and produced a reference signal of 1KHz at a level of 94dB.



**Fig. 4-5.** Acoustic Calibrator

The screen of the SPL meter was checked and should show the same level 94dB.



If not and since the instruments are digital, a calibration procedure via preset calibration menus inherent in the specific instruments should be performed, but there was no need for this since the instruments were within the accepted limits.

The procedure was repeated with the same calibrator regulated to produce a level of 104dB and, again, there was no need to adjust the instruments.

It has to be noted that for absolute accuracy, the above procedures were performed with the 5 meter extension cables connected, even though they are reference low noise cables provided by the SPL meter manufacturer.

*(The extension cables were used for distant operation of the instruments during the field tests)*

So both SPL meters were calibrated.

#### Step 2:

Each SPL meter's unweighted output port was connected to the laptop's DSP board input and each one was driving the left and right channel respectively, of the two channel sound board.

The procedure mentioned in Step 1 above was repeated but, in this case, the DSP's input gain and the software's calibration menu were regulated accordingly, so the measuring spectral program showed the same level that the calibrator was producing and simultaneously shown on the SPL meter's screen.

All settings were kept unchanged throughout the project and, for cross checking purposes, they were repeated each time measurements were performed.



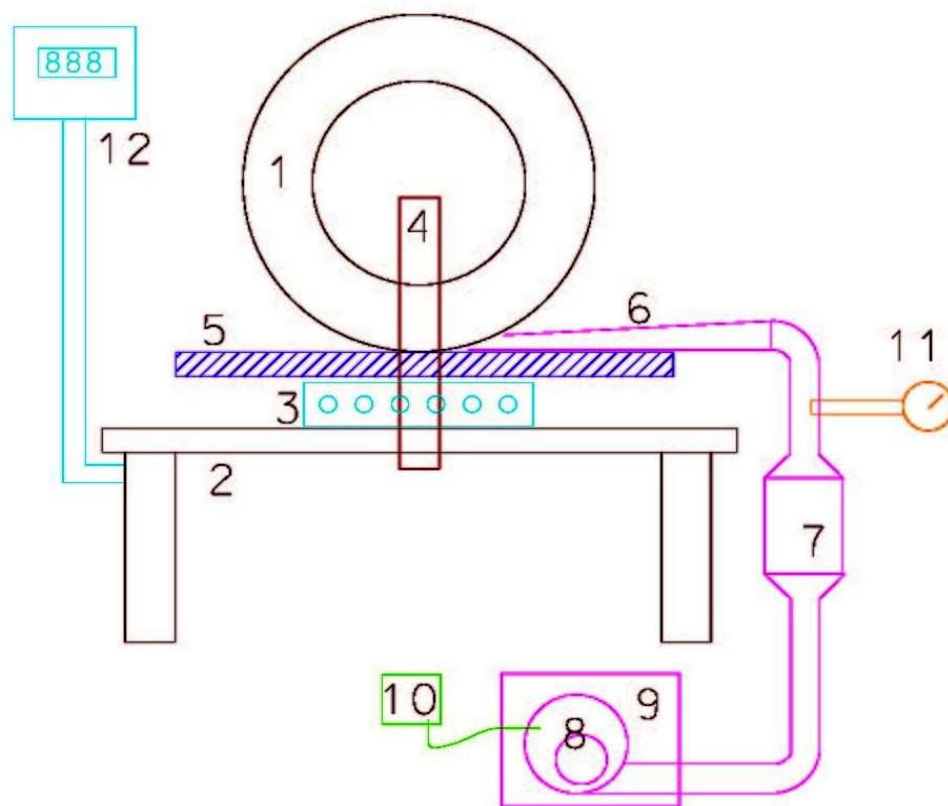
## 5 EXPERIMENTAL AND CONSTRUCTION WORK

### 5.1 Device experimental work - Overview

As mentioned in previous chapters, the device that is to be constructed must perform a series of tasks and be capable of making several kinds of tyre noise measurements.

As a general design, it must have a tyre holding mechanism, a noise generating mechanism, measuring instrumentation and a general holding structure.

The main constructional idea is:



**Fig. 5-1.** Prototype device design - general layout

1. Tyre or tyre model to be examined/measured
2. Table or supporting structure
3. Force scale (electronic)
4. Supporting mechanism of tyre and force applicator in order to simulate loading of tyre
5. Flat metallic surface or “textured” pavement material
6. Air orifice and interchangeable adaptor (according to tyre dimensions)
7. Sound Attenuator
8. High pressure fan
9. Sound insulated box
10. Control panel
11. Air Velocity instrumentation
12. Electronic Scale readout with output option to P/C

### **5.1.1 Device - Part description**

#### **5.1.1.1 *Tyre or model to be examined/measured***

(See 1) Different car tyres can be put on the apparatus/device, or even portion of tyres or real scale models or hand grooved models, etc. One of the objectives is to be able to measure existing tyres and the other one is to be able to measure non-existing tyres but only models of a tyre. The only restriction will be that the models must have a tyre/pavement contact area of actual dimensions and not under scale.

Diameter and width of tyre are not a problem (within limits) since different air adaptors (see 5) can be constructed at a minimum cost in order to have the better possible contact with the tyre or model's curvature.

#### **5.1.1.2 *Table or supporting structure***

(See 2) A rigid structure with metallic sections will be constructed, in order to support the total weight, the tyre and all necessary equipment.

#### **5.1.1.3 *Force Scale (electronic)***

(See 3) A measuring device is necessary in order to have control of the load force applied to the tyre and obtain repeatable conditions when comparing different tyres or experiments performed on different days. It is essential due to the expected deformation of the tyre's circumference, when under load, in real situations. The tyre/pavement contact area

will be different when the tyre is not loaded as per manufacturers' specifications, but also when the pneumatic air pressure is less or higher than the optimum or as suggested by the manufacturer. So air pressure must be monitored as well when a real tyre is measured.

#### **5.1.1.4 Supporting mechanism of tyre**

(See 4) It is known no tyre is a perfect circle, especially under load or having different air pressure at its contact area with the road/pavement. A "vice" will hold the tyre firmly in position and press it down and must be able to be regulated in order to apply the required loading force and produce the required "footprint" of the tyre. If a tyre model is to be used, it has to hold it down and produce the same expected footprint.

#### **5.1.1.5 Flat metallic surface or "textured" pavement**

(See 5) The main objective is to use a perfectly flat, smooth and thick (to avoid deformations) metallic plate. By using the flat, smooth surface all measured tyres will have one of the worst "variables" eliminated (that is pavement surface texture and porosity), so a tyre noise classification could be obtained since the only factor that changes is the tread pattern of the tyre itself.

However, with the same apparatus, all kinds of different textures of pavement could be prefabricated, standardized, and used. For example, porous asphalt, clogged asphalt, rough or smooth concrete, rubber road products, special mixtures, commercially available precast items, dry or wet pavement, etc.

#### **5.1.1.6 Air orifice and interchangeable adaptor**

(See 6) Since tyre dimensions and tread pattern design vary per tyre, this part must be interchangeable. It must guide the air to a specific area under constant velocity and pressure. The air volume should be able to be adjusted in order to simulate different car travelling speeds.

#### **5.1.1.7 Sound attenuator**

(See 7) A sound attenuator will be incorporated in order to minimize the noise from the high pressure air fan that is expected to travel through the duct and may alter the noise pattern from the tyre's tread. In order to keep backpressure to a minimum, the sound attenuator will be of a straight through design and, internally, all 4 walls will be lined with

12cm thick Rockwool, protected by a sound transparent perforated metal sheet.

#### **5.1.1.8 High pressure fan**

(See 8) The fan will produce the air velocity and volume needed. A high pressure fan was selected since a typical air compressor would not be able to produce the required air volume, and a simple fan would not be able to produce the required constant pressure to overcome the tread's back pressure.

#### **5.1.1.9 Sound insulated box**

(See 9) Since noise measurements will be taken in different locations, the surrounding environment must be as quiet as possible and not affect the measurement, so fan noise must be kept to a minimum.

#### **5.1.1.10 Control panel**

(See 10) User controllable variations in air flow can be obtained by varying the speed of the air high pressure fan, so installing an electronic inverter would be the best option.

#### **5.1.1.11 Air velocity instrumentation**

(See 11) A measure of the ducted air velocity must be taken in order to simulate the "vehicle's" velocity. Instead of a fixed instrument, a portable propeller-type anemometer can be used as well.

#### **5.1.1.12 Force readout**

(See 12) This is connected to the electronic scale (paragraph 3 above) and from its readout, the "loading" of the tyre can be altered by adjusting the "supporting vice" (paragraph 4 above) and the force applied by it.

### **5.2 Expected versatility**

As seen with the above device, a measurement could be performed fast, inexpensively, different tread patterns can be investigated prior to construction of the tyre, and even noise classification can be obtained.

With the above approach, the tyre's groove and tread noise behaviour can be determined regardless of the pavement's texture, roughness and porosity, and different tread noise behaviours can be easily compared. Another critical factor that can be measured is the tyre/pavement interaction when different "textured" surfaces are used.

## 5.3 Construction of Device prototype

### 5.3.1 Main structure (frame)



**Fig. 5-2.** Main Frame

The main supporting structure is constructed from heavy duty metallic profiles (tubular with orthogonal cross section) in order to withstand the applied forces and be as rigid as possible.

The platform height is ~70cm, being ergonomic for the working personnel.

On the horizontal frame (main platform), 4 holes are predrilled in order to fix firmly the “force cell” and all the surfaces it will bear.

The vertical tyre holding and pressurizing mechanism can be seen, consisting of a long M22 axis bolt.

### 5.3.2 Force scale (load cell)



**Fig. 5-3.** Force scale / load cell

The force scale is constructed from 2 parallel 60x60mm L profiles, a 10mm horizontal supporting plate and a commercially available “load cell”, that under flexural stress, sends progressive signals to the LCD readout panel. The readout panel can be calibrated to produce “0” result when no weight is applied.

Four safety reasons, “stoppers” are incorporated (see the vertical galvanized M8 bolts with the regulating nuts) that serve their purpose when excessive force is applied to the tyre and the range of the load cell is exceeded.



**Fig. 5-4.** LCD panel supporting structure

On the left side of the main supporting structure, a small platform is fixed in order to hold firmly the force “LCD readout panel”.

The readout panel itself is not fixed but is detachable and it can be stored in a secure place when the measuring device will not be used for long periods of time.



**Fig. 5-5.** LCD panel in Kgr

The LCD readout panel is in place and firmly bolted to the supporting platform.

Inside the panel, the electronic controller and power transformer take the signal from the loading cell and project it as a readout in Kgr.



### 5.3.3 Pressure pads / Holding device



**Fig. 5-6.** Pressure pads

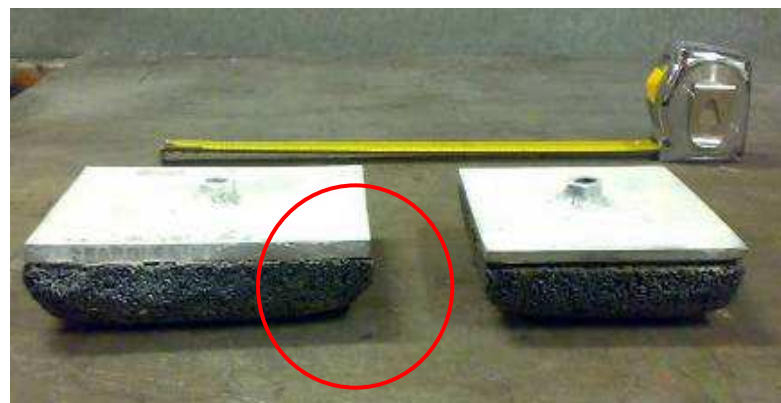
If a tyre mounted on a rim is used, these pressure pads are not needed, but if a tyre without a rim or a small scale model tyre is used, then pressure to the whole tyre/pavement contact area must be evenly applied, simulating the real contact area.

Since the cross section of the inner circumference of the tyre is “elliptical”, no pressure can be applied directly to it with a simple flat pressure pad, since the tyre’s contact area would be deformed.

In order to simulate pneumatic air pressure, the “pressure pads” are constructed, with a main connection nut (seen in the middle of each) welded on to a thick metal plate, that is connected to the vertical pressure rod, so different forces can be applied.

Below the metal plate, a rubber porous material is casted to eliminate the “hard” interaction between the stiff metal plate and inner soft surface of the tyre.

The rubber material is “rounded” (as seen in the picture) in order to avoid “edge contact” with the inner tyre, simulating much better air pressure under typical working conditions of the tyre.



**Fig. 5-7.** Pressure pads

The holding device is fixed on the upper structure by a welded hexagonal nut and regulated by a rod with full length thread. On top one can see the handling grips and one complete revolution lowers the holding device by 1mm.

The lower elastic surface and curvature may be altered in order to fit best with the inner tyre profile and depending on the tyre width to be tested.

In the picture (right), one can see the positioning of the “pressure pad” inside the tyre (without rim).

In any case, before starting the measuring procedure, one must be sure that the produced tyre’s footprint is the same as when the tyre is mounted on a car and bearing the car’s weight.



**Fig. 5-8.** Pressure pad inside tyre



**Fig. 5-9.** Holding mechanism

In the picture (left), the long M22 axis bolt is seen, that acts as a different tyre holding mechanism and down force / pressure regulator.

According to the pressure pad used or any different tyre holding mechanism used, the lower end of the vertical axis bolt can be easily changed.

### 5.3.4 Air orifice / adaptors

The main concept of the project is to guide the pressurized and velocity controlled air directly to the tyre / pavement interaction area.

So, depending on the tyre's circumference and width, several adaptors have to be constructed.



**Fig. 5-10.** Air orifices / Front view

Attention must be paid to the design of the air orifice, since the air flow must be as “normalized” as possible in order to produce the lowest amount of regenerated noise. Turbulence and other aerodynamic properties of the air stream are not considered to be a problem for the measuring procedure since, in real road situations, similar aerodynamic and turbulent phenomena do exist and are unavoidable.



**Fig. 5-11.** Air orifices / Side view

In these pictures only two of the constructed orifices are shown.

During preliminary testing, it was found that the slimmer profile orifice performed better than others, since it guided the air stream directly to the point of interest, which is the tyre/pavement thin

interaction line just in front of the contact area. (leading edge)

This orifice produced the best results and had a progressive downsizing of its cross section so a better air stream quality can be obtained, and it is much easier to insulate the air escaping at the tyre contact edges using typical elastomeric mastic that covered part of the lateral sipes as well, so the air stream is far better controlled and guided towards the tyre's grooves.

The term "laminar" air flow is not used since it is very difficult to be obtained at high air speeds even with these orifices.

### 5.3.5 Textured surface - pavement

The tyre to be measured can be placed either on a smooth and flat surface, such as a thick metal plate or even on a thick glass, or glazed marble or granite, to obtain a very smooth and flat surface/pavement, and studied on such a smooth reference surface.



**Fig. 5-12.** Flat pavement surface (metal)

By using a "reference" smooth material as a pavement, a noise classification of the tyre can be performed and used in legislation, public authorities, tyre manufacturers, etc., instead of using an uncontrollable textured surface.

With this method, all tyres may be measured under the same conditions and the noise results of the tyre behaviour may be comparable.

However, on top of the flat metal plate, any kind of textured material can be placed in order to study its acoustic behaviour as well.



A rubber compound constructed from recycled automotive tyres can be seen (right picture).

Any type of textured road surface can be used, such as asphalt, open or closed porous asphalt, concrete, antispin surfaces, in dry or wet conditions.

By measuring a specific tyre on a smooth surface and by repeating the measurement on a textured surface, a lot of information may be collected for the acoustic behaviour of the surface itself.

Another asset of the method is that, standard surfaces can be easily constructed (with measurable deviations) and used for a long period of time, with the same expectancy of

results, since they do not wear or alter themselves after each measurement, as is the case with the “revolving drum” or “revolving tyre” method or, even worse, in the “pass-by” method.



**Fig. 5-13.** Porous surface pavement

### 5.3.6 General device assembly

All the pictures in this review are taken from the construction of the prototype measuring device.

In the following figures one can see (from two different angles) the main platform and the tyre pressed on the metallic base surface (pavement) with the holding screw and the pressure pad in place.

The orifice is also in place but still not connected to the high pressure fan or attenuator.

The LCD readout is also connected to the force scale with the appropriate cable.



**Fig. 5-14.** First stage general assembly

### 5.3.7 Air pressure fan and noise attenuators

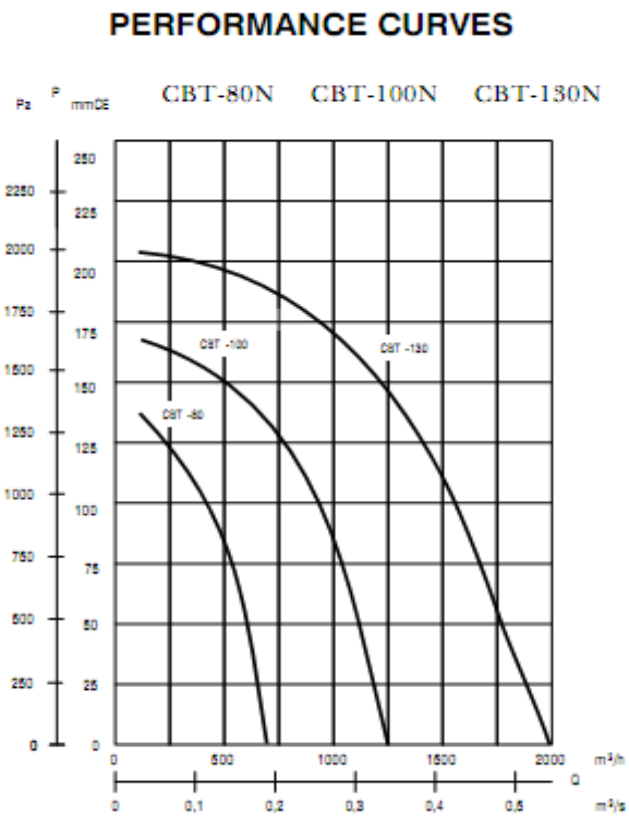
The measuring device needs pressurized air at controlled high speed and volume, to be guided via the orifice adaptor, through the grooves and treads of the tyre.

To achieve the above parameters a high pressure axial fan was selected (code CBT80N with max 1250Pa),



**Fig. 5-15.** High pressure fan regulated by a single face inverter (from 0-max rpm).

Centrifugal fans with axial propellers are considered to be able to supply considerable air volume at high or very high static pressure, thus being able to overcome the backpressure of the system and conform to the design parameters.



**Fig. 5-16.** Pressure fan performance curve

The above graph was taken from the fan's data sheet.

The selected fan is capable of producing 1250Pa maximum static pressure.

In order to reduce the noise from the fan that will travel through the connecting air duct to the measuring device, an exhaust attenuator was fitted to the fan and another one at the intake to reduce the noise from the intake opening.

In the final stage, the exhaust attenuator was placed in a horizontal position to obtain even smoother air flow and reduced backpressure.

The measured noise attenuation of each attenuator is -25dB, and this is more than sufficient for the project.

In contrast simple axial fans can provide high flow rates but are unable to produce high static pressures and typical centrifugal fans with frontcurved or backcurved blades may produce high flow rates (depending on fan size) but medium static pressure.

A metal base was also constructed, to carry the fan and the attenuators.

The selected fan was a centrifugal axial type since this can provide the required pressure for the experiment.



**Fig. 5-17.** Fan attenuators

### 5.3.8 Measuring device, alteration

One of the alterations to the early design was to incorporate a new holding fixing that can be used to support the tyre on its own rim instead of the tyre without the rim; this was due to tyre changing efficiency since less time was needed per tyre change. So if an existing tyre (instead of a tyre model) is measured, it may be measured mounted on its own rim with the appropriate air inflation pressure.

The new fixing plate was installed on the device and all tyre/rim changes were much faster and easier (such as changing a tyre in a typical car). This alteration is reversible and if only a portion of a tyre is available or if a model of a tyre is investigated, this can be done with the old special pressure pads, explained in earlier paragraphs.

Another test was performed with a much bigger backward curved industrial fan, that provided more air supply ( $12.000\text{m}^3/\text{h}$ ) but with lower pressure characteristics, in comparison with the initial high pressure fan.

The need was to investigate, if higher volume and less static pressure was beneficiary to the project or not.



**Fig. 5-18.** Tyre mounted on rim & new high supply /low pressure fan



The performance of the low pressure fan was not satisfactory; it produced a high level of background noise and low pressure, so it was disregarded.

Another alteration was a second fan with similar supply capability as the pressure fan and in line with the old one, of mixed axial and centrifugal behaviour.

This was investigated since during preliminary tests a question arose and should be investigated, which was, “what happens to the tyre’s noise pattern if pressure and air volume is increased?” and after a preliminary measuring set, noise level is getting higher but the frequency pattern is not changing.



**Fig. 5-19.** Auxillary fan mounted on main high pressure fan

The high pressure fan’s Rpm, is regulated with an electronic inverter from 0-100%.

A further alteration is that the distance between fan and measured tyre was increased to 2m. In the next photo, one can see the horizontal attenuator of 125cm and the smoother air orifice of 75cm that drives air in a straight axis gaining better air flow and less back pressure.



**Fig. 5-20.** Complete measuring setup

A sound absorbing barrier is erected between fan and tyre in order to minimize the background noise, and in a later stage, the barrier was converted to a closed sound insulated cover with internal sound absorbing lining.

## **5.4 Instrument setup**

The two calibrated class 1, SPL meters are mounted with 30cm distance between them; one is aimed at the side of the tyre so it can collect noise data from the lateral tread pattern of the tyre (in the graphs this is the “right” channel), and the left SPL meter is aimed at the end of the tyre (in the graphs this is the “left” channel) so it can collect noise data from the main grooves of the tyre.

Both carry a reference windshield and the microphones are off the axis of the air stream to avoid air stream noise generation on the microphone membrane.

Data from the SPL instruments is transferred analyzed and recorded to the spectral program installed in the laptop.

In each measurement the noise data should be crosschecked comparing the reading on each SPL meter and the reading of the spectral analyzer per each channel, to avoid the possibility of over\_loading one of the instruments.

Over\_loading will not harm the instruments but it may produce invalid noise data. All instruments have an overload sign flashing on screen when this happens.



**Fig. 5-21.** Measuring setup

Class 1 SPL meters & Laptop with 2 channel DSP board & FFT software

The placement of the Spectral analyzer is better to be near the SPL meters since with only a glance the operator can detect possible problems or deviations of the measured data.

It has to be emphasized that the placement of the SPL meters must be on a rigid tripod or rigid holding structure that can guarantee the lack of floor vibrations and the same placement per each measurement.

## 5.5 Orifice air velocity calculations

In order to calculate the velocity of the air that is guided to the tyre/pavement intersection, the fan's air intake flow is calculated from the following basic equation.

$$Q = S * V \text{ (in volume/time units)}$$

where

Q = Air flow (in volume/time units)

S = Cross section (in area units)

V = Velocity (in distance/time units)

The fan's air intake diameter is  $D=10\text{cm}$ , so according to the above equation, the air intake cross section is  $0,007854\text{m}^2$ .



**Fig. 5-22** Anemometer

The air's velocity can be calculated, according to the fan's electronic inverter adjustment, that control the fan's speed, in 6 or more steps.

Since an inverter is used, the fan can be regulated in any user defined speed but in this project only 6 steps are selected.

The air velocity is measured by a 10cm diameter propeller-type anemometer, so the fan's intake cross section is completely sealed by the anemometer's propeller and, thus, an average measurement of air velocity, per step, is recorded.

**Table 5-1.** Fan adjustment

Fan's Adjustment	Measured air velocity (m/sec)	Fan's intake cross section ( $\text{m}^2$ )	Intake air flow $\text{m}^3/\text{sec}$	Intake air flow $\text{m}^3/\text{h}$
Step 1	3,5	0,007854	0,0274890	98,96
Step 2	4,4	0,007854	0,0345576	124,40
Step 3	5,1	0,007854	0,0400554	144,19
Step 4	5,7	0,007854	0,0447678	161,16
Step 5	6,5	0,007854	0,0510510	183,78
Step 6	7,4	0,007854	0,0581196	209,23

All three tyres used are 185/60/14 so the orifice of the device that is guiding the air to the tyre/pavement intersection is designed to be 140mm wide and 14mm high, so

$$\text{Orifice cross section} = 0,14\text{m} \times 0,014\text{m} = 0,00196\text{m}^2$$

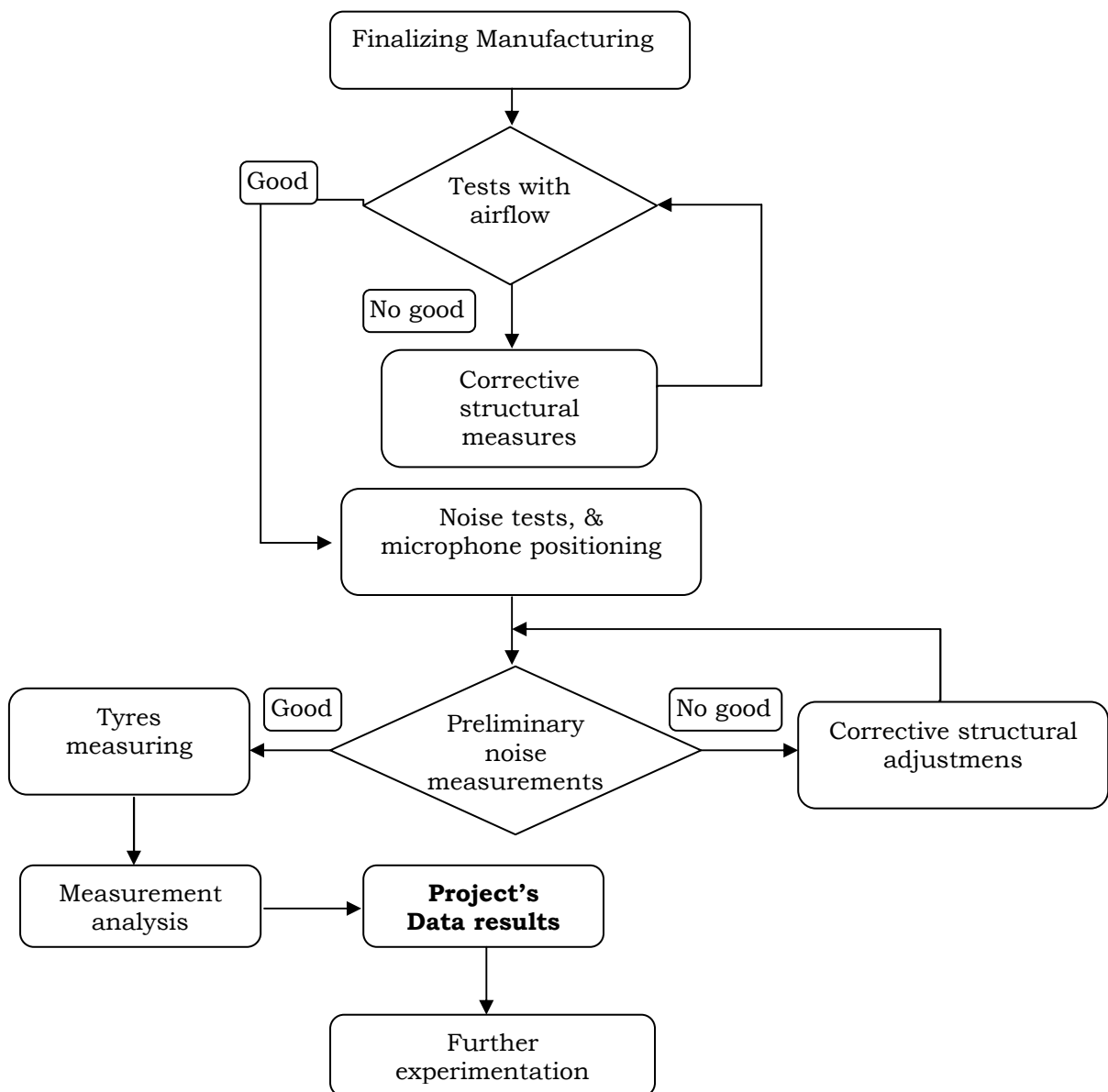
**Table 5-2.** Orifice air velocity

Fan's Adjustment	Intake air flow m <sup>3</sup> /h	Orifice cross section m <sup>2</sup>	Orif. Calculated air velocity (m/h)	Orif. Calculated air velocity (Km/h)
<b>Step 1</b>	98,96	0,00196	50489,79	<b>50,5</b>
Step 2	124,40	0,00196	63469,38	63,5
Step 3	144,19	0,00196	73566,32	73,6
<b>Step 4</b>	161,16	0,00196	82224,48	<b>82,2</b>
Step 5	183,78	0,00196	93765,30	93,8
<b>Step 6</b>	209,23	0,00196	106750,00	<b>106,8</b>

Since in the CPX trailer measurements, the car was travelling at 50, 80 and 110 Km/h, the corresponding calculated velocities will be used (Steps 1, 4 and 6) as the nearest approximation and Steps 2,3,5 will be discarded.

### 5.5.1 Logical diagram of tasks

The following diagram is a general task diagram for the device construction and measuring procedure.



**Fig. 5-23.** Task diagram

The above task diagram proved to be valid, and has been followed throughout this project.

## **5.6 CPX Trailer experimental work**

### **5.6.1 CPX Trailer requirements**

In the following paragraphs, some requirements of the newly available (2013) Draft ISO Standard 11819-2 Annex E , are mentioned in brief.

It has to be stated that all of them were met well in advance of the Standard's availability, in the construction of this specific trailer, due to typical mechanical engineering procedure, common sense and acoustic expertise of the author.

The following guidelines (from the Standard) are provided to assist in the design and operation of test vehicles. The guidelines are informative but will assist in ensuring that the performance requirements (certification of the test vehicle) can be satisfactorily achieved.

- For test vehicles incorporating an enclosure, it is recommended that the enclosure, including any skirts, reaches down to within 50 mm of the ground level. The lowest part may consist of flexible material which is not fluttering during driving (incorporated in this trailer).
- Parts of the vehicle (trailer) may be covered by an enclosure which screens the test tyre(s) and the microphones from unwanted noise sources, and specifies the requirements for any sound absorbing materials used to line the enclosure or to cover other sound reflective surfaces in order to reduce sound reflections (incorporated in this trailer).
- The inside walls of the enclosure shall be covered by acoustically absorptive material to make the influence of sound reflections negligible. Sound absorbing materials having a total thickness of (for example) 75 mm which may give sound absorption coefficients of 0,6 or higher in the range 315 Hz to 400 Hz and 0,90 or higher in the range 500 Hz to 5000 Hz, which is the minimum performance recommended (incorporated in this trailer).
- When designing a test vehicle, the dimensions should be sufficient to allow an appropriate distance between microphones and reflecting surfaces, including sound absorbing materials. This

distance is recommended to be at least 0,2 m (incorporated in this trailer).

- Normally, the underbody of the vehicle is covered with sound absorbing material, in order to avoid reflections on the underbody of sound coming from those tyres other than the test tyre(s) (incorporated in this trailer).
- The suspension of the trailer should be designed in such a way so as to have a spring rate and damping coefficient similar to those of the suspension of a car (incorporated in this trailer).

### **5.6.2 CPX Trailer construction Standards**

All of the above Standard requirements were met in advance.

### **5.6.3 Trailer construction overview**

The author decided that a one wheel trailer would perform acoustically better than a two wheel trailer since no noise interaction from the second wheel will be present.

Even if construction of a one wheel trailer is more difficult and expensive than a two wheel trailer and poses potential stability problems, the requirements were set so that the towed trailer would be constructed of:

#### A metal supporting frame

To serve as a rigid platform, avoiding flexural deformations since it will be loaded with ~300kgr (the approximate load per typical wheel of a passenger car) and must withstand external impact forces from road bumps. Loading is essential since all tyres deform under load and the contact area is increased compared to a stationary unloaded tyre.

#### A suspension system

To absorb any road bumps or pavement deformations, to guarantee constant contact with the road pavement and for traffic safety reasons. A spring suspension system is superior to a rubber one.



### Interchangeable wheel

To be changed on site with minimum effort by one person, for testing of several different tyres that must be pre-mounted on the same type of wheel rim in order to gain time and effort.

### A 3-axis towing hook

A special x,y,z design for holding the trailer in an upright position (especially at low speeds) since it has only one wheel. The hook allows the trailer to move up/down and turn left/right but does not allow over-tipping from the vertical axis and tip to the left or right.

A secondary special rigid bracket was constructed and mounted on the pulling's car under chassis, since maximum stability is required and over-tipping must be avoided at all costs due to safety reasons.

### An aerodynamic hood

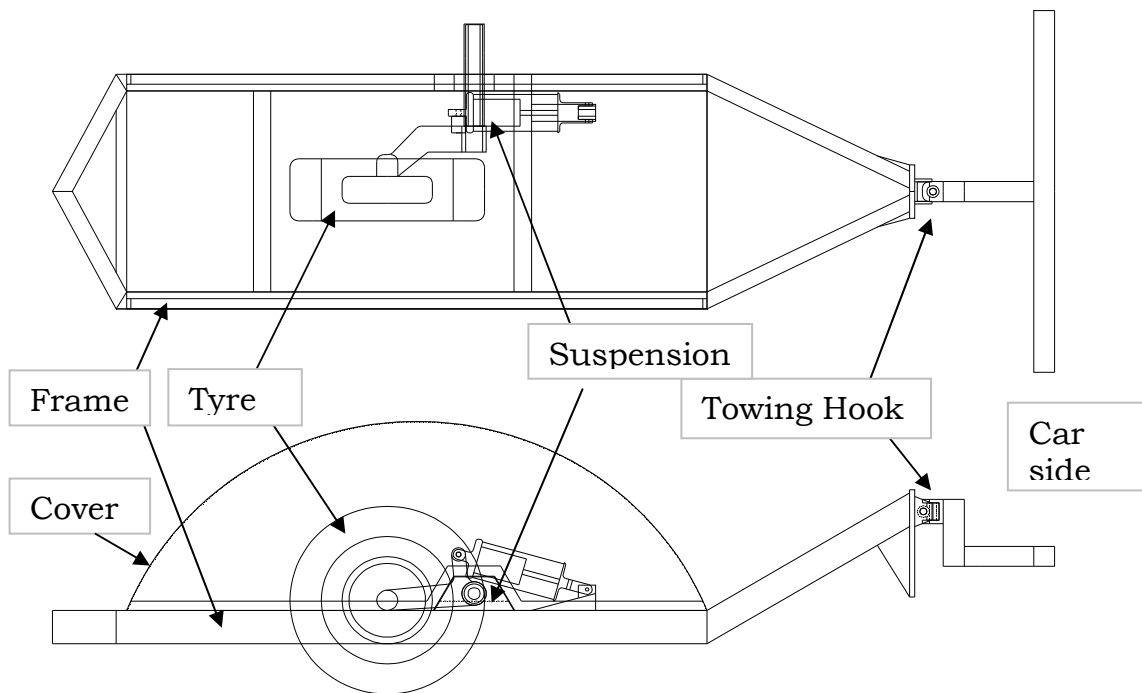
Constructed to cover the complete trailer structure and to protect it from aerodynamic noise, falling debris, and minimize the environmental or general traffic, or environmental noise, so the noise measurements will be as clear and accurate as possible.

### Internal sound absorbing lining

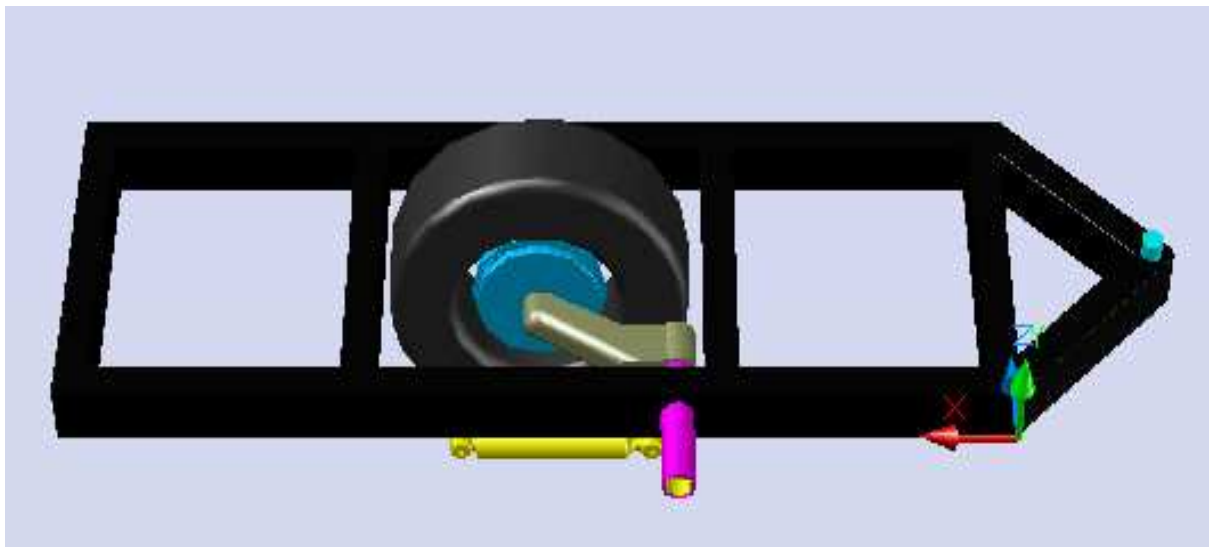
Since the thicker the porous lining is, the better it behaves as a sound absorber even in the low frequency area. All the internal walls are lined with 12cm Rockwool of 80kg/m<sup>3</sup> density and protected with a sound transparent perforated galvanized metal sheet with a 40% perforation and multiple 6mm diameter holes. The same absorbing lining was used as an underliner in order to absorb the reflection generated between the road pavement and the underbody of the trailer's floor.

### Microphone holding structure

The structure is a simple adjustable holding device for keeping the two microphones safely in place and allowing them to be regulated for different height and distance from the road surface or tyre.



**Fig. 5-24.** Top & side view of Trailer



**Fig. 5-25.** Simplified 3D view of main frame & suspension

#### **5.6.4 Expected results**

With the above one wheel trailer, it is easy to obtain actual noise measurements that can be used for comparison reasons and optimization of the data that will be obtained from the stationary measuring device under development.

Since the trailer has only one wheel, there is no interference from the second wheel of a typical trailer, but would be more difficult to construct.

The expected results will be actual data from the tyre/pavement interaction, so they can be considered as reference data and can be validated over and over using the same pavement surface.

Typical parameters that can affect the measurement are:

- Type of tyre
- Type of groove and tread of tyre
- New or old tyre
- Footprint of tyre on road
- Mounting of tyre
- Loading of tyre
- Type and construction of road pavement
- Roughness and texture of road surface
- Speed of travel

All the above parameters can be reproduced in the measuring device under development, so noise data could be cross referenced to the actual measurements since the very same tyres will be used in the device as well.

After the conclusion of the comparison of both sets of measurements (trailer versus new device), the spectral noise data obtained from the stationary device, can be either:

- a) Consistent and, thus, considered to be valid.
- b) Non consistent and needs to be further investigated or isolated as a different phenomenon.

In either case, the noise level that is expected to be measured from the developing device should be of a lower level (Sound Pressure Level), since any dynamic phenomena (that are contributing to the overall noise during tyre pavement interaction in a real life situation) are not present.

The main interest will be: is the spectral noise data from the device following a similar spectral behaviour or not and is this behaviour altering under different speeds according to the trailer's data?

If the answer is yes, the prototype device will be satisfactory.

### 5.6.5 Construction of Main structure (frame)



**Fig. 5-26** Frame view & suspension

All metal work was performed in the author's workshop at his own expense.

The placement of the spring loaded suspension was inclined to save height, center of gravity and the ability to regulate the

The frame is built for durability from hollow metal sections, and the suspension was from a passenger vehicle that was cut and reconstructed according to the requirements of the new design.

All sections are precision cut and welded together (not bolted) for maximum rigidity.



**Fig. 5-27.** Trailer test - mounting on car

preload of the tyre provided better and safer road handling of the trailer.

Before the completion of the construction, static tests were performed to check for problematic points.

The trailer is pre-painted and covered (at the moment without inner sound absorption) in order to perform a small scale stability test.

It can be seen that the trailer is narrow compared to other existing 2 wheel trailers, and thus safer to navigate on open roads.

### 5.6.6 Road test



**Fig. 5-28.** First road test

In accordance with the requirements of other worldwide trailer measurements, the travelling speed of the CPX trailer was selected to be 50, 80 & 110km/h in order to obtain a reliable noise index per measured tyre.

For safety reasons, the old Athens airport taxi runway was chosen, since no other cars were present and repeated passes could be safely performed.



**Fig. 5-29.** Final and actual test drive

Note that a composite material made from porous air filter and rubber (blue colour) was added as a skirt in front and on both sides of the trailer, to restrain air flow even more, and to further reduce the noise from the pulling car.

The rubber is not touching the road surface and no “hissing” noise is produced.

The road behaviour of the car and CPX trailer was excellent at all speeds (even higher than 110Km/h) and no wobbling, either under or over steering, was observed.



### 5.6.7 Tyre changing



**Fig. 5-30.** Changing the wheel

Three different tyres were measured, all pre-fitted on the same type of 14" rim that have been pre-balanced at a tyre shop.

The cover opens from one side, and for operator safety reasons, a metal rod holds the cover in its upright position (not seen in the picture).

The CPX trailer also has four reclining legs incorporated under its underbody, that when lowered keep the tyre ~30mm above ground, so tyre changing is easier and safer at the end of each measuring set.

In the picture, it can be seen that the cover is lined inside with sound absorbing Rockwool, 12cm thick and protected by a 40% perforated galvanized 0,7mm sheet.

The small platforms at the front and back of the tyre are lined with sound absorbing material (face down) to eliminate sound ground reflection, and serve as a loading platform if the trailer needs to be loaded with more weight.

### 5.6.8 Microphone position



**Fig. 5-31.** Microphone position – here seen with only one mic

The microphones are placed on the opposite side of the suspension on adjustable brackets and carry their own sound transparent foam cap.

The sound transparent foam cap is always placed on top of the microphones, when making noise measurements in an environment of expected air steam, since it minimizes the possibility of affecting the microphone's membrane with unwanted vibrations or deformations due to the air pressure waves, producing false noise readings. In this case, air stream will be high so the foam caps must be used.

The brackets need to be adjustable only for the preliminary testing and afterwards they will be fixed on antivibration mounts, so the measuring position will not be altered by a random event (for example, hitting it when changing the tyre).



### **5.6.9 Noise measurement with the CPX trailer**

Prior to conducting the noise measurements, the car was sent to a specialized car outlet where the speedometer was calibrated.

Each time the car reached the specific speed, the laptop's "record" button was pressed and noise data was recorded for a period of 2-5 sec.

This is another factor why the airfield was selected, as it provided a lot of safe space for the car acceleration, steady speed, and deceleration in a straight line.

The microphone inside the CPX trailer was connected with a low resistance calibrated cable (provided by the SPL manufacturer) to the SPL meter, and the output of the meter was sent to the input of the laptop's sound card, where data was analyzed and stored in real time.

It has to be noted that the instruments that are used have an exceptional benefit. They come with a detachable microphone and a 5m long connection cable, so both instruments as well as the laptop are protected and used from inside the car (passenger seat).

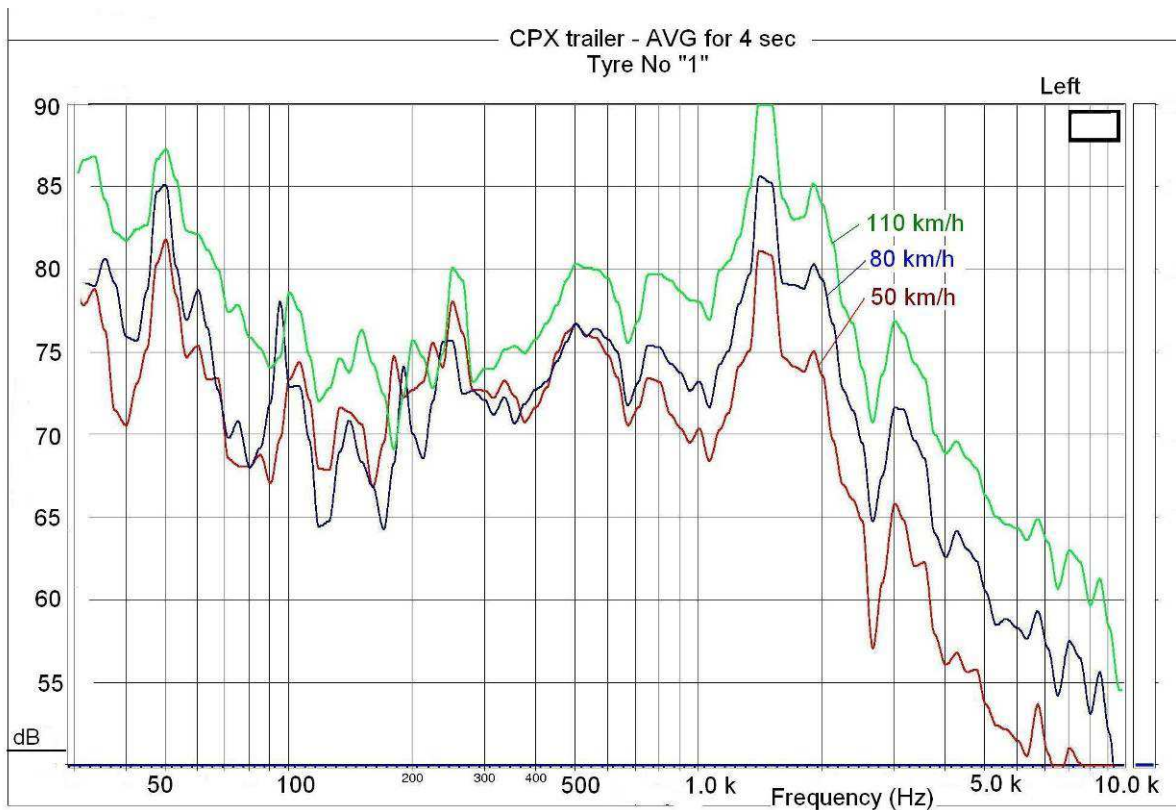
Cross checking of SPL meter and laptop data was also performed under real time measuring conditions by the operator, in order to detect possible malfunction in the measuring chain.

### **5.6.10 Preliminary noise data**

The following data is preliminary and unweighted (without the "A" weighting filter) and is used only for the evaluation of the measuring setup, in order to fix any structural problems or to further study any unwanted noise data.

For example, a problem not foreseen was that, especially at high speeds, a lot of small, loose gravel from the unused airport taxi runway surface was hitting the trailer producing an impulsive unwanted noise.

A good sweep of the complete runway measuring length had to be performed when the actual measurements were to be performed.



**Fig. 5-32.** Preliminary Spectral data from tyre "No 1" in dBA  
(x-x axis is Frequency in Hz and y-y axis is sound level in dB)

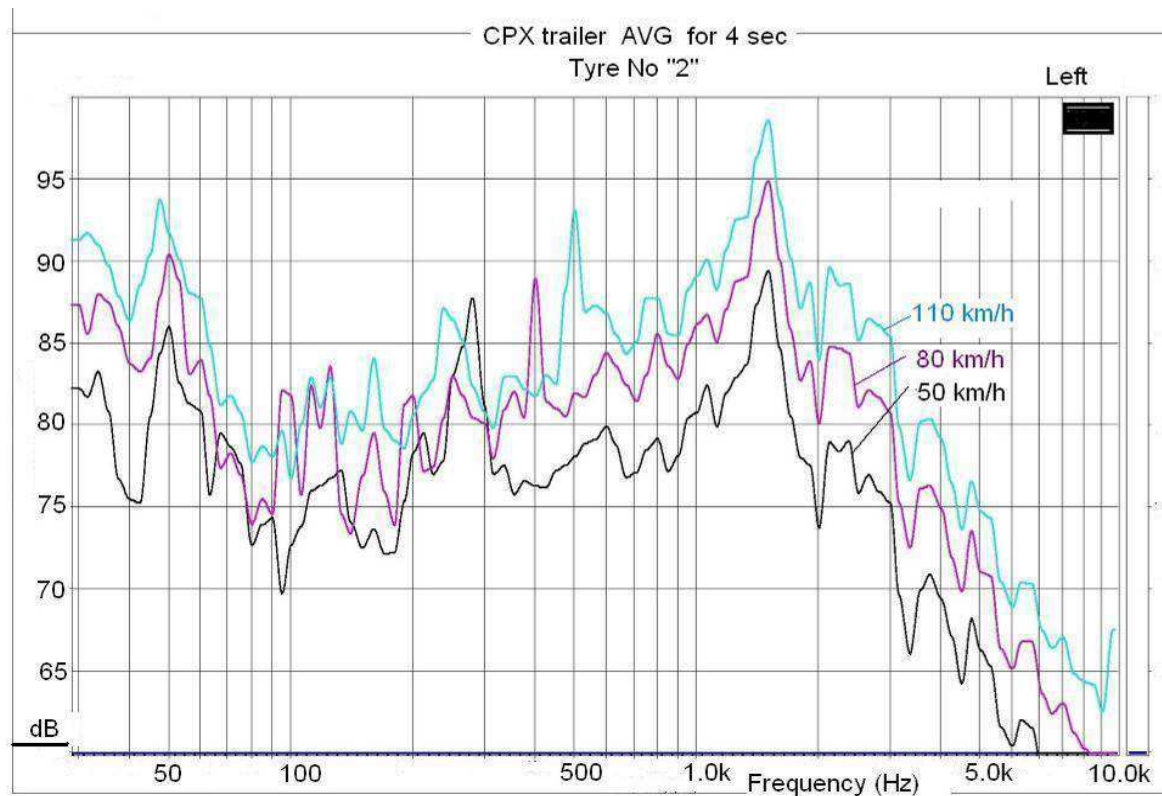
The preliminary graph shows the Averaged spectral data of tyre "No 1" at speeds of 50km/h (red line), 80km/h (blue line) and 110km/h (green line).

(the name of the tyre manufacturer and tyre type are available but will not be stated)

Since the only parameter that was altered was the travel speed, the uniform increase of the spectrum level is something to be expected, especially at mid-high frequencies.

From the progressive increase of the complete spectrum per travelling speed, one can understand that tyre noise is independent from tyre revolution, to some extent. Otherwise, a frequency shift of the spectrum towards the higher frequencies should be observed.

Even the distinct tones are not shifting putting forward another strong point for the development of the static measuring device, that is, why make measurements of rotating tyres, since rotation is not affecting, to some point, its noise producing mechanism?



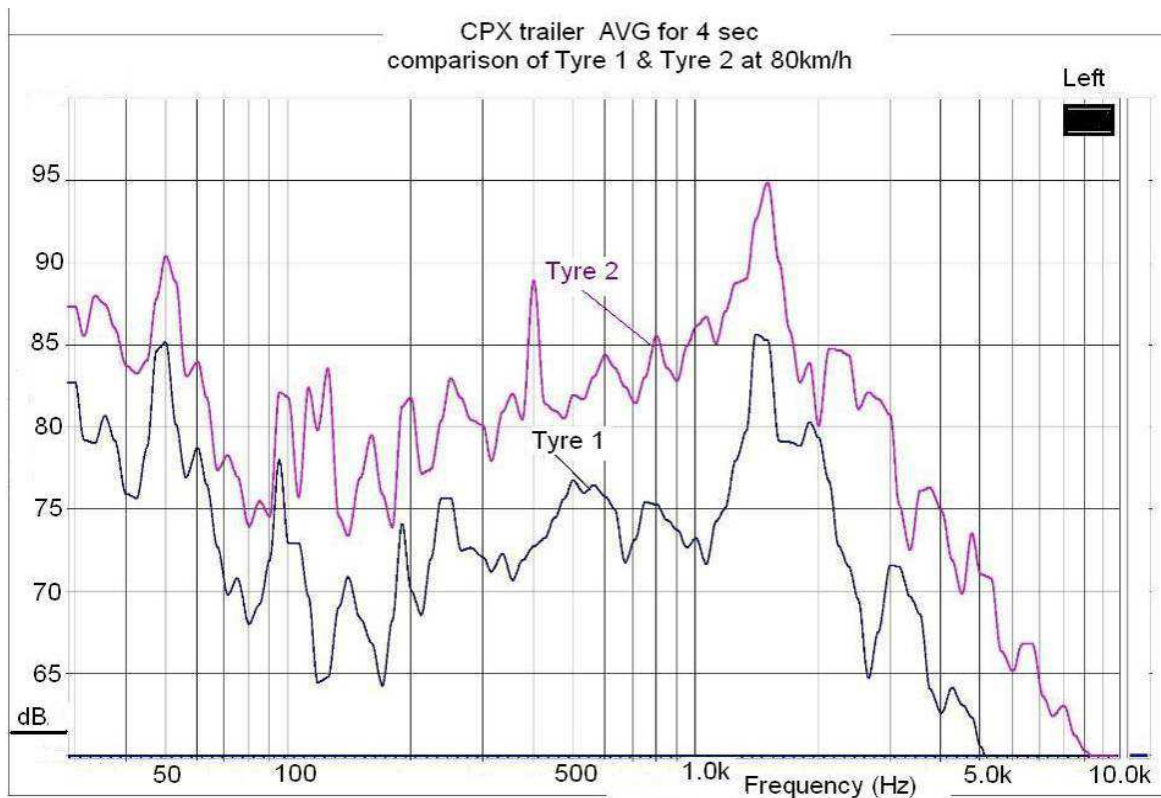
**Fig. 5-33.** Preliminary Spectral data from tyre "No 2"

(x-x axis is Frequency in Hz and y-y axis is sound level in dB)

The preliminary graph shows the Averaged spectral data of tyre "No 2" at speeds of 50km/h (black line), 80km/h (purple line) and 110km/h (turquoise line).

The uniform increase of the spectrum level, especially at mid-high frequencies is something to be expected as well, but it is clear that this tyre has a more sharp tonal presence in the area 1000-2000Hz than tyre No 1.

In both graphs, one can clearly see that in the low frequency area the spectral data is "fuzzy" and overlapping, in the mid frequency area it is more clear and predominant, and in the high frequency area it is clearly distinct and progressively deteriorating in level.



**Fig. 5-34** Preliminary Spectral data – comparison of tyre No 1 & No 2  
(x-x axis is Frequency in Hz and y-y axis is sound level in dB)

The preliminary graph compares the Averaged spectral data of tyre No 1 (black line) and No 2 (purple line) at the speed of 80km/h.

The tyres are used tyres (not new) from different manufacturers and with a completely different groove and tread pattern.

It is clear that tyre No 2 produces more noise than tyre No 1, by 7-8dB.

So, as proven in this project, the trailer can produce comparable results. The same tyres that will be measured with the static device are expected to produce a different and lower noise level but it is expected to perform in a similar spectral pattern.

## **5.7 CPX Trailer structural results and conclusions**

### **5.7.1 Structural results**

The construction of the CPX trailer was expected to be a major contributing factor to the validation of the acoustic data derived from the main static measuring device, so its good behaviour was critical.

All design parameters performed excellently, such as structural rigidity, stable driving and turning conditions, data transfer, and first-glance data comparison on site had no problems, and best of all, no problems have been detected with the chain of noise measuring instruments.

In order to verify the data from the main static measuring device for commercially available tyres or models of a tyre, a calibration procedure by comparison can be performed with several tyres used with the trailer in actual conditions and re-measured with the measuring device under development.

With the selected Reverse Engineering procedure, it was possible to understand any unexpected or strange data produced by the main measuring device, make any structural alterations if needed, or decide on what frequency band the derived noise data is accurate or inaccurate and make the relevant clarifications.

### **5.7.2 CPX Trailer conclusions**

- From the road tests with the CPX trailer, the excellent handling and damping of the surface anomalies were substantiated.
- From the measurements, it is clear that the CPX trailer may contribute to the study and evaluation of the acoustic behaviour of different types of tyres and pavements by itself, and also it can be used as a base for further acoustic studies, comparing data from other measuring devices.
- It can be used to design low noise tyres.

- It can be used to study the particle grading size of new or reference road pavements.

It is the author's belief that this was a well spent amount of money and will be useful in years to come to promote further research.

## **5.8 Construction and development costs**

As mentioned in previous chapters, the cost for all structural materials, molds, electric and electronic devices, technical improvements, air and noise measuring instrumentation, spectral analysis software, calibrations, fans, attenuators and a major part of the construction was undertaken by the author himself.

Help was requested from 3 employed technicians for the heavier parts manufacturing, crane transportation, site preparation, driving and also during measuring periods as safety personnel.

The total amount spend for this project was about 31.000,00 E

No effort or labour costs of the Phd candidate are calculated in the above cost.

## **6 CPX TRAILER METHODOLOGY – SURFACE/PAVEMENT SELECTION**

### **6.1 Road surface**

#### **6.1.1 Typical road pavement surface**

The measured tyre/pavement noise distribution is strongly affected by several uncontrollable factors that are, road roughness, road porosity, type of asphalt or aggregates used, flatness of pavement, macro and microtexture, etc.

Another major factor is that a pavement ages (thus altering its acoustic characteristics) either due to wear from the tyres or even from environmental conditions and may be open pored, semi-clogged or completely clogged by road dust.

From the bibliographic and standard literature search, it became evident that it is difficult to reproduce the exact surface despite using the same contractor and same materials, under strict supervision and quality control. Hence, different measuring sites are not expected to produce exactly the same spectral results or sound levels but only similar ones.

The 32 page Standard, ISO 10844/94, was examined thoroughly, since it describes in detail the final texture and construction procedure for a typical standard measuring surface to be used in tyre noise measurements and the need for refinishing.

The only way to tackle this problem is to perform several measurements per tyre and calculate the average noise per measuring set, which as understood, is very time and effort consuming and may involve inaccurate results.

### **6.1.2 Smooth road pavement surface**

As proven in this thesis, during the preliminary CPX noise measurements tests, the produced low frequency noise is a magnitude that should not be taken into account, due to its fuzzy behaviour, but mid and high frequency noises are those that produce the high level noise pollution from traffic and should be further examined.

Mid and high frequency noise is expected to be produced when a tyre is rolling on a smooth surface, so the author believes the scientific community should reconsider that the best way to compare noise from tyres should be on a flat, smooth reference surface which (to its advantage) would be fast and easy to construct by any contractor worldwide and would be inexpensive.

If the tyre noise measurements could be performed on a smooth reference surface which has fewer uncontrollable factors than typical asphalt or concrete, the expected tyre noise data could be easily reproduced, better evaluated and carefully compared.

The author wishes to propose to all parties that they evaluate this methodology, to make tyre noise measurements on a flat, closed pore and very smooth surface.

A similar “paradox” measuring procedure applies in acoustic ‘anechoic’ measurements, as mentioned in an earlier chapter, that even anechoic conditions do not exist, especially in an urban environment, they are used worldwide with success.

The anechoic measuring procedure is of great importance to all acoustic engineers with undisputed results, and is widely used for machinery noise classification and sound power calculations.

The proposed smooth surface could be made from any kind of material that offers the smooth finish, but a fast, inexpensive method is to pour a self-levelling epoxy, or polyurethanic or polyurea resin, on any noise measuring path which has the benefit that when it ages, it is not expected to alter its porosity or texture.



If the compound is self-levelling, then the flatness of the test site is obtained and no humps or bumps, even very small ones, will be present.

Since the material is in a liquid form prior to hardening, it enters all pavement irregularities and seals the pavement's pores completely.

When the material hardens, it can withstand all environmental conditions (depending on the quality of the material used) and also heavy traffic. One should consider that these materials have been used for many years for industrial flooring (which experiences very heavy fork lift use).

### **6.1.3 Existing pavement and smoothed pavement**

The noise data obtained with the CPX trailer (in this thesis) are of 2 types, depending on surface texture.

1<sup>st</sup>) typical porous untreated asphalt road surface

2<sup>nd</sup>) treated smooth closed pore road surface

In order to keep the cost of the smoothing of the existing porous asphalt pavement to a minimum, bitumen slurry was used on the test track, as it did not require a long life expectancy being used only for the duration of this measuring set.

From the high frequency data obtained in this measuring set, one can understand the "hissing" effect that is perceived by any typical driver during every day travel. When a road surface is old, it becomes gradually polished and smoothed by wear or clogged by dust, or when the pavement is humid, its pores are filled/clogged with water.

These comparison tests have been performed in order to substantiate that the spectral noise differences are the same for all tyres, at all speeds, for the treated smooth pavement compared to the untreated, porous one.

## 6.2 Measuring field

The selected measuring field was a “taxi” runway at the old Athens Airport because its surface is similar to a typical asphalt road surface, it is closed to the general public, and is a safe and quiet place to conduct measurements with minimum environmental background noise.

In all standards and measuring procedures, it is proposed that the background noise is lower in amplitude from the measured signal by 10dB in order not to affect the noise measurement. So, even though the CPX trailer has a protective sound-insulated and sound-absorbent cover, the quieter the testing area is, the more accurate results can be expected.

Several background noise measurements across the measuring field produced a sound level of 40-45dBA, which is more than acceptable.

The main landing runway was not considered, since it was rougher than the parallel taxi runway, and the noise data would be strongly altered by it.

The car/trailer was gradually accelerated to the required speed (50, 80 or 110km/h) in a straight line (see red line in picture).

When the car reached the measuring area, the speed was kept constant and data recording was started.

At the end of the measuring area the car /trailer was gradually decelerated and returned to the starting point to repeat the measurement or to start a new one.

Most problems were encountered in the first 5-6 measurements, until all involved personnel were familiarized and coordinated to obtain the best measuring accuracy.

Once the driver was familiar in observing the car’s speedometer and the author (who was using the instrumentation from the passenger seat) became more competent in starting the recording at the desired point, the measurements started and all data was recorded (as a WAV file on the laptop’s hard drive).



**Fig. 6-1.** Old Athens Airport - Measuring Field

### 6.3 Noise data recording validation

As mentioned in the “Acoustics” Chapter, a noise-calibrated, 2 channel laptop with a DSP (Digital Signal Processing) sound card was used to record the noise data in .wav files.

*(WAV files are selected since they have complete spectral information compared to mp3 or other compressed formats where the data’s noise floor is disregarded)*

Simultaneously, the installed FFT (Fast Fourier Transformation) software was performing and showing on screen the real time spectral analysis and the overall sound level (in dBA) of the recorded noise per channel.

It should be noted that since the computer DSP input and output level can easily be manipulated by the operator, all values of the digital input/output panel are kept constant at all times.



**Fig. 6-2.** Operator’s measuring position

The only time the input level of the DSP board was adjusted was during the first trial measurements, in order to avoid “over or under loading” of the signal and during the calibration stage.

The signal input to the laptop was taken from the unweighted output jack (line out) of each of the two sound level meters used.

Inside the trailer, only the microphones of the two sound level instruments were installed, and via special low loss cables (provided by the instrument's manufacturer), the signal was transmitted to the instruments and then to the laptop input.

All instrumentation was inside the car on the passenger side.

Every time a measurement was taken, an on-site validation of the recorded data could be performed by cross checking the data shown on each sound level instrument screen and the sound level of the FFT analyser on the laptop's screen.

If a deviation of more than 1dB was present, the measurement was discarded and the test run was repeated.

All measurements were repeated 3 times, per tyre, per surface texture and per travelling speed, and if the deviation was within 1dB, the measurement set was kept and averaged as a single spectral measurement, however, if not, each measurement was repeated until a 1dB deviation was obtained.

## **6.4 Test track length**

Since the top speed of the trailer has to be 110km/h and since a steady state noise was required, the length of the measuring area was selected to be  $110.000\text{m/h} (3600\text{sec}) = 30,5\text{m/sec}$ .

Also, since a 2sec measuring window was required so that the noise emission can become as steady as possible, it is calculated that  $30,5\text{m/sec} \times 2\text{sec} = 61\text{m}$  is the minimum length of the measuring area.

A total straight length of track - 61m + 70m before + 30m after (total of ~161m) - was selected and cleaned of any debris and loose gravel with a hard broom (typically used by street sweepers), especially over the selected path and wide enough to accommodate the trailer's one wheel and the car's four wheels. It was also a concern that the car's wheels

could pollute the area with loose gravel, as it travelled at high speed and for several passes.

After 5 passes, the area was cleaned again since it was noted that there was a slight “hammering” of the trailer from gravel that was either not swept or had become detached from the road surface.



**Fig. 6-3.** Car & one wheel CPX trailer during measurements

## 6.5 Test track alteration

As previously mentioned, a “smooth” and closed pore reference surface is required, so in parallel with the untreated, porous travelling path, a second one was selected and was altered to be as smooth and closed pore as possible.

For this reason, the painted section of the taxi runway was selected, since the paint used by airport authorities is usually thick and level.

On top of this already closed pore section, a cold asphalt slurry without aggregates overlay [47] was applied to form a line, 70m long and 50cm wide, but prior to this, the entire length was swept and cleaned in order to avoid encapsulation of sand, loose gravel or debris.



With this extra material, the pores of the surface were completely closed and a smooth surface path was created, parallel to the porous untreated path [36].

The slurry compound was left to harden for 3 days and then the measurements commenced.



**Fig. 6-4.** Levelling of asphalt slurry



**Fig. 6-5.** Pouring asphalt slurry



**Fig. 6-6.** View of final close pore 'smooth' measuring strip

## 6.6 Test track porosity

The two following pictures show the open porosity and texture of the original, untreated surface, and the smooth, closed pore surface of the area treated with the cold asphalt slurry.



**Fig. 6-7.** Untreated rough surface – note the 1 Euro coin



**Fig. 6-8.** Cold asphalt, treated smooth surface

It can be noted that the treated area is closed pore but not extremely smooth, but even so, the expected results are obtained (a rise in the mid-high frequency range – the so called hissing effect).

For tyre authority testing conditions, a better smoother strip should be constructed.



## 6.7 Tyre types

Three 14” rim, pneumatic tyres were used, from three different manufacturers, both for the trailer measurements and for the laboratory measurement set with the under development device. One can note the different grooves and tread patterns.

The names of the manufacturers are not stated.



**Fig. 6-9.** Tyre named “Tyre A”

Tyre A has three (3) equal sized peripheral grooves with no intermediate sipes and without a complex tread pattern. Both internal and external shoulders have unevenly spaced curved lateral sipes. One of the shoulders has a peripheral groove of small cross section as well.

The unevenly spaced lateral shoulder sipes are claimed (by the manufacturers or marketing departments) to be designed specifically in an unevenly spaced pattern, thus no resonance is present and the tyre is claimed to be quieter. Something that was not confirmed during this limited measuring test, as explained in a previous chapter.

Tyre B has one (1) major peripheral groove in the middle and two smaller lateral peripheral ones near the curved shoulders. It has no intermediate sipes and its curved treads are unevenly spaced of major length and cross section.

It has to be noted that when the tyre is in contact with the pavement, the major curved treads do not extend beyond the contact area, thus encapsulating air in each of the treads, which is forced to the lateral side of the tyre, thus this tyre is expected to behave in a tonal manner even though the curved treads are unevenly spaced.



**Fig. 6-10.** Tyre named “Tyre B”

Tyre C has two (2) equal sized peripheral grooves with no intermediate sipes and without a tread pattern in the middle.

The tread pattern extends on both shoulders as lightly curved treads instead of small sipes.



**Fig. 6-11.** Tyre named “Tyre C”

The above-mentioned three tyres are used throughout all measurements in this thesis.

## **7 MEASURED NOISE DATA**

This chapter is divided into three major sections.

- a) Noise data collected with the CPX trailer method
- b) Validation data from other CPX trailers
- c) Noise data collected with the Device method

### **7.1 Noise data collected with the CPX trailer**

In this chapter, one of the objectives is to measure and compare the noise produced on very smooth pavement surfaces, both with the CPX trailer and with the device under development.

The measurements over the smooth surface are selected since the aim of this paper is to evaluate if the data produced from the developed device is logical, well documented, and able to stand up in any scientific technical evaluation.

In order to compare the noise data between the CPX trailer method and the device method, all data must be taken from the smooth surface.

The measurements performed over the open pore, typical asphalt pavement are not cross checked nor further evaluated since they may contain uncontrollable factors due to surface texture.

The blue line on each of the following graphs is the data from the smooth, closed pore surface (that will be compared to the device data),

and only in this chapter it is compared to the red line that is the untreated, typical porous pavement.

One can, therefore, evaluate the noise difference produced by the same tyre with same travelling speed, over the two different surfaces.

The method used to collect the noise data is called Close Proximity Method (CPX) and is described in the ISO 11819-2, which states that the investigated tyre is mounted on a specific trailer, pulled by a car, and noise is measured by a microphone array mounted on the trailer but very close to the tyre and the pavement.

Travelling Velocity is set at 50km/h, 80km/h and 110km/h.

Microphone distance = 10cm from the external side of the tyre.

Microphones = 2 per tyre at a 90° between them and 45° from tyre.

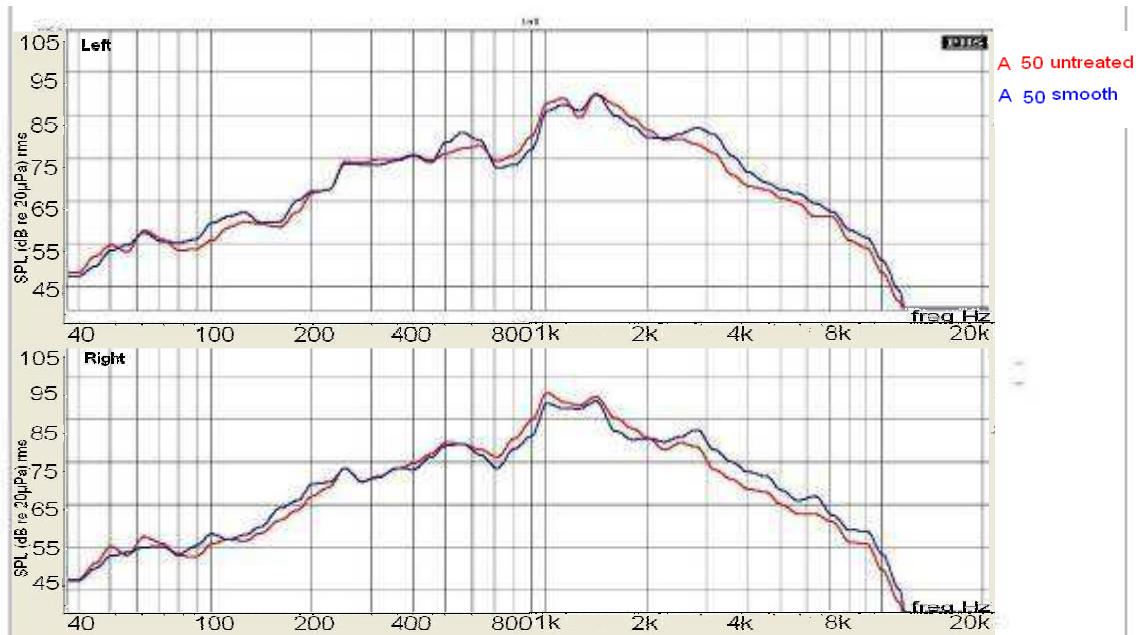
Each of the following pages contains noise graphs, and are summarized as follows:

Top graph = left channel = mic at the side rear end of the tyre

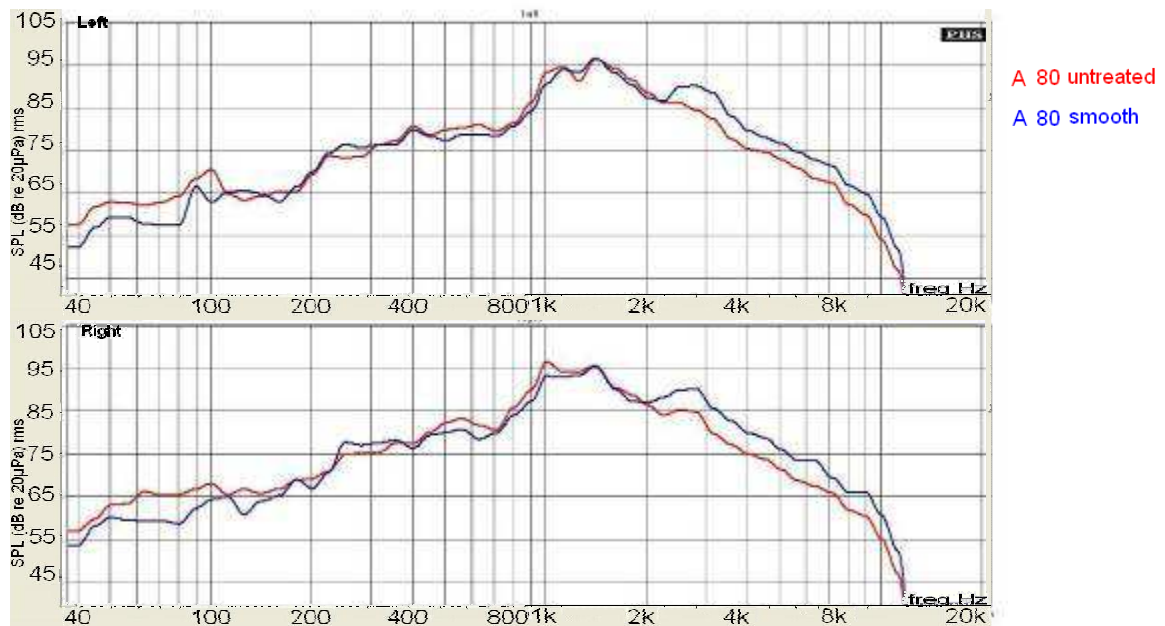
Lower graph = right channel = mic at the side front end of the tyre

Horizontal axis = frequency in Hz

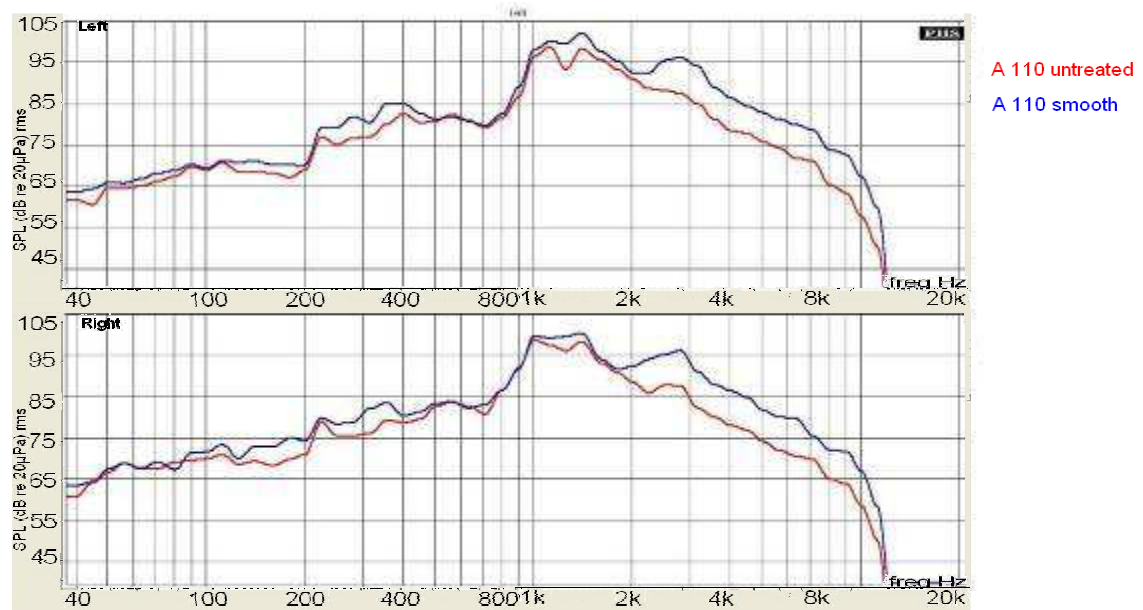
Vertical axis = rms sound pressure level (SPL) in dB re $2 \times 10^{-5}$ Nt/m<sup>2</sup>



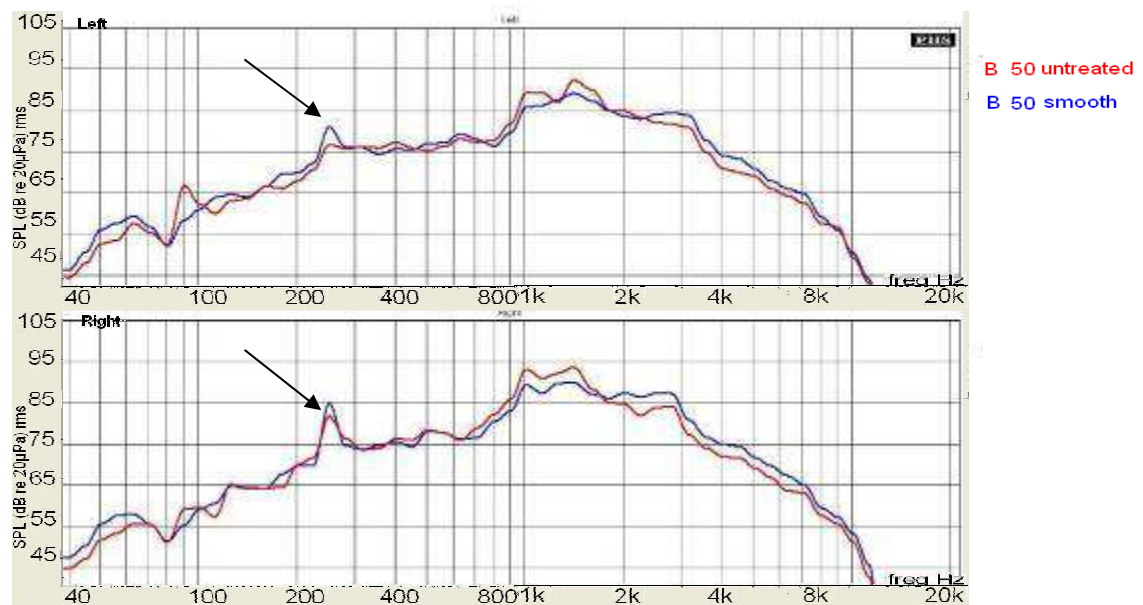
**Fig. 7-1** Tyre A over smooth and over untreated surface at 50km/h



**Fig. 7-2** Tyre A over smooth and over untreated surface at 80km/h



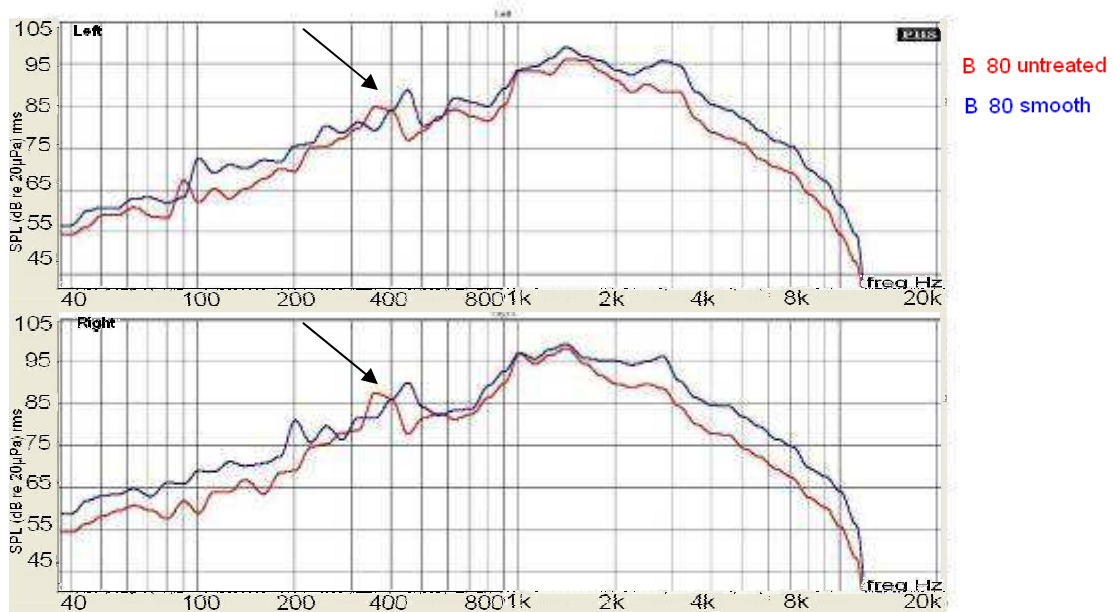
**Fig. 7-3.** Tyre A over smooth and over untreated surface at 110km/h



**Fig. 7-4.** Tyre B over smooth and over untreated surface at 50km/h

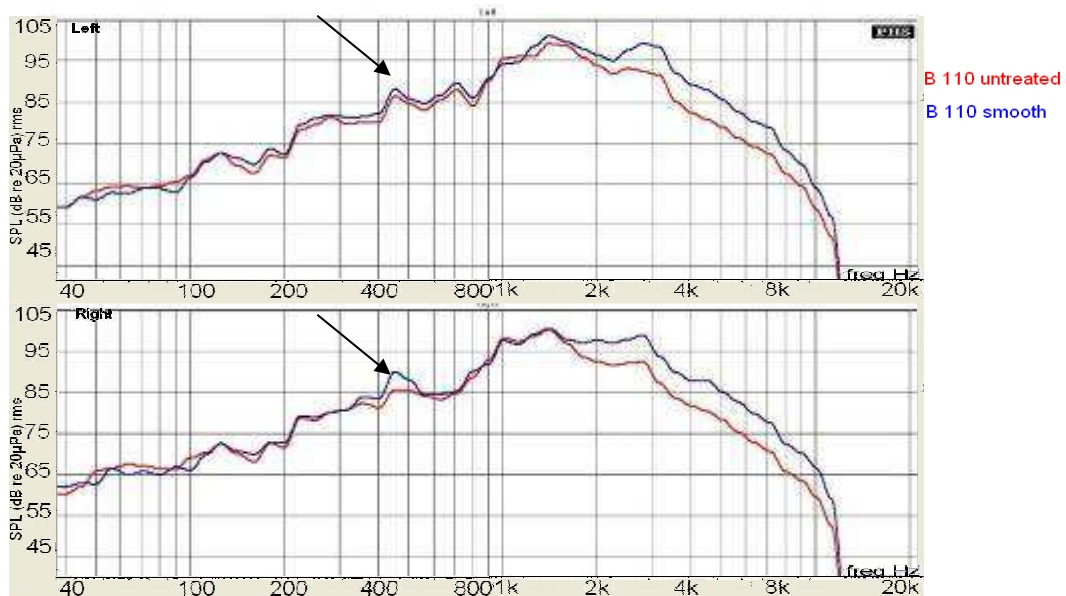
[arrow = see comments for tonal noise]



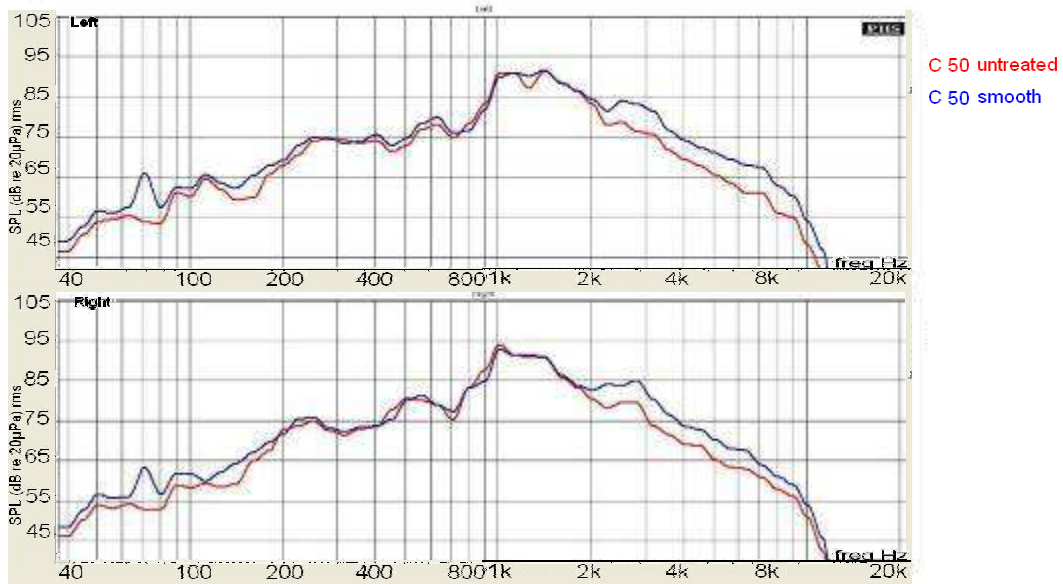


**Fig. 7-5** Tyre B over smooth and over untreated surface at 80km/h

[arrow = see comments for tonal noise]



**Fig. 7-6.** Tyre B over smooth and over untreated surface at 110km/h

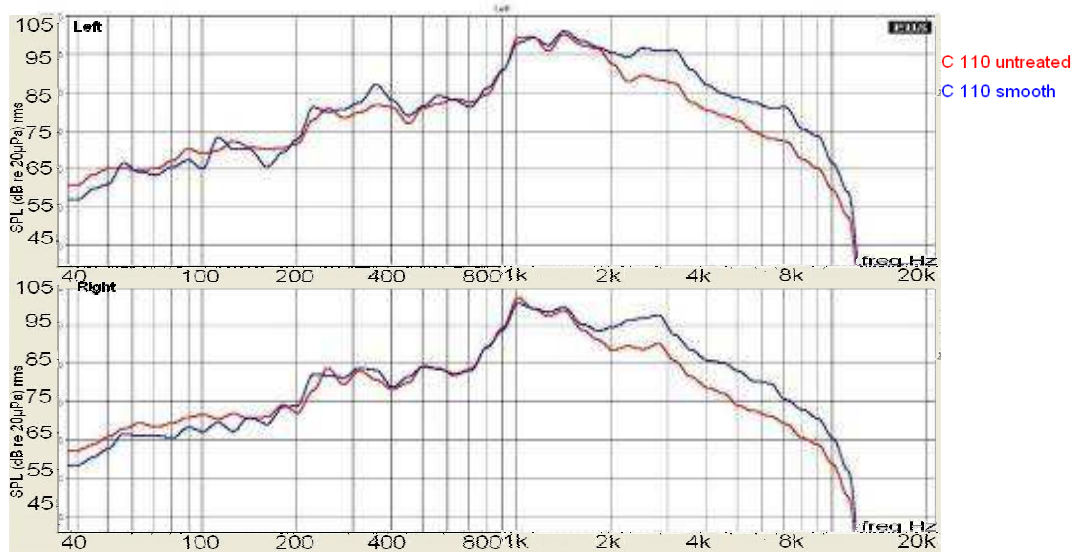


**Fig. 7-7.** Tyre C over smooth and over untreated surface at 50km/h



**Fig. 7-8.** Tyre C over smooth and over untreated surface at 80km/h





**Fig. 7-9.** Tyre C over smooth and over untreated surface at 110km/h

In the graphs (for all three tyres and for all travelling velocities), it is clear that:

- a) There is a similar spectral distribution
- b) There is an elevated sound level in the mid frequency range
- c) There is an unclear spectral distribution in the low and mid-low frequency range (lower than 600Hz)
- d) There is a clear and steep level drop in the high frequency area
- e) The noise level over the smooth surface (blue line) is significantly higher in the high frequency area

The tonal noise of tyre B at 50, 80 & 110km/h, that is marked with an arrow, is explained in a following chapter, named “Comments on tonal noise”.

## 7.2 Noise data table from CPX trailer over smooth surface

The following tables are summarized data with noise in 1/3 octave of tyre “A”, tyre “B”, and tyre “C”, when each tyre is travelling over a flat and smooth closed pore pavement, as constructed in this thesis.

It has to be noted that the data presented in the following summarized tables start from the 250Hz Frequency and not from the 40Hz as shown in the graphs, since the graphs show the spectral distribution capable to be measured by the instruments.

The frequency range 40-250Hz is considered to be VLF, “Very Low Frequency”, and due to its very large wave length, it must be disregarded completely, since it is a) not within the remit of this project, and b) with the measuring method used, all such data are false.

**Table 7-1.** Tyre “A” over Smooth surface - CPX

CPX TRAILER measurements on <b>SMOOTH</b> Surface (units in dBA re20 $\mu$ Pa)						
Frq (Hz)	TYRE A at 50km/h		TYRE A at 80km/h		TYRE A at 110km/h	
	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
<b>250</b>	73,1	71,8	76,7	76,9	81,5	81,5
<b>315</b>	75,6	71,4	75,4	76,9	82,4	82,0
<b>400</b>	77,9	76,5	76,9	77,2	87,3	85,4
<b>500</b>	79,3	81,5	79,1	81,8	84,8	83,3
<b>630</b>	79,9	78,5	79,9	80,8	82,0	81,2
<b>800</b>	75,0	79,6	83,1	85,3	87,8	88,5
<b>1000</b>	86,2	90,0	95,4	96,3	98,6	99,5
<b>1250</b>	88,5	88,8	96,9	95,6	99,8	99,2
<b>1600</b>	88,9	85,4	94,3	91,9	98,6	96,6
<b>2000</b>	82,7	84,3	88,4	90,0	93,4	94,5
<b>2500</b>	85,0	85,4	92,1	93,0	95,8	96,5
<b>3150</b>	84,9	83,5	88,8	87,8	96,4	93,8
<b>4000</b>	76,5	79,7	82,7	82,0	88,2	87,6
<b>5000</b>	71,2	72,2	78,9	78,4	82,5	82,4
<b>6300</b>	68,1	69,6	74,2	73,9	81,5	81,0
<b>8000</b>	62,1	64,7	68,4	68,0	76,2	73,6

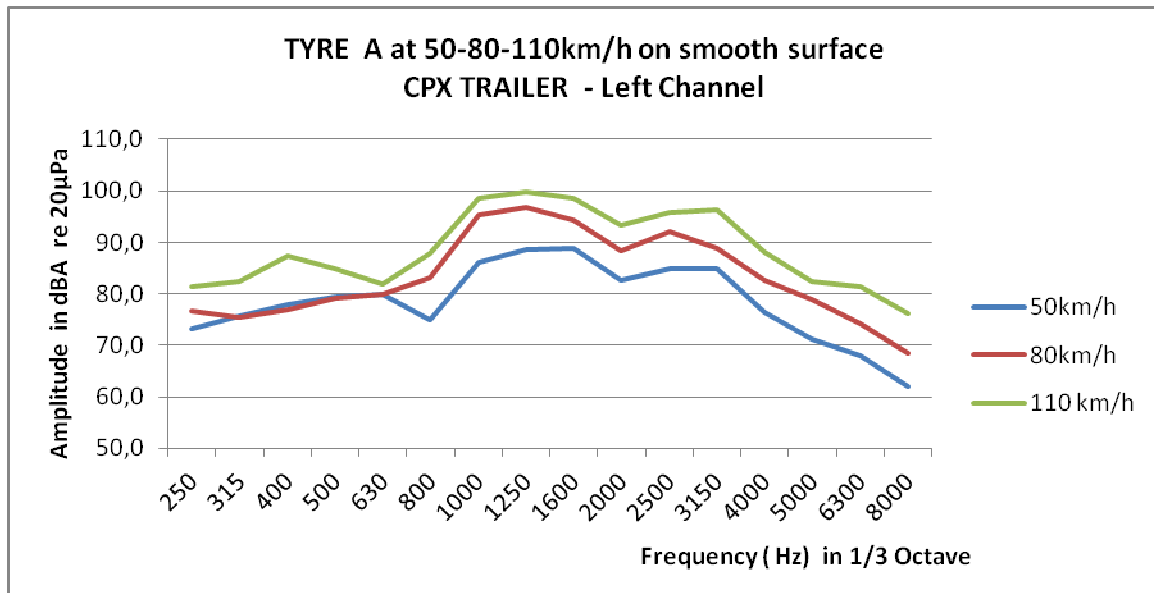
**Table 7-2.** Tyre “B” over Smooth surface - CPX

CPX TRAILER measurements on <b>SMOOTH</b> Surface (units in dBA re20 $\mu$ Pa)						
Frq (Hz)	TYRE B at 50km/h		TYRE B at 80km/h		TYRE B at 110km/h	
	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
250	80,1	82,2	78,9	80,1	82,5	78,9
315	80,0	79,3	78,3	80,2	85,9	83,4
400	79,0	76,4	87,1	87,2	87,6	84,5
500	80,5	81,4	83,8	86,1	89,3	87,9
630	80,4	77,9	85,4	82,6	87,2	84,2
800	79,7	83,7	88,1	92,1	89,1	90,7
1000	86,0	88,4	96,5	98,0	95,0	97,6
1250	89,7	89,1	97,1	99,0	100,4	97,7
1600	90,7	91,0	96,8	97,0	99,2	98,5
2000	88,9	90,7	92,8	94,0	97,3	99,0
2500	88,7	90,3	92,4	93,3	98,7	99,3
3150	86,2	85,7	91,8	88,2	97,1	95,8
4000	78,6	78,7	83,0	81,7	89,5	88,6
5000	75,9	75,9	78,6	78,8	86,4	86,4
6300	72,7	71,5	73,7	74,0	81,5	82,3
8000	63,5	64,5	69,5	67,7	75,8	75,7

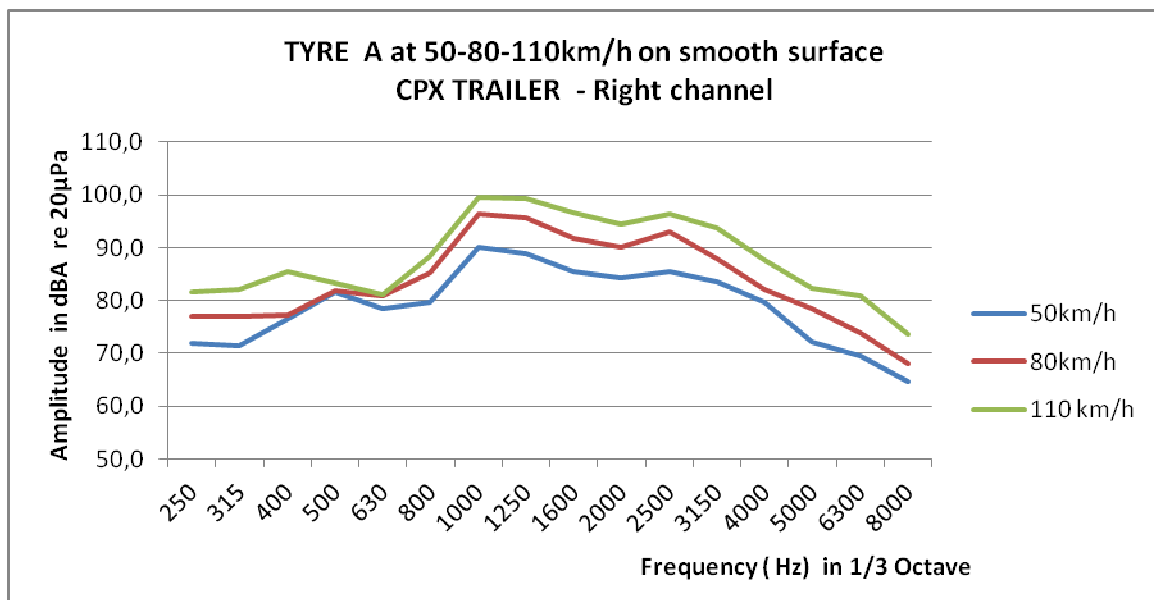
**Table 7-3.** Tyre “C” over Smooth surface - CPX

CPX TRAILER measurements on <b>SMOOTH</b> Surface (units in dBA re20 $\mu$ Pa)						
Frq (Hz)	TYRE C at 50km/h		TYRE C at 80km/h		TYRE C at 110km/h	
	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
250	74,0	76,3	77,7	82,0	82,7	82,5
315	76,7	74,2	82,3	80,9	84,2	83,9
400	79,0	77,1	80,5	78,5	83,2	82,0
500	77,2	80,5	79,2	82,0	81,5	83,2
630	81,4	79,0	82,3	80,6	84,4	83,8
800	82,4	84,9	85,9	89,2	85,9	88,7
1000	90,2	93,2	93,6	94,8	97,0	99,2
1250	89,2	92,0	96,2	96,4	100,0	99,9
1600	90,1	88,3	94,5	92,9	101,0	98,9
2000	87,0	86,6	91,7	89,7	95,8	94,7
2500	86,7	89,0	90,8	92,5	96,0	98,3
3150	85,4	85,5	88,9	90,2	94,6	94,8
4000	78,1	78,2	85,6	82,8	88,9	86,4
5000	75,6	75,3	80,2	80,1	84,5	82,4
6300	72,0	73,5	78,0	76,3	81,4	77,5
8000	67,8	66,3	73,7	71,1	76,8	73,0

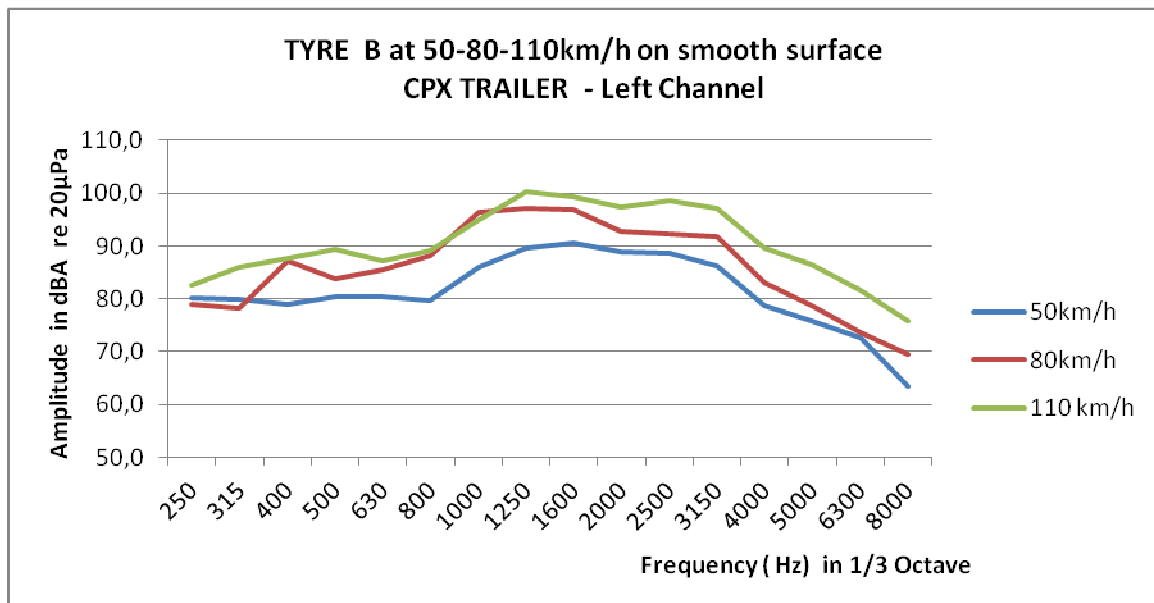
### 7.3 Graphs per tyre - CPX noise data over smooth surface



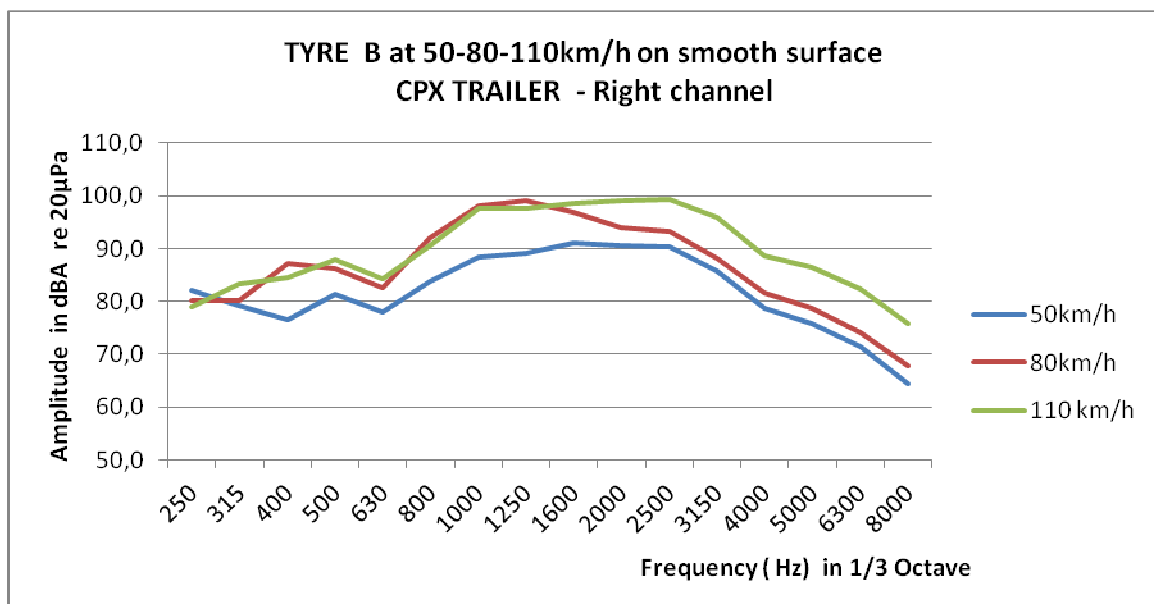
**Fig. 7-10.** CPX data – Tyre A at 50-80-110Km/h – Left Channel



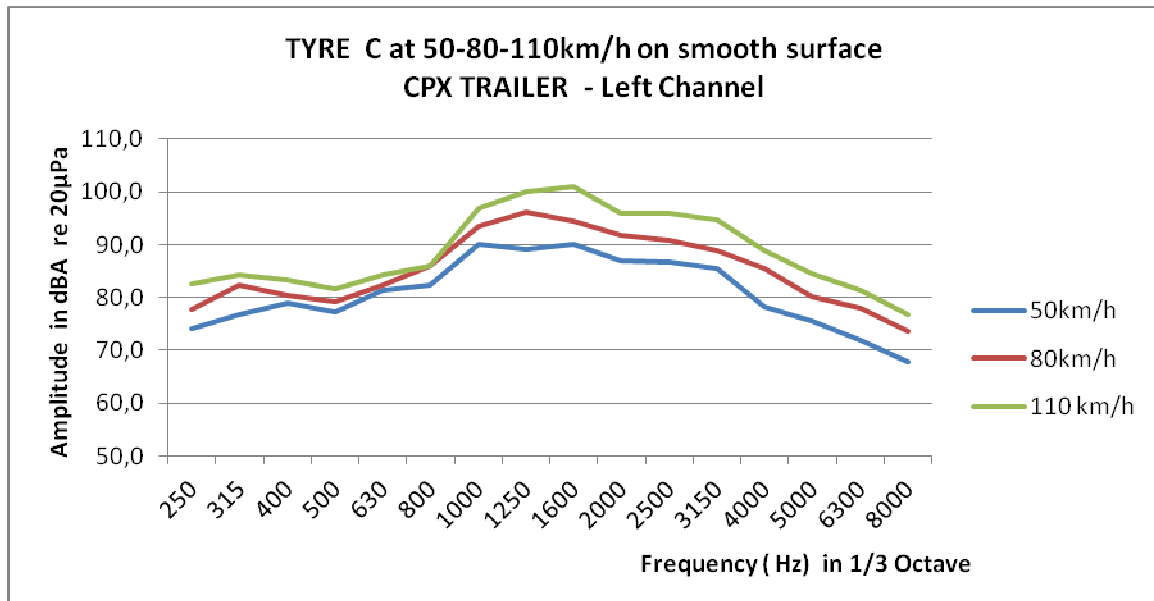
**Fig. 7-11.** CPX data – Tyre A at 50-80-110Km/h – Right Channel



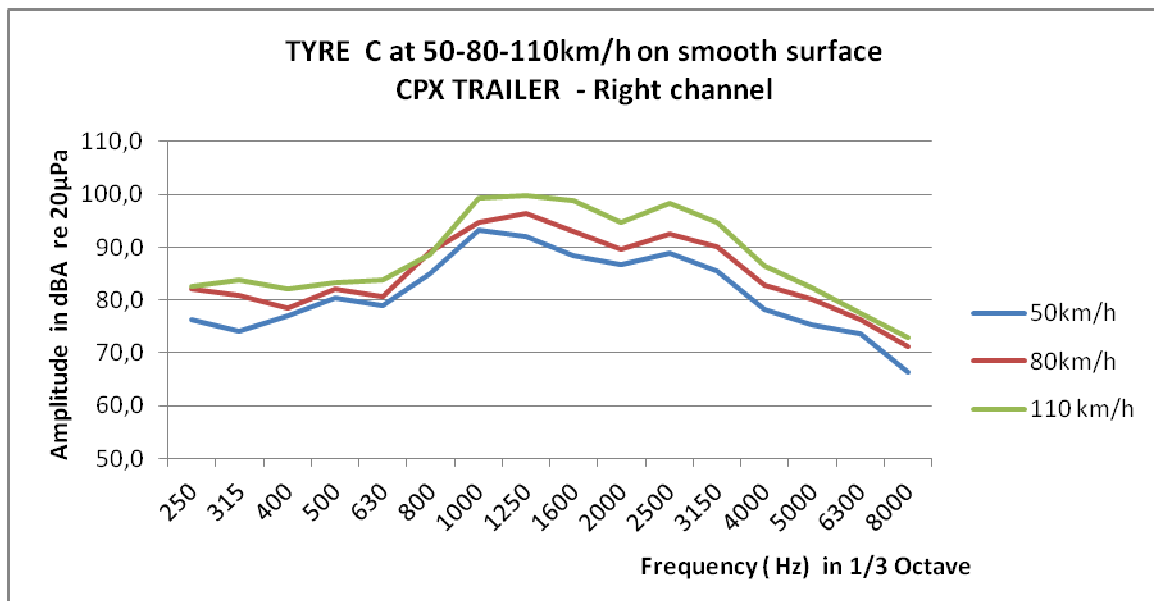
**Fig. 7-12.** CPX data – Tyre B at 50-80-110Km/h – Left Channel



**Fig. 7-13.** CPX data – Tyre B at 50-80-110Km/h – Right Channel



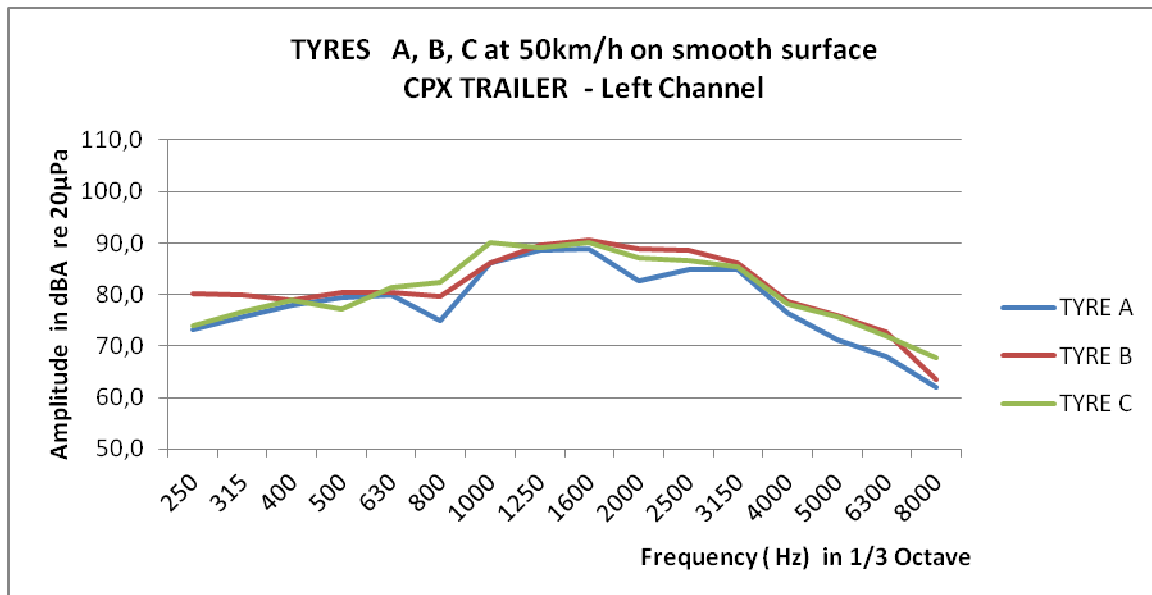
**Fig. 7-14.** CPX data – Tyre C at 50-80-110Km/h – Left Channel



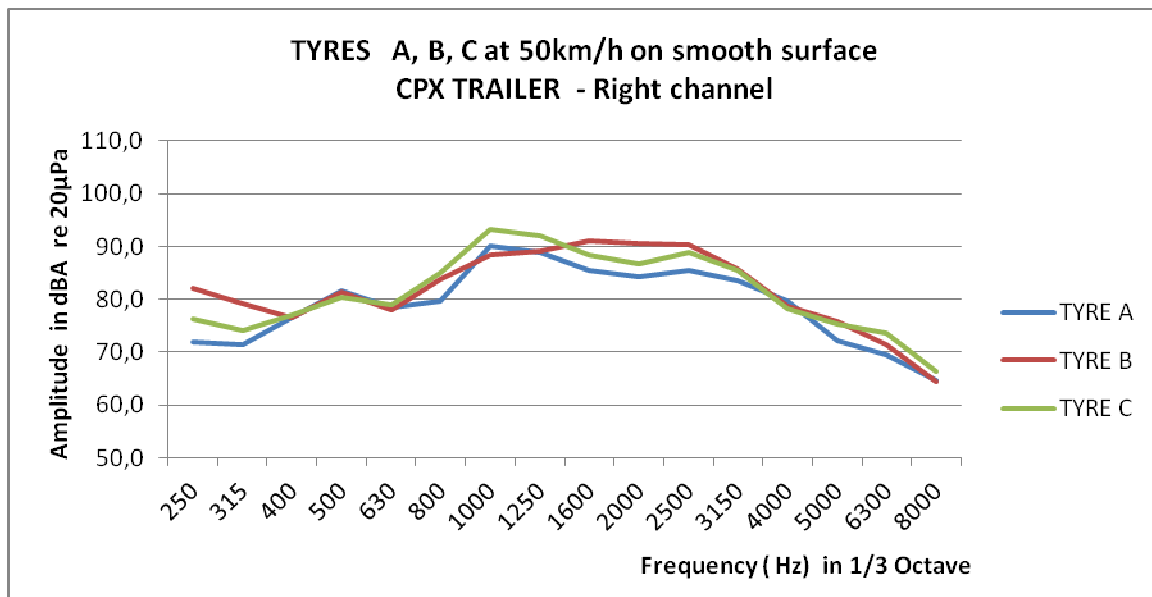
**Fig. 7-15.** CPX data – Tyre C at 50-80-110Km/h – Right Channel

On all sets of measurements for all 3 tyres, it is clear that there is a noticeable increase in the noise level in all the spectrum ranges as the travelling velocity increases.

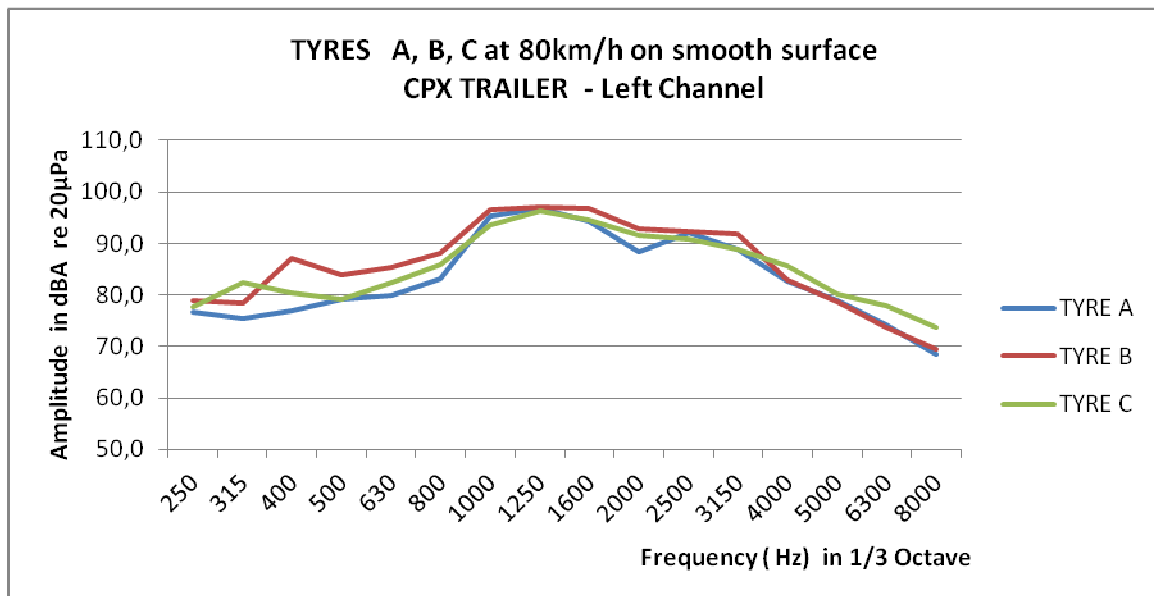
## 7.4 Comparison graphs per velocity - CPX noise data



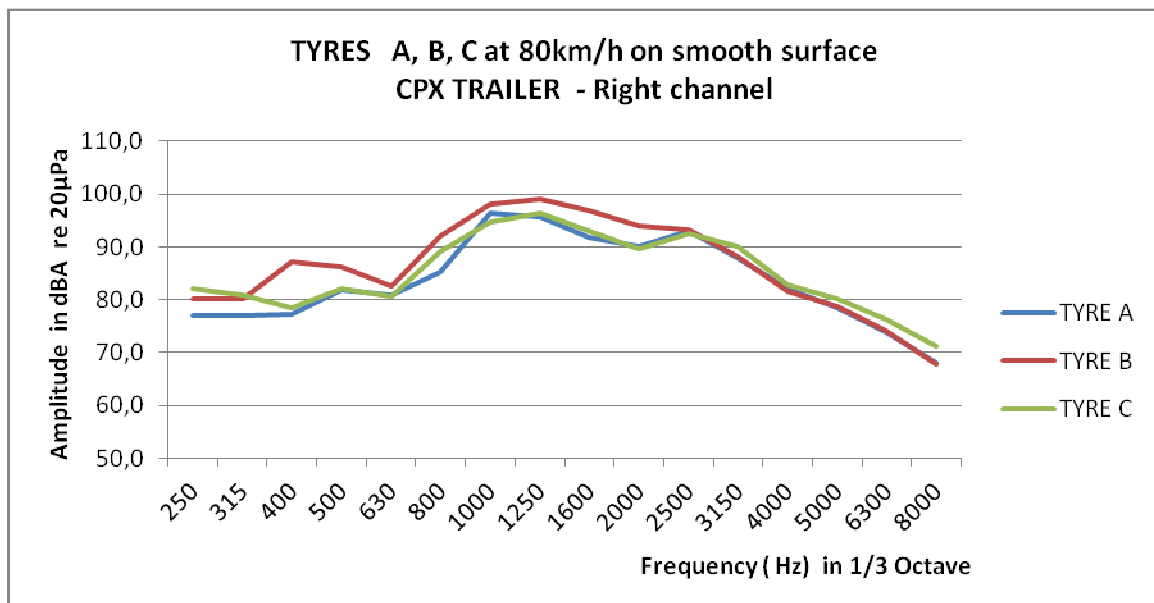
**Fig. 7-16.** CPX data – Tyres A-B-C at 50Km/h – Left Channel



**Fig. 7-17.** CPX data – Tyres A-B-C at 50Km/h – Right Channel

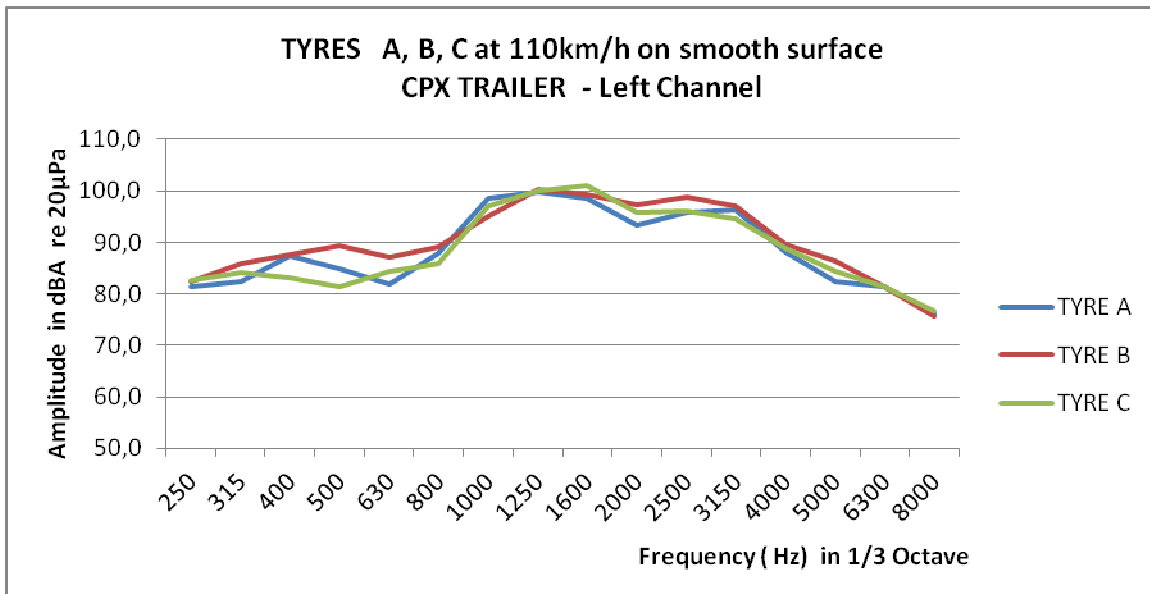


**Fig. 7-18.** CPX data – Tyres A-B-C at 80Km/h – Left Channel

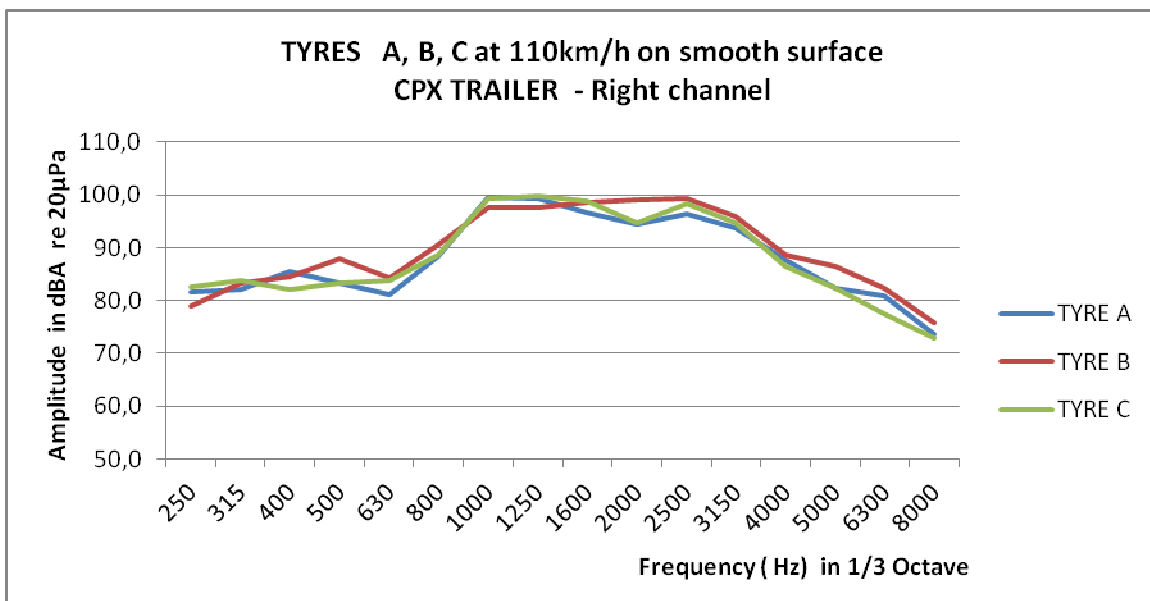


**Fig. 7-19.** CPX data – Tyres A-B-C at 80Km/h – Right Channel





**Fig. 7-20.** CPX data – Tyres A-B-C at 110Km/h – Left Channel



**Fig. 7-21.** CPX data – Tyres A-B-C at 110Km/h – Right Channel

### **7.4.1 Comments on CPX spectral distribution**

The spectral distribution of the noise per tyre is similar if some noise spikes in the low/mid frequency areas are smoothed out. The main interest should be focused in the mid and high frequency areas of the graphs and all the data in the lower frequency range should be ignored.

Ignoring the low frequency data is not something the author wants but is obliged to do, since as mentioned in the chapter about the CPX trailer “microphone distance selection”, the correct signal perception is dependent on the wave length the noise signal has. Since all low frequency noises have large wave lengths, the shorter the distance the microphones are placed to the noise source (tyre) is a guarantee of false data readings.

Low frequency data has, by general definition, a large wave length ( $\lambda$ ) and the close proximity type of measurement performed has an inherent problem to safely evaluate such data. One must bear in mind that the newly available Standard, DRAFT ISO 11819-2, acknowledges this problem and requests that the measuring acoustic span should be between 315Hz and 5000Hz.

Although a wider acoustic span is usually welcome as it allows the acoustic engineer to have more information, low and very low frequency data, as well as very high frequency data, it may produce conflicting results for a great variety of reasons, one of which is the small noise expansion area in “near field” measurement procedures.

Thus, in order to avoid noise data from any uncontrolled structure borne effects, from vibrating surfaces, from suspension vibrations and from aerodynamic turbulence, etc., in this thesis, the evaluated frequency range will be between 800-5000Hz but with not strictly defined boundaries.

## 7.4.2 Comments on CPX noise data

From the collected noise data, it is clear that:

- Tyre B is the noisiest of all
- Tyre A is the quietest of all
- Tyre C is in the middle.

All tyres have the same increased noise behaviour at high frequencies, when passing over a very smooth and closed pore surface and, proportionally, they behave accordingly (lower noise) when passing over a plain, typical porous and untreated road asphalt surface.

It is obvious that with the CPX method, the noise produced is an amalgamation of static and dynamic factors during the tyre/road interaction.

So, if only the noise data over a smooth area is measured it could be easy to calculate the tyre's noise, over a typical porous asphalt pavement, if its porosity and its sound absorption characteristics are known, measured or calculated.

Asphalt surface can be measured using the:

**ISO 13472** 'Measurement of sound absorption properties of road surfaces in situ', Parts 1-2 [154, 155]

**ISO BS EN 13036** 'Road and airfield surface characteristics – Test methods', Parts 1-8 [156-163]

Other ISO standards can be used as well for measuring and calculating noise generation and propagation (not mentioned here).

All the noise data from the CPX method is consistent and no measurement has shown any extraordinary or significant strange noise behaviour, so it is safe to regard this set of measurements as usable and accurate, since each graph shows a time and energy average of at least 3 different sets of measurements, and each measurement is a time

and energy average of a 2-5 second data logging, and each data logging is an average of at least 8 complete spectral width data instances.

All the above is performed automatically by the algorithms installed in the SPL instruments and the spectral analyzer, and no specialized calculations are needed to obtain the average spectral distribution.

### **7.4.3 Comments on tonal noise**

- *Refer to previous graphs of tyre B with the “arrow”*

As all acoustic engineers say, the human ear is the best measuring instrument that can distinguish small or undetected data variations, so the first question arose on site during the measurements, when a tonal noise was heard but only with tyre (B).

As proven with the spectral analysis, on all graphs for tyre “B”, there is a tonal component present in the low frequency area, that is not stable but velocity dependent.

At 50km/h it lies in the area of 250Hz, at 80km/h in the area of 400Hz, and at 110Km/h in the area of 450Hz.

This tone could be produced from a variety of reasons and its origin could be only estimated just by looking at the spectral data of a graph.

Verification by a different method is most helpful, and in this case the recording of the noise data in .wav files proved to provide the answer.

By listening again to the recorded data, it was obvious that a low frequency tone was present and its frequency was changing when the trailer accelerated or decelerated during the measurements.

The only tyre that had such a peak in the low frequency area is tyre B and one must look at its tread design to understand it.

Tyre B has one longitudinal deep groove in the middle, but has a distinct pattern of multiple oblique deep treads as its main water drainage.

It has 31 oblique sets of treads in its circumference, spaced between them at a slightly different distance.

Considering that the length of each oblique tread “l” was smaller than the longitudinal tyre / pavement contact area/length “L”, it is understood that there was a periodic compression and decompression of the entrapped air that was trying to escape from the pavement contact area (yellow ellipse).



**Fig. 7-22.** Estimated tyre/pavement contact area

This design with the multiple oblique treads could be perceived by a customer to be a “quiet” design, but measured data shows it is not, and it is a poor design as far as tonal noise emission is concerned.

It has to be clear to the reader of this thesis, that the presence of the tonal spike (although clearly heard and perceived) is not contributing to the overall measured noise (since the rest of the acoustic spectrum has a much higher energy content, meaning that it is much louder than the energy of this specific tone, but as said before, the human ear is perhaps the best measuring and perceiving instrument than most high quality electronic instruments.

Hence, the tread design of tyre “B” should be re-examined by the manufacturer.

#### **7.4.4 Tonal noise verification**

Hertz (Hz) is expressed also as cycles per second, and if an object is “hitting” a surface periodically, it produces a frequency that, if within the hearing spectra of humans, is perceived as sound.

Therefore, to verify that the tone is produced by the tread design of tyre B, the following calculations are performed.

Tyre external diameter = 56cm, consisting of 31 sets of oblique treads

Tyre circumference =  $\pi \times D = 3,1416 \times 0,56\text{m} = 1,76\text{m}$

Travelling speed = 50Km/h = 50.000m/h

=  $50.000\text{m}/3600\text{sec} = 13,9\text{m}/\text{sec} / 1,76\text{m} = 7,9 \text{ cycles}/\text{sec} \times 31 \text{ treads} =$

= 245Hz = consistent with graph's tone

Travelling speed = 80Km/h = 80.000m/h

=  $80.000\text{m}/3600\text{sec} = 22,2\text{m}/\text{sec} / 1,76\text{m} = 12,6 \text{ cycles} / \text{sec} \times 31 \text{ treads}$

= 390Hz = consistent with graph's tone

The reader must have noticed the frequency deviation when the tyre is rolling on the untreated pavement surface (that consists of a lot of pores and air escaping passages) in comparison with when rolling on a closed pore smooth surface.

Travelling speed = 110Km/h = 110.000m/h

=  $110.000\text{m}/3600\text{sec} = 30,5\text{m}/\text{sec} / 1,76\text{m} = 17,3 \text{ cycles}/\text{sec} \times 31 \text{ treads}$

= 538Hz = small deviation from graph's tone

Another noticeable factor is that the right channel (the lower graph of each set), where the microphone is placed at the tyre's front lateral side, has a higher tonal noise level in this particular frequency than the left channel, where the microphone is placed behind the tyre's back lateral side shoulder at the trailing edge.

This is true since the oblique treads end at the side of the tyre instead of its back shoulder, so a multiple orifice is created at the side of the tyre and the tonal noise is louder.

A correction to this poor design could be to elongate each tread so that it is considerably longer than the tyre / pavement contact length, allowing the compressed air to escape more easily and avoiding periodic “passing” over the enclosed contact area.

#### **7.4.5 Broadband noise design**

When a car is turning or manoeuvring, tyre manufacturers do not use a circumferential longitudinal deep groove at the far left or far right side (left or right shoulder) of the tyre, due to stability reasons and better grip at high speed turns, thus providing a safer cornering tyre.

However, they need water drainage especially when the car is cornering at high speeds, and the elastic material should provide as little deformation of its structure as possible, so they incorporate lateral shallow “sipes” both on the left and right shoulder of the tyre. Those shoulder sipes are incorporated vertically or at a small angle to the longitudinal axis of the tyre at travelling direction.

The periodic passing of the tyre’s lateral sipes over the pavement is a known theoretical tonal generation factor, and manufacturers claim to avoid designing them with equal distances between them in order to avoid excess tonal noise. Therefore, they try to broaden the radiated acoustic frequency to behave as broadband as possible.

The same methodology of unequal distances but between the oblique main treads of the tyre is also present in this particular tyre “B”, as mentioned earlier, and if one looks closely, it can be noted that they are set apart from each other by considerable millimetres.

But from the extensive measurements of the tyres used (in this thesis) and due to their specific shoulder sipes design, it is proven that the lateral sipes are not playing a significant role in tonal noise production, due mostly to the minimum contact area with the pavement.

Tonal noise generation from the lateral shoulder sipes may be present in other tyres, if they are not constructed as small sipes but as longer length sipes or lateral treads that significantly cross over the tyre’s shoulder, such as with winter tyres.

## 7.5 Noise data from other CPX trailers

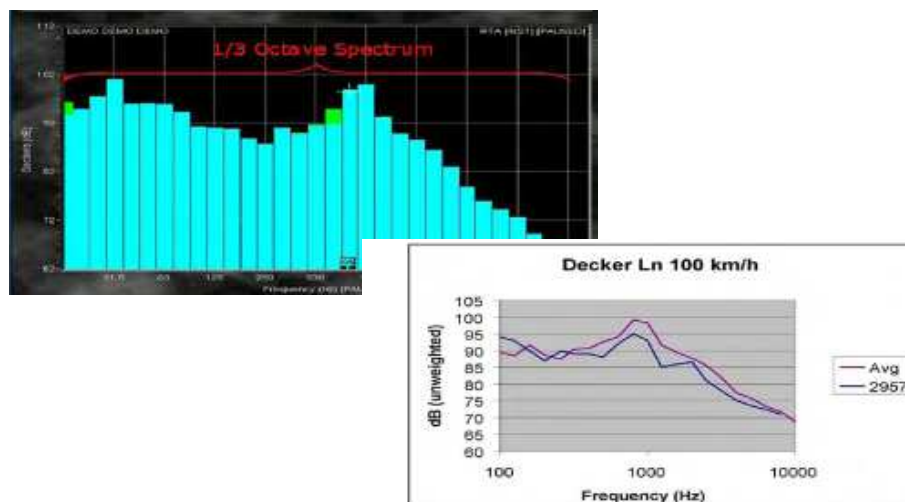
The data collected with the CPX trailer, that was constructed for this specific thesis, is cross checked with data published in other papers, or measurements performed by third party road authorities in different countries with similar trailers.

### 7.5.1 The Center for Transportation Research

A) The Center for Transportation Research – University of Texas Austin issued a 132 page report entitled, ‘A Research plan for measuring noise levels in Highway pavements in Texas’ [111]

They used the CPX method and two of the graphs published are presented below, where one can observe the same spectral distribution as with the measurements in this thesis. They, too, have a major peak in the mid-high frequency range and then a steep decline in the high frequency area of the spectrum.

It has to be noted that the two following graphs contain A-unweighted data (that means that low frequency data is not filtered out by the A weighting filter/network) and this is the reason the low frequencies are shown quite high in both graphs.

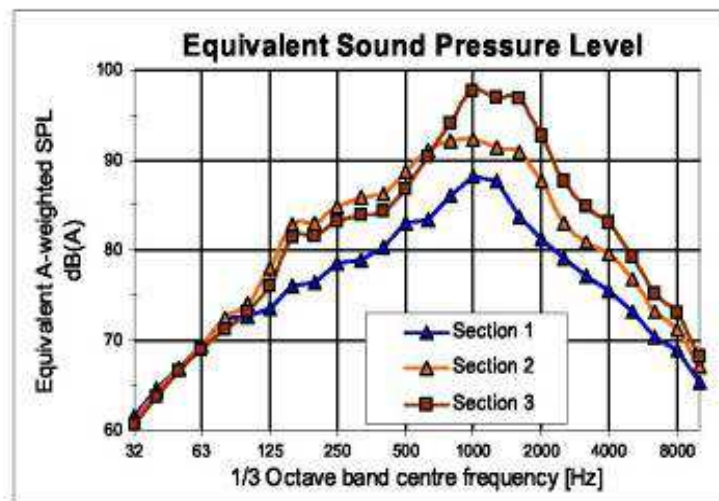


**Fig. 7-23.** Data from University of Texas project [111]



### 7.5.2 Eurnoise 2008 Acoustics Conference

B) A paper presented by Hojer and Nielsson (2008) at the Eurnoise Acoustics Conference titled, 'A single wheel trailer for tyre/road noise measurements enabling both the CPX and pass-by methods', published the right graph [76]

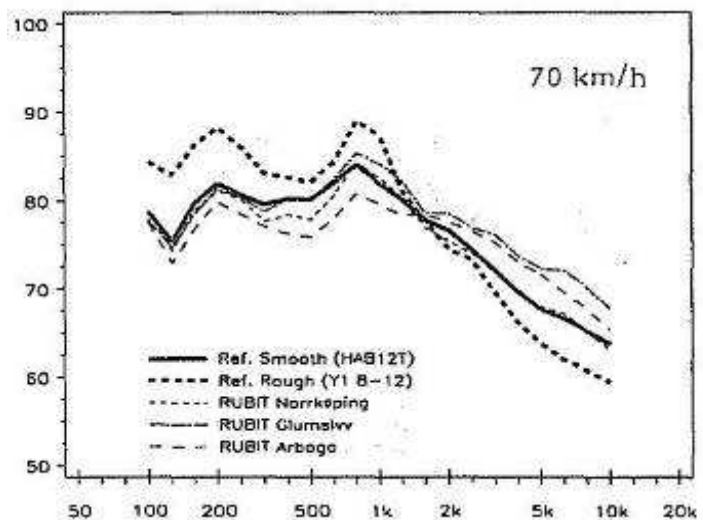


**Fig. 7-24.** Data from Eurnoise conference [76]

Depending on the road type (mentioned here as Section-x), the spectral distribution is very similar to the measurements performed by the trailer in this thesis, with a peak in the mid-high frequencies. Low frequency noise is low in level in the above chart, since it shows 'A' weighted noise data, meaning that the low frequency data are filtered out, similar to the measurements performed in this thesis.

### 7.5.3 Tyre/road noise on rubberized asphalt

C) A 36 page paper by Ulf Sandberg, *et al.* (1990) with the title, 'Tyre/road noise on rubberized asphalt and cement concrete surfaces in Sweden' [77], presents a variety of measurements performed with the CPX method on several types of surfaces.



**Fig. 7-25.** Data from Sandberg *et al.* project [77]

They used different tyres, and in all the graphs the spectral distribution was

similar to the author's trailer, with the same peak in the mid-high frequency range, and rapid decline in the high frequency range.

Note that in this graph, the vertical axis contains A-unweighted values (dB) so the low frequency data seems to be high in level, but if A-weighted, it will be much lower and consistent with the author's measurements.

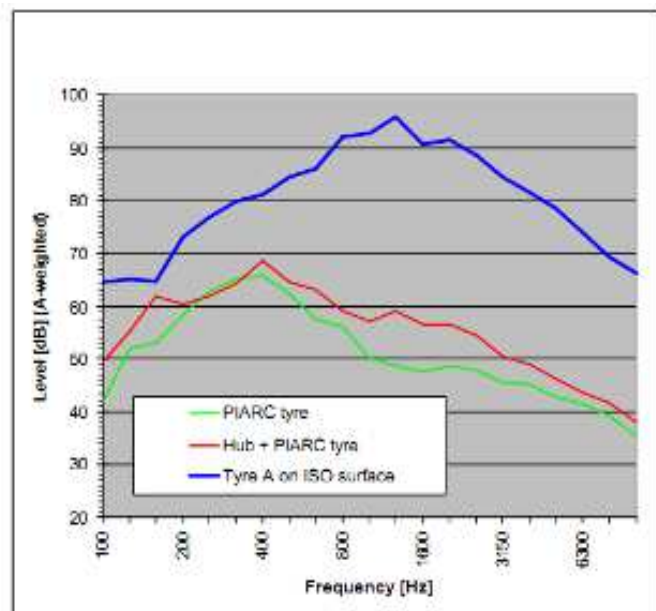
It has to be clarified that "A" weighting is used only as a spectral filter in order to simulate better the human ear perception. According to the adjustments done on the instrumentation used, one can expect "unweighted" or "A weighted" data, that have a specific relevance between them (not explained here).

#### 7.5.4 Silvia Project

D) The 117 page project of the European Commission with the title, 'Silvia Project - Development of procedures for certifying noise testing equipment' [123], is an experimental certification procedure and several CPX trailers are used and evaluated, from which the graph (right) is extracted.

The blue line is a typical measurement of one of the trailers using the CPX method on an ISO standard pavement, with the tyre named 'A' (red and green lines are not tyre noise).

Here, too, appears the same pattern on the graph: peak in the mid-high frequency area of the spectrum and sharp decline in the high frequency area. Values on the vertical axis are 'A' weighted.



**Fig. 7-26.** Data from SILVIA project [123]

Seemingly, on all CPX trailers (also seen in other projects but not mentioned here), the acoustic behaviour is quite the same and only level differences are present, or frequency shifts left or right of the spectrum, or extreme or broader tonal distribution, but the general spectral distribution is similar to each other.

## **7.6 Comments on CPX trailer data validation**

As shown in all measurements performed with our trailer and in all measurements performed by other trailers (with one or two wheels), the spectral pattern distribution is very similar.

There are some level differences, tonal peaks, or spectral shift but they are being expected due to the difference of the road surface, the tyre type, and tyre manufacturer used each time.

It should be noted that according to the standards all measurements were performed on a dry road surface.

Concluding from all the above, our CPX trailer may be considered to be validated and it behaves as it should. It shows data consistency with other trailers and its noise data will be used for cross checking the noise data that will be collected by the measuring device which is under development.



## **8 NOISE MEASUREMENTS USING THE CONSTRUCTED DEVICE**

### **8.1 Schematic measuring setup**

The data in this chapter is collected with the constructed device, as described in previous chapters.

Prior to recording the final data, 3 sets of preliminary measurements were performed per tyre and per velocity, and since no significant noise variations were observed, the measurements were finalised and recorded.

During each set of measurements, it became obvious, as expected, that the data from the left and right channels are not exactly the same since they are set to measure the «near field» of a different noise source (the lateral or the axial to the tyre orientation.)

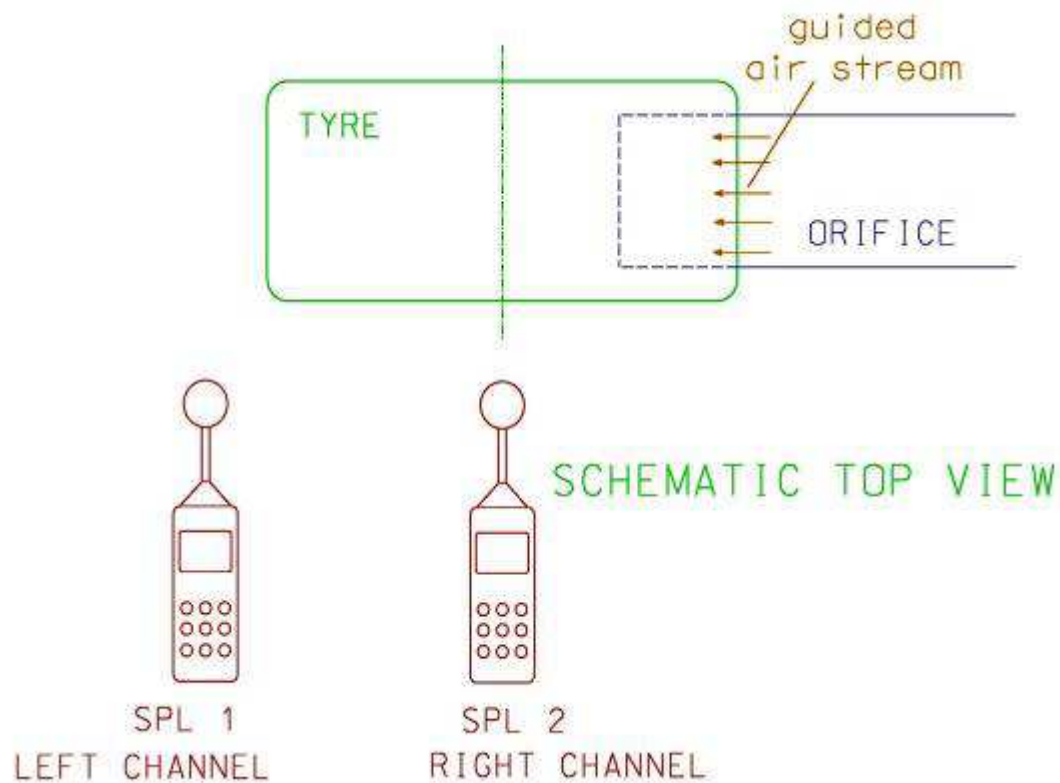
The following graphic illustration is a Top View of the measuring setup, where one can see the guided air stream from the orifice to the tyre's front edge with the pavement (the pavement is not shown in the illustration).

The SPL meter 1 is measuring the acoustic near field from axial back side of the tyre (trailing edge) and is driven to the spectral software as "left channel"

The SPL meter 2 is measuring the acoustic near field from lateral side of the tyre and is driven to the spectral software as "right channel"

All the measurements were performed in a quiet, closed room and the background noise during the measurements was negligible all the time and did not affect the tyre measurements.

The measured background noise was constant and less than 30dBA.



**Fig. 8-1** Schematic Top view of measuring setup

## 8.2 Noise data collected from the developed device

All measured data shown throughout this chapter and thesis are in dBA units re $20\mu\text{Pa}$ , since this is the typical human perception of noise and all the acoustic data and graphs are frequency weighted with the “A” network. So, all data is marked as dBA.

An acoustic engineer might argue that acoustic pressure (noise) over 85-90dB should be recorded and classified in dBC units, since this is the human ear’s behaviour at high noise levels, and although it is scientifically true, it is not used since data in dBA and dBC are actually different units and cannot be compared.

In acoustics it is common practice to compare dB units weighted with the “A” network when most of the data is under 85-90 dB, even when the level of some of the data is above 85-90dB. In contrast, it is common practice to compare dB units weighted with the “C” network

when most of the data is over 85-90 dB, even when some of the data is lower than 85-90dB.

The following tables contain summarized values with noise data in 1/3 octave of tyre "A", tyre "B", and tyre "C", when each tyre is pressed against a very smooth pavement.

**Table 8-1.** Tyre "A" on Device's Smooth surface

Frq (Hz)	DEVICE measurements on <b>SMOOTH</b> Surface (units in dBA re 20 $\mu$ Pa)					
	TYRE A at 50km/h		TYRE A at 80km/h		TYRE A at 110km/h	
	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
<b>250</b>	37,1	36,9	43,0	40,6	52,4	49,7
<b>315</b>	36,3	33,9	43,4	44,0	48,7	47,0
<b>400</b>	36,8	36,4	40,2	45,5	54,2	58,5
<b>500</b>	37,2	37,3	42,8	43,7	48,2	56,0
<b>630</b>	44,1	38,8	48,2	47,8	53,2	52,0
<b>800</b>	45,8	43,9	51,4	52,4	64,1	63,5
<b>1000</b>	56,7	45,6	62,4	55,9	68,3	57,9
<b>1250</b>	60,1	49,1	65,9	55,6	73,7	59,2
<b>1600</b>	63,8	55,2	68,8	62,5	72,8	66,0
<b>2000</b>	67,7	58,9	69,3	63,7	74,0	64,0
<b>2500</b>	64,1	56,4	64,0	61,1	67,8	60,2
<b>3150</b>	62,8	56,7	63,6	59,7	69,3	62,1
<b>4000</b>	61,6	48,1	62,9	54,0	66,4	56,4
<b>5000</b>	59,2	45,8	62,0	55,5	65,5	55,7
<b>6300</b>	48,9	43,2	57,9	56,6	63,4	53,6
<b>8000</b>	47,8	40,1	56,2	51,8	60,1	50,2

**Table 8-2.** Tyre “B” on Device’s Smooth surface

Frq (Hz)	DEVICE measurements on <b>SMOOTH</b> Surface (units in dBA re 20 $\mu$ Pa)					
	TYRE B at 50km/h		TYRE B at 80km/h		TYRE B at 110km/h	
	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
250	45,8	42,3	50,3	49,5	60,7	54,0
315	42,3	40,6	54,1	55,0	58,3	55,0
400	43,9	41,5	48,5	49,4	58,7	54,0
500	45,0	46,9	51,5	52,0	58,2	54,3
630	50,5	47,0	54,7	56,1	60,2	56,7
800	50,6	47,9	57,0	55,9	67,9	65,9
1000	65,6	58,2	70,2	62,3	75,9	63,3
1250	70,3	58,7	74,1	62,5	79,9	68,7
1600	73,7	62,8	76,2	67,6	80,0	71,1
2000	73,4	63,3	72,9	70,8	78,1	71,6
2500	70,3	60,8	70,9	66,0	76,8	67,4
3150	71,3	65,6	71,7	65,0	75,6	67,9
4000	64,2	54,9	67,1	62,5	72,2	63,3
5000	65,1	54,5	65,4	62,2	73,6	63,6
6300	53,4	53,0	62,2	64,8	68,2	63,1
8000	51,2	46,1	61,1	57,6	65,6	57,3

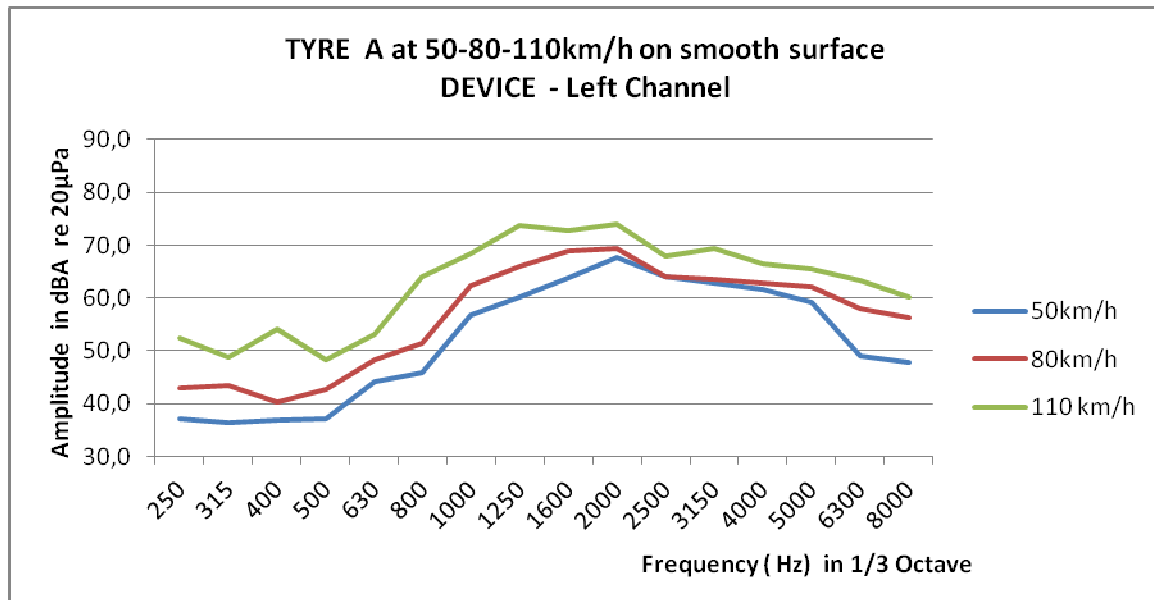
**Table 8-3.** Tyre “C” on Device’s Smooth surface

Frq (Hz)	DEVICE measurements on <b>SMOOTH</b> Surface (units in dBA re 20 $\mu$ Pa)					
	TYRE C at 50km/h		TYRE C at 80km/h		TYRE C at 110km/h	
	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
250	37,6	39,7	41,5	44,4	51,7	55,1
315	34,0	36,1	43,2	45,4	48,8	51,1
400	35,3	38,6	50,8	52,1	53,1	57,2
500	37,9	40,2	46,4	50,3	53,6	57,3
630	41,1	42,0	52,6	50,7	56,1	54,6
800	50,9	45,1	60,9	53,7	67,5	65,4
1000	61,0	51,5	66,5	55,6	70,5	62,1
1250	62,6	51,4	67,8	59,8	73,6	63,8
1600	64,8	56,4	71,7	62,7	76,8	67,5
2000	69,2	63,0	71,7	66,9	77,8	68,0
2500	67,3	60,5	66,5	63,7	70,3	64,4
3150	71,0	61,0	65,9	59,8	71,6	64,9
4000	62,1	54,2	63,2	57,1	67,2	56,8
5000	61,2	52,0	64,4	57,8	70,2	58,7
6300	53,1	46,6	60,3	58,0	64,6	57,9
8000	45,8	41,2	57,5	51,3	60,2	52,3

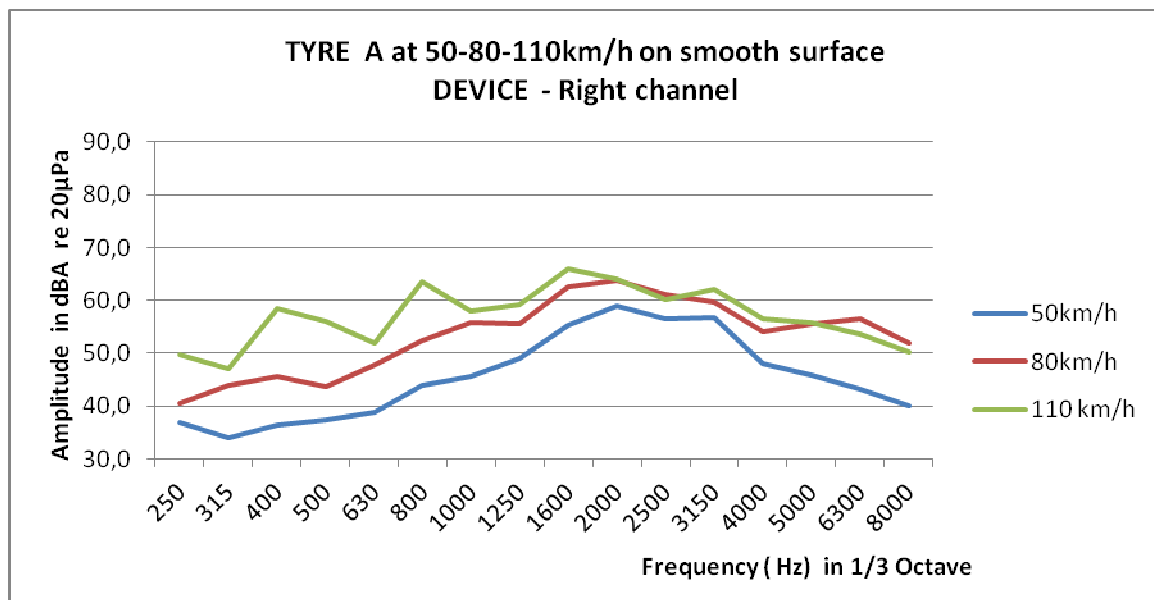
All the above data is shown in graphical form in the following graphs.



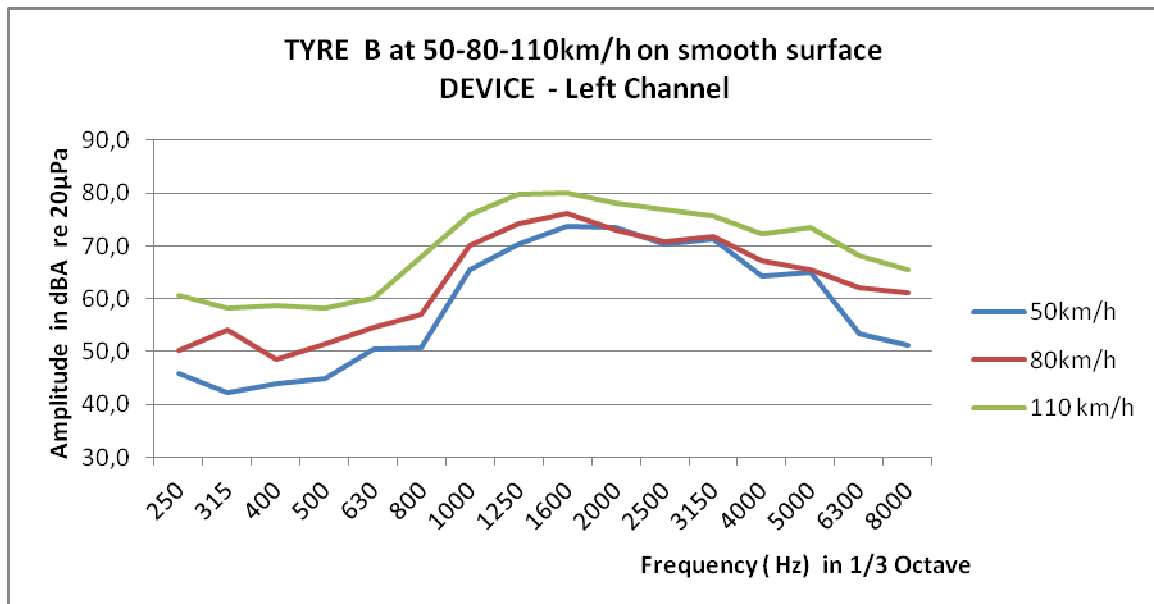
### 8.3 Graphs per tyre - Device noise data



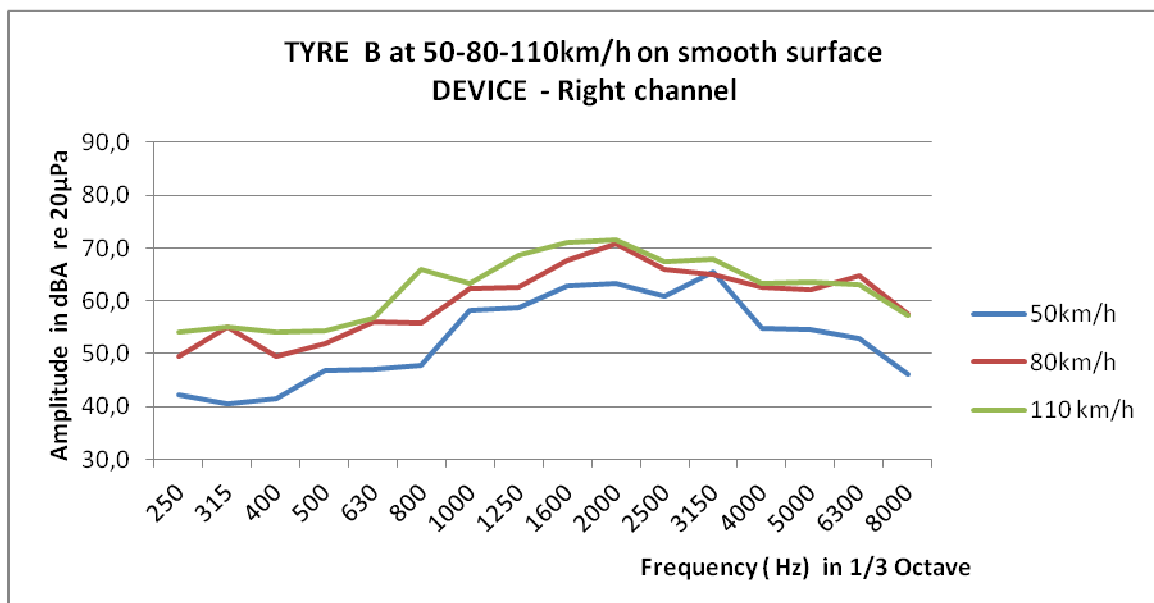
**Fig. 8-2.** Device data – Tyre A at 50-80-110Km/h – Left Channel



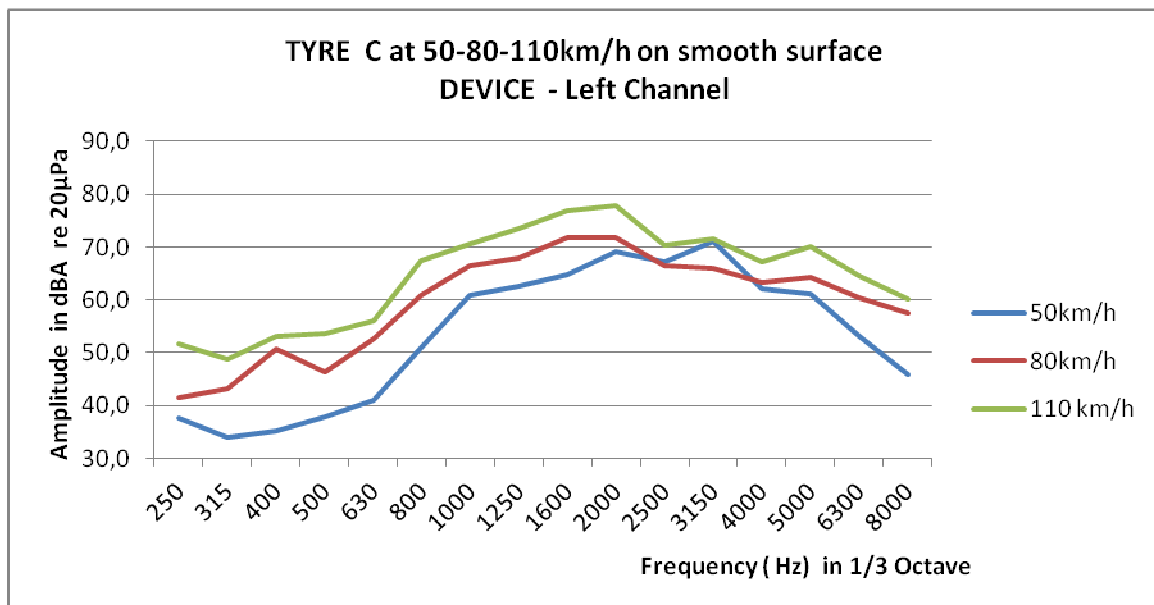
**Fig. 8-3.** Device data – Tyre A at 50-80-110Km/h – Right Channel



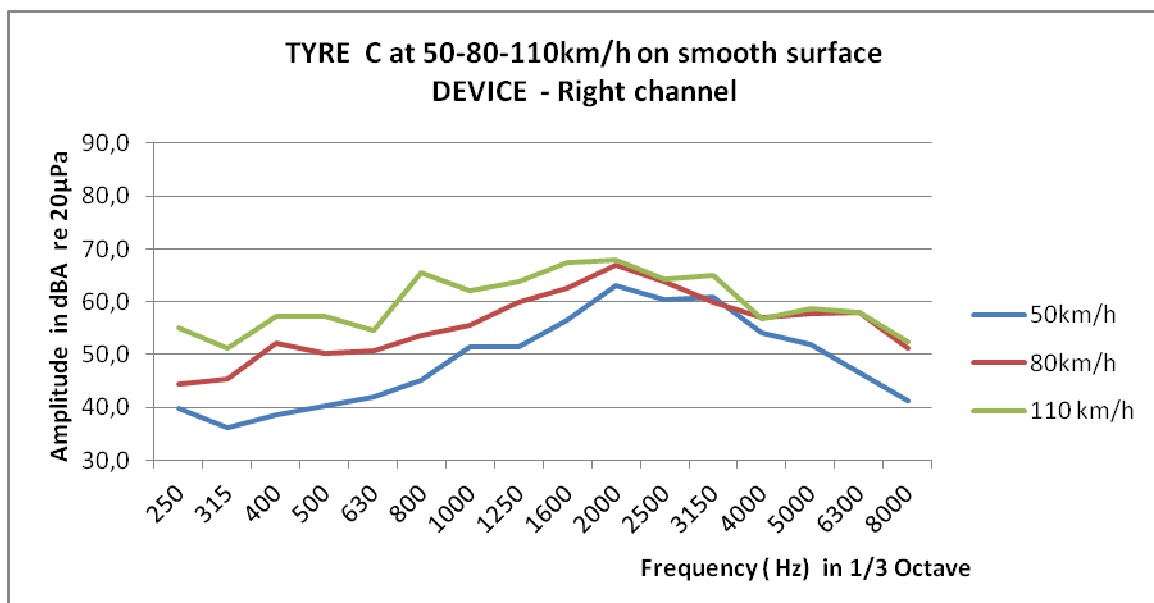
**Fig. 8-4.** Device data – Tyre B at 50-80-110Km/h – Left Channel



**Fig. 8-5.** Device data – Tyre B at 50-80-110Km/h – Right Channel



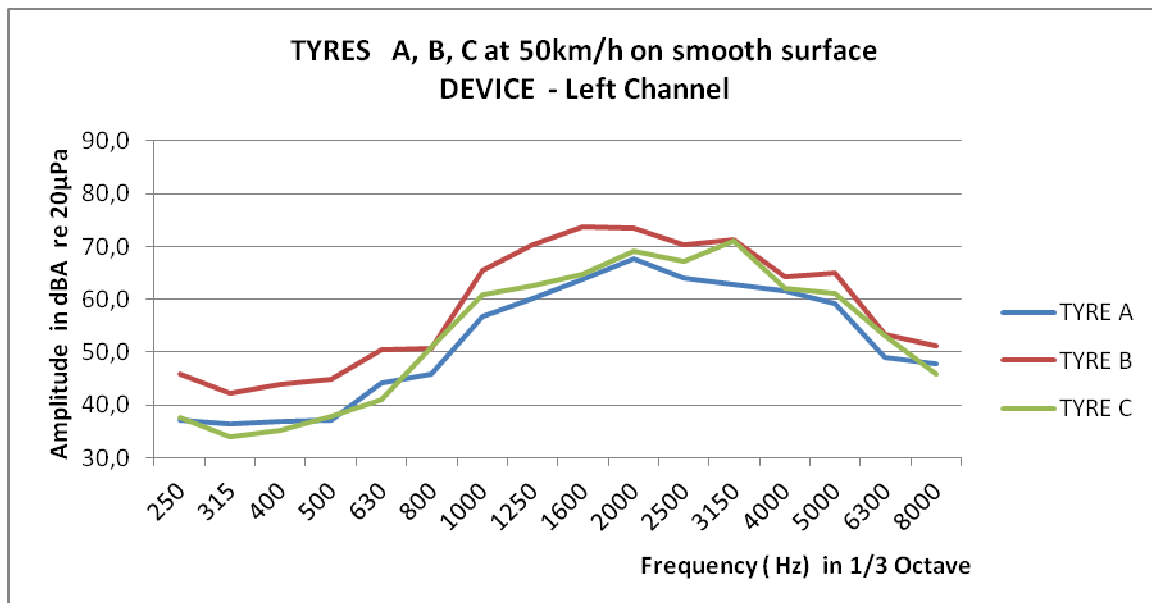
**Fig. 8-6.** Device data – Tyre C at 50-80-110Km/h – Left Channel



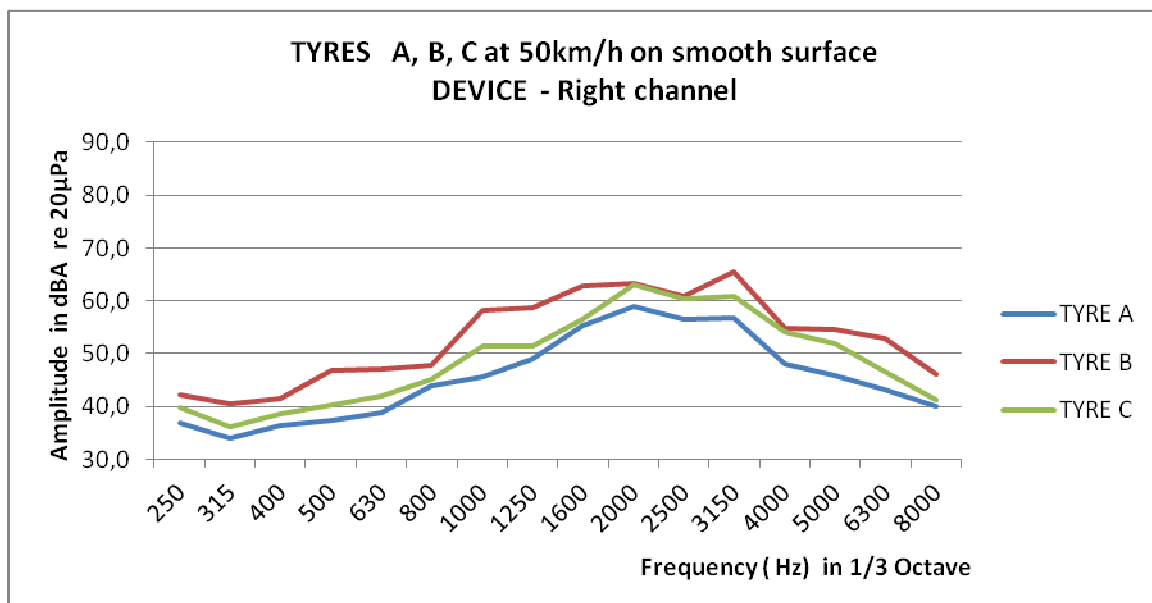
**Fig. 8-7.** Device data – Tyre C at 50-80-110Km/h – Right Channel

On all sets of measurements for all 3 tyres, it is clear that there is a noticeable increase in the noise level in all the spectrum ranges as the air passing velocity increases. So the device performs in a similar manner as the CPX trailer measurements. Another noticeable factor is that the spectral pattern (elevated in the mid-high frequency range) is similar to the CPX trailer measurements, especially in the left channel measurements.

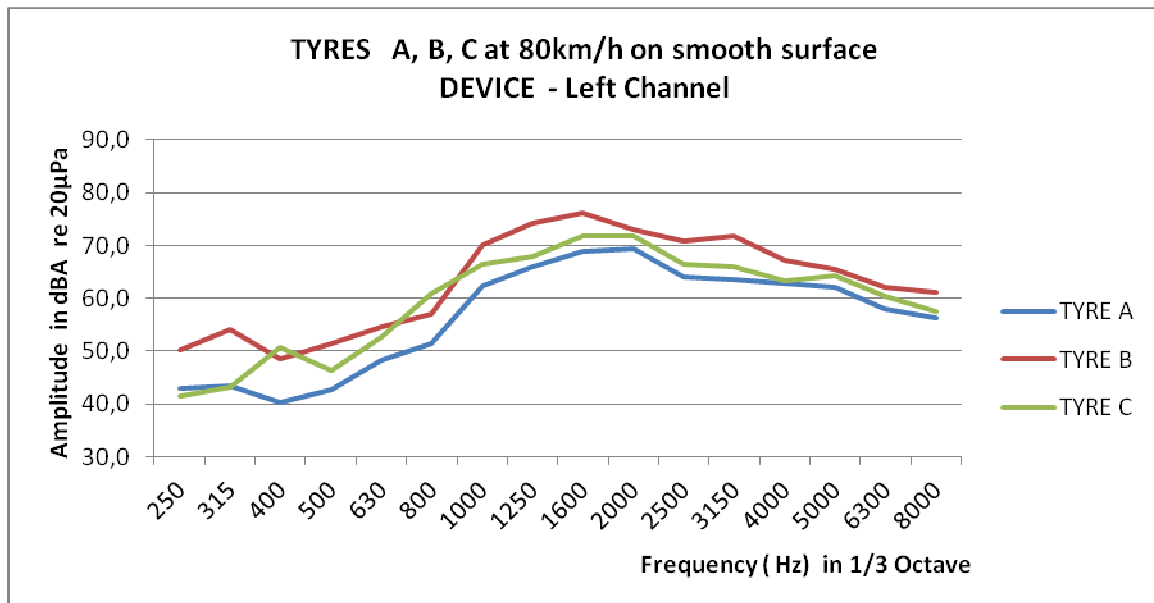
## 8.4 Comparison graphs per velocity - Device noise data



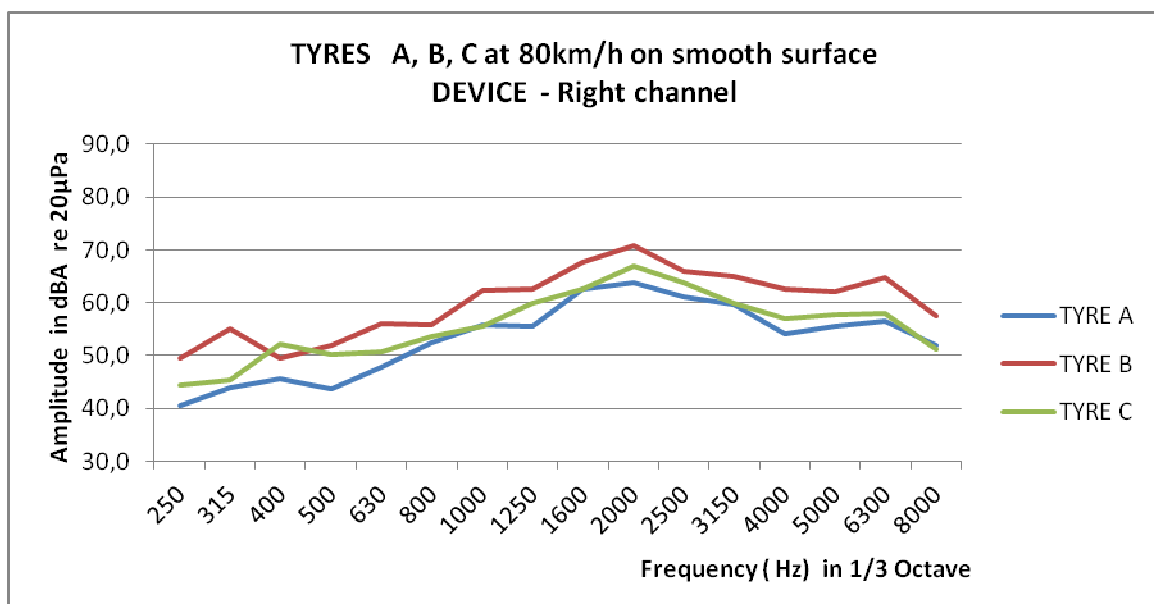
**Fig. 8-8.** Device data – Tyre A-B-C at 50Km/h – Left Channel



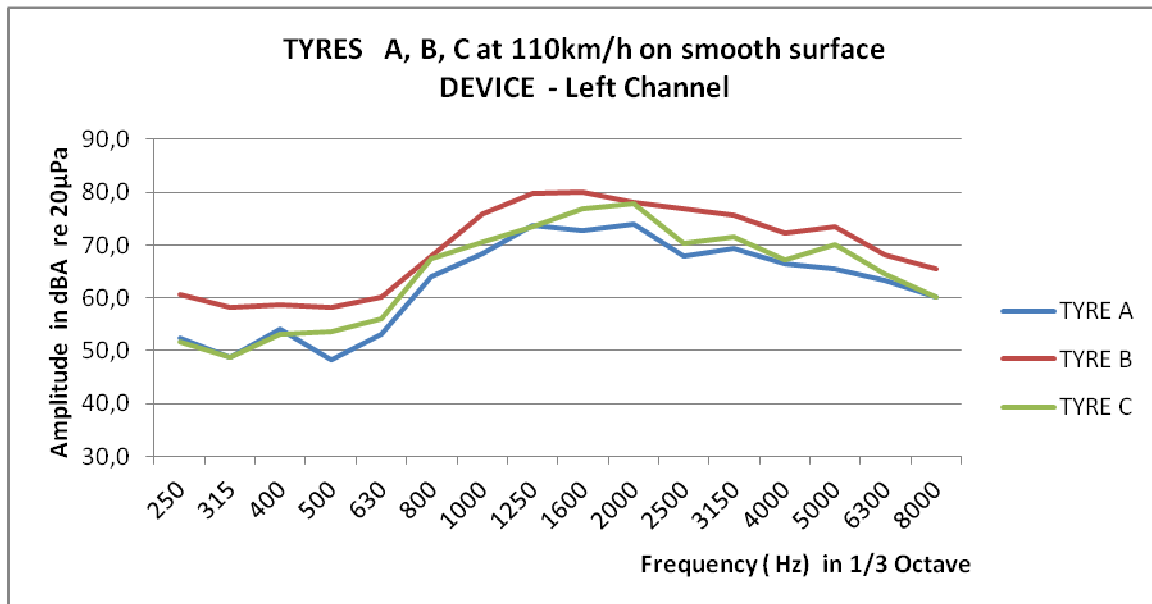
**Fig. 8-9.** Device data – Tyre A-B-C at 50Km/h – Right Channel



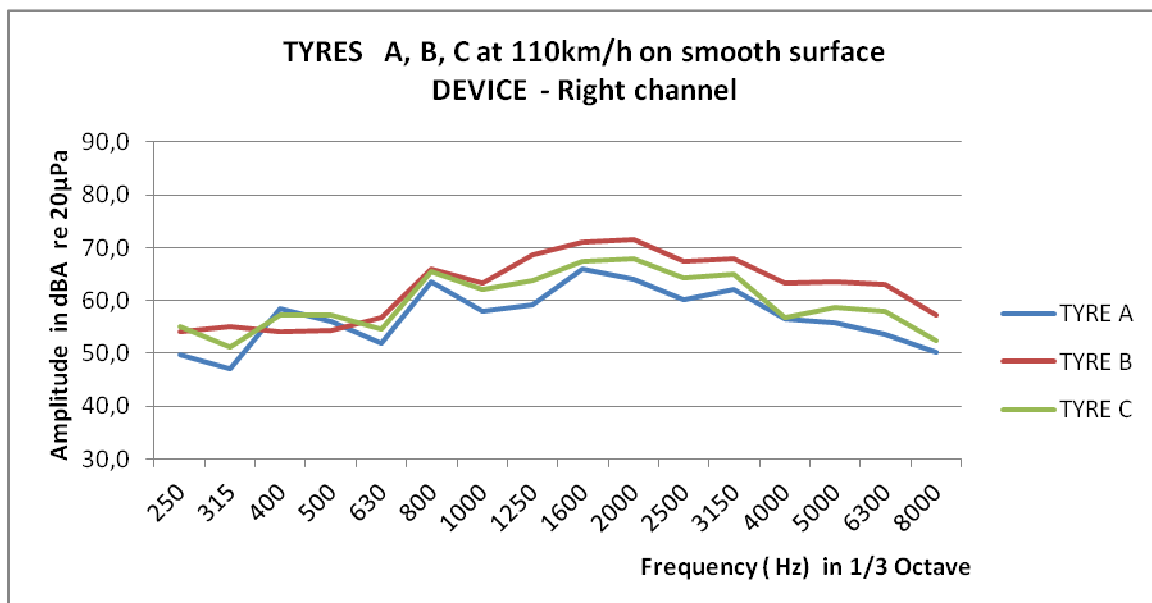
**Fig. 8-10.** Device data – Tyre A-B-C at 80Km/h – Left Channel



**Fig. 8-11.** Device data – Tyre A-B-C at 80Km/h – Right Channel



**Fig. 8-12.** Device data – Tyre A-B-C at 110Km/h – Left Channel



**Fig. 8-13.** Device data – Tyre A-B-C at 110Km/h – Right Channel

In all measurements, the general acoustic behaviour is:

- Tyre B is the noisiest of all
- Tyre A is the quietest of all
- Tyre C is in the middle.

So the classification is the same as the CPX trailer measurements, although the amplitude level is lower.

## **9 DATA DISCUSSION**

### **9.1 Comparison of graphs**

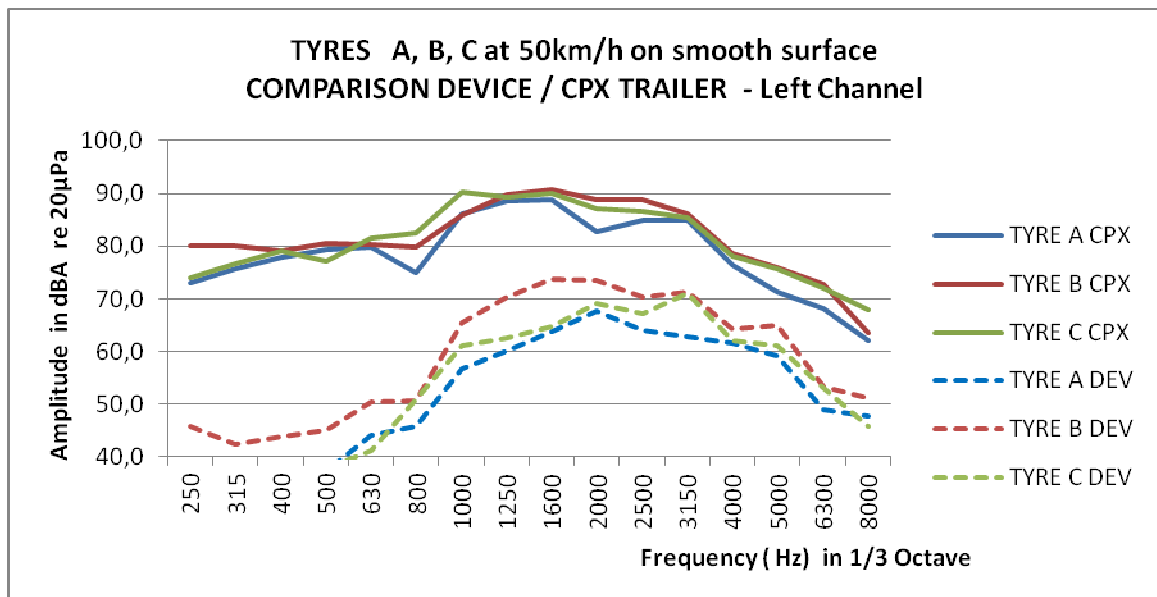
#### **9.1.1 Comparison of CPX trailer and device noise graphs**

The following set of graphs compares the data collected from the CPX trailer at speeds of 50, 80, 110km/h over a smooth, non-porous surface against the measurements of the same tyres, mounted on the device and pressed with calculated force over a smooth, non-porous flat surface, with the high pressure fan regulated to produce/simulate the vehicle's same travelling speeds.

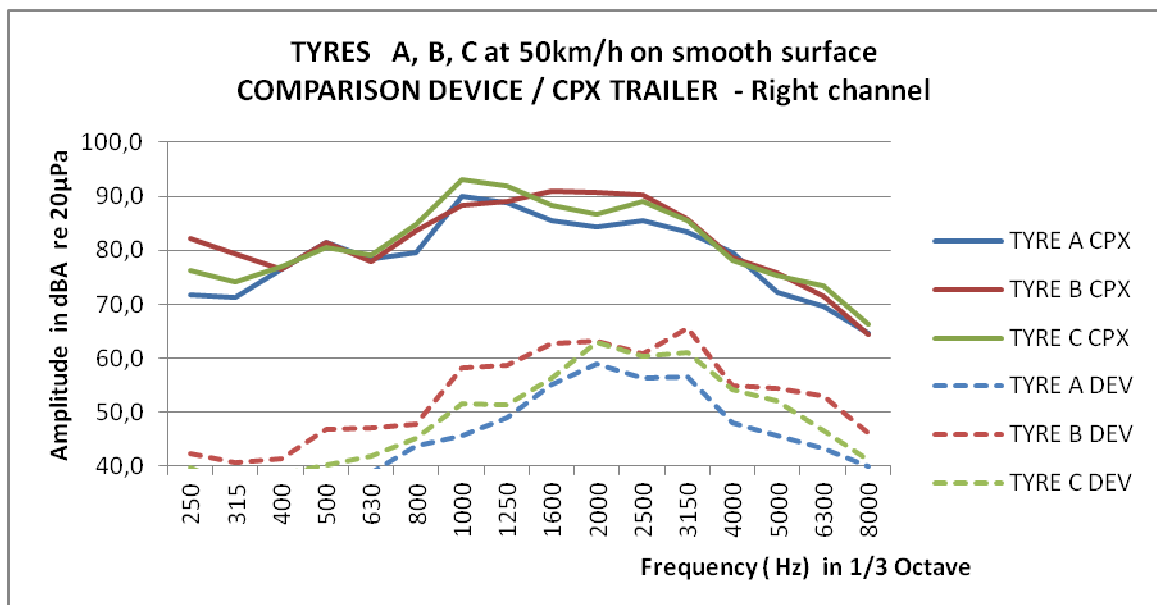
The main goal of this chapter and this thesis is to see if the spectral distribution from both procedures is similar or if they are completely different and no comparison can be performed between them.

As proven with the following graphs, there is a consistent pattern that correlates both measuring procedures.

As expected, the overall noise level of the measurements with the device is lower than the CPX trailer measurements, since there are no dynamic factors present with the device measurements, so the noise level differences are something to, a) be expected, and b) be welcomed, since the aerodynamically produced noise from the grooves and treads should be less than the overall produced noise produced with the CPX method.

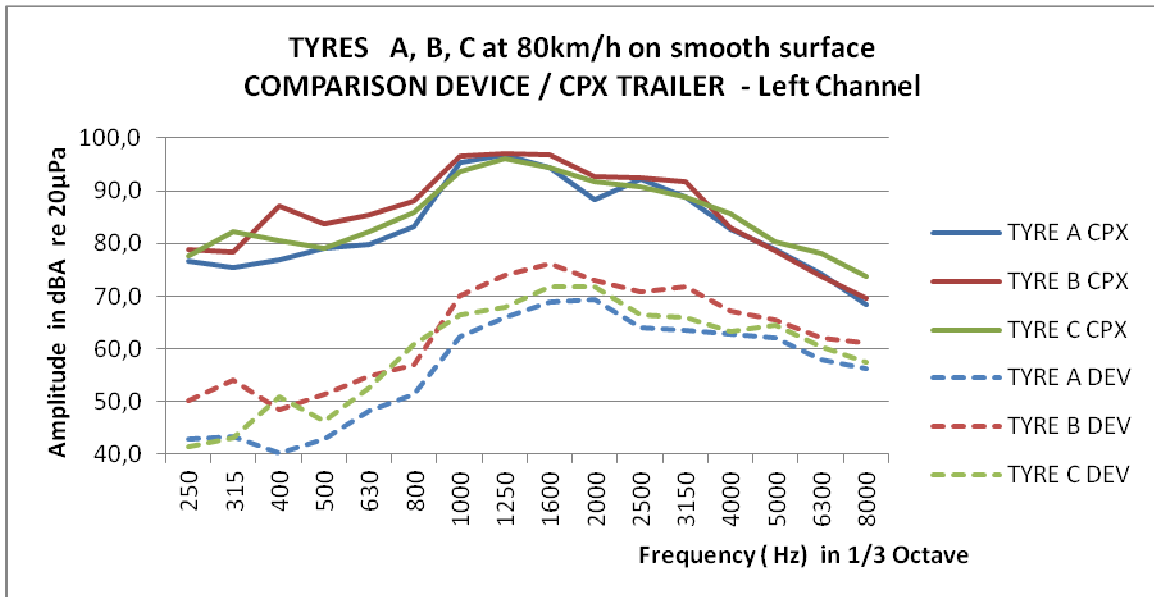


**Fig. 9-1.** Comparison of Device/CPX at 50km/h - Left Channel

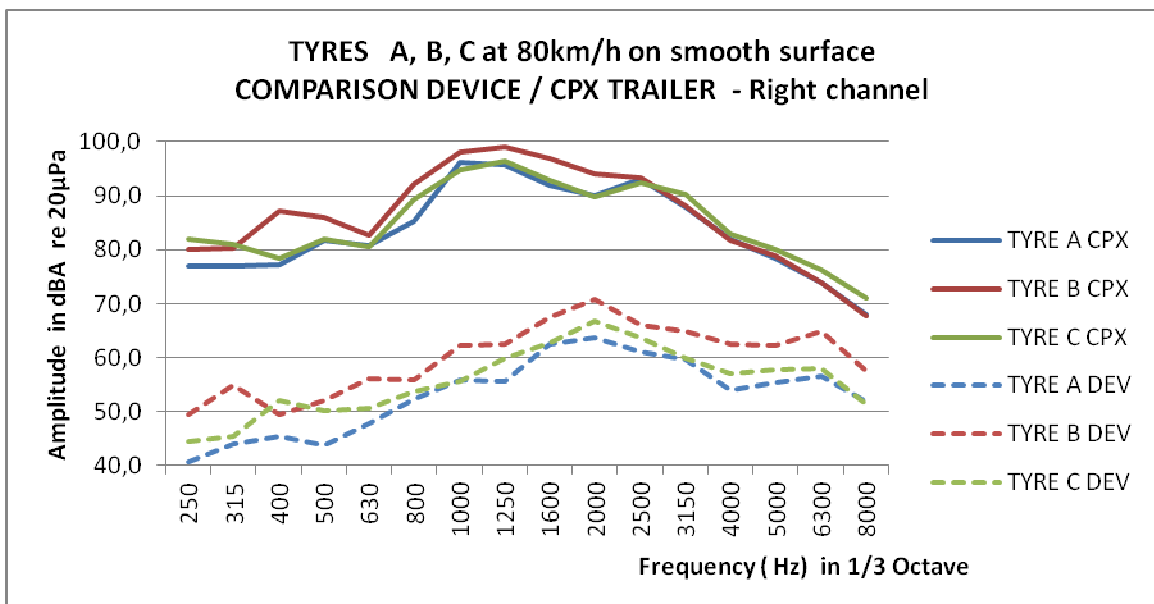


**Fig. 9-2.** Comparison of Device/CPX at 50km/h - Right Channel

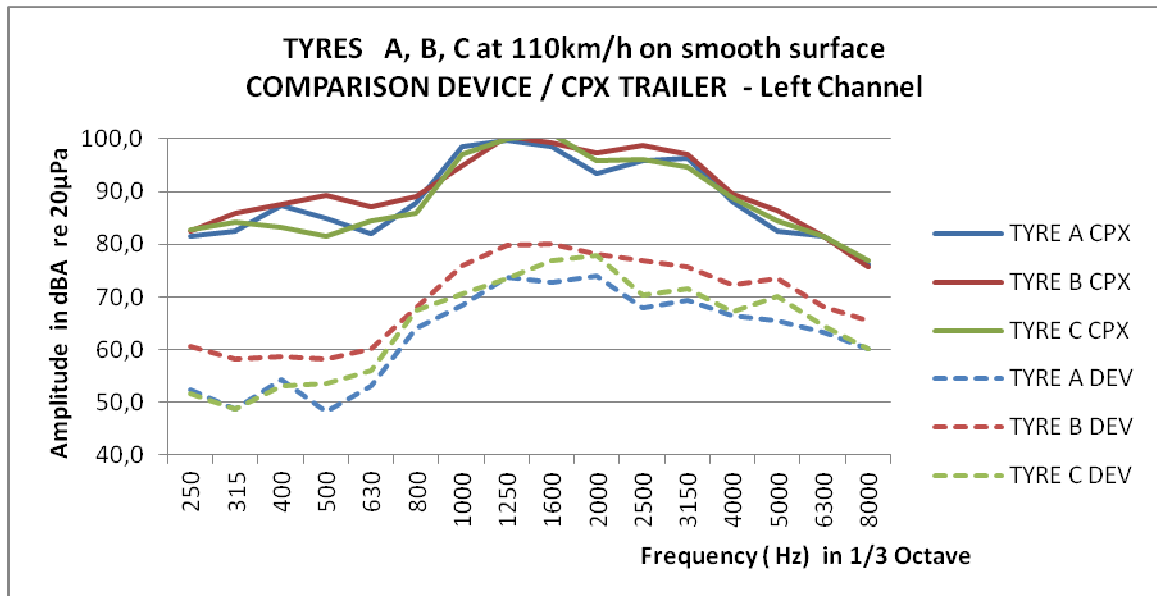




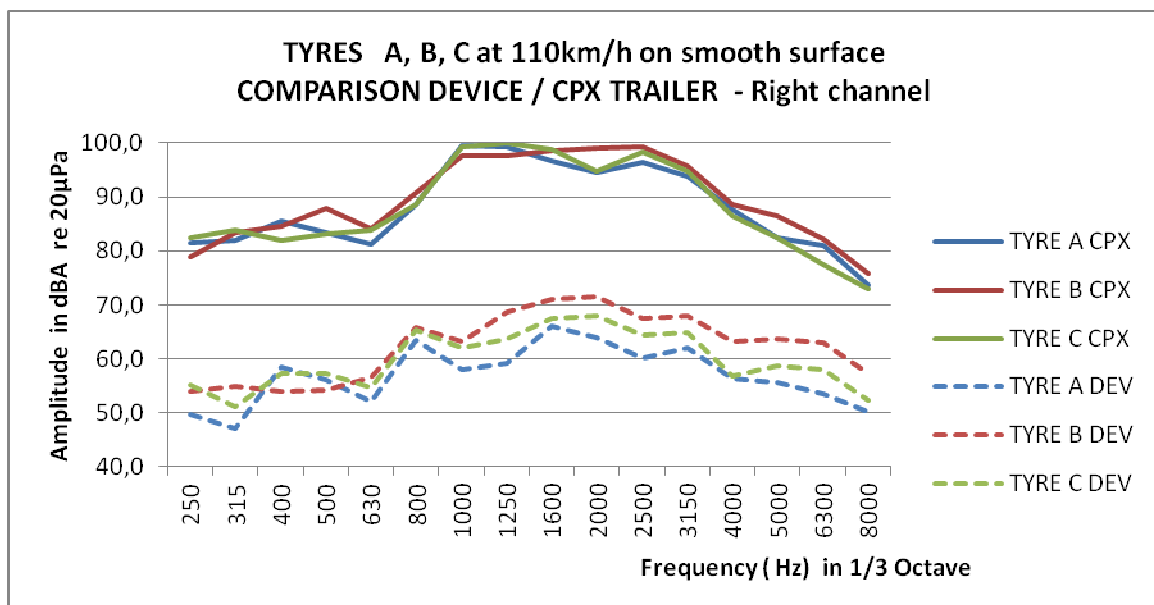
**Fig. 9-3.** Comparison of Device/CPX at 80km/h - Left Channel



**Fig. 9-4.** Comparison of Device/CPX at 80km/h - Right Channel



**Fig. 9-5.** Comparison of Device/CPX at 110km/h - Left Channel



**Fig. 9-6.** Comparison of Device/CPX at 110km/h - Right Channel

### 9.1.2 Comments on graph comparisons

As seen from all graphs, the measurements collected with the left SPL meter (left channel) is frequency consistent in both methodologies; which means that due to its position at the rear end of the tyre's travelling direction, the spectral distribution is very similar (low in the low frequency area, high in the mid frequency area, and dropping fast in the high frequency area).

The right SPL meter (right channel) has a similar spectral distribution but shows a frequency drift towards the high frequency area, which can be explained due to the air escaping from the lateral side of the tyre, through the lateral shoulder sipes of the tyre.

Comparing the noise data per method in each of the above graphs, it is shown that:

- a) The noise spectrum data per tyre, regardless of the speed of travel, is rather "squeezed" for the CPX trailer method, meaning that all three spectral lines are very close to each other.
- b) But the three spectral lines from the Device measurements are clearly apart from each other by 2 – 7dB, providing clearer results that are tyre dependent.

The explanation is that during the CPX trailer measurements, the noise that is recorded is not only due to the tyre's treads, but more noise data is recorded (from all dynamic phenomena affecting the tyre's rotation) that are interfering with the tread's noise.

In the device measurements such phenomena are not present and only the tread's noise is measured, thus providing a clearer noise set and more distinguishable graphs.

### 9.1.3 Comparing tyre behaviour with multiple grooves

As seen in the results with the CPX trailer and with the developed device, tyre B is the noisiest of all, tyre A is the quietest of all and tyre C is in the middle.

It happens that tyre B has only one perimetric groove, tyre C has two grooves and tyre A has three grooves. All grooves have about the same cross section.

Since the grooves and at a lesser degree the tread pattern contribute to the development of turbulence at the trailing edge, the author suspects two phenomena that could be responsible for the high or low noise level/amplitude.

#### 1<sup>st</sup> hypothesis

As the tyre rotates, a portion of the air that is in front of the leading edge is forced inside the groove as a way to escape its displacement to the side of the tyre.

Since the width of the tyre is the same in all three measured tyres one can suppose that in the tyre with only one groove, all the air is travelling through the groove and in contrast in the tyre with two or three grooves, the air is split in two or three sections.

In this scenario, since the air volume in front of all three tyres is the same, one may suppose that the air velocity in the tyre with one groove will be double or triple than in the tyres with two or three grooves.

This means that at the trailing edge the expelled air is very faster for the one groove tyre and  $\frac{1}{2}$  or  $\frac{1}{3}$  slower for the two or three groove tyre, thus creating stronger turbulences and as a result higher level of noise.

One may argue why the leading edge air will be forced to enter in one groove and not travel around the tyre, but we have to bear in mind that the grooves are designed to guide water away from under the tyre contact area, and if one groove is able to supply all the water safely, why is it incapable to supply the air as well?

## 2<sup>nd</sup> hypothesis

A reverse hypothesis is that if the tyre has two or three grooves instead of one then it has two or three noise sources at the trailing edge instead of one.

Theoretically adding noise from two noise sources of same amplitude, yields to a +3dB level increase and adding three equal level noise sources yields to a +4,8dB

But if this was the case then the three groove tyre should be the noisiest, something that did not happen.

## 3<sup>rd</sup> hypothesis

It is common practice to direct a secondary air jet with lower velocity, to the lateral boundaries of a main air jet (primary jet) in order to prevent or reduce the formation of turbulence at the edges of the main air jet, obtaining a smoother mixed air flow. [70], [71].

If one considers the central groove as the main air jet (the one with high velocity) and the left and right groove as the air jets with smaller velocity, then one can expect a combined reduction of turbulence generation, thus a smoother air flow.

## 4<sup>th</sup> hypothesis

Since all three hypothesis could be considered logical one may suppose that the mixing of the above is what really is happening, that is:

- The three grooves produce less turbulence at the trailing edge, compared to the one groove.
- Each of the three grooves should supply about the same volume of air (the middle one may supply some more since it seems easier for the air to avoid to some extent the two lateral grooves that are closer to the tyre's face)
- So they can be considered to be of equal or similar noise amplitude between them, but of less amplitude per groove than the one groove tyre.

Simplistically one may consider this turbulence to be 1/3 for the three groove tyre compared to the one groove tyre, but as known the pressure drop is developed to the square of the velocity, which means that the turbulence development is not known exactly per groove, but

nevertheless it must be significantly lower than with the one groove tyre.

These three lower noise sources (not by 1/3 compared to the one groove tyre) are added, as three noise sources of similar amplitude, at the trailing edge,

Taking into account the theory of multiple parallel air jets, then one more phenomenon is present, that builds up a single pressure wave “wall” that has a smoother reology behaviour than each of the three single grooves.

and the final result is lower noise level, compared to the one groove tyre, as the measurements have shown.

## **9.2 Comparison of data equality**

### **9.2.1 Comparison of CPX trailer and device data equality**

The tables of data for both measuring procedures presented in earlier chapters have a frequency span from 250Hz to 8000Hz, derived from all measured data previously presented.

However, in acoustics, the very low and very high frequency areas are ignored since they have, respectively, very large and very small wave lengths, so data collected in these areas may be strongly influenced by external factors or measuring irregularities.

Hence, the same tables are presented but only with a portion of the frequency span, from 800Hz to 4000Hz.

The following tables contain:

- a) The above mentioned portion of the main measured data
- b) The AVerAge of the tabled data
- c) The Difference of the Measured data minus the AVG values
- d) The T-Test results

### 9.2.1.1 Data equality for tyre A

**Table 9-1.** Difference of Values for tyre A

		DEVICE measurements on SMOOTH Surface								CPX TRAILER measurements on SMOOTH Surface					
		TYRE A at 50km/h		TYRE A at 80km/h		TYRE A at 110km/h				TYRE A at 50km/h		TYRE A at 80km/h		TYRE A at 110km/h	
Frq (Hz)		LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	Frq (Hz)		LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
		measured data								measured data					
<b>800</b>		45,8	43,9	51,4	52,4	64,1	63,5	<b>800</b>		75,0	79,6	83,1	85,3	87,8	88,5
<b>1000</b>		56,7	45,6	62,4	55,9	68,3	57,9	<b>1000</b>		86,2	90,0	95,4	96,3	98,6	99,5
<b>1250</b>		60,1	49,1	65,9	55,6	73,7	59,2	<b>1250</b>		88,5	88,8	96,9	95,6	99,8	99,2
<b>1600</b>		63,8	55,2	68,8	62,5	72,8	66,0	<b>1600</b>		88,9	85,4	94,3	91,9	98,6	96,6
<b>2000</b>		67,7	58,9	69,3	63,7	74,0	64,0	<b>2000</b>		82,7	84,3	88,4	90,0	93,4	94,5
<b>2500</b>		64,1	56,4	64,0	61,1	67,8	60,2	<b>2500</b>		85,0	85,4	92,1	93,0	95,8	96,5
<b>3150</b>		62,8	56,7	63,6	59,7	69,3	62,1	<b>3150</b>		84,9	83,5	88,8	87,8	96,4	93,8
<b>4000</b>		61,6	48,1	62,9	54,0	66,4	56,4	<b>4000</b>		76,5	79,7	82,7	82,0	88,2	87,6

		AVERAGE values								AVERAGE values					
AVG=		60,3	51,7	63,5	58,1	69,6	61,2	AVG=		83,5	84,6	90,2	90,2	94,8	94,5
		DIFFERENCE (Measured data minus AVG)								DIFFERENCE (Measured data minus AVG)					
<b>800</b>		-14,5	-7,8	-12,1	-5,7	-5,5	2,3	<b>800</b>		-8,5	-5,0	-7,1	-4,9	-7,0	-6,0
<b>1000</b>		-3,6	-6,1	-1,1	-2,2	-1,3	-3,3	<b>1000</b>		2,7	5,4	5,2	6,1	3,8	5,0
<b>1250</b>		-0,2	-2,6	2,4	-2,5	4,2	-2,0	<b>1250</b>		5,0	4,2	6,7	5,4	5,0	4,7
<b>1600</b>		3,5	3,5	5,3	4,4	3,3	4,8	<b>1600</b>		5,4	0,8	4,1	1,7	3,8	2,1
<b>2000</b>		7,4	7,2	5,8	5,6	4,5	2,8	<b>2000</b>		-0,8	-0,3	-1,8	-0,2	-1,4	0,0
<b>2500</b>		3,8	4,7	0,5	3,0	-1,8	-1,0	<b>2500</b>		1,5	0,8	1,9	2,8	1,0	2,0
<b>3150</b>		2,5	5,0	0,1	1,6	-0,3	0,9	<b>3150</b>		1,4	-1,1	-1,4	-2,4	1,6	-0,7
<b>4000</b>		1,3	-3,6	-0,6	-4,1	-3,1	-4,8	<b>4000</b>		-7,0	-4,9	-7,5	-8,2	-6,6	-6,9

### T-Test for tyre A

for the equality of the means between the two data series, DEV & CPX

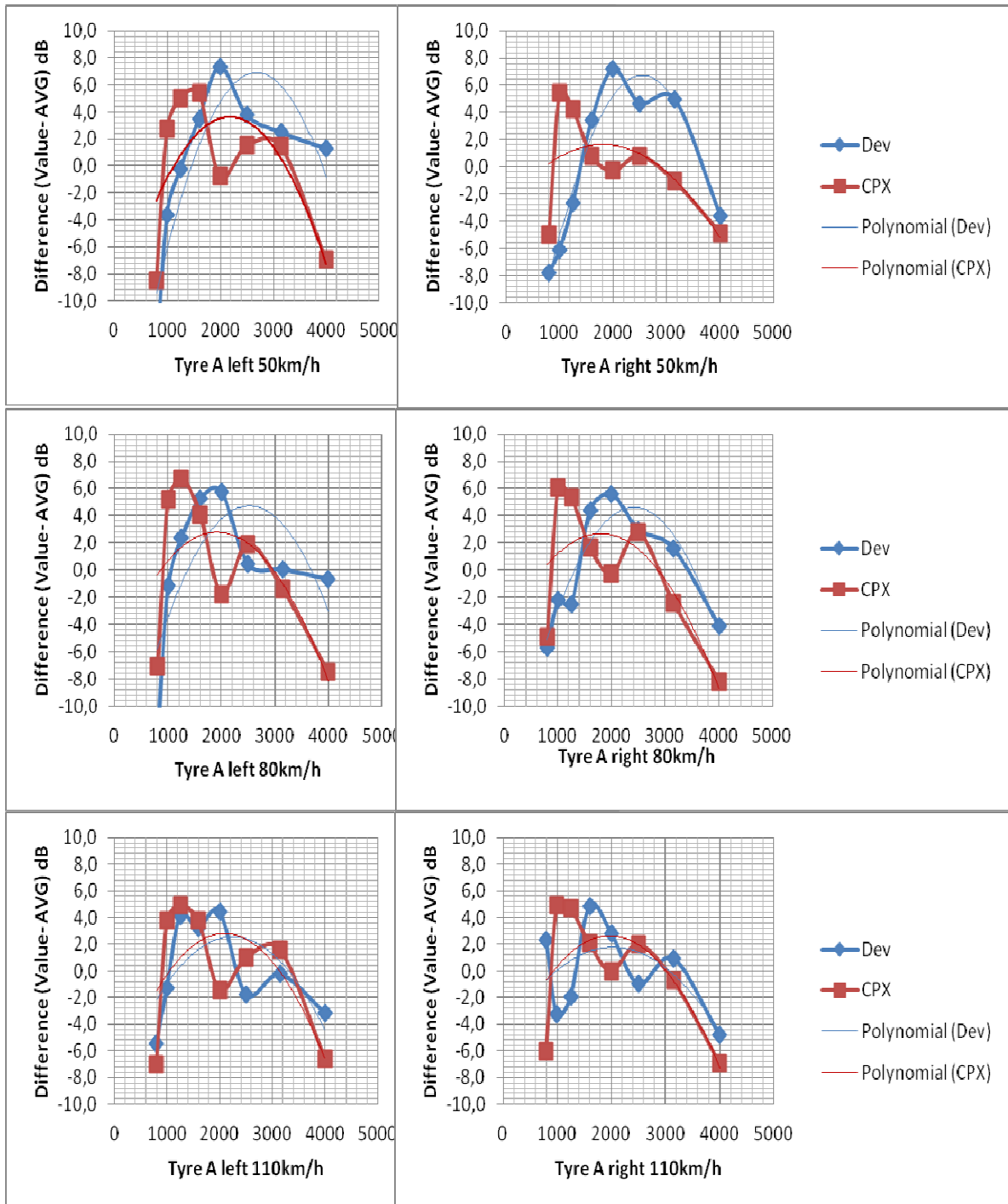
**Table 9-2.** T-Test for tyre A

TYRE A at 50km/h		TYRE A at 80km/h		TYRE A at 110km/h	
Left	Right	Left	Right	Left	Right
0,0000020	0,0000000	0,0000001	0,0000000	0,0000000	0,0000000

The above table gives the resulting p-values from the T-test.



**9.2.1.2 Graph equality for tyre A**



**Fig. 9-7.** Equality for tyre A

### 9.2.1.3 Data equality for tyre B

**Table 9-3.** Difference of Values for tyre B

DEVICE measurements on SMOOTH Surface							CPX TRAILER measurements on SMOOTH Surface						
TYRE B at 50km/h		TYRE B at 80km/h		TYRE B at 110km/h			TYRE B at 50km/h		TYRE B at 80km/h		TYRE B at 110km/h		
Frq (Hz)	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	Frq (Hz)	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
800	50,6	47,9	57,0	55,9	67,9	65,9	800	79,7	83,7	88,1	92,1	89,1	90,7
1000	65,6	58,2	70,2	62,3	75,9	63,3	1000	86,0	88,4	96,5	98,0	95,0	97,6
1250	70,3	58,7	74,1	62,5	79,9	68,7	1250	89,7	89,1	97,1	99,0	100,4	97,7
1600	73,7	62,8	76,2	67,6	80,0	71,1	1600	90,7	91,0	96,8	97,0	99,2	98,5
2000	73,4	63,3	72,9	70,8	78,1	71,6	2000	88,9	90,7	92,8	94,0	97,3	99,0
2500	70,3	60,8	70,9	66,0	76,8	67,4	2500	88,7	90,3	92,4	93,3	98,7	99,3
3150	71,3	65,6	71,7	65,0	75,6	67,9	3150	86,2	85,7	91,8	88,2	97,1	95,8
4000	64,2	54,9	67,1	62,5	72,2	63,3	4000	78,6	78,7	83,0	81,7	89,5	88,6

AVERAGE values							AVERAGE values								
AVG=	67,4	59,0	70,0	64,1	75,8	67,4	AVG=	86,1	87,2	92,3	92,9	95,8	95,9		
	DIFFERENCE		(Measured data minus AVG)						DIFFERENCE		(Measured data minus AVG)				
800	-16,8	-11,1	-13,0	-8,2	-7,9	-1,5	800	-6,4	-3,5	-4,2	-0,8	-6,7	-5,2		
1000	-1,8	-0,8	0,2	-1,8	0,1	-4,1	1000	-0,1	1,2	4,2	5,1	-0,8	1,7		
1250	2,9	-0,3	4,1	-1,6	4,1	1,3	1250	3,6	1,9	4,8	6,1	4,6	1,8		
1600	6,3	3,8	6,2	3,5	4,2	3,7	1600	4,6	3,8	4,5	4,1	3,4	2,6		
2000	6,0	4,3	2,9	6,7	2,3	4,2	2000	2,8	3,5	0,5	1,1	1,5	3,1		
2500	2,9	1,8	0,9	1,9	1,0	0,0	2500	2,6	3,1	0,1	0,4	2,9	3,4		
3150	3,9	6,6	1,7	0,9	-0,2	0,5	3150	0,1	-1,5	-0,5	-4,7	1,3	-0,1		
4000	-3,2	-4,1	-2,9	-1,6	-3,6	-4,1	4000	-7,5	-8,5	-9,3	-11,2	-6,3	-7,3		

#### T-Test for tyre B

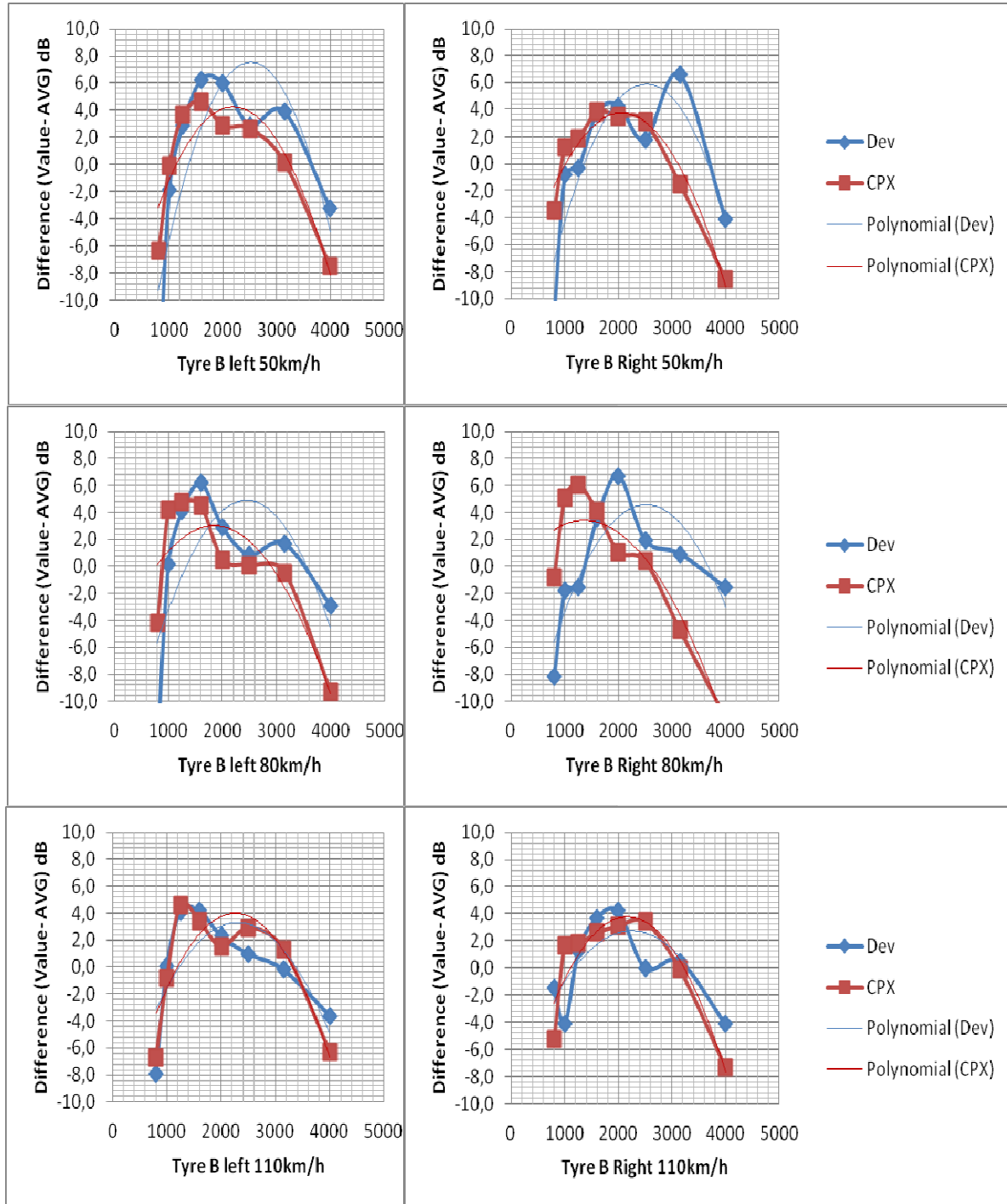
for the equality of the means between the two data series, DEV & CPX

**Table 9-4.** T-Test for tyre B

TYRE B at 50km/h		TYRE B at 80km/h		TYRE B at 110km/h	
Left	Right	Left	Right	Left	Right
0,0000354	0,0000000	0,0000010	0,0000000	0,0000002	0,0000000

The above table gives the resulting p-values from the T-test.

**9.2.1.4 Graph equality for tyre B**



**Fig. 9-8.** Equality for tyre B

### 9.2.1.5 Data equality for tyre C

**Table 9-5.** Difference of Values for tyre C

		DEVICE measurements on SMOOTH Surface								CPX TRAILER measurements on SMOOTH Surface					
		TYRE C at 50km/h		TYRE C at 80km/h		TYRE C at 110km/h				TYRE C at 50km/h		TYRE C at 80km/h		TYRE C at 110km/h	
Frq (Hz)		LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	Frq (Hz)		LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
<b>800</b>		50,9	45,1	60,9	53,7	67,5	65,4	<b>800</b>		82,4	84,9	85,9	89,2	85,9	88,7
<b>1000</b>		61,0	51,5	66,5	55,6	70,5	62,1	<b>1000</b>		90,2	93,2	93,6	94,8	97,0	99,2
<b>1250</b>		62,6	51,4	67,8	59,8	73,6	63,8	<b>1250</b>		89,2	92,0	96,2	96,4	100,0	99,9
<b>1600</b>		64,8	56,4	71,7	62,7	76,8	67,5	<b>1600</b>		90,1	88,3	94,5	92,9	101,0	98,9
<b>2000</b>		69,2	63,0	71,7	66,9	77,8	68,0	<b>2000</b>		87,0	86,6	91,7	89,7	95,8	94,7
<b>2500</b>		67,3	60,5	66,5	63,7	70,3	64,4	<b>2500</b>		86,7	89,0	90,8	92,5	96,0	98,3
<b>3150</b>		71,0	61,0	65,9	59,8	71,6	64,9	<b>3150</b>		85,4	85,5	88,9	90,2	94,6	94,8
<b>4000</b>		62,1	54,2	63,2	57,1	67,2	56,8	<b>4000</b>		78,1	78,2	85,6	82,8	88,9	86,4

AVERAGE values							AVERAGE values						
AVG=	63,61	55,39	66,78	59,91	71,91	64,11	AVG=	86,14	87,21	90,90	91,06	94,90	95,11
	DIFFERENCE (Measured data minus AVG)							DIFFERENCE (Measured data minus AVG)					
<b>800</b>	-12,71	-10,29	-5,88	-6,21	-4,41	1,29	<b>800</b>	-3,74	-2,31	-5,00	-1,86	-9,00	-6,41
<b>1000</b>	-2,61	-3,89	-0,28	-4,31	-1,41	-2,01	<b>1000</b>	4,06	5,99	2,70	3,74	2,10	4,09
<b>1250</b>	-1,01	-3,99	1,02	-0,11	1,69	-0,31	<b>1250</b>	3,06	4,79	5,30	5,34	5,10	4,79
<b>1600</b>	1,19	1,01	4,93	2,79	4,89	3,39	<b>1600</b>	3,96	1,09	3,60	1,84	6,10	3,79
<b>2000</b>	5,59	7,61	4,93	6,99	5,89	3,89	<b>2000</b>	0,86	-0,61	0,80	-1,36	0,90	-0,41
<b>2500</b>	3,69	5,11	-0,28	3,79	-1,61	0,29	<b>2500</b>	0,56	1,79	-0,10	1,44	1,10	3,19
<b>3150</b>	7,39	5,61	-0,88	-0,11	-0,31	0,79	<b>3150</b>	-0,74	-1,71	-2,00	-0,86	-0,30	-0,31
<b>4000</b>	-1,51	-1,19	-3,58	-2,81	-4,71	-7,31	<b>4000</b>	-8,04	-9,01	-5,30	-8,26	-6,00	-8,71

### T-Test for tyre C

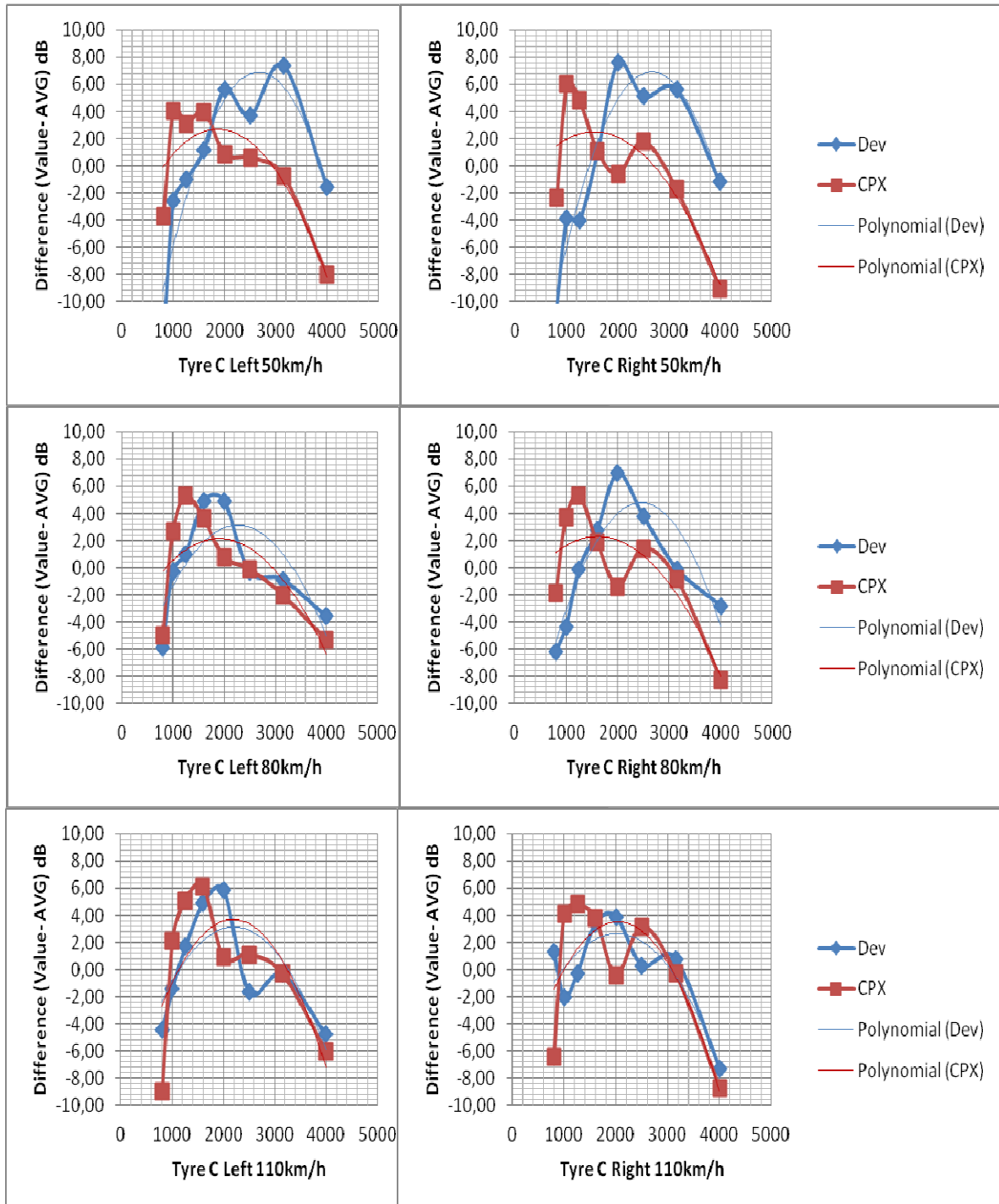
for the equality of the means between the two data series, DEV & CPX

**Table 9-6.** T-Test for tyre C

TYRE C at 50km/h		TYRE C at 80km/h		TYRE C at 110km/h	
Left	Right	Left	Right	Left	Right
0,0000007	0,0000000	0,0000000	0,0000000	0,0000001	0,0000000

The above table gives the resulting p-values from the T-test.

**9.2.1.6 Graph equality for tyre C**



**Fig. 9-9.** Equality for tyre C

### 9.2.2 Summary of T-Test data equality

From the p-values of the T-Test tables on the previous pages, it is seen that since all the values are lower than 0,05, one can conclude that the means are statistically different from each other at 95% level of significance.

Therefore, it is more interesting to test whether the variances between the two data series (Device and CPX trailer) are the same or not.

If it is true, then one can conclude that the two data series follow the same pattern across the frequencies, but with different magnitudes. Although this seems to be the case for the initial graphs prior to de-meaning analysis, it will be verified by using the F-test for the equality of the variances.

In the graphs where the difference in dB is shown (Value minus Average), one can see that for all tyres and especially at the high travelling speeds, the polynomial tendency lines are fairly matched, which could be explained that both methods behave the same and the aerodynamic / turbulence factor is predominant in both methods.

### 9.2.3 F-Test, equality of the variances

The following table gives the resulting p-values from the F-test. Since all the values are higher than 0,05, one can conclude that the variances between the two data series (Device & CPX trailer) are not statistically different at 95% level of significance.

As a result of the two tests, one can verify that the two ways of measuring the noise from the tyre/pavement interaction are very similar in terms of volatility but different in terms of magnitude.

**Table 9-7.** F-Values

	50km/h		80km/h		110km/h	
	Left	Right	Left	Right	Left	Right
Tyre A	0,516307	0,287641	0,944197	0,655461	0,522966	0,439980
Tyre B	0,203142	0,490736	0,618657	0,513030	0,883529	0,522406
Tyre C	0,309751	0,517061	0,917120	0,891188	0,485419	0,350026

### **9.3 Comments on noise data collected from device**

It has to be noted that both spectrums are not expected to be exactly the same since, when using the CPX trailer, more than one uncontrollable noise producing factors are measured.

From the collected noise data performed with the CPX trailer procedure and with the device procedure, it is clear that:

The device is able to make tyre noise measurements and classifications with a spectral distribution similar to the one obtained from the trailer, with much less effort, much cheaper, much faster, and with reliable data, so the main goal of this thesis is believed to be achieved.

### **9.4 Techno economical use**

Besides the acoustic data that proved the good behaviour of the constructed device, another major factor is the economics which such a measurement procedure requires.

It is difficult for science to evolve if it is left in the hands of the few, with expensive test facilities and all the other existing tyre measuring procedures, requiring very large and expensive mechanical installations, large testing areas with a reference pavement, and a CPX trailer to undertake testing.

From all the above, the least expensive is the use of the CPX trailer, but a factor that is not favourable for this testing method, is that all measured data is influenced by a random or uncontrollable surface texture, so always there will be a question mark about the reliability of the tyre's tread noise.

The only method that is able to measure the tyre's tread noise on a reference, non-aging pavement, either smooth or of any selected texture or porosity, is the proposed device.

However, one should be reminded that it would be wise to use the proposed device in the first testing phase of the tyre's development stage, in order to evaluate the tyre's tread noise, and all other testing

methods that take into account the dynamic phenomena could be used at a later stage.

The following economic and ergonomic data are estimated from the author's industrial experience and not documented.

**Table 9-8.** Estimation of Economic Use

Description	Other large facilities	Pass-By method	CPX Trailer method	Device method
Investment cost of machinery & equipment	very big	none	small	small
Building cost	very big	none	none	very small
Sound absorbing walls	Yes	no	no	no
Area or test track	Some	very big	yes	no
Acoustic instrumentation	yes	yes	yes	yes
Other instrumentation	significant	some	little	little
Protected Control booth	no	yes	no	no
Electric power	big	no	no	little
Service personnel	significant	periodically	minimum	minimum
User personnel	some	2 persons	1 person	1 person
Support personnel	yes	yes	yes	no
Logistics personnel	yes	yes	no	no
Traffic safety personnel	no	yes	yes	no
Spare parts availability	yes	no	no	no
Spare parts warehouse	yes	yes	no	no
Downtime cost	very big	big	small	small
Difficulty of measurement start up	big	big	some	none
Difficulty of parameter adjustment	yes	no	no	no
Difficulty of tyre mounting	yes	yes	some	no
Able to use tyre models	no	no	no	yes
Able to use tyre part	no	no	no	yes
Able to use any surface texture	yes	no	yes with limits	yes
Able to use any tyre rim	no	yes	no	yes
Ease of transportation to other area or country	no	no	yes	yes
Is statistical averaging of data needed?	no	yes	yes	no



Are dynamic phenomena affecting the measurements?	yes	yes	yes	no
Are environmental conditions affecting the measurements?	no	yes	yes	no
Is environmental noise affecting measurements	no	yes	yes	no

From the economic and ergonomic correlation of the existing testing methods, it seems that all the advantages lie in favour of the proposed device method as more cost effective, safer to use, ergonomic and easier to obtain accurate noise data from the groove and tread design.



## 10 HORN EFFECT

### 10.1 Further experimentation

The following chapter is dealing with a further capability the manufactured device implements, as an acoustic research platform.

Although the author proposes that the term “horn effect” should be reconsidered, it will be used throughout this thesis as a compromise.

The conducted experiment was divided in the following research parts:

- pipe resonance investigation
- pressurized air investigation
- device’s measuring alterations
- pressurized air as a grazing noise source
- pressurized air as a horn effect noise source

In all papers during the literature research the author didn’t encounter a documented opinion on why there is a coincidence peak at around 1000 Hz, regardless of tyre tread pattern and regardless of pavement surface.

From the above two facts became clear, that neither the tread pattern nor the pavement texture is responsible for this high level peak to develop. Only one common item is always present but not elaborated in most papers as deep as the author wanted. That is nothing else than the perimetric groove that all tyres have.

The author believes that the major noise amplitude and coincidence frequency at 1000Hz is due to the air channels that are created between the tyre and the pavement.

It has to be mentioned however that in Iwao *et al.* (1996) the measurements of a slick tyre produced the same 1000Hz peak even if the tyre had no grooves. He didn’t mention the roughness of the road surface (so one can only guess) but as known no road surface is completely level and so smooth that the tyre contact area will be absolute.

So, one can safely suppose that there are some longitudinally spaced gaps between tyre and pavement, that can be considered as crooked pipes.

Under any circumstances even with perimetric grooves or with small cross section crooked pipes the result is the same, the tyre/pavement contact produces pipes about 16cm of length, that are expelling air (or water in rainy situations) under the tyre.

The 16cm length was measured in our investigation with the tyre under load and deformed accordingly. If a tyre is of different diameter the above mentioned pipe length may be a little shorter or longer, but is not altering dramatically the noise results.

The major question now is how to consider this tyre/pavement pipe, as an open pipe (with both ends open to the environment) or as a one end closed pipe?

Using the acoustic wind instruments equivalent, are the above tyre grooves / pipes, behaving as a flute or as a clarinet?

The flute is open at both ends and has a cylindrical body.

The clarinet on the other hand is open at the bellmouth. But it is (almost) closed at the other end. For a sound wave this is enough to cause a reflection almost like that from a completely closed end.

The rest of the clarinet is approximately cylindrical.



**Fig. 10-1** Flute



**Fig. 10-2** Clarinet

### 10.1.1 Open pipe (flute).

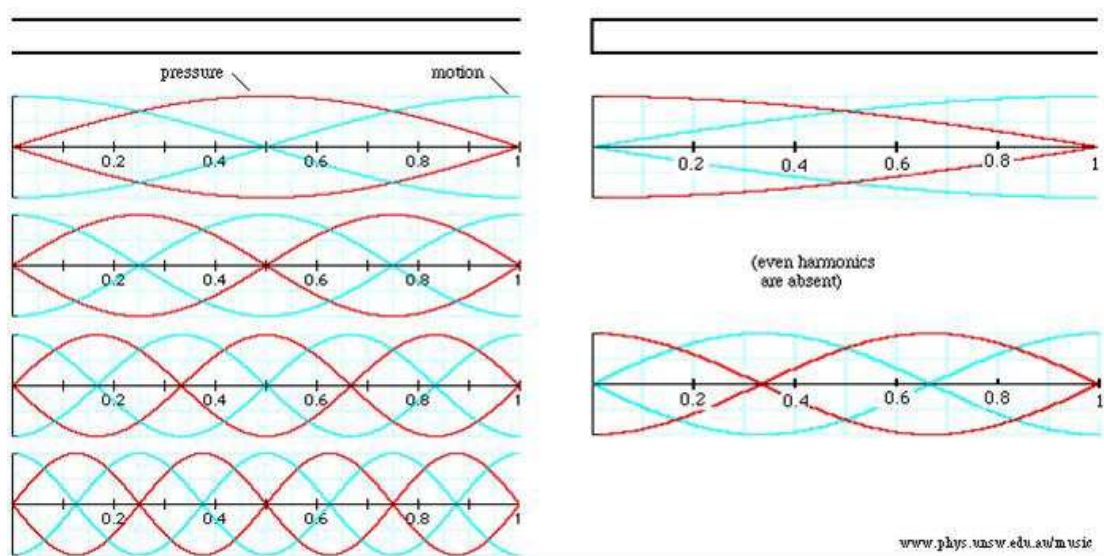
Note that, in the following left side diagram, the red curve has only half a cycle of a sine wave. So the longest sine wave that fits into the open pipe is twice as long as the pipe.

A flute is about 0.6 m long, so it can produce a wavelength that is about twice as long, which is about  $2L = 1.2$  m.

### 10.1.2 Closed pipe (clarinet).

The curve in the following right side diagram has only quarter of a cycle of a sine wave, so the longest sine wave that fits into the closed pipe is four times as long as the pipe.

Therefore a clarinet can produce a wavelength that is about four times as long as a clarinet, which is about  $4L = 2.4$  m.



**Fig. 10-3** Wavelength in open end and closed end wind instruments

Now let's make the approximation with our tyre pipes.

The equation of the open pipe resonance is :

$$f = (n * c) / (2L + 0,8d)$$

The equation of the closed pipe resonance is :

$$f = (n * c) / (4L + 0,8d)$$

Where

f = resonance frequency (Hz)

n = number of harmonic (first, second, third etc)

c = speed of sound in air (m/sec)

L = pipe length (m)

d = pipe diameter (m)

If the groove pipe is acting as an open 16cm pipe it should resonate at:  
( $n=1,2,3$ )

1014 Hz for the first harmonic  
2028 Hz for the second harmonic  
3042 Hz for the third harmonic . etc

If the groove pipe is acting as a closed 16cm pipe it should resonate at:  
( $n=1,3,5$ )

507 Hz for the first harmonic  
1521 Hz for the second harmonic  
2535 Hz for the third harmonic . etc

If the pipe length is a little larger (for example 20mm) but has the same diameter then it should resonate as an open pipe at: ( $n=1,2,3$ )

977 Hz for the first harmonic  
1955 Hz for the second harmonic  
2932 Hz for the third harmonic . etc

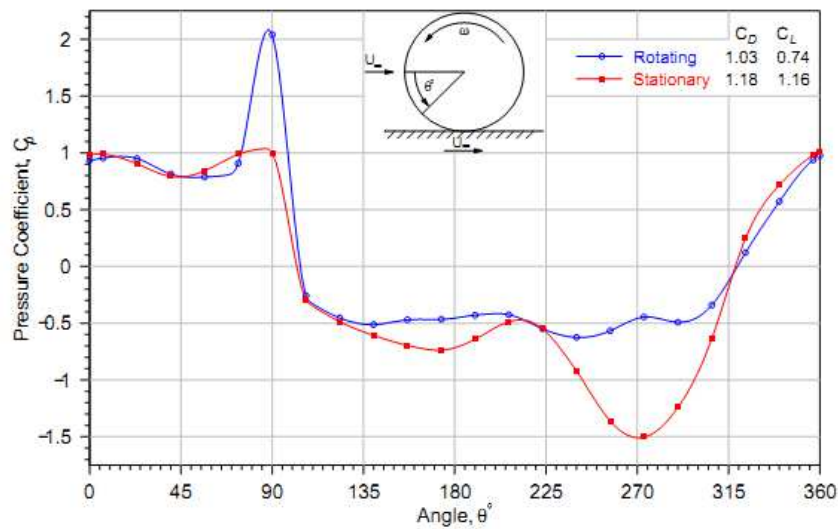
And as a closed pipe, at: ( $n=1,3,5$ )

489 Hz for the first harmonic  
1466 Hz for the second harmonic  
2443 Hz for the third harmonic . etc

It is getting clearer that since in all literature and in this thesis as well, all coincidence peaks are around 1000Hz the groove pipes are likely to behave as an open pipe, since the first resonance is stronger than the rest resonances.

It has to be mentioned that in the author's mind there was a doubt since at the leading contact edge there is an air pressure build up that could behave as a blockage to the sound wave reflection, and the groove pipe could act as a closed pipe, but it seems that this is not the case, as measurements have shown.

As seen in the following graph by Knowles (2005) there is a different behaviour comparing a stationary wheel exposed to an air stream and a rotating wheel at the precise leading edge contact point, where a significant pressure build-up is created when the wheel is rotating. This pressure build up at the leading edge could be acting as a barrier to the noise reflections at this pipe end.



**Fig. 10-4** Pressure distribution for rotating & stationary Wheel

## 10.2 Experimental measurements

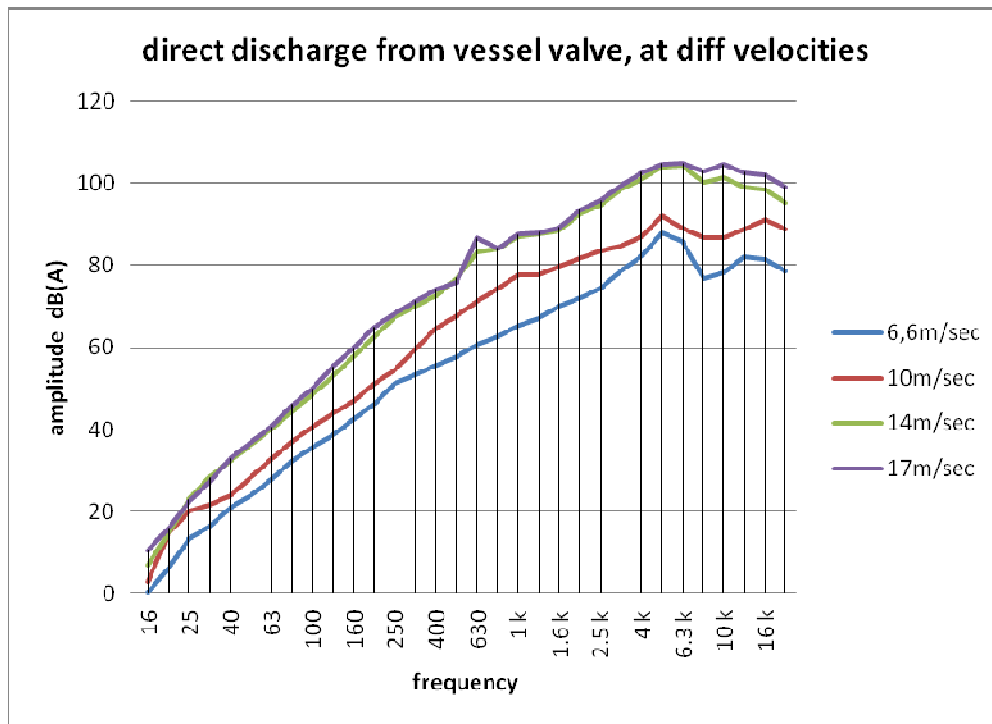
First and for cross checking purposes a set of measurements was performed, measuring the direct air discharge from a pressurized air compressor vessel, via his direct discharge valve installed on the vessel, with the valve open at 4 different positions that allowed for an air exhaust velocity of 6,6m/sec – 10m/sec – 14m/sec and 17m/sec.

The discharged air is as turbulent as possible since no guiding pipes or orifices are used and as seen the spectral amplitude is progressively climbing and is the highest in the very high frequency area.

It is clear that this spectral pattern is not consistent with the spectral pattern the tyre/pavement interaction is producing, so further experiments, with different configurations were carried out.



**Fig. 10-5** Compressed air discharge



**Fig. 10-6** Spectral pattern of compressed air direct discharge

### 10.3 Tyre groove simulation

In order to investigate the tyre groove noise that is supposed to produce the peak at 1000Hz it was decided to use something similar to the tyre groove configuration.

It is known that the groove is of orthogonal cross section of  $\sim 10 \times 10 \text{mm}$ , it is straight through, it is 16cm long (measured from leading edge to trailing edge) and has 4 smooth walls if the pavement that the tyre is pressed upon is closed pore and smooth.



**Fig. 10-7** Tyre/pavement contact length

The need to use something else than the tyre itself, is to disconnect the tyre completely from the investigation procedure just in case someone would argue that the tread of the tyre or the softness of the rubber or any other unknown factor is affecting the measurements.



For this reason a copper pipe of 12mm diameter was selected and was cut in 16cm long pipes. In order to simulate the orthogonal cross section of the tyre's groove the pipe was machined to become orthogonal with the progressive insertion of an orthogonal metallic ram that at the end was removed but was able to shape the pipe's cross section.



**Fig. 10-8** Cross section from circle to rectangular

Using the 16cm orthogonal pipe, compressed air from an air pistol at 8bar was guided perpendicular to the pipe end (at 90° direction) from a distance of 10cm (to allow for air jet dispersion and formulation of turbulence).

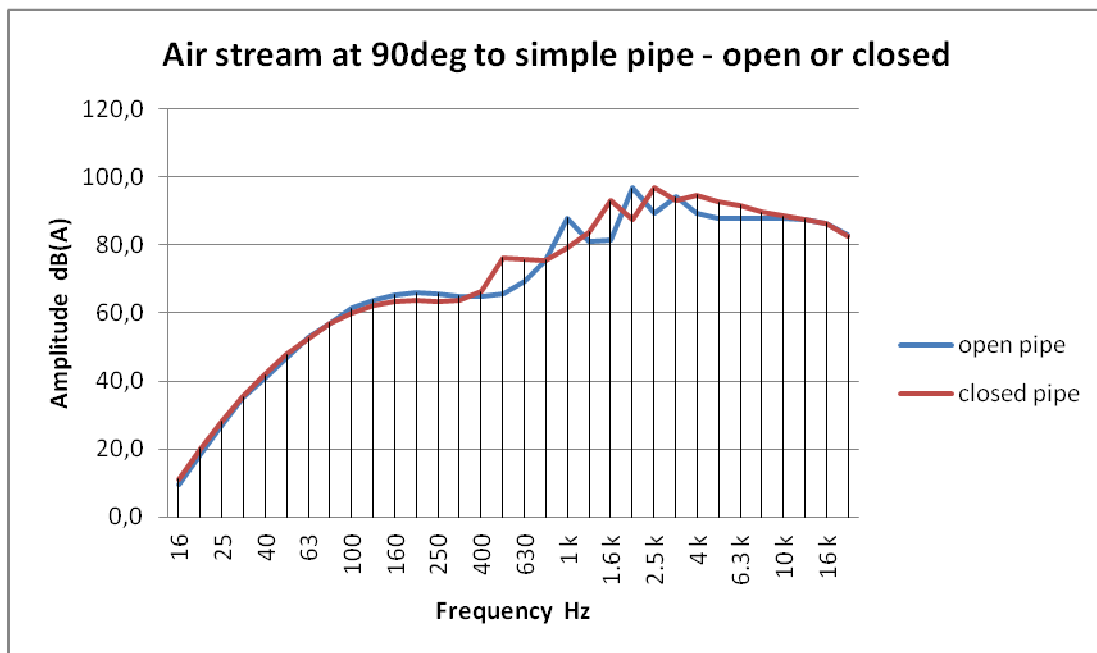


In the following picture one can see the dark sound absorptive material that was used to avoid sound reflections of the table surface that could interfere with the measurements.

**Fig. 10-9** Copper pipe - to simulate tyre groove



**Fig. 10-10** Air stream at 90deg. to pipe



**Fig. 10-11** Spectral distribution of open end & closed end pipe at 90deg.

In the graph the blue line represents data obtained with the above procedure with both pipe ends open (simulated flute) and the red line represents data obtained with one end of the pipe closed (the one opposite to the air stream) (simulated clarinet)

It is interesting to see that the measured open pipe peak of the :

first harmonic is at 1000Hz  
second harmonic is at 2000Hz and  
third harmonic is at 3000Hz.

One must observe that the graph is of 1/3 octave bands and the slight deviation from the calculated data is within each specific 1/3 octave band boundaries.

The previously Open pipe calculated data was:

1014Hz 1<sup>st</sup> harmonic, 2028 2nd harmonic, 3042Hz 3rd harmonic)

The one end closed pipe measured peak in the graph of the :

first harmonic is at 500Hz  
second harmonic is at 1600Hz and  
third harmonic is at 2500Hz.

The previously one end Closed pipe calculated data was:

507Hz 1<sup>st</sup> harmonic, 1521 2nd harmonic, 2535Hz 3rd harmonic)

So, comparing the above, one can safely argue that the tyre/pavement groove, must be behaving as an open end, pipe resonator.

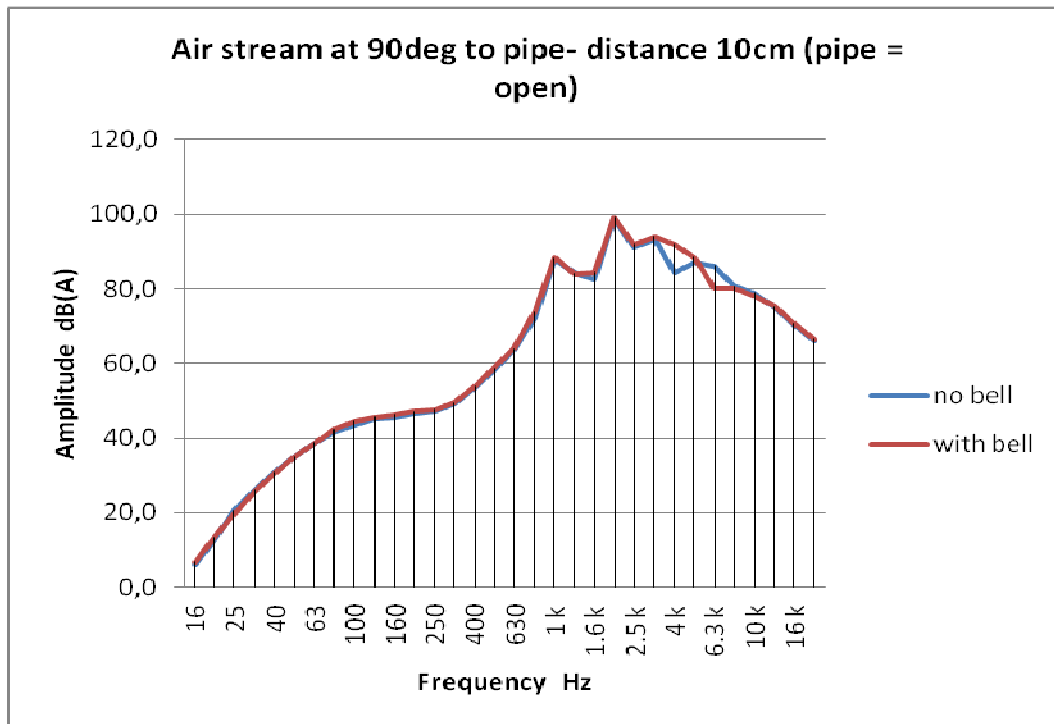
In order to investigate the horn effect and its spectral behaviour, a small bellmouth from a metal sheet was manufactured with one side flat (simulating the flat pavement) and the other side concave (simulating the curvature of the tyre). This bellmouth will be inserted to one end of the copper pipe and simulate the trailing edge of the tyre.



**Fig. 10-12** Small bellmouth manufacturing



**Fig. 10-13** Air stream at 90 deg to pipe with small bellmouth



**Fig. 10-14** Air stream at 90deg to pipe with & without the small bellmouth

In the graph one can see the resonant peaks of the open pipe (explained earlier) but the influence of such a small bellmouth is already present.

The red line is the data obtained from the same open pipe with the bellmouth inserted at the trailing edge and the difference at 4,0 and 6,3KHz is noticeable.

Which means that: the presence of a bellmouth contributes to the generated and radiated noise, in specific frequency bands.

The following experiment was performed with the pipe in line with the air stream since this is the typical scenario of tyre behaviour in real tyre travelling conditions.





**Fig. 10-15** Air stream in line (only pipe)

A set of measurements was performed with only the pipe in a straight line with the air stream at 8,0bar air pressure and at 4,0bar air pressure.



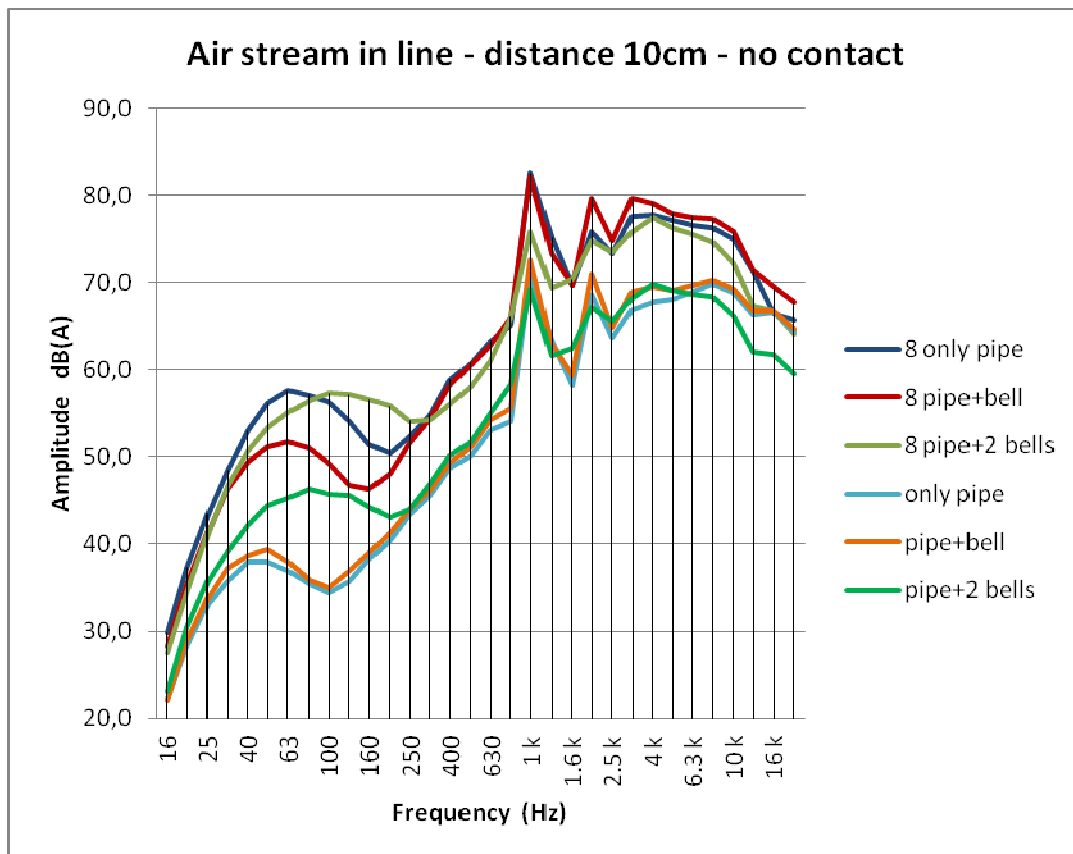
**Fig. 10-16** Air stream in line (one bellmouth)

A second set of measurements was performed with the pipe and one bellmouth at the trailing edge, in a straight line with the air stream at 8,0bar air pressure and at 4,0bar air pressure.



**Fig. 10-17** Air stream in line (two bellmouths)

A third set of measurements was performed with the pipe and both bellmouths at the trailing edge and leading edge, in a straight line with the air stream at 8,0bar air pressure and at 4,0bar air pressure.



**Fig. 10-18** Air stream in line – different setup configurations

In the graph, 6 data lines are shown. 3 concern 8,0 bar pressure inside the compressor vessel and the next 3 concern 4,0 bar pressure.

The term “only pipe” means that no bellmouths were attached to the pipe. The term “pipe + bell” means that one bellmouth was installed at the trailing edge and the term “pipe+2bells” means that both bellmouths were installed.

**At a glance the graph looks very similar to the actual tyre/pavement noise spectra, with all the peaks in their right position, specially the pronounced one at 1000Hz.**

The high frequency spectra is dropping progressively and at the low frequency spectra it is noticeable how the pipe with the two bellmouths behaves (green lines), that is more uniform and spread over more low frequency bands, something quite different with one or without any bellmouth.

An other point that can be drawn from this graph is that it is quite similar to the actual tyre behaviour if one compares the progressive amplitude increase as the car's speed increases during the CPX tests under different speeds and the amplitude increase as the air stream's pressure increases from 4,0 to 8,0 bar.

In both situations no spectral shift is observed, which can be interpreted that when a car is increasing its speed, the air pressure in the tyre grooves must be increasing in order to conform to the above graph.

#### **10.4 Horn effect polar distribution**

After the completion of the experiments with the small bellmouths installed on the 16cm pipe, where it was documented that there is some contribution of the small bellmouths concerning the spectral distribution, it was decided to go to a real scale model, and instead of using a manufactured bellmouth, the actual tyre undertook this role.

The author needs the measurements to be as undisputed as possible so the less parameters change during the experiment, the better for the measuring quality.

As mentioned the actual tyre will play the part of the horn, but its groove will not be used. Instead of the tyre's groove the pipe used in the previous experiment will play the part of the groove since its spectral behaviour is now known, so the pipe will be inserted in the tyre's groove position.

By using this substitute it is sure that no other component of the tyre's design will alter, or will be suspected to alter the measured results, such as the tread design, the sipe design, the rubber compound, the new or worn tyre etc.

By using the same 16cm orthogonal copper pipe as a noise source two sets of measurements will be performed.

1<sup>st</sup> set. Pipe placed directly on the pavement surface, without a tyre. In this way providing 8,0 bar of air pressure at the leading opening of the pipe, its trailing opening will behave as a sound source. The sound source will be at grazing incidence with the pavement (substituting the actual position of the tyre's groove)

2<sup>nd</sup> set. Actual tyre placed over the above mentioned pipe. In this way the pipe will simulate the tyre's groove, and the tyre will simulate the horn.



The expected results during the comparison of both measuring sets, will determine the significance of the horn effect and its origin.

During the preliminary tests of this procedure (before actual measurements started) with and without the tyre in place it was discovered that there is a considerable turbulence present with the tyre in place, in contrast without the tyre this turbulence was not observed.

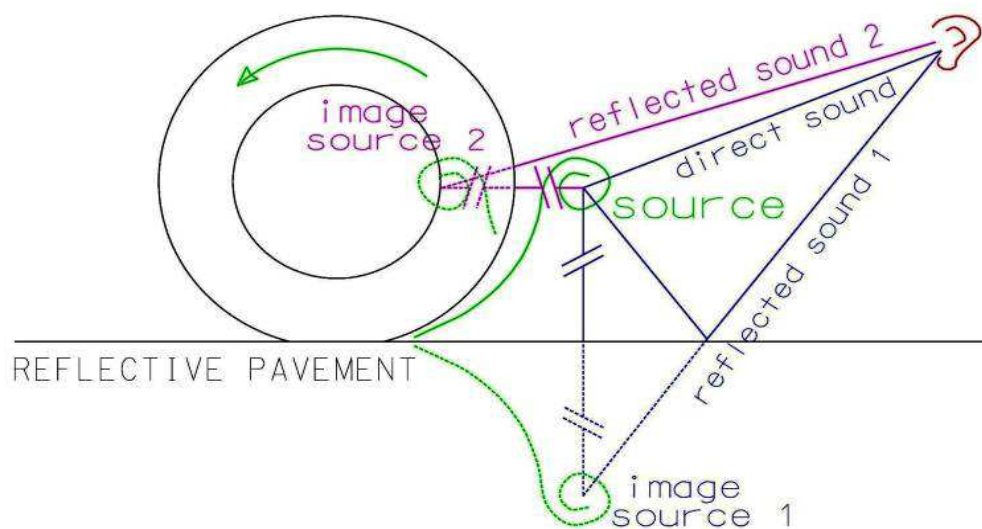
The turbulence was felt with bare hand (even if the tyre is not rotating) at a height of ~25cm above the pavement surface, meaning that there must be a strong boundary effect present.

By boundary effect it is meant that the air turbulence is not detaching from the curved tyre surface and the air stream is following the tyre's curvature for a considerable distance.

Hahn (2008), describes the Large Eddy development in contact to curved surfaces and states "If the flow follows a convex curvature, the external pressure outside the boundary level has to rise, hence the flow experiences an adverse pressure gradient inside the boundary as it progresses further downstream. At the same time the fluid is retarded near the wall due to friction forces".

In contrast when only the pipe was pressurized (without the tyre) no air turbulence was felt by bare hand in this distance from the pavement surface, nor at a significant lower distance.

It is proposed during future repetition of the above procedure, to use pressurized smoke instead of air and a high speed camera in order to visualize and analyze better both air steams. Unfortunately the author's laboratory equipment does not include such devices.



**Fig. 10-19** Mirror image reflections

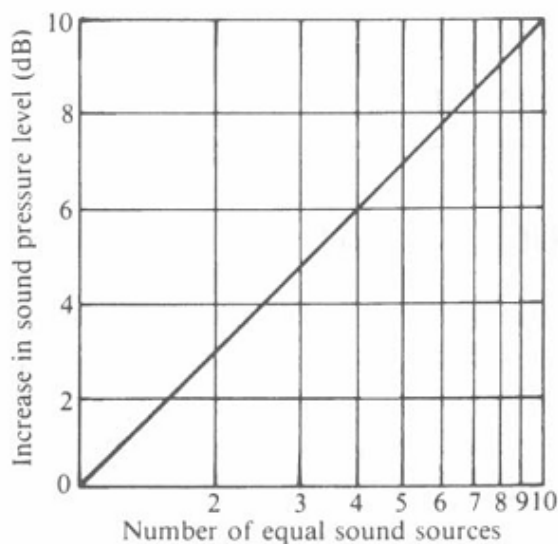
The above mentioned air turbulence, at some distance from the pavement and very close to the tyre's curved surface, is another strong point that the produced and radiated noise is not due to the reflections at the tyre/pavement horn, but due to multiple large eddies (that behave as multiple noise sources).

As expected each noise source (each large eddy) may produce multiple reflections over the curved surface of the tyre and over the pavement due to its distance from the tyre and the pavement, that allows for theoretical mirror images to be created per noise source.

In Acoustics the term "mirror image" refers to a theoretical image source having the same level and spectral pattern as the original noise source and is placed at the same distance to the reflective boundary as the main noise source (just like a mirror).

These distances of a noise source from any reflective boundary are what determines if the noise reflection will be generated or not (in the case when the noise source is flush level with the reflective boundary e.g tyre groove over the road pavement, reflections can not be created)

So a listener will perceive the acoustic energy from the noise source as "direct path" (without any obstacles) and at the same time the reflections form image source 1, 2, 3, 4, 5, etc



**Fig. 10-20** adding of sound sources

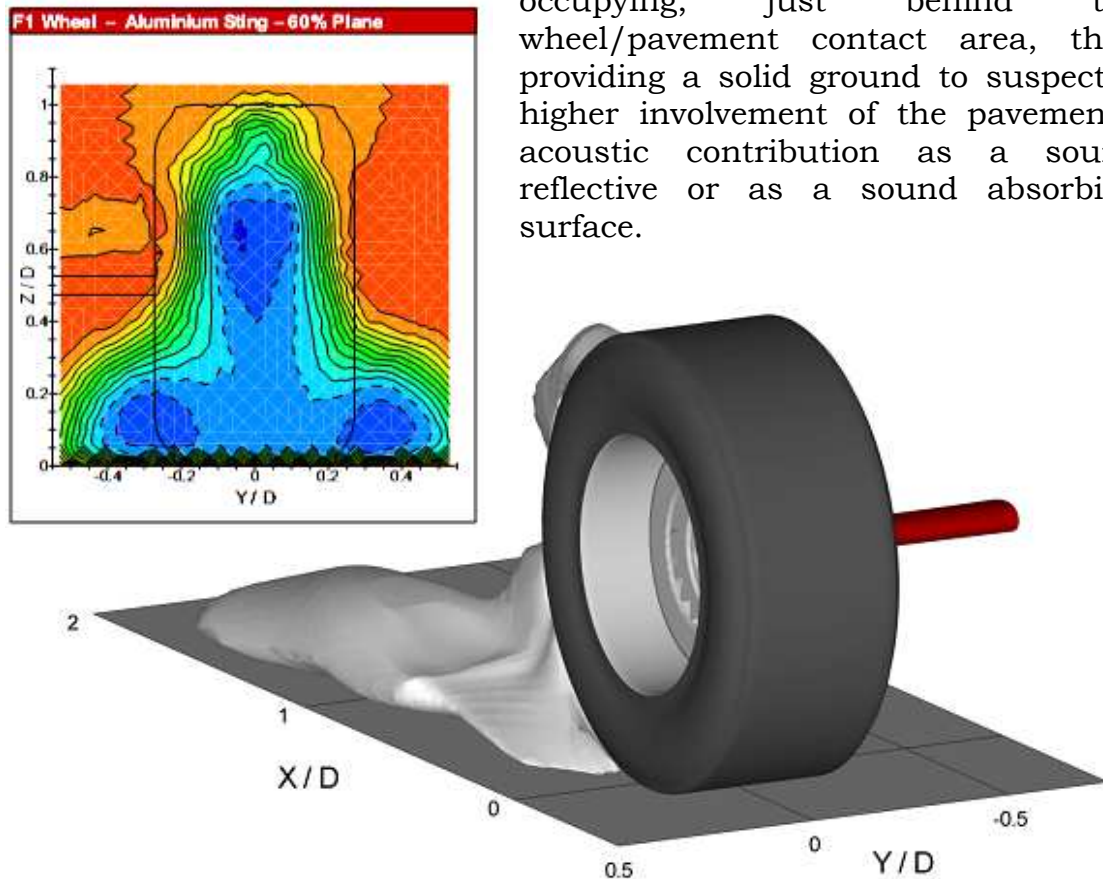
One has to bear in mind that one reflection over a 100% reflective surface increases the radiated noise by only 3dB.

So if level differences more than 10dB are measured, considering that the road surface is never 100% reflective but has some inherent noise absorption characteristics, the only logical assumption is that there must be more than 10 sound sources and reflections present.

Knowles (2005) has studied the aerodynamic behaviour of an isolated formula 1 wheel and has demonstrated a complex wake that is created after the wheel's circumference. His project was experimental in a wind tunnel and validated theoretically.

The following figure is from his project and supports the creation of a highly turbulent flow, that is suspected to be responsible for the increased tyre noise level, since the large numbers of vortices act as multiple noise sources.

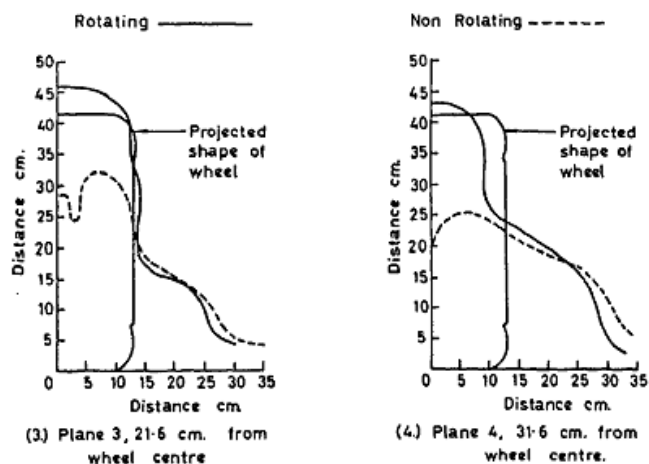
One may also note the increased floor coverage the turbulence is occupying, just behind the wheel/pavement contact area, thus providing a solid ground to suspect a higher involvement of the pavement's acoustic contribution as a sound reflective or as a sound absorbing surface.



**Fig. 10-21** Turbulence build up – near wake / Knowles (2005)

Axon (1999) incorporates a figure by Fackrell, that provides measured distances of the wake behind and at the side of the wheel, for a stationary and for a rotating isolated wheel.

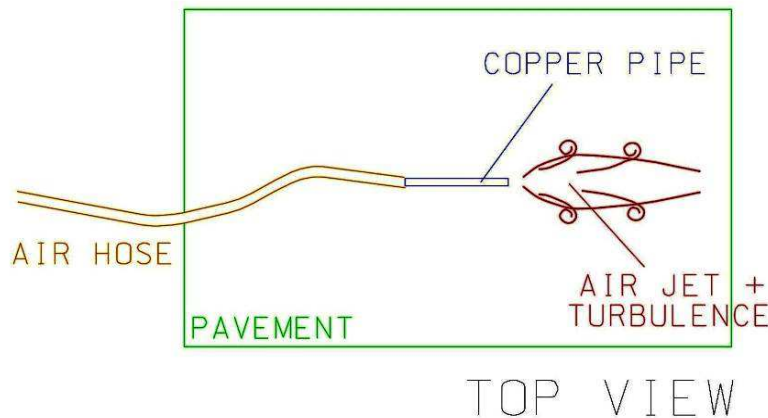
One can see that the turbulent flow is dispersing as long as ~32cm to the side (measured from tyre's CL)



**Fig. 10-22** Wake for isolated wheel

### 10.4.1 1<sup>st</sup> set of measurements configuration

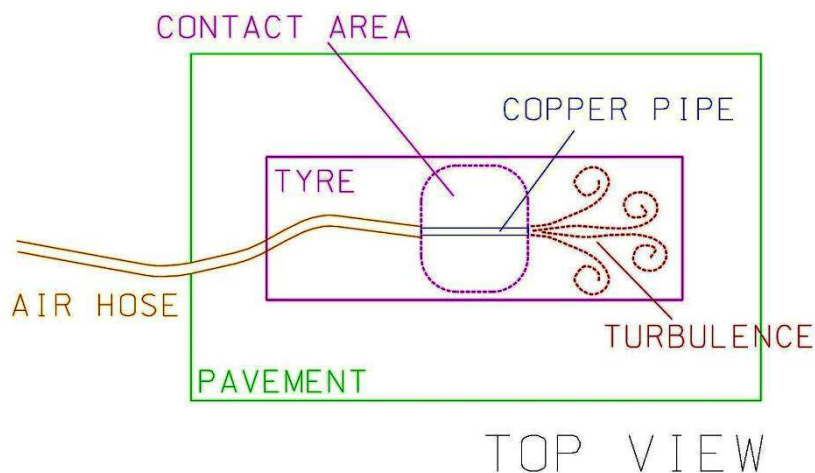
The 16cm copper pipe was secured on the device's smooth metal surface, simulating a smooth road pavement and air pressure was supplied from the compressor. A typical air jet with some expected turbulence was created.



**Fig. 10-23** Pipe (simulated groove) over smooth pavement

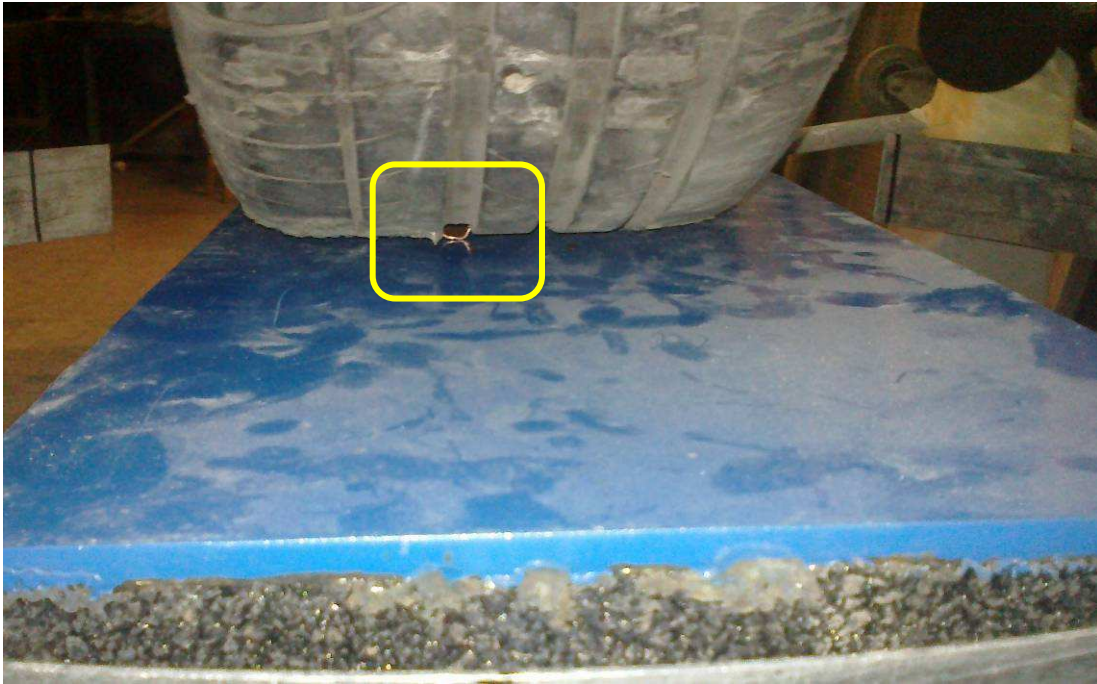
### 10.4.2 2<sup>nd</sup> set of measurements configuration

The 16cm copper pipe was left as it was secured, in the same position, on the device's smooth surface, the tyre was placed and compressed on the pavement (as if it was loaded) and the copper pipe was inserted in a tyre's groove. Air pressure was supplied to the pipe and the mentioned above, large eddies were observed and felt with bare hand at a significant height from the pavement surface.



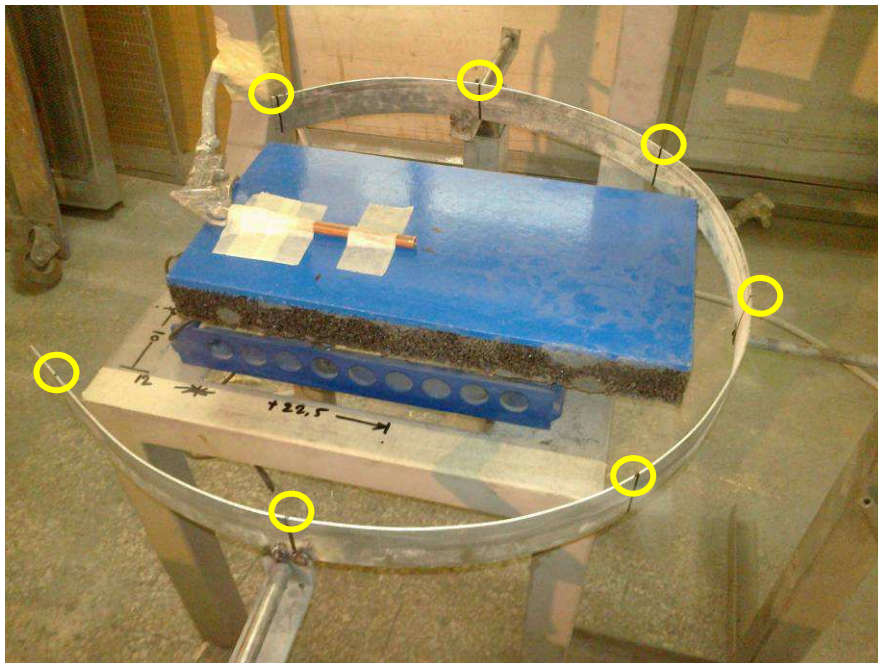
**Fig. 10-24** Copper pipe inside tyre's groove (over smooth surface)



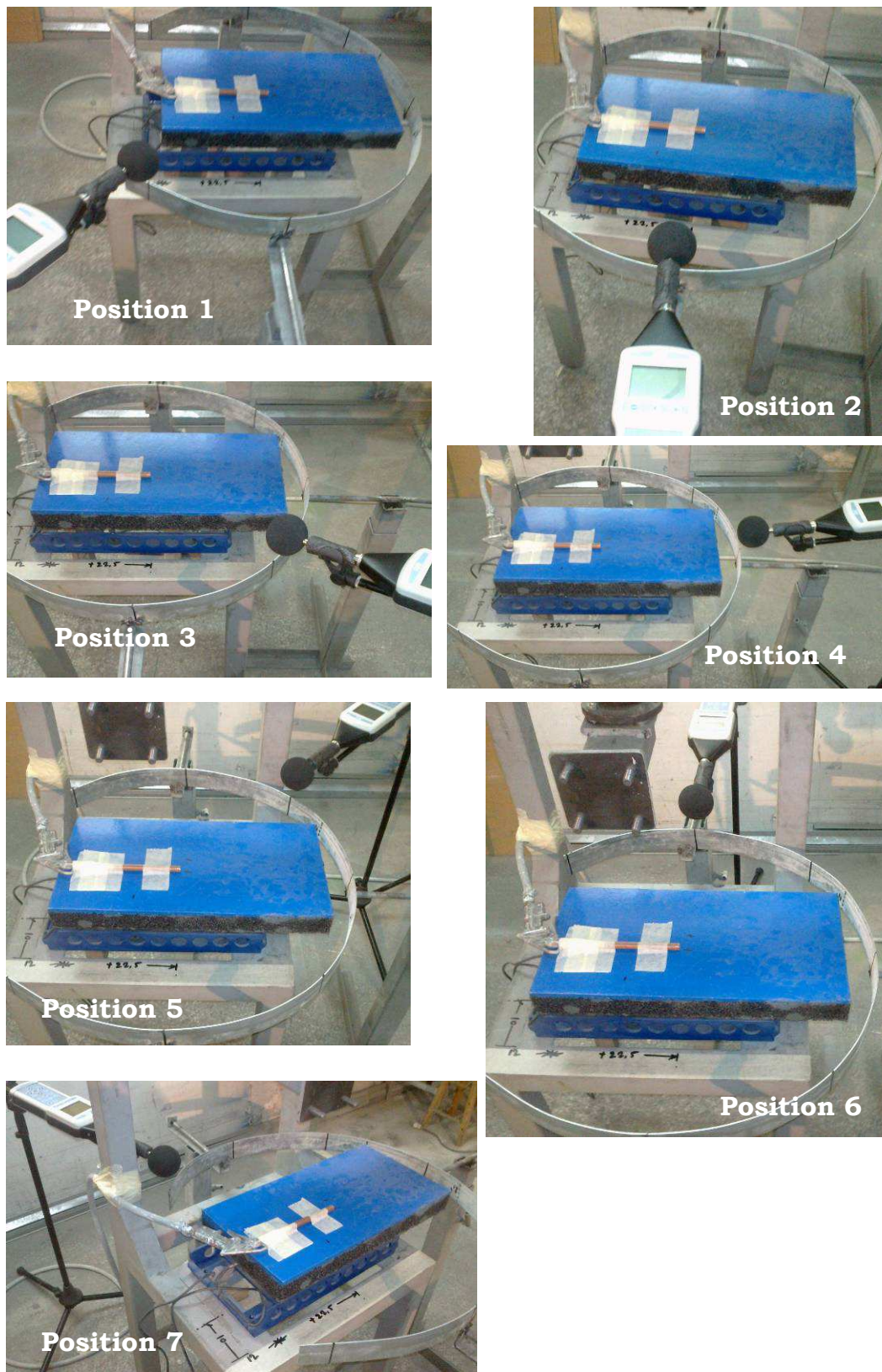


**Fig. 10-25** Picture of pipe, inside the tyre's groove

In both sets, seven positions  $45^{\circ}$  apart, were predetermined at an equal circular distance (with a positioning metal ring) with the trailing edge as the center of the measuring circle.



**Fig. 10-26** Device alteration to handle 7 measuring positions

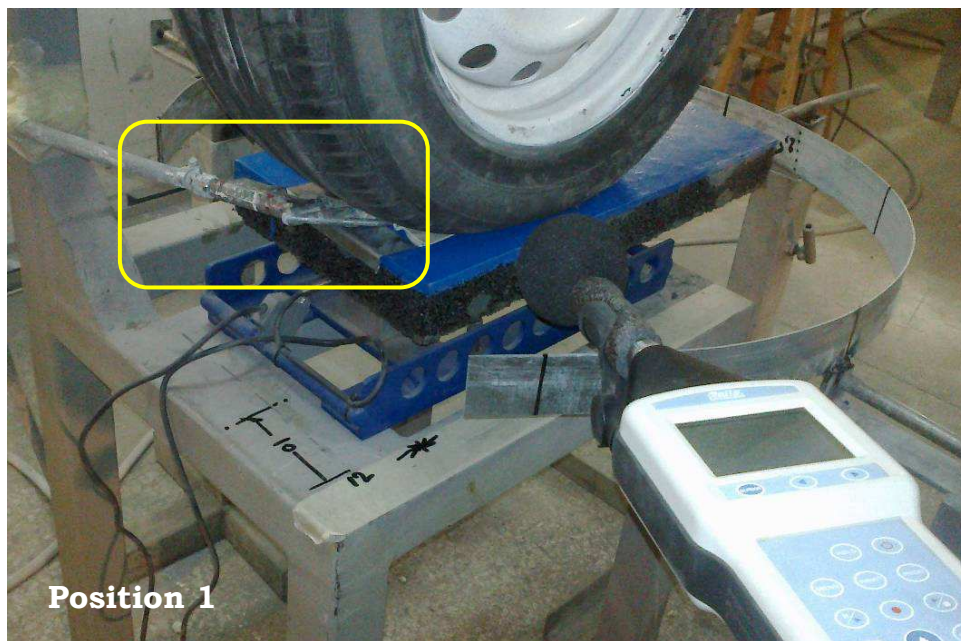
**10.4.3 1<sup>st</sup> measuring set.****Fig. 10-27** 7 measuring positions



In the above photos, all 7 positions are shown and were kept the same during the completion of the measurements without and with the tyre in place.

Note that in position No 4 the microphone is in straight line to the pipe / tyre axis, so at this position the louder and unobstructed noise is expected.

#### 10.4.4 2<sup>nd</sup> measuring set.



The tyre is in place. The rest measuring configuration and measuring positions are kept the same as with the 1<sup>st</sup> measuring set.

In the top picture, the air gun can be seen. The 16cm copper pipe is inside the tyre's groove and can not be seen.

**Fig. 10-28** tyre is in place – Air gun is in the same position

It has to be noted that with the air gun firmly fixed to the resonant copper pipe, it is expected to alter its resonance to a lower frequency band and behave as a closed resonant pipe.

From the following measurements the above claim can be verified and resonance peaks are developed at ~500Hz (1<sup>st</sup> harmonic) & ~1600Hz (2<sup>nd</sup> harmonic), meaning that the firm attachment of the air gun nozzle to the copper pipe alters its resonant behaviour to a “closed” end pipe.

This alteration however (with frequency spikes at lower frequencies than the actual tyre “open end” pipe measurements), is not affecting the evaluation and explanation of the noise dissipation due to the presence of the horn.

The measurements are comparison measurements with and without the tyre in place, so all measurements can be considered to be accurate and absolute, between them, and describe the noise polar distribution and radiation due to the presence of the horn, regardless if the source is an “open end” or “closed end” resonant pipe.

The reason why to connect the resonant pipe to the air hose is very simple and was selected to avoid creating a noise source different than the pipe’s only exit point.

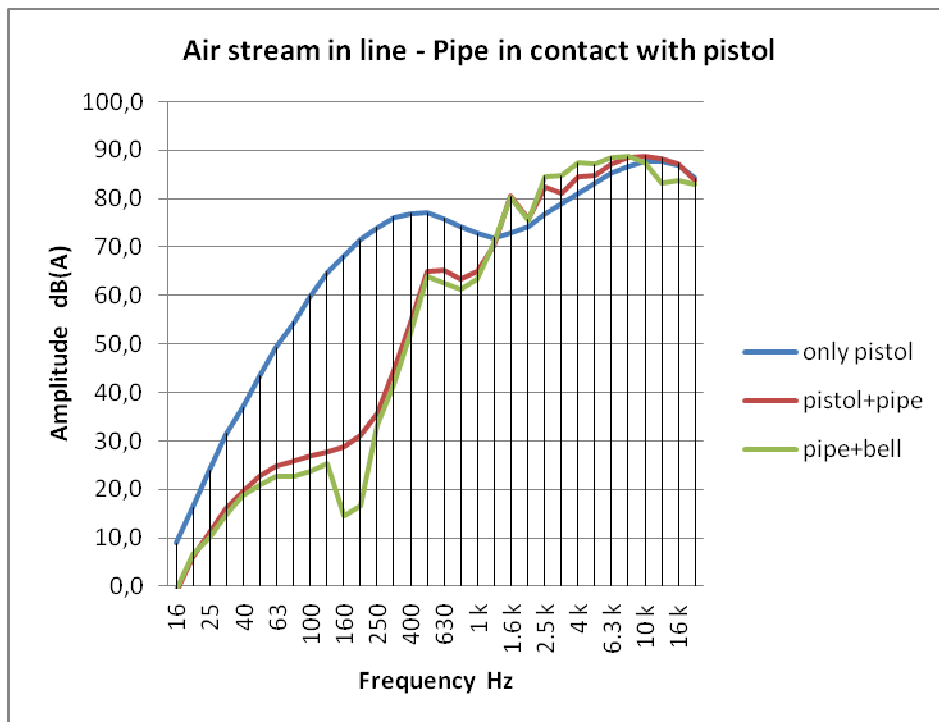
If the air hose was not connected to the pipe and was only blowing at the pipe from a distance, then there would be another noise source present, at the leading edge of the tyre and at a distance from the horn area thus would have interfered with the radiated noise due to the presence of the horn.

The following graph shows the acoustic behaviour of the same 16cm pipe when in direct contact to the air gun (closed end pipe resonance), that is significant different if the pipe is not fixed to the air gun (open end pipe resonance).

The 3 measurements are performed with the air gun (with and without the pipe and bell) far away from any reflective surface, aiming at mid air / free space and not over the device’s platform/pavement.

In order to be sure that this acoustic behaviour is not enforced or produced by the air gun itself, a 1<sup>st</sup> measurement was performed, with only the air gun (pistol) blowing air to the environment without the attachment of the pipe.





**Fig. 10-29** air gun with & without resonant pipe

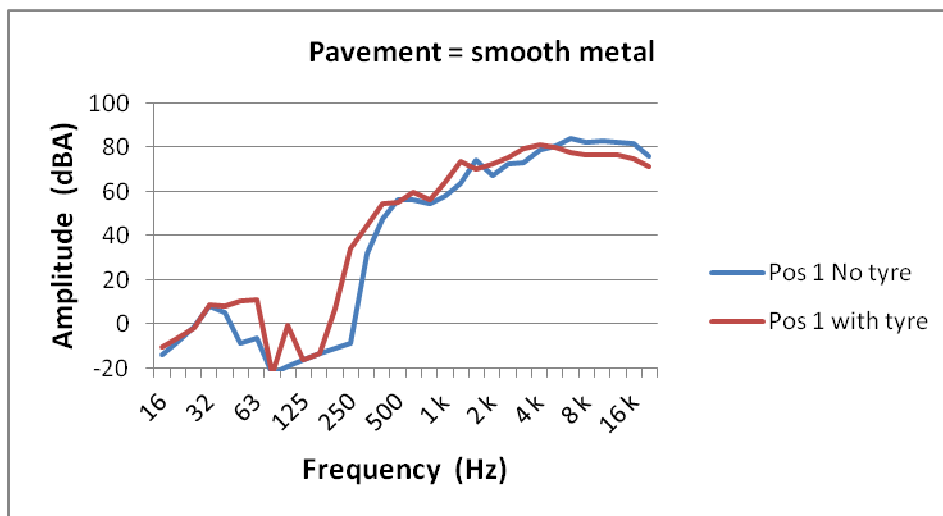
In the 2<sup>nd</sup> measurement only the pipe was fixed to the air gun as an elongation of the air gun. (pistol + pipe)

In the 3<sup>rd</sup> measurement the small bellmouth was fixed to the pipe (at the trailing edge). It can be seen that the 1<sup>st</sup> & 2<sup>nd</sup> harmonics have not been altered, but some alteration of the spectral pattern in the low and high frequency areas is obvious.

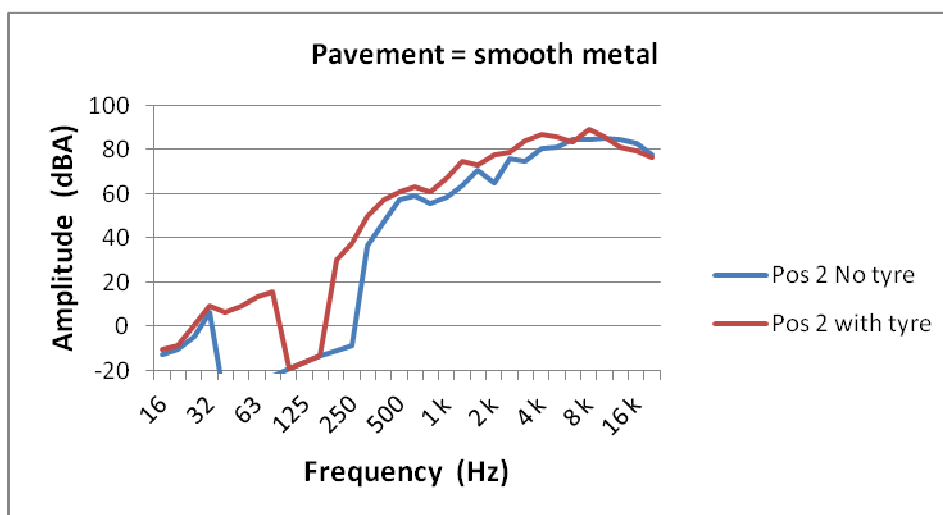
Especially the negative peak at ~160Hz (with the bellmouth in place) was noted and is believed to be due to the formation of excessive turbulence from the destruction of the air flow jet due to the presence of the bellmouth.

### 10.5 Measured data 1 & 2

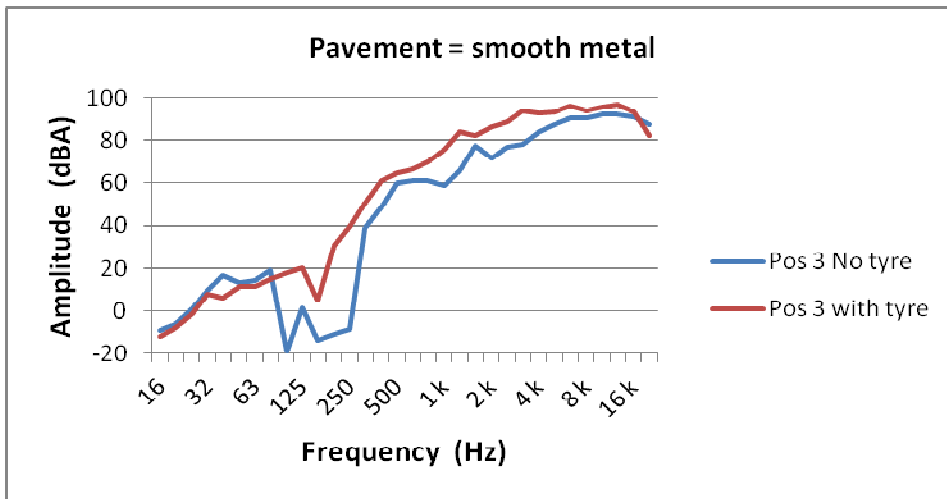
The following spectral data is from the 1<sup>st</sup> measuring set (air source at grazing incidence to the flat metal smooth surface, simulating the tyre's groove, without the tyre's horn) compared to the data of the 2<sup>nd</sup> measuring set (same air source, but the tyre is in place, so a horn is created with the pavement). Noise is measured at the trailing edge of the supposed tyre rotation.



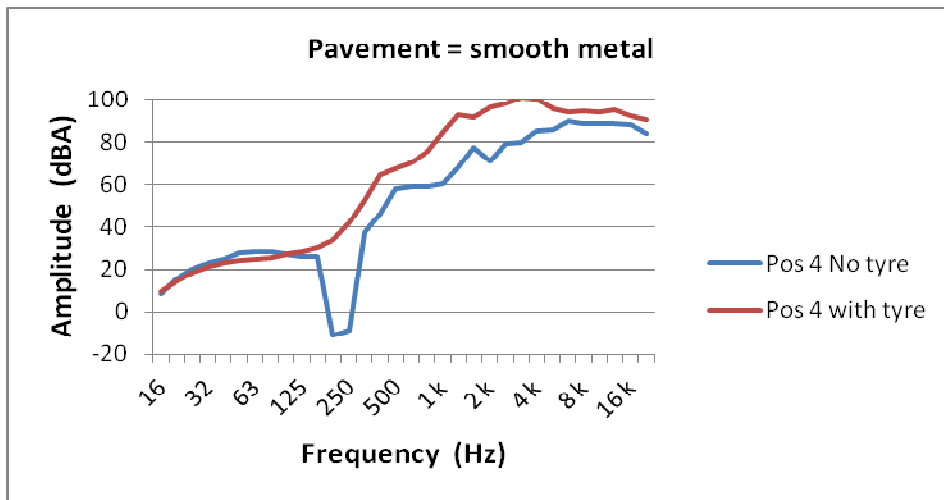
**Fig. 10-30** smooth pavement – with/without tyre - Position 1



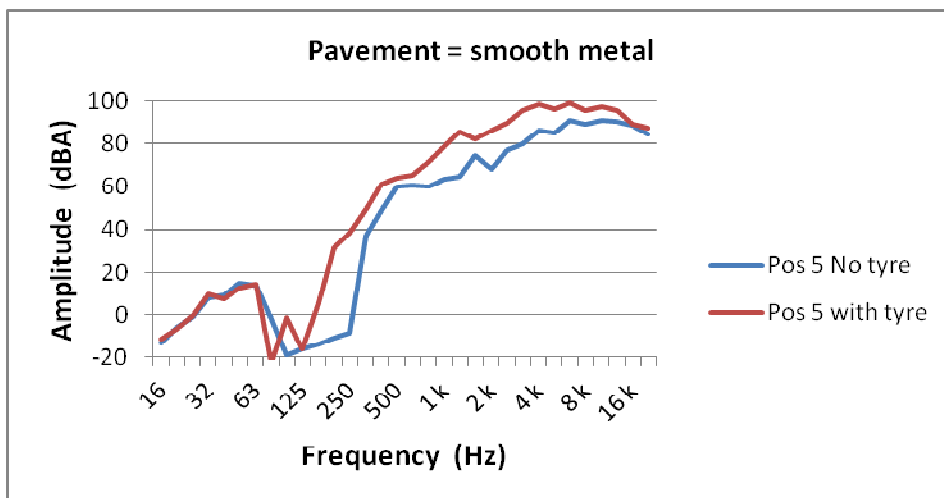
**Fig. 10-31** smooth pavement – with/without tyre - Position 2



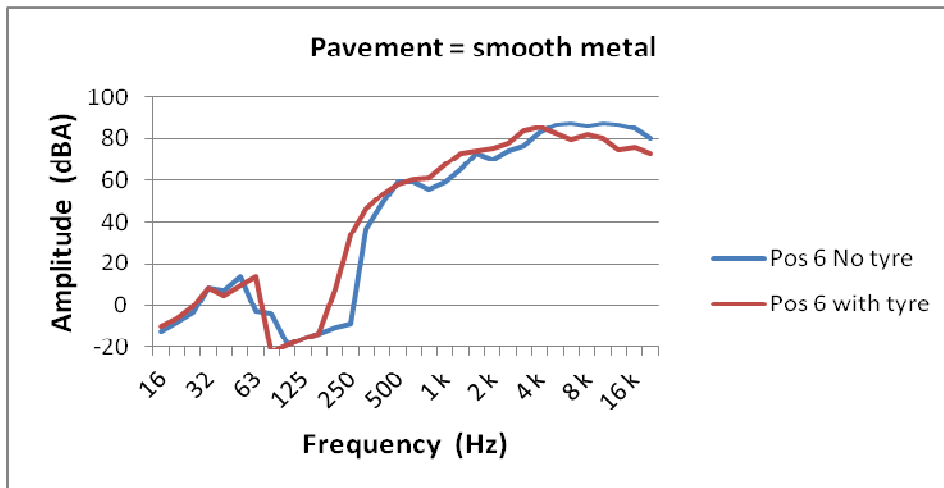
**Fig. 10-32** smooth pavement – with/without tyre - Position 3



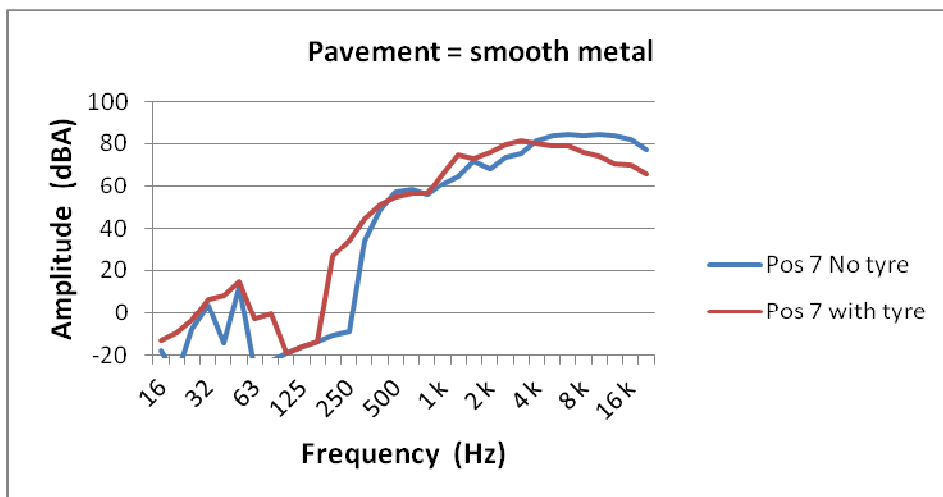
**Fig. 10-33** smooth pavement – with/without tyre - Position 4



**Fig. 10-34** smooth pavement – with/without tyre - Position 5



**Fig. 10-35** smooth pavement – with/without tyre - Position 6



**Fig. 10-36** smooth pavement – with/without tyre - Position 7

**Comments:**

In the graphs 3, 4, 5 (measured over a flat, smooth and reflective metal pavement) it is shown that the noise with the tyre in place is louder than without the tyre in place.

In the left and right extreme lateral positions 1,2 & 6,7 respectively it is shown that the very high frequencies in the measurements with the tyre in place, are lower in amplitude over the ~4Kz range, that may be explained due to the barrier effect that the tyre is producing to the radiation of the sound waves having small wave number " $\lambda$ ".

So the system, noise source and tyre, is producing a non uniform radiating pattern and a distinct "polar pattern" is emerging.

It is also responsible for the amplitude increase in the area 200-500Hz when the tyre is in place, that by itself is something that does not affect

the overall noise, but suggests that something is happening in this frequency area, since it is developed in all measuring positions.

It is suspected that this spectral noise generation is due to the development of air turbulence, since it is typical noise behaviour of air vortices. So considering that the tyre is stationary and not rotating, it is impressive how large eddies are developed only due to the presence of a curved surface.

Frequencies below ~200Hz are not evaluated due to the large wave number they possess that may be affected by other, not investigated in this thesis, phenomena.

To avoid any misunderstandings it is emphasized once more that the air gun is firmly fixed to the resonant copper pipe, and as expected it has altered the pipe resonance from an open end resonance pipe to a closed end resonant pipe thus the 1<sup>st</sup> harmonic is developed at ~500Hz (instead of 1000Hz) and the 2<sup>nd</sup> harmonic is developed at ~1600Hz (instead of 2000Hz) etc.

The produced spectral pattern that is consistent with the closed end resonance pipe is not affecting the validity of the project since at this stage only the differences (with or without a tyre in place) and in later paragraphs (over smooth reflective or porous sound absorptive surfaces) are studied and compared between them.

A future investigator should not use these results as absolute data or as actual tyre behaviour. The data, as mentioned, provide only comparative results, developed to try to study and understand the acoustic polar response and the horn effect in different situations. The differences though, can be safely used.

The following are summary graphs (taken from the above graphs) and it is clearer that:

- a) Below ~250Hz the data is fuzzy and could not be used safely.
- b) In the graph with only the pipe in place (Pos x No tyre) the polar distribution is quite uniform per mid-high frequency and may be considered as an "Omni directional" noise source.
- c) In the graph, with the tyre placed over the copper pipe only the measurements 3,4,5 have quite the same distribution, since position 4 is in the same axis of the noise source, but in 1,2 & 6,7 the tyre itself is acting as a noise barrier, altering the previous omni directional pattern of the system, by as much as -20dB
- d) The unblocked by the tyre paths (measurements No 3 ,4 ,5) have higher amplitude by ~10dB compared to the absence of the tyre at the same positions.

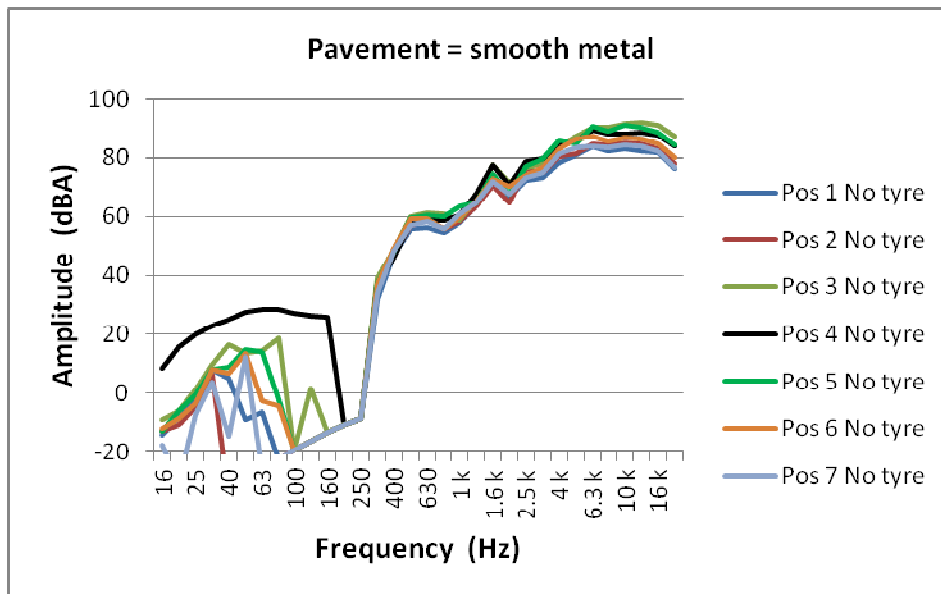


Fig. 10-37 smooth pavement – without tyre – All positions

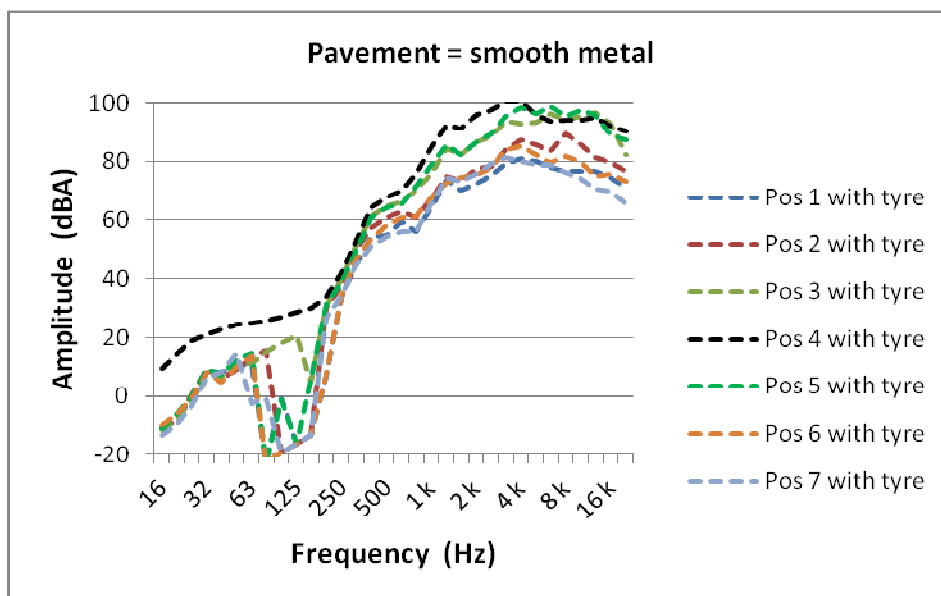


Fig. 10-38 smooth pavement – with tyre – All positions

The two above graphs are cumulative ones to be easier to observe the “omnidirectional” noise source obtained with only the pipe and the destruction of the polar radiation due to the barrier effect the tyre is introducing to the system. One can also note the interesting behaviour in the area 250-500HZ with and without the tyre in place

### 10.5.1 3<sup>rd</sup> and 4<sup>th</sup> measuring set

The idea

In the researched literature there is quite a lot of influence awarded to the sound reflection or sound absorption characteristics of the pavement. Reflections over closed pore, smooth surfaces are expected to develop and some sound absorption over porous surfaces is also expected.

But there is something puzzling in the author's mind, that could not be explained logically, concerning the extend of the contribution of pavement's reflection or pavement's absorption to the radiated noise amplitude.

In Acoustics, when in a room 3 of its surfaces behave as a 100% sound absorber, the reverberation time is expected not to increase at all in this room if one surface is altered to be extra reflective. If one looks closer to the tyre/pavement horn area then one may see a small room composed of 5 surfaces.

- 1<sup>st</sup> the pavement
- 2<sup>nd</sup> the curved tyre rubber
- 3<sup>rd</sup> air space left of the horn
- 4<sup>th</sup> air space right of the horn
- 5<sup>th</sup> air space opposite of the tyre's rubber

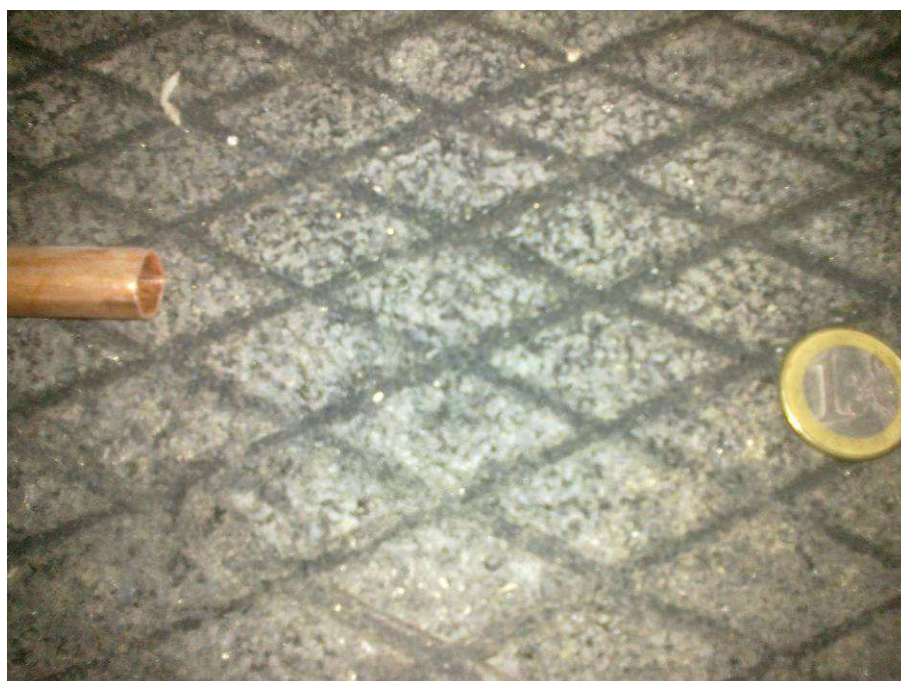
Since the 3 above surfaces are "air space" that in acoustics is considered to be a 100% sound absorber, how is it possible to have an amplitude raise in the horn due to reverberation / reflection? It is not logical, nor should be expected.

So in order to investigate this situation as well, a porous surface was manufactured from recycled tyre rubber and compressed in a press to produce a flat but porous surface. The texture of this porous pavement is the same as the commercial ones used in resilient road texturing or at railway crossings.

The same configuration (device, instrument, measuring positions and air pressure) is used as in the 1<sup>st</sup> and 2<sup>nd</sup> measuring set, but the smooth metal plate pavement was changed with the porous elastic one.



**Fig. 10-39** Porous rubber pavement



**Fig. 10-40** Porous rubber pavement – close up



The same as above 7 measuring positions were used to measure the air jet noise of the same 16cm copper pipe, placed at grazing incidence to the porous pavement.



**Fig. 10-41** Measurement - Only pipe over porous surface

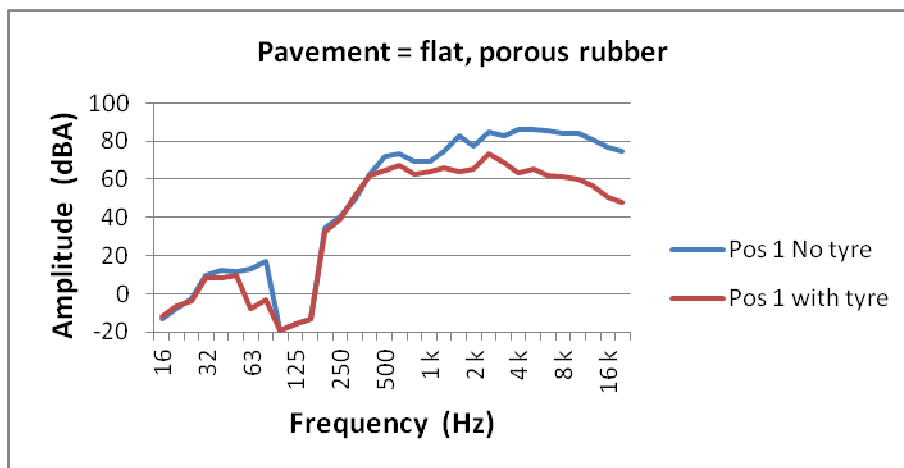
As in the previous situation, the copper pipe was inserted into the tyre's groove in order to alter the external factors as less as possible and try to investigate only the horn's acoustic behaviour.



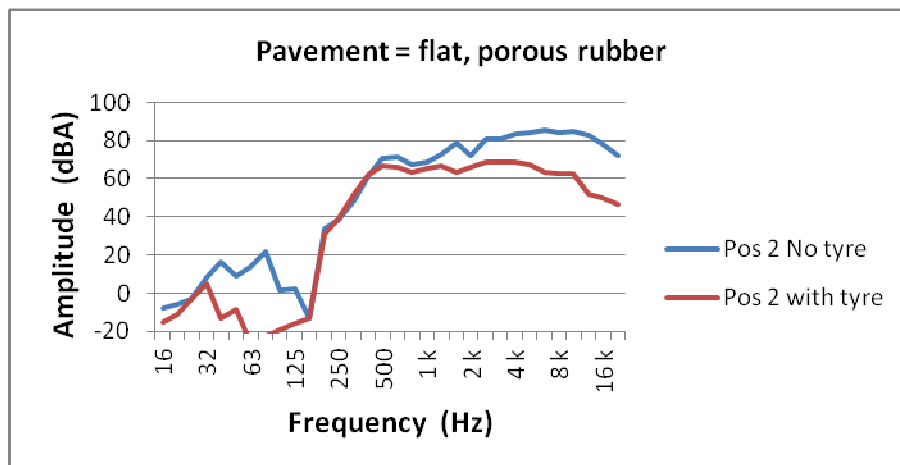
**Fig. 10-42** Measurement - Pipe & tyre over porous surface

### 10.6 Measured data 3 & 4

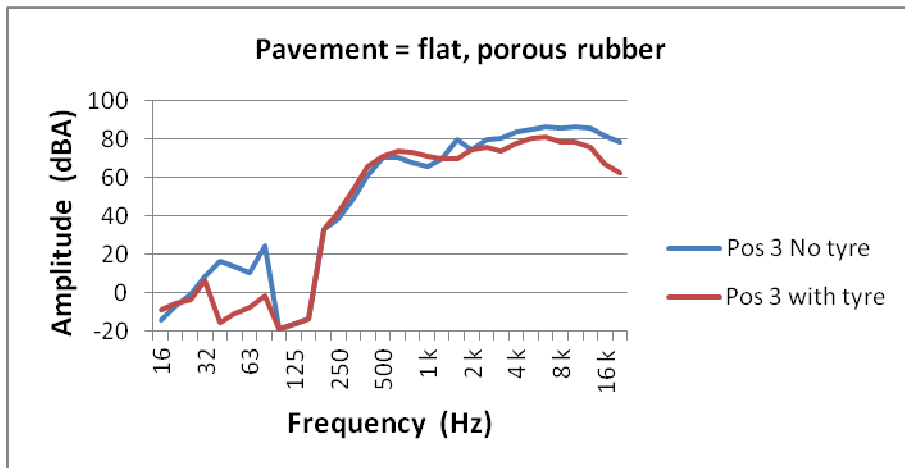
The following spectral data is from the 3<sup>rd</sup> measuring set (air source at grazing incidence to the porous elastic flat surface, simulating the tyre's groove, without the tyre's horn) compared to the data of the 4<sup>th</sup> measuring set (same air source, but the tyre is in place, so a horn with the porous pavement is created). Noise is measured at the trailing edge of the supposed tyre rotation.



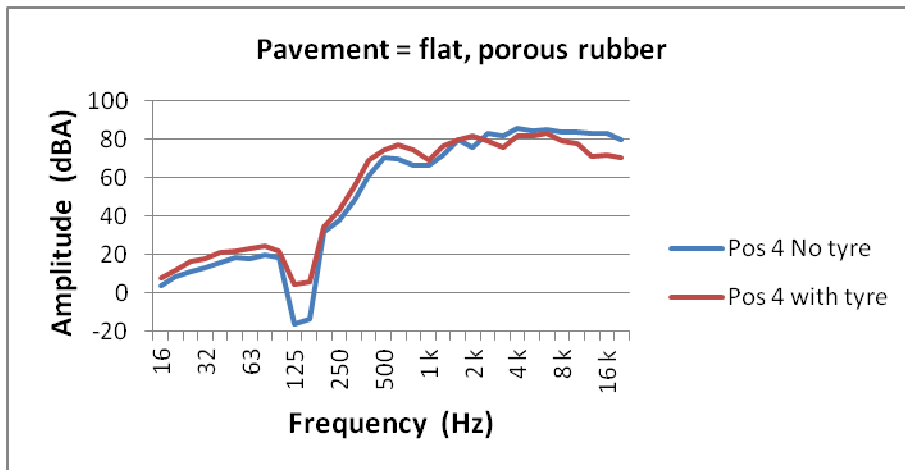
**Fig. 10-43** Porous pavement – with/without tyre - Position 1



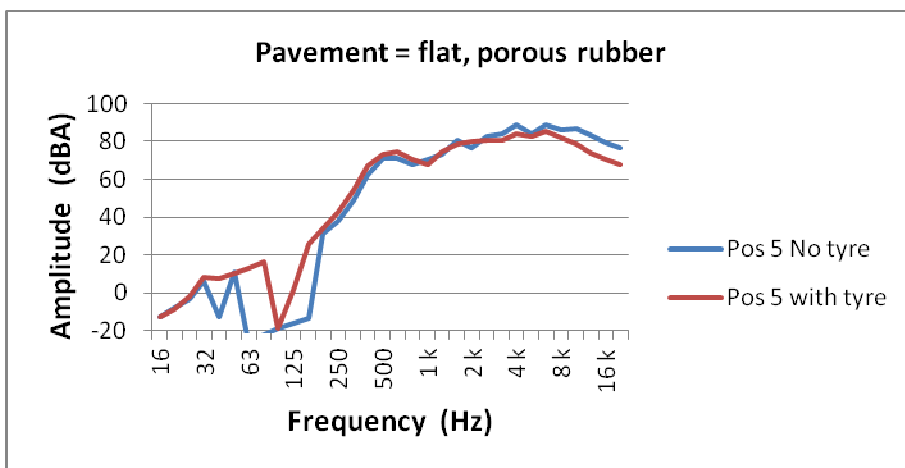
**Fig. 10-44** Porous pavement – with/without tyre - Position 2



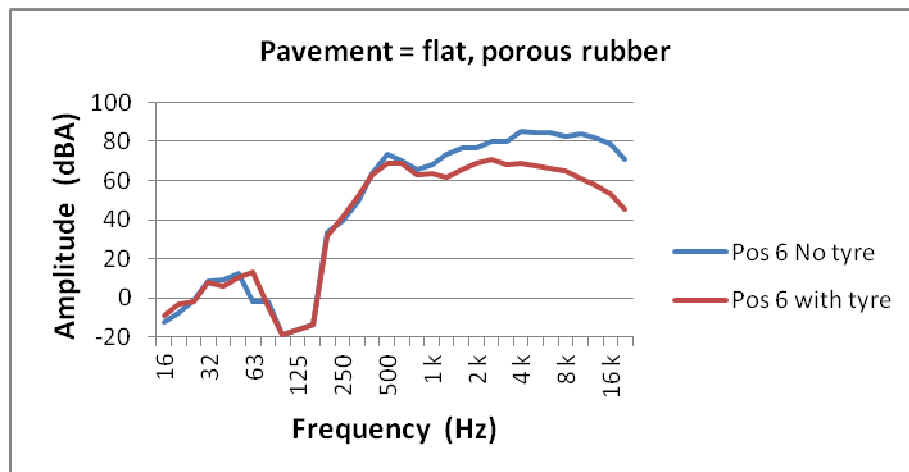
**Fig. 10-45** Porous pavement – with/without tyre - Position 3



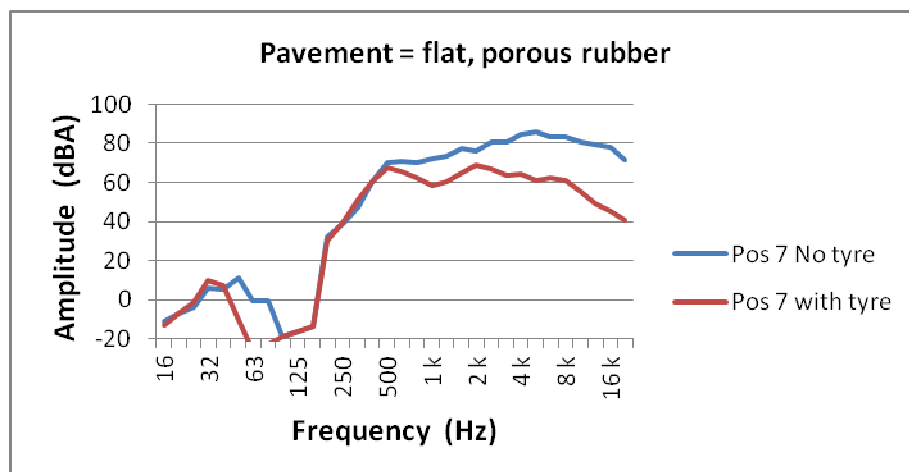
**Fig. 10-46** Porous pavement – with/without tyre - Position 4



**Fig. 10-47** Porous pavement – with/without tyre - Position 5



**Fig. 10-48** Porous pavement – with/without tyre - Position 6



**Fig. 10-49** Porous pavement – with/without tyre - Position 7

Comments:

In all graphs (measured over a flat, porous rubber and absorptive pavement) it is shown that the radiated noise with the tyre in place is more quiet than without the tyre in place.

In position 3,4,5 (No4 being in the center line of the microphone) one can see that the spectral amplitude difference is not as significant compared to the larger difference at the extreme left and right lateral positions 1,2 & 6,7

It seems that the barrier effect that the tyre is producing to the radiation of the sound waves over a porous surface is quite large (in the area of -20dB) that by itself is a questionable number.

From the above measurements it seems that a pavement affects a greater area (to the left and right of the tyre) and not only the tyre/pavement contact area since at position 3,4,5 the difference is rather small and not influenced by the pavement's porosity.

A possible explanation is that the large eddies dispersed left and right of the tyre's body, produce pavement reflections that over a sound absorbent pavement are strongly absorbed, but even so a -20dB reduction is still a very large number to be only reflection depended.

**Another possible explanation may be that due to the rough surface of the porous pavement, the large eddy creation is kept close to the pavement, in contrast when the pavement was the smooth metallic one, were this phenomenon was not observed.**

**It is believed that the created vortexes are not allowed to raise over the pavement, thus minimizing their potential to create image noise sources and reflections.**

The above analyzed cumulative response, could be responsible for implementing noise reductions as much as -20dB

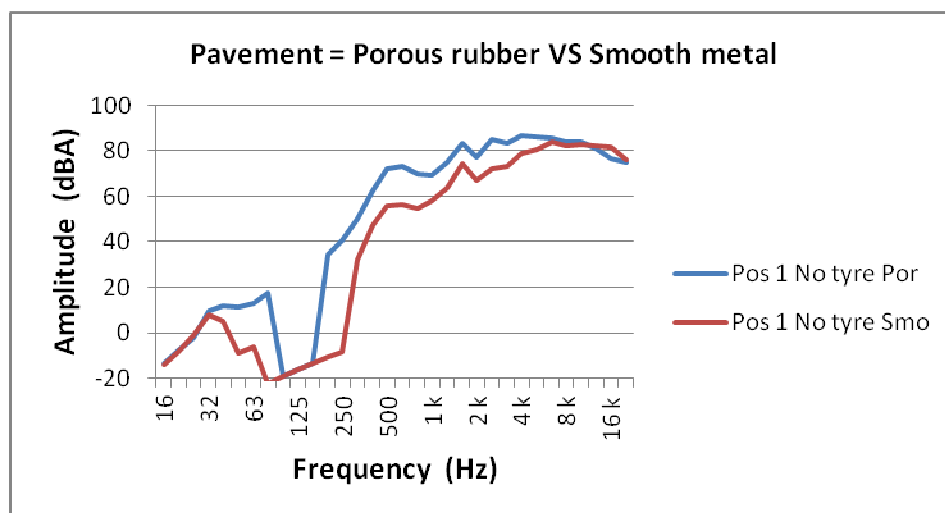
## 10.7 Data comparison

Due to the above unexplained behaviour, a further comparison of data is shown and tried to be explained.

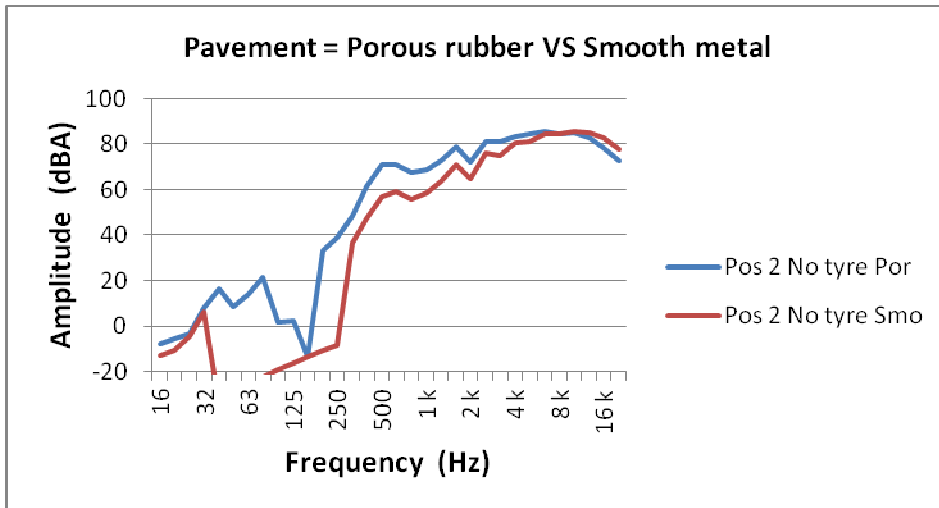
Comparing data set of measurement 1 and 3 and data set 2 and 4 may produce some interesting results and help understanding the phenomena.

The following spectral data is form the 1<sup>st</sup> measuring set (air source at grazing incidence to the flat metal smooth surface, simulating the tyre's groove, without the tyre's horn) compared to the data of the 3<sup>rd</sup> measuring set (air source at grazing incidence to the porous elastic flat surface, simulating the tyre's groove, without the tyre's horn).

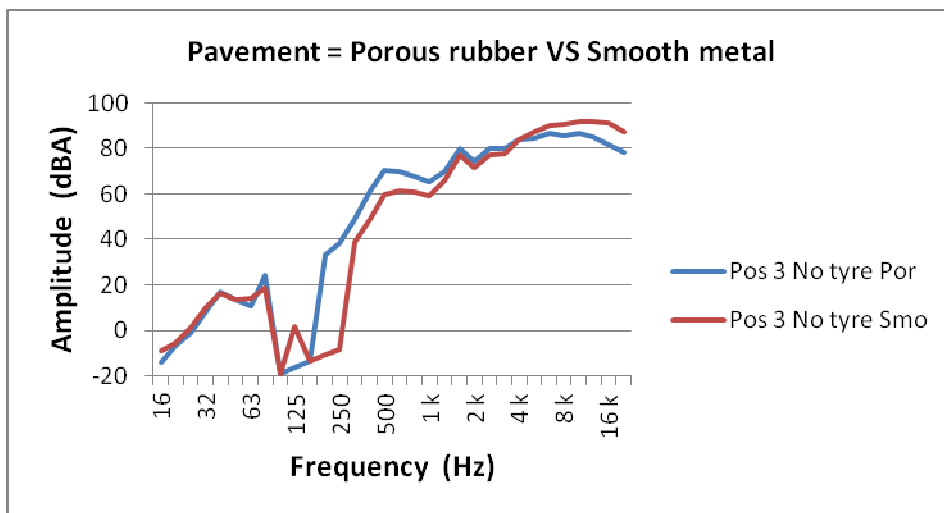
In all the graphs "Por" stands for "porous" pavement and "Smo" stands for "Smooth" pavement.



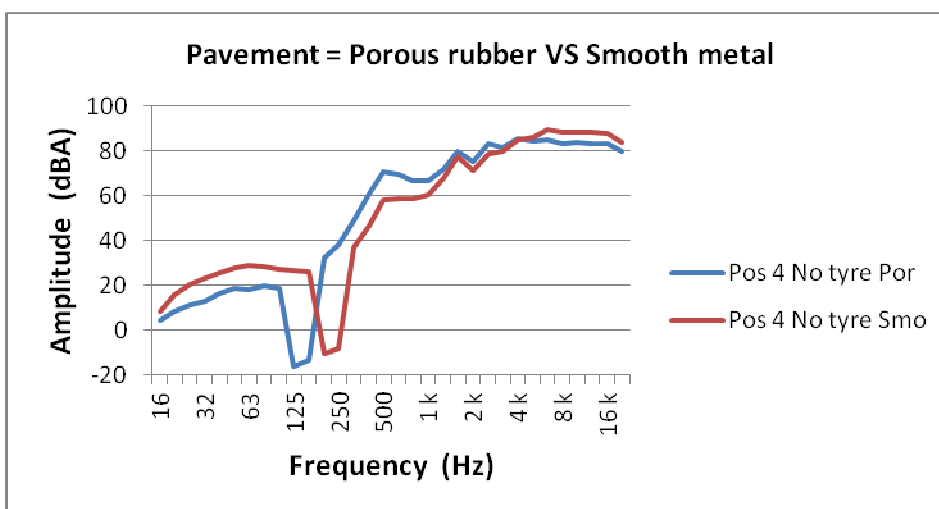
**Fig. 10-50** Porous / Smooth pavement –without tyre - Position 1



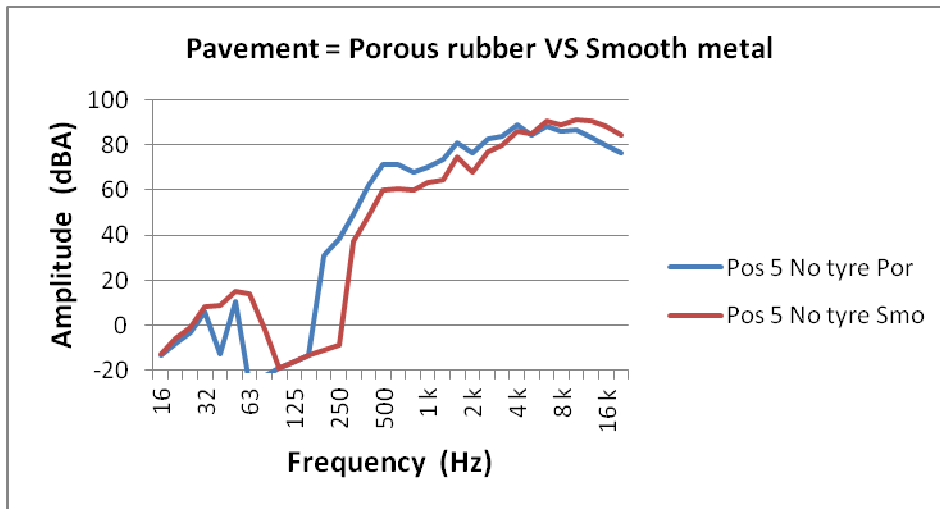
**Fig. 10-51** Porous / Smooth pavement –without tyre - Position 2



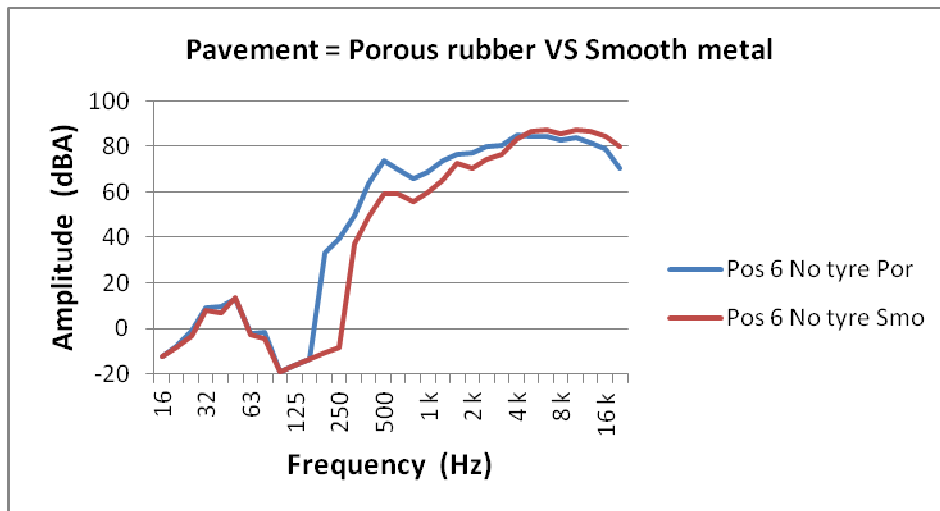
**Fig. 10-52** Porous / Smooth pavement –without tyre - Position 3



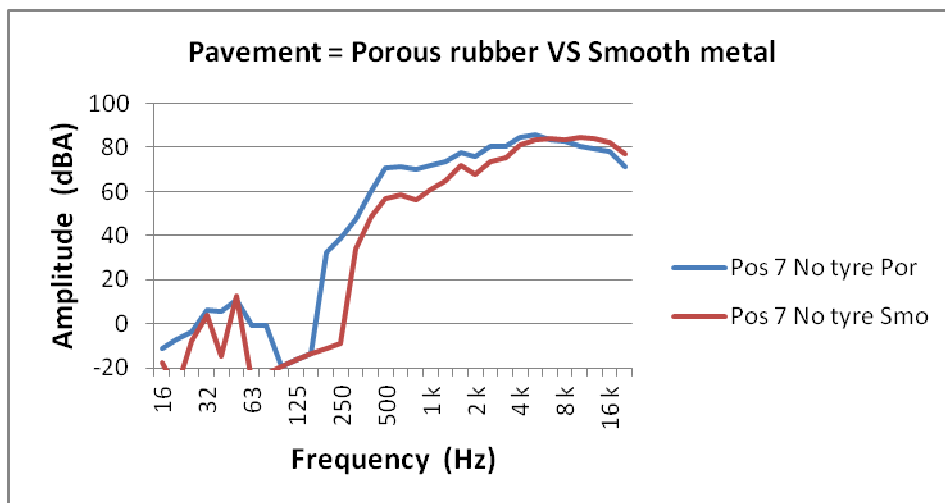
**Fig. 10-53** Porous / Smooth pavement –without tyre - Position 4



**Fig. 10-54** Porous / Smooth pavement –without tyre - Position 5



**Fig. 10-55** Porous / Smooth pavement –without tyre - Position 6



**Fig. 10-56** Porous / Smooth pavement –without tyre - Position 7



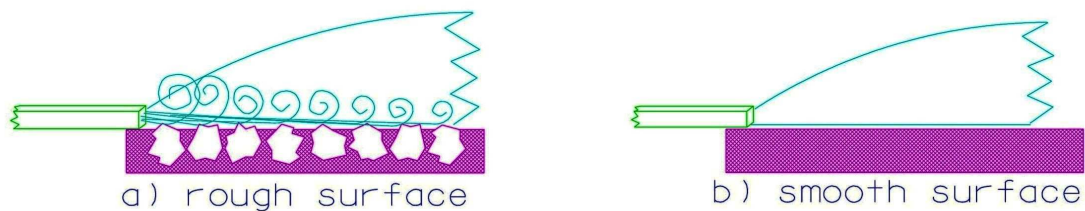
### Comments:

In all graphs the same copper pipe noise source (measured over a flat, porous rough pavement and over a smooth metal surface, without a tyre) has shown that the noise over the porous surface is louder than over the smooth surface !!.

The elevated amplitude is dominating the low-medium frequency area and is normalized in the high frequency area.

It has to be noted that the data line of the rough surface is not shifted to the low frequency area since the spectral notches are always in the same position in all the graphs, so there is new noise generation.

It seems that the texture roughness of the porous pavement introduces grazing turbulence of the passing air, that over a very smooth surface is not created, and by itself this is a very interesting and useful observation and should be further investigated.



**Fig. 10-57** Noise regeneration over rough surface

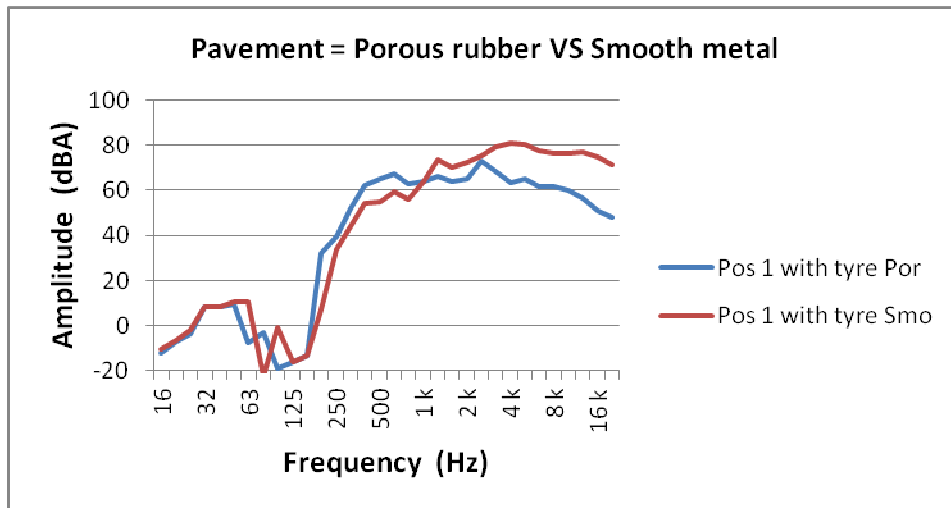
There is a high possibility that the lower frequency noise that is perceived by a driver when travelling over a porous or rough surface to be of double origin.

- a) From the vibrations that are introduced to the tyre/spring/chassis system due to the surface roughness & tyre oscillations and
- b) From the regenerated noise due to the multiple turbulence point sources created by the aggregate peaks when blasted by a violent air jet, as air is exiting each tyre groove.

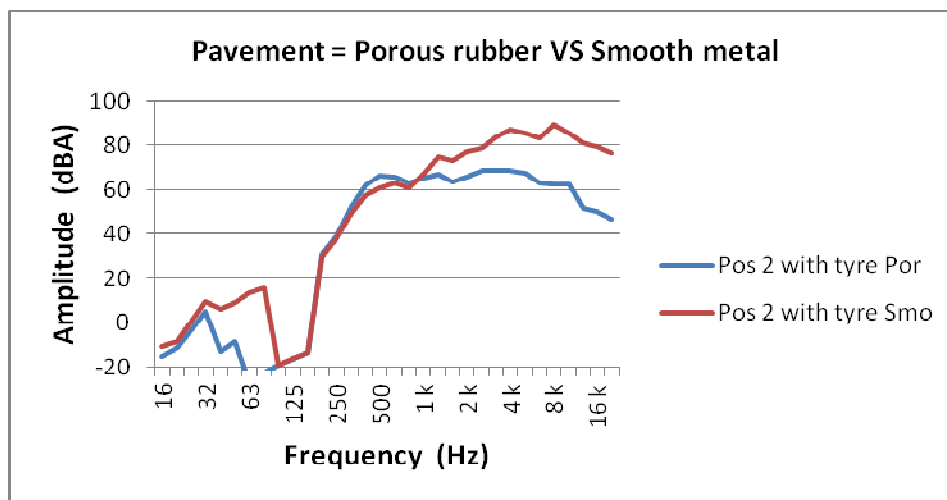
### 10.7.1 Tyre in Place.

The following spectral data is from the 2<sup>nd</sup> measuring set (same air source, and the tyre is in place, so a horn is created with the smooth pavement) compared to the data of the 4<sup>th</sup> measuring set (same air source, and the tyre is in place, so a horn is created with the porous pavement).

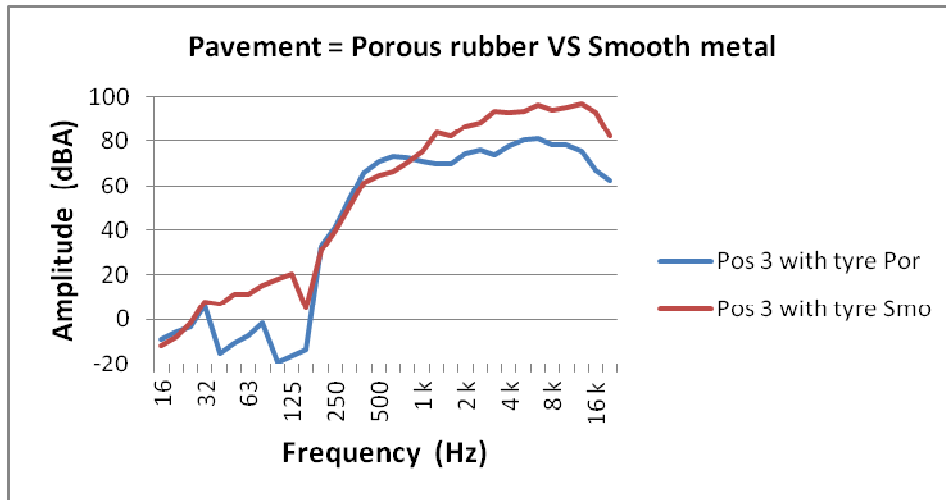
Noise is measured at the trailing edge of the supposed tyre rotation.



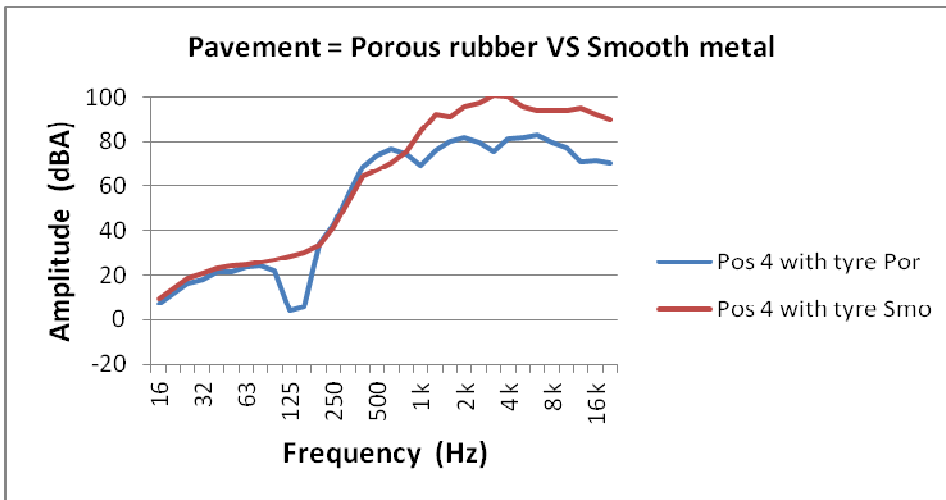
**Fig. 10-58** Porous / Smooth pavement –with tyre - Position 1



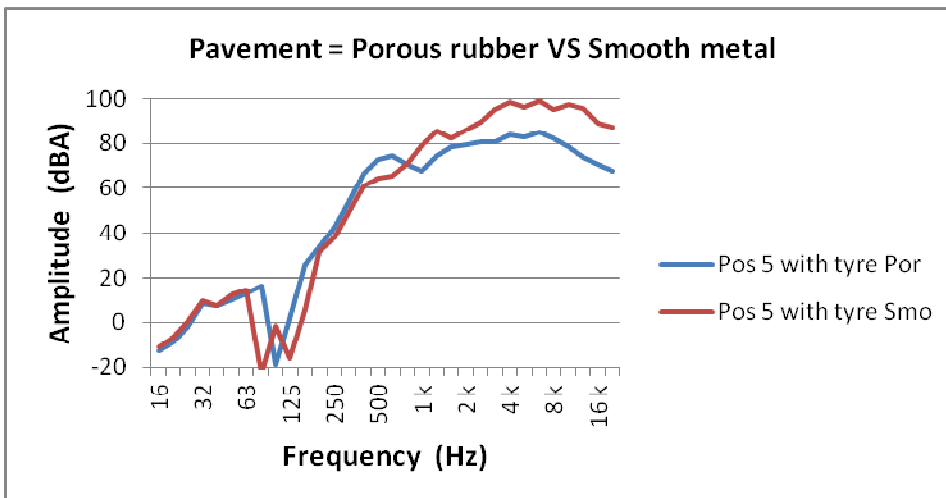
**Fig. 10-59** Porous / Smooth pavement –with tyre - Position 2



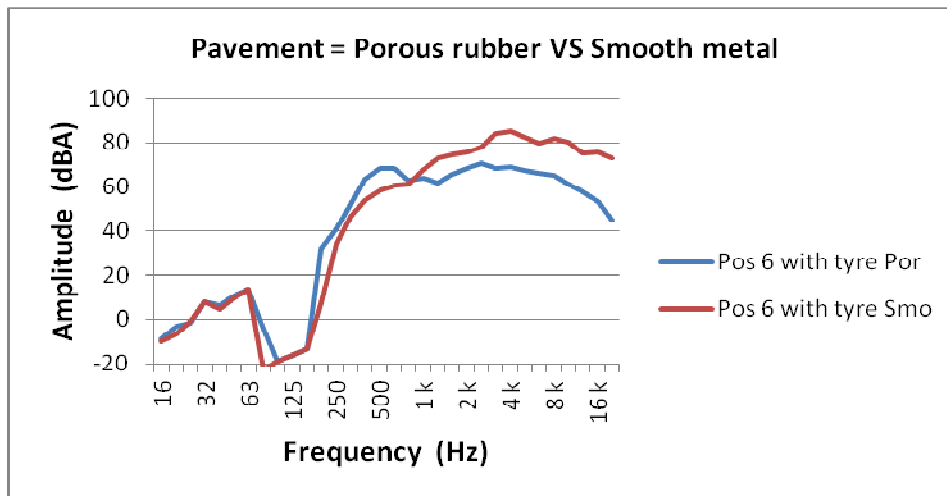
**Fig. 10-60** Porous / Smooth pavement –with tyre - Position 3



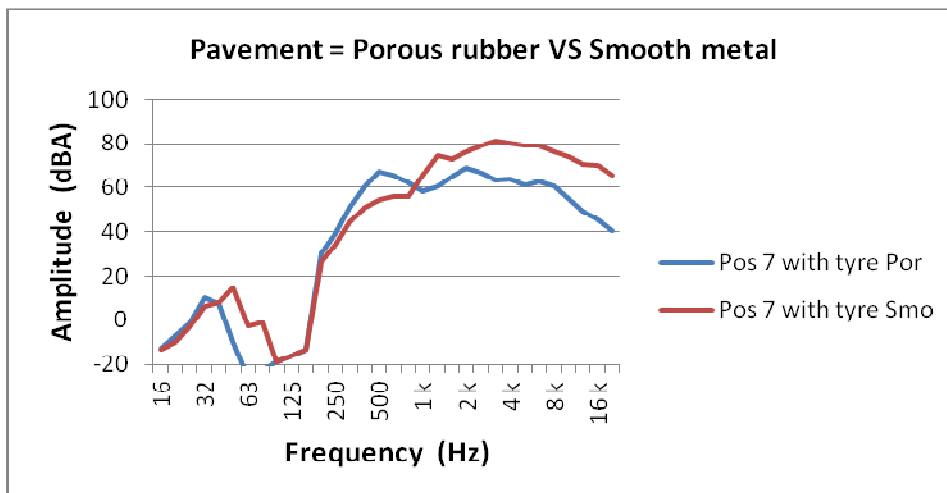
**Fig. 10-61** Porous / Smooth pavement –with tyre - Position 4



**Fig. 10-62** Porous / Smooth pavement –with tyre - Position 5



**Fig. 10-63** Porous / Smooth pavement –with tyre - Position 6



**Fig. 10-64** Porous / Smooth pavement –with tyre - Position 7

#### Comments:

In all graphs the same copper pipe noise source (measured over a flat, porous rubber, absorptive pavement and compared over a smooth metal surface, both with the tyre in place) has shown that the noise over the smooth surface is louder than over the porous surface, that is a quiet opposite behaviour to the measured results without the tyre in place.

It has to be noted that the results with the tyre over a smooth surface are of higher amplitude of ~20dB in the high frequency area at all measuring positions compared to the same measurements over a

porous surface where in contrast a distinct peak in the low-mid frequency is always present at 500Hz.

If one examines measurements 3,4,5 that are not obstructed by the tyre's body acting as a barrier, the ~20dB difference with only the altered pavement, is not logical to be produced only by the sound absorption characteristics of the pavement.

As mentioned in earlier paragraphs the substitution of one surface (in a total of 5 surfaces that consists a small triangular room) should not produce such a large difference in noise level.

One has also to note that in all measurements with the tyre in place in the low frequency area 250-500Hz, there is a matching of both data lines, in contrast to measurements performed without the tyre in place, where there is quite a difference measured over smooth and porous surface.

**The only hypothesis the author may rely on is that the textured rough surface alters the flow pattern of the expelled air via the tyre's grooves and keeps the airflow near the road surface, not allowing the air flow to be bended upwards (following the tyre's curvature) and thus the creation of large eddies at a height over the pavement's surface is avoided, thus excessive noise sources and their reflections are minimized.**

Judging from the above sensitive acoustic relationships and difficult to explain behaviour, it has to be reminded that all measurements have been performed using the developed static device and measurements with a rotating tyre may produce different results.



## **11 RESULTS AND CONCLUSIONS**

### **11.1 Results**

With the use of the developed device and the comparison measurements with the use of the supporting CPX trailer the critical evaluation of several noise producing phenomena have resulted in:

#### ***11.1.1 Lateral sipe noise.***

It was concluded that due to the minimum contact area the lateral sipes have, when in contact to the pavement, compared to the overall width of the tyre, their noise contribution is overestimated by tyre manufacturers and the random carving of sipes on a tyre, although theoretically sound, has little effect on producing loud tonal noises.

#### ***11.1.2 Tonal noise.***

The phenomenon was clearly heard (and measured) when measuring tyre “B” with the CPX trailer and from a closer inspection it was concluded that the main oblique treads the tyre incorporated as its main drainage system, are shorter in length compared to the overall contact area length. Due to this short design they could not expel the air at the trailing edge, but by design they expel the air by-laterally of the tyre. This had the effect to trap the air periodically and produce a tonal noise, even if the manufacturer had carved them in different distances between them, in order to avoid such phenomenon.

### **11.1.3 Pavement noise.**

During the evaluation of the measurements with the CPX trailer over a porous and over a closed pore smooth pavement, considerable noise differences are developed specially in the high frequency area. The close pore pavement proved to be louder over 1000Hz as expected, but the spectral lines of the FFT graph are much clearer and apart between them, providing a safer to interpret spectral readout, compared to the mixed and fuzzy spectral lines measured over the porous surface. All other aerodynamic factors that consider the tyre as a rotating body are the same in both pavements, but the only factor that is altered is the tyre/pavement contact area interaction. On the smooth pavement the aerodynamics of tread design is the major noise contributor in contrast to the porous pavement where the pores and texture of the pavement has also a major contribution and perhaps are responsible for some noise regeneration.

### **11.1.4 Testing tracks.**

From the literature search it was discovered that even the test tracks constructed with the ISO standard designation, suffer and are problematic to perform absolute measurements. This is due to the unavoidable texture differences from site to site. One has to consider that the pavements are aging and getting smoother as time passes (traffic dependent) so the expected results per testing track could be even more disputed and seem to lack validation.

### **11.1.5 Smooth pavement.**

Continuing the above elaboration, it was decided by the author to perform his measurements over a smooth close pore surface since the project was to investigate the tyre's noise and not the pavement's uncontrolled interaction. In the future, by doing measurements over a reference smooth closed pore surface as suggested by the author, better comparable results between tyres could be obtained, and a potential customer would evaluate his needs better (when selecting a tyre) than with today's labelling system and measuring techniques.



#### **11.1.6 Velocity spectral shift.**

It was known from the literature that there is no shifting of the frequency pattern to the higher or lower frequencies, as travelling velocity increases and was confirmed during the CPX trailer measurements. This non spectral shift and the steady positioning of spectral peaks at specific frequencies regardless of tyre revolution velocity, should not happen in rotating systems, except if the rotation is not influencing at all the noise producing mechanism, which seems to be the case in tyre noise.

#### **11.1.7 Amplitude increase.**

The CPX measurements have shown that the only factor that is affected from the car's increasing travelling speed is the overall noise level and it is remarkable how consistent the spectral amplitude increase is per velocity increase. The same result although at a lower level was observed using the device when the air supply from the fan was increased and during the further experimentation with the compressed air, the same amplitude increase was observed when the air compressor pressure was increased. It seems that the overall noise level is proportionally depended on air volume and air pressure, passing through the tyre's grooves and treads.

#### **11.1.8 Pipe resonance.**

The groove when in contact to the pavement, creates a pipe that seems to be responsible for the pronounced peak in the 1000Hz band, in all tyre measurements in all published papers and projects. It was concluded that since tyre revolution velocity is not responsible for this pronounced peak, the only possible factor that could radiate such noise regardless of pavement texture must be the groove/pipe. This was shown while conducting further experiments using the device, with a pressure air gun and a simulated copper pipe instead of the tyre groove itself, in order to isolate any unknown factors that the tyre may introduce to the system. The results from the simple theoretic calculation of pipe resonance, matches exactly the measured data and one must bear in mind that resonance in a specific frequency is not affected by air volume or air pressure but only on the physical dimensions

of the pipe and if it has open or closed ends. The air volume and pressure may alter the noise level but not the frequency resonance.

#### **11.1.9 Open / closed pipe resonance.**

During the validation of the acoustic behaviour of the tyre's groove with the simulated copper pipe, there was a doubt concerning the air pressure build up that is being generated due to tyre revolution, at the leading edge of a rotating tyre. This pressure build up could act as a partial barrier to the pipe inner reflection and alter significantly the pipe's acoustic response. It was concluded that the groove must behave as an open resonance pipe in order to generate the spectral peak at around 1000Hz.

#### **11.1.10 Pavement response.**

Comparing only a smooth closed pore pavement with a porous one (without a tyre present) during the further experimentation with the device, it was found that a smooth pavement radiates to the environment a different spectral pattern than the porous one. The above is not dependent on the sound absorbing characteristics of the pavement but on its roughness, since the air gun and pipe sound source were the same both times, placed directly over the pavement at grazing incidence and driven with the same compressed air volume. It seems that the pronounced aggregates of a rough pavement introduce more noise to the system due to local small scale turbulences that are created locally and sound is regenerated at a lower frequency. So one can suppose that the grooves of the tyres may be acting as air jets and set in motion more mechanisms that were expected previously. There is a major task for further investigation that will confirm or totally challenge and overturn the perceived theory, that low frequency noise (of a rotating tyre) when travelling over a rough pavement is generated due to the hammering effect the tyre's rubber is implementing to the rough pavement. It has been proven that a rough pavement is able to regenerate noise when a concentrated air stream (the air from the groove) is at grazing incidence to the pavement surface.

#### **11.1.11 Groove behaviour as air jet.**

In the experiments it was found that the one groove tyre is noisier than the three groove tyre and the author has made an assumption that the one groove is acting as a single air jet, in contrast the three grooves may be acting as a combination of a primary and two secondary air jets of lower air volume. By doing so a more progressive and better mixing of the air expelled by the three grooves is obtained, a wider air front is created and the overall turbulence at the trailing edge is more progressive and uniform, having as a result a smoother combined air flow and a lower noise level.

#### **11.1.12 Horn effect.**

Trying to understand the acoustic behaviour of a tyre due to the so called horn effect, it was found that even a small bellmouth placed at the end of the copper tube (simulating the tyre groove) introduces some small high frequency differences to the radiated sound even though no other parameter was altered in the experiment. By placing the actual tyre on the measuring device in order to simulate the exact horn dimensions, the tyre introduces to the tyre/pavement system several interesting behaviours.

a) the tyre acts as a sound barrier to the laterally radiated sound produced at the tyre's trailing edge, and creates a polar pattern to the radiated noise

b) the tyre's curved surface is guiding the expelled from the grooves air jet upwards, enabling the production of large Eddies at a significant distance from the pavement surface. Each Large Eddy is a sound source by itself since it disturbs locally the air pressure in the region behind the tyre and as expected more than one large Eddies are created and are created continuously as the tyre rotates. So the so called tyre horn is not acting as a wind instrument's horn radiator but as a Large Eddy creator.

#### **11.1.13 Reflections.**

Most literature depend the tyre/pavement noise on reflections or absorption over the pavement at the trailing edge area. But if the tyre groove is the main noise source, then since it is at grazing

incidence over the pavement it is impossible to be able to create reflections or to be absorbed, since both need some physical distance to be created. Reflections can not be created on a surface, if the sound source is flush level or imbedded in this rigid surface of large (or infinite) dimensions. So reflections due to the grooves or treads are not expected to be created.

#### ***11.1.14 Multiple sound sources.***

Due to the previously mentioned large Eddy creation mechanism at the tyre's curvature, it is understood that they are created at some distance over the pavement and at some distance from the tyre's curved surface as well. Large Eddy is a sound source by itself and is strongly affected by its energy and turbulent flow. If each new noise source (large eddy) is at a distance from a reflective surface, (pavement or tyre) then mirror images are created, that tend to radiate even more noise, depending on the absorption characteristics the reflective surface incorporates. The author concludes that if a level increase more than 10dBA is recorded with the tyre in place compared to the measurement where the tyre is not in place but with the same pipe (simulated groove) producing the same noise in both measurements, then several mirror images of each large Eddy must be present in order to have such a large noise level increase.

## 11.2 Comments on device performance

As it is clearly proven with this project, one of the contributing factors to the general tyre/pavement noise is the forced air noise generation when it escapes through the groove, treads and sipes of the tyre,

and is split into two major noise sources:

- a) the air escaping from the side through lateral treads and sipes
- b) the air escaping from the rear through the perimetric deeper grooves

Using the proposed device methodology (measurements on a smooth and standard, non-porous surface) in a controlled environment, a difficult to predict factor such as the surface texture and porosity is disregarded.

Noise data is easy to collect and used on a global database for tyre noise performance.

The proposed device is small in dimensions, rather inexpensive, very easy to use, allows for fast tyre changes, and since noise measurements are performed in the 'acoustic near field', no anechoic or specially treated room is necessary.

The author believes that the device's structural and acoustical behaviour exceeded his expectations for accurate noise measurements, and believes strongly that it could be used as a research platform for all treaded tyre profiles (except slick tyres) for the study of tyre tread pattern acoustic behaviour.

### 11.3 Conclusions on device performance

After using the constructed device under different situations, making cross references with the constructed trailer, and evaluating the obtained data, it became clear that all the objectives in this thesis have been met successfully and the device is a friendly-to-use acoustic measuring platform.

The following objectives from using the device are met as well:

- The noise producing mechanism by the device is capable to be regulated and adjusted by the user, easily.
- The noise data collection proved to be very easy.
- The measuring procedure also proved to be very fast.
- The noise measurement is able to be repeated as many times as required, and the same noise results are obtained.
- The device is an inexpensive construction, has minimum usage costs, and can be used as an acoustic research platform.
- The device can perform noise measurements, not only using an existing tyre, but also tyre models, or parts of tyres.
- The device can alter its contact surface very fast and easily, so different surface/pavement textures or porosities can be acoustically studied.
- It can be used under dry or wet pavement conditions.
- It can alter the tyre/pavement contact pressure, with minimum labour effort under controllable conditions.
- It can be used inside a protected environment (laboratory), so regardless of environmental conditions, measurements can be performed at all times.
- The measuring instrumentation used are reference digital “type I” Sound Level Meters and spectral analysis platforms.
- The obtained spectral noise data can easily be adjusted from 1/1 octave to any desired octave band.
- The device or part of the device can be used to perform further acoustic investigations.

## 11.4 Future tasks

The constructed tyre tread noise measuring device and the one wheel CPX trailer may be used to:

- Measure more tyres, by different manufacturers, with both procedures in order to make more comparison measurements.
- Perform noise measurements using the device and placing the SPL instruments at different distances and positions, to evaluate noise propagation mechanism.
- Make different textured surfaces to be used with the device and study the tyre/pavement interaction.
- Study the acoustic behaviour of textured surfaces always using one same standard, reference tyre.
- Use the results from different measurements to inform public road authorities on how to acoustically improve the road texture.
- Help any road construction authority to measure road noise by using the CPX trailer in order to evaluate community traffic noise.
- Be part of European road noise measuring projects.
- Help to improve tyre noise measuring standards.
- Help to improve tyre noise classifications.
- Help tyre manufacturers to design low noise tyres.

### **11.4.1 Proposal to standardize tyre/pavement noise measurements**

- Using the prototype device

It is proposed that the constructed device be used for first stage noise measurements or tread noise classification.

The methodology should be standardized and physical limits of the method should be integrated in order to avoid untrained personnel or non-acoustic engineers to make any simplifications or bad selections or wrong adjustments during measurements.

- Using the today existing methods

It is proposed not to make tyre noise classifications on standard road surfaces (as mentioned in ISO 10844/94) but on a reference smooth and closed pore surface, since by doing so, absolute values and comparison measurements of the tyres will be obtained.

With this smooth surface procedure, one can eliminate all uncontrollable pavement factors, as explained in earlier chapters.

If noise data over a smooth pavement is measured, it is easy to calculate the tyre's noise propagation, at different distances, over a typical porous asphalt pavement, if its texture, porosity, thickness and sound absorption characteristics are known.

For instance, all the above factors could be entered into a simulation model to calculate tyre noise propagation.

It is suggested that in the official E.U. labelling the absolute values of noise level, to be removed and replaced by a more subjective scale, since as mentioned in previous chapters level differences of 1 or 2 dB are misleading.

The subjective scale could be extracted by comparing each tyre to an ISO standard tyre, both travelling on a smooth closed pore pavement.



The scale could be described as “very quiet” “quiet” “reference” “loud” “very loud” with the following limits

“very quiet” = less than 5-7 dBA compared to reference tyre  
 “quiet” = less than 2-4 dBA compared to reference tyre  
 “reference” = same noise level when compared to reference tyre  
 “loud” = more than 2-4 dBA compared to reference tyre  
 “very loud” = more than 5-7 dBA compared to reference tyre

With the above proposed subjective scaling there is no limit depending on future tyre design improvement and more scales could be added without disrupting the logic of the scale, for example “extra quiet” “ultra quiet” and “extra loud” “ultra loud”

The above subjective scale is proposed by the author instead of an absolute one or one using numbers or letters from his bad experience while reading “energy” consumption of electric appliances. The A,B,C,D,E scaling has already reached his limit and the new more efficient appliances are using a “comic” scale such as A+++ !

#### **11.4.2 Proposal to develop a software model**

As mentioned in earlier chapters, the developed device is producing a noise spectrum of lower amplitude, as expected, compared to the CPX trailer noise spectrum.

With the use of the device, a software model could be developed in order to predict the noise emission of different tyres over different pavements at different speeds and environmental conditions.

The noise spectrum measured with the device can be the base for the software model and other parameters and correcting factors could be added, following the general guidance of the ISO 17534 “*software for the calculation of sound outdoors*”.

The data of the pavement could be theoretical (from bibliographic references) or estimations, but could also be measured data, using the appropriate international standards and instruments per parameter.

The input parameters of the model could be at least the following: (mentioned in brief an elaborated in later paragraphs).

**MEASURED NOISE - DATA INPUT**

(with the use of the developed device, measured over a flat and smooth pavement surface)

Measured noise spectrum in dB or dBA “left channel”

Measured noise spectrum in dB or dBA “right channel”

at 50km/h, 80km/h, 110km/h, “other”

**TYRE DATA INPUT**

Tyre diameter

Tyre width

Tyre height

Tyre air pressure

Tyre condition: “new”, “slightly used”, “old”

Tyre type: “winter” “summer” “snow” “rain”

Cross section of perimetric groove: “1” , “2” , “3” , “4”

Tread pattern: “A” , “B” , “C” , “D” “other – user defined”

Lateral sipe pattern: “A” , “B” , “C” , “D” “other – user defined”

**PAVEMENT DATA INPUT**

Road type: “urban”, “suburban”, “highway”

Pavement material: “asphalt”, “concrete”, “rubberized” “other”

Pavement condition: “clogged from dust”, “open pore”, “other”

Pavement microtexture: “glazed”, “smooth”, “rough”, “other”

Pavement macrotexture: “level” “with irregularities” “other”

Environmental condition 1: (surface) “dry”, “wet”

Environmental condition 2: (weather) “cold”, “typical”, “hot”, “other”

**VEHICLE VELOCITY INPUT**

Input the requested vehicle’s travelling speed

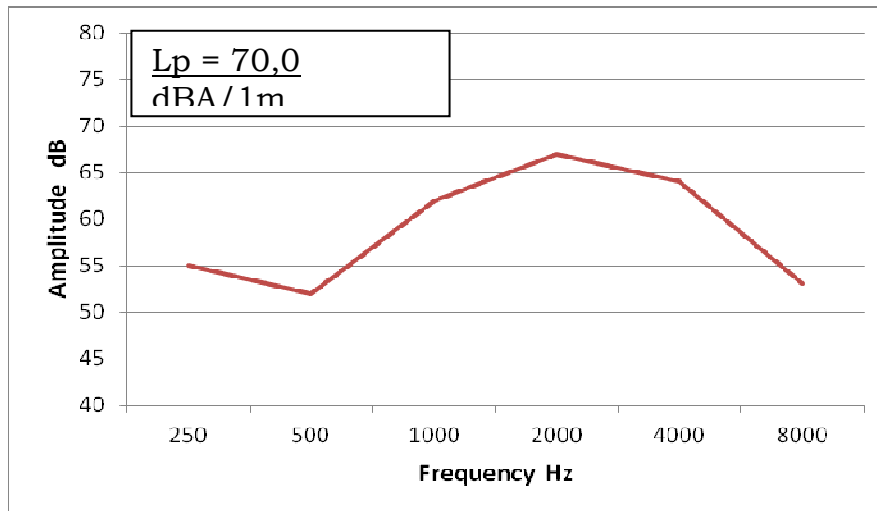
**COMMENTS**

Input comments (to be shown on result printout)

**RESULTS - CALCULATED SPECTRAL DATA**

*( Table example with 1/1 octave bands)*

Herz	250	500	1k	2k	4k	8k		Lp/1m	Lw
								dBA	dB
dBA	55,0	53,0	63,0	67,0	64,0	56,0		70,0	74,0

*Graph example*

If needed, more calculated data can be derived, in order to produce further acoustic or grip or safety results (for evaluating the acoustic environment of the surrounding area or for evaluating the safety, grip and traction of the road).

**RECEIVER NOISE - PER DISTANCE**

Input the distance path (noise source to receiver point)

Input the height of the noise source from pavement

Input the height of the receiver from pavement

Input the presence of a noise barrier

Input height and length of the noise barrier

Input the texture of intermediate terrain

Input if other reflecting planes are near the source

Input if other reflecting planes are near the receiver

**11.4.3 Parameter elaboration**

Each of the above brief mentioned parameters has a logical function in the noise producing mechanism and is elaborated in the following paragraphs.

**11.4.3.1 Measured noise – data input**

Since the constructed device can be used in a limited space and indoors, one could use the spectral data per channel, as input to the software model as basic data.

It is best to use 1/3 octave noise data (providing a 1/3 octave spectral analyzer is available) but a 1/1 octave spectral analyzer can also be used. It is not advised to use overall or single figure noise data.

The author believes strongly that all data should be measured on a rigid smooth flat surface.

The model should accept sound pressure ( $L_p$ ) unweighted spectral data (in dB) or “A” weighted spectral data (in dBA) and provide 3 predetermined velocity boxes of 50km/h, 80km/h, 110km/h.

It should also provide the benefit to the engineer to input a different or user defined velocity in the “other” input box, if measurements have been performed with different velocities.

It is suggested that spectral data lower than 250Hz should not be used, due to all the problems explained in the previous chapters.

#### **11.4.3.2 Tyre data input**

One of the noise producing items in the tyre/pavement interaction, is the tyre, so all its characteristics should be entered in the model.

**Tyre diameter:** determines the flexural behaviour of the circumference of the tyre and its deformation when in contact with the pavement.

**Tyre width:** if the tyre diameter is known, the width determines the contact area “Footprint” on the pavement, it also interferes with the shoulder sipes contact area since the wider the footprint is, the less percentage of contact area is occupied by the lateral sipes.

**Tyre height:** determines the internal volume of the tyre and the internal noise reverberation and resonance can be calculated.

**Tyre air pressure:** if the air pressure is different than the optimum one stated by the car manufacturer, the tyre is expected to produce a different noise spectrum. It could be of higher or lower amplitude but it is expected to be considerably different.

**Tyre condition:** If the tyre is new it is expected a) to have the deepest possible groove and tread so it provides the largest possible cross section per groove and tread and b) to have the softest possible rubber material. Accordingly the “slightly used” has smaller cross sections and

harder rubber and the “old” has the smallest cross section and hardest rubber.

The cross section is affecting the velocity of the air stream inside the grooves and treads, thus affecting the exiting turbulence and noise production mechanism.

The hardness of the rubber (usually expressed as “Shore A”) is not expected to alter the noise produced by the air turbulence but it may affect the noise produced from the continuous and consistent hammering of the tyre especially over a rough pavement and at high speeds.

Tyre type: winter tyres have a more open drainage system, and wider grooves than summer tyres and in some cases use softer rubber so they are expected to produce a different noise spectrum. Snow or specialized rain tyres have a more aggressive tread design, that allows the tyres to self clean during rotation, so they are expected to produce a tonal noise and more pavement hammering noise.

Cross section of perimetric groove: the cross section of the perimetric grooves can be measured (it is also depended on the previous data input “tyre condition”) and may be the worst noise producing mechanism, since as proven with the constructed device, the main noise is generated from the “orifice” effect of the grooves.

Different tyres may have different numbers of grooves with different cross section each, so a choice must be given to the research engineer to input groove “1” , “2” , “3” , “4” or even more.

Tread pattern: different manufacturers use different designs, so figures or pictures or drawings of several tread patterns should be available to be selected from a tread data base “A” , “B” , “C” , “D”

The model should provide the researcher the option to insert more or different user defined designs expecting future new designs from the tyre manufacturers.

As measured and proven in the thesis, the tread pattern may be responsible for tonal noise production depending on its design.

Lateral sipe pattern: same as above

### **11.4.3.3 Road or pavement data input**

If the noise measurements are performed on a smooth flat surface with the device, as the author suggests, the pavement type and condition is of major importance to the noise producing mechanism and noise dissipation to the environment.

Some of the following input data may be estimated by an experienced engineer and some may be measured with the appropriate instrumentation and use of international standards.

**Road type:** road use is a parameter evaluated in the design of a road, using different aggregates, base thickness, water drainage etc so a simple classification as “urban” “suburban” or “highway” will give to the model the desired constructional limits that affect the noise generation.

The use of the above parameters also affects the noise radiation to the environment at larger distances. For example a car travelling with slow speed in an urban road should be considered by the model as a moving spot source, thus radiation in a quasi omnidirectional polar pattern is expected.

If multiple vehicles are travelling in a highway with high velocities, then the noise diffusion behaves as a linear noise source. Spot and linear noise sources are calculated with different equations and provide different spatial radiation.

**Pavement material:** since the model could be used worldwide the most common surface material used for road construction is asphalt with hard aggregates. In other countries or in different territories concrete may be used that is of more closed pore consistency than asphalt. In new roads it is common to use recycled rubber in the asphalt or concrete mixture so this and “other” options should be available.

**Pavement condition:** As clearly stated in the relevant ISO standard, one of the problems when making measurements even on reference test tracks, is the “aging” of the pavement it self. In this way the pores of the surface are or are not open, affecting the passage of the air between their structure. In this way a noticeable spectrum and amplitude difference is detected.

One can see the measurements performed with the CPX trailer on open pore and smoothed asphalt pavement in an earlier chapter in this thesis and see the noticeable difference especially in the high frequency area. So the model should have an option to select if the pavement pores are open or closed.

**Pavement microtexture:** With the term microtexture (in Greek, micro, means very small or very near) one understands that the roughness of the surface as seen from a very close distance may seem like a flat valley or rocky mountains, thus affecting or not the continuous hammering of the tyre, implemented by the pavement's rough or smooth aggregates.

At least 3 options should be available regarding a) a very smooth and glazed surface where the aggregates are level with the rest asphalt surface b) a smooth option, where the aggregates are smoothed but not level with the asphalt (or concrete) surface, and c) a rough option where the aggregates are still in good condition.

**Pavement macrotexture:** If the pavement has no gaps or bumps or humps then it can be considered as "level". If it has a lot of irregularities, then the non periodic hitting of the tyre on those irregularities produces a very distinct noise of high amplitude, that can't be safely predicted.

**Environmental condition 1 (surface):** All traffic noise measuring methodologies are clearly mentioning that tyre noise measuring should be made on dry pavement, but since models are used for research purposes a "wet" option should be included. With the term wet, it is supposed that only a thin layer of water is present clogging the pores of the pavement. If the layer of water is thick then no measurement can be performed to evaluate the tyre/pavement interaction and aquaplaning starts to take effect (velocity dependent).

**Environmental condition 2 (weather):** In all acoustic environmental measurements besides the actual measured noise data, the air temperature and humidity of the surrounding air is measured as well and stated on the test reports since it may affect the perceived noise, especially over large distances. This is the case too in this input request, but if the weather in the test area is too cold or too hot, then it is expected to alter the resilience behaviour of the pavement surface as

well. If the temperature is other than “typical” 20°C then it should be taken into account from the model’s algorithm.

#### **11.4.3.4 Vehicle velocity input**

Input vehicle’s travelling speed: as seen in all measurements in this thesis, the noise amplitude is increasing when the travelling speed increases.

So the model could be used a) to verify it self, b) to insert a correction coefficient, c) to predict the noise spectrum and amplitude under different conditions.

Regarding the possibility “a” the model could be used to check it’s own spectral results. For example if one inputs spectral data for the speed of 50km/h, then it should be able to calculate the spectral data at a different speed, for example at 110km/h and its validity could be cross checked by measurements.

Regarding the possibility “b” the model could have a correction coefficient input box, and if the self cross checking data is slightly of, then it could be corrected. In case the difference is large (for example more than 3-5dB) then re-evaluation of the input or calculated data should be performed.

Regarding the possibility “c” the model’s main task should be to predict the produced noise from the tyre/pavement interaction under different pavement conditions.

#### **11.4.3.5 Comments**

Input comments: The engineer should be able to insert text legends and comments per each data result sheet or per each saved computer file. The comments should be printable on the test sheet to inform the reader for any anomalies detected or for any adaptations or for any correction coefficient used.



#### **11.4.3.6 Results – calculated spectral data**

The model should take into account all the above parameters and according to the logical diagram and implemented equations, it could produce at least the following results.

Since equations do not exist for most of the above parameters, (on how they affect the total noise) they have to be developed, based on measured data, so indexes and correction factors can be used in the model.

The expected result may be :

- Final spectral data in 1/3 octave bands, if measured data from the device was entered as 1/3 octave figures.
- Final spectral data in 1/1 octave bands, if measured data from the device was entered as 1/1 octave figures.
- Single number of sound pressure Level ( $L_p$ ) at a predetermined distance (usually at 1 meter) with unweighted data (dB)
- Single number of sound pressure Level ( $L_p$ ) at a predetermined distance (usually at 1 meter) with weighted data (dBA)
- Single number of sound power ( $L_w$ ) with unweighted data (dB)
- Single number of sound power ( $L_w$ ) with weighted data (dBA)

If the model developer wishes, he can express all partial data as distinct results per parameter, and the final total spectral noise may be derived from all the above parameters. So the engineer or tyre designer can understand better the complete noise producing mechanism.

#### **11.4.3.7 Receiver noise per distance**

If the model developer wishes, he can calculate the noise level at several distances away from the noise source using a typical methodology known to all acoustic engineers.

The data needed in order to calculate the noise level at a distance is the following:

Input the distance path (noise source - receiving point)

Input the height of the noise source from pavement

Input the height of the receiver from pavement  
Input the presence of a noise barrier  
Input height and length of the noise barrier  
Input the texture of intermediate terrain  
Input if other reflecting Plains are near the source  
Input if other reflecting Plains are near the receiver

If the future model developer needs support or tips from the author, he will be glad to help in any possible way.

***With the conclusion of this thesis the author believes that***

- a) he has acquired more knowledge
- b) he has contributed to the better understanding of a complex noise producing mechanism and has not been limited to a theoretical approach of the problem, but has proposed a new and more efficient device and methodology to measure the tyre's groove and tread noise.
- c) he has proposed new methods to enhance the today's used measuring techniques.

## REFERENCES

The following bibliography is separated into 3 major sections:

1. Doctoral dissertations, master's thesis, journals, conference papers, technical reports and European legislation.
2. US patents
3. ISO Standards (International Standard Organization)

1.	John Charles Walker (1981) <i>Noise generated at the tyre/road interface,</i> Doctoral dissertation, University of Aston, p.212
2.	Lee Axon (1999) <i>The aerodynamic characteristics of automotive wheels – cfd prediction and wind tunnel experiment,</i> Doctoral Dissertation, Cranfield University, p.262
3.	Francois Xavier Becot (2003) <i>Tyre noise over impedance surfaces, Efficient application of the equivalent sources method,</i> Doctoral dissertation, Charlmers university of technology, p.195
4.	Antonius J. Schmeitz (2004) <i>A semi-empirical three dimensional model of the Pneumatic tyre rolling over arbitrary uneven road surfaces,</i> Doctoral dissertation, Technical university Delft, p.159
5.	Leonardo Molisani (2004) <i>A coupled tire structure Acoustic cavity model,</i> Doctoral dissertation, Virginia Polytechnic Institute and state university, p.181

6.	Carl-Magnus Nilsson (2004) <i>Waveguide finite elements applied on a car tyre,</i> Doctoral Dissertation, Royal Institute of Technology, p.237
7.	Raitanen Nina (2004) <i>Measuring of noise and wearing of quiet surfaces,</i> Doctoral dissertation, Helsinki university of technology, p.105
8.	Robin D. Knowles (2005) <i>Monoposto racecar wheel aerodynamics: Investigation of near wake structure &amp; support sting interference,</i> Doctoral dissertation, Cranfield university, p.171
9.	Eric Torra and I Fernandez (2006) <i>The influence of tyre air cavities on vehicle acoustics,</i> Doctoral Dissertation, Kungliga Techick university, p.190
10.	Martin Fraggstedt (2006) <i>Power Dissipation in Car Tyres</i> Licentiate Thesis, Royal Institute of technology, p.25
11.	Marco Hahn (2008) <i>Implicit large-eddy simulation of low speed separated flows using high resolution methods,</i> Doctoral dissertation, Cranfield university, p. 204
12.	Karin Liljegren (2008) <i>Visual and acoustic tyre tread design,</i> Master's thesis, Chalmers Univ of thechnology, Goteborg, p.57
13.	Hans Arnold Nijland (2008) <i>Theory and practice of the assessment and valuation of noise from roads and railroads in Europe,</i> Doctoral dissertation, University of Delft, p.112
14.	Jochen Eisenblaetter (2008) <i>Experimental investigation of air related tyre/road noise mechanisms,</i> Doctoral dissertation, Loughborough university, p.246

15.	Peter Kindt (2009) <i>Structure borne tyre/road noise due to road surface discontinuities,</i> Doctoral dissertation, Katholike Universiteit Leuven, p.376
16.	Magnus Löfdahl (2011) <i>Model development for auralization of interior tyre noise,</i> Licentiate Thesis, Luleå University of Technology, p.88
17.	Salih Kocak (2011) <i>The impact of material characteristics on tire pavement interaction noise for flexible pavements,</i> Master's thesis, Michigan state university, p.104
18.	Ho Ka Yee (2011) <i>Identifying Tyre influence on tyre/road noise emission using Close proximity method,</i> Master's thesis, Hong Kong polytechnic university, p.172
19.	Bernard Igbafen Izevbekhai (2012) <i>Tire-Pavement interaction noise of concrete pavements,</i> Doctoral dissertation, University of Minnesota, p.116
20.	Daniel E. Mogrovejo <i>et al.</i> (2013) <i>Effect of Air Temperature and Vehicle Speed on Tire/Pavement Noise Measured with On-Board Sound Intensity Methodology,</i> Master Thesis, Virginia Tech Institute, p.21
21.	Mingliang Li (2013) <i>Tyre-road noise, surface characteristics and material properties,</i> Doctoral dissertation, University of Delft, p.279
22.	Jens Slama, (2012) <i>Evaluation of a new measurement method for tire/road noise,</i> Master's thesis, Royal Institute of Technology, p.59
23.	Daniel Mogrovejo Carrasco, (2012) <i>Effect of air temperature, vehicle speed and pavement surface aging on tire/pavement noise measured with on board sound intensity methodology,</i> Master's thesis, Virginia Polytechnic institute and state university, p. 203

24.	Yang Jiasheng (2013) <i>Tire pavement noise simulation and analysis</i> , Doctoral dissertation, National university of Singapore, p.267
25.	Sandra Buss (2006) <i>Subjective perception of pattern noise, a tonal component of the tyre/road noise and its objective characterisation by spectral analysis and calculating contours</i> , Doctoral dissertation, Oldenburg universitat, p.315
26.	Mukesh Chandra Mishra (2010) <i>Study and development of road traffic noise model</i> , Master's thesis, Thapar university, p.105
27.	Wuttiwat Kongrattana Prasert (2010) <i>Studies on the detection of road surface states using tire noise from passing vehicles</i> , Doctoral dissertation, University of Electrocommunications, p.135
28.	Florentina Farcas (2008) <i>Road traffic noise, a study of Skane region Sweden</i> , Master's thesis, Lincoping University, p.89
29.	P Lesniewicz <i>et al.</i> (2014) "Aerodynamic analysis of an isolated vehicle wheel", <i>Journal of Physics, conference series 530</i> , p.9
30.	Haran Periyathamby (2004) "Helmoltz resonator for reducing tire cavity resonance and in vehicle noise", <i>Journal of Canadian Acoustics, Vol 32</i> , p.5
31.	Bert Peeters <i>et al.</i> (2010) "Reduction of the horn effect for car and truck tyres by sound absorbing road surfaces", <i>Internoise congress conference</i> , p.10
32.	Besnard F. <i>et al.</i> (1999) "Updating the vehicle noise emission values used in French traffic noise prediction models", <i>Internoise congress conference</i> , p. 6

33.	Besnard F. <i>et al.</i> (2003) “The procedure of updating the vehicle noise emission values of the French “Guide du Bruit” <i>Euronoise conference Naples</i> , p. 6
34.	Soon Hong Park and Yang Hann Kim (2001) “Visualization of pass by noise by means of moving frame acoustic holography”, <i>Journal Acoustical society of America</i> , vol 110, p.2326-2339
35.	Paje S.E <i>et al.</i> (2007) “Monitoring road surfaces by close proximity noise of the tire/road interaction”, <i>Journal Acoustical society of America</i> , vol. 122, p.2636-2641
36.	Wai Keung Lui and Kai Ming Li, (2004) “A theoretical study for the propagation of rolling noise over a porous road pavement”, <i>Journal Acoustical society of America</i> , vol. 116, p.331-322
37.	Andreas Schuhmacher and Jørgen Hald (2003) “Sound source reconstruction using inverse boundary element calculations” <i>Journal Acoustical society of America</i> , vol. 113, p.114-127
38.	Arvind Kumar Shukla (2011) “An approach for design of noise barriers on flyovers in urban areas in india” <i>Int. journal for traffic and transport engineering</i> , p.158 – 167
39.	C. González Díaz, <i>et al.</i> (2012) “Numerical prediction of the dynamic behaviour of rolling Tyres” <i>Proceedings of isma</i> , p.1541-1552
40.	Guang tong and xiaoxiong jin (2012) “Study on the Simulation of Radial Tire Wear Characteristics wseas transactions on systems” <i>E-ISSN: 2224-2678 Issue 8, Volume 11</i> , p. 419-429
41.	E. Rustighi <i>et al.</i> (2007) “Linear stochastic evaluation of tyre vibration due to tyre/road excitation”, <i>Journal of Sound and Vibration</i> , p.12

42.	Anfosso-Ledee <i>et al.</i> (2000) “Tyre road noise: comparison of 2D and 3D models for horn effect”, <i>Internoise congress</i> , p.5
43.	Truls Berge (2013) “Noise performance of the SRTT tyre compared to normal passenger car tyres”, <i>Internoise congress</i> , p.10
44.	Gillian Adams <i>et al.</i> (2000) “Dynamic Measurement of Tyre/Road Noise” <i>29th Australasian Transport Research Forum</i> , p.12
45.	C.K.Wong <i>et al.</i> (2013) “The Ageing Effect of Mechanical Joints on the Tyre/Joint Noises Monitored by a Control Vehicle Method without Traffic Disturbance”, <i>Journal Advances in Mechanical Engineering</i> , p.10
46.	Erik Bühlmann and Toni Ziegler (2013) “Temperature effects on tyre/road noise measurements and the main reasons for their variation” <i>Internoise congress</i> , p.10
47.	Moisés Bueno <i>et al.</i> (2014) “Noise Reduction Properties of an Experimental Bituminous Slurry with Crumb Rubber Incorporated by the Dry Process” <i>Coatings journal</i> , p.602-613
48.	Ines Lopez Arteaga (2014) “Tyre/road noise and vibration: understanding their interaction and contribution to vehicle noise and fuel consumption” <i>21st International congress on Sound and Vibration, Beijing</i> , p.13
49.	Ulf Sandberg (2001) “Tyre/road noise – Myths and realities” <i>Proceedings of the International Congress and Exhibition on Noise Control Engineering</i> , p.24
50.	David Woodward <i>et al.</i> (2008) “Review Research into sustainable asphalt surfacing mixes in the uk”, <i>University of Ulster</i> , p.5



51.	Jan Urban and Vojtěch Máca (2013) “Linking Traffic Noise, Noise Annoyance and Life Satisfaction: A Case Study” <i>International Journal of Environmental Research and Public Health</i> , p.1895-1915
52.	Guillame Dubois et al. (2012) “Numerical evaluation of tyre/road contact pressures using a multi-asperity approach”, <i>International Journal of Mechanical Sciences, Elsevier</i> , p.84-94
53.	Zamri Mohamed (2013) “A survey of wheel tyre cavity resonance noise” <i>Int. Journal Vehicle Noise and Vibration, Vol. 9</i> , p.276-294
54.	Ard Kuijpers and Gijsjan van Blokland (2001) “Tyre/road noise models in the last two decades: a critical evaluation”, <i>Internoise congress</i> , p.6
55.	Phil Morgan <i>et al.</i> (2009) “The selection of new reference test tyres for use with the CPX method, to be specified in ISO/TS 11819-3” <i>Internoise congress</i> , p.9
56.	Ulf Sandberg (2003) “The Multi-Coincidence Peak around 1000 Hz in Tyre/Road Noise Spectra” <i>Euronoise Conference Naples</i> , p.498-506
57.	Narayanan Neithalath <i>et al.</i> (2005) “Tire-Pavement Interaction Noise: Recent Research on Concrete Pavement Surface Type and Texture” <i>8<sup>th</sup> International Conference on Concrete Pavements</i> , p.523-541
58.	Stephen Pugh <i>et al.</i> (2008) “Tyre/road noise measurements in Queensland- Noise characteristics of various road surfaces” <i>Proceedings of Acoustics</i> , p.8
59.	Steve Phillips <i>et al.</i> (2001) “Noise Testing of Tyres” <i>Itec Conference</i> , p.6

60.	Joseph Ponniah (2010) “Evaluation of the Effectiveness of Different Mix Types to Reduce Noise Level at the Tire/Pavement Interface” <i>Conference of the Transportation Association of Canada</i> , p.20
61.	Jochen Eisenblaetter (2006) “Experimental investigation into the air pumping effect at the tyre/road interface”, <i>Proceedings institute of acoustics, Vol 28</i> , p.356-361
62.	N. Tsujiuchi (2002) An investigation of rolling tire noise generated by vibration <i>Conference &amp; Exposition on Structural Dynamics</i> , p.305-401
63.	Feng Z. and Gu P. (2011) “Modeling and Experimental Verification of Vibration and Noise Caused by the Cavity Modes of a Rolling Tire under Static Loading”, <i>SAE Technical Paper</i> , p.27
64.	Keijiro Iwao and Ichiro Yamazaki (1996) “A study on the mechanism of tire/road noise” <i>SAE of Japan journal review 17</i> , p.139-144
65.	Steffen Muller <i>et al.</i> (2003) “Estimation of the Maximum Tire-Road Friction Coefficient” <i>Journal of Dynamic Systems, Measurement, and Control Vol. 125</i> , p.607-617
66.	G.J. van Blokland (2014) “Modelling of aging of low noise road surfaces” <i>Transport Research Arena</i> , p.8
67.	Junoh, A. K <i>et al.</i> (2011) “A Study on the Effects of Tyre Vibration to the Noise in Passenger Car Cabin”, <i>Advanced Modeling and Optimization, Vol. 13</i> , p.15

68.	Byoung Sam Kim (2003) “Sound Radiation due to Tire Tread Vibration” <i>JSME International Journal, Vol 46 No2, p.8</i>
69.	A. Selamat <i>et al</i> (2000) “Wave reflections from duct terminations”, <i>J. Acoust. Soc. Am., Vol. 109, No. 4, April 2001</i>
70.	Abbas Khavaran and Milo Dahl (2012) “Acoustic Investigation of jet mixing noise in Dual stream nozzles”. <i>NASA report TM-217226, 17<sup>th</sup> Aeroacoustics Conference p.31</i>
71.	Brenda Henderson and Thomas Norum (2008) “Impact of azimuthally controlled fluidic chevrons on Noise”, <i>NASA Langley Research center, American institute of Aeroacoustics and Astronautics, p.13</i>
72.	Sungtae Kim <i>et al.</i> (2006) “Prediction method for tire air-pumping noise using a hybrid technique” <i>Journal Acoustical Society of America Vol 119, p.3799-3812</i>
73.	Wolfgang Probst (2009) “Accuracy and precision of prediction models for road noise”, <i>Euronoise congress, p.10</i>
74.	Panu Sainio and Ismo Halen, (2001) “Noise measurement trailer HUT NOTRA- Means for measuring noise during evolution of road surface” <i>Internoise congress, p.6</i>
75.	Varady, T <i>et al.</i> (1997) “Reverse engineering of geometric models-an introduction” <i>Computer-Aided Design, p.255–268</i>
76.	M. Hojer and N. A. Nilsson (2008) “A single wheel trailer for tyre/road noise measurements enabling both the CPX and pass-by methods”, <i>Euronoise Acoustics Conference, p.12</i>

77.	Ulf Sandberg <i>et al.</i> (1990) <i>Tyre/road noise on rubberized asphalt and cement concrete surfaces in Sweden,</i> VTI-meddelande, p.36
78.	G.J. Blockland and D.F De Graff, (2005) <i>Technical aspect of road traffic noise mitigation measures,</i> report no: M+P. MVM03.2.1 revision 2, p. 47
79.	D.F De Graff and G.J. Blockland (2007) <i>Public Consultation on modification of 2001/43/EC tyre/road noise,</i> report no: M+P.MVW.05.1.C1, p.31
80.	M.S Roovers, and G.J. Blockland (2002) <i>Literature study on the Rolling Noise of Truck Tyres,</i> report no: M+P.MVW.01.7.1 revision 1, p.p, 92
81.	M. Kuijpers (2001) <i>Tyre/road noise modelling: the road from a tyre's point-of-view</i> report no: M+P.MVW.01.8.1 revision: 2, p.63
82.	D.F. de Graaff, A.A. Peeters and H.M. Peeters (2005) <i>Tyre/road noise measurements of truck tyres</i> report no: M+P.DWW.03.7.1 revision: 2, p.126
83.	Ulf Sandber (2006) <i>Possibilities to Replace Outdoor Coast-by Tyre/Road Noise Measurements with Laboratory Drum Measurements,</i> European Com. 6th Framework, Milestone Report C.MS8, p.31
84.	Ard Kuijpers, and Gijsjan van Blokland (2006) <i>Simulation tool for Road/Tyre modelling The influence of road parameters on tyre/road noise,</i> European Com. 6th Framework priority 6 -SILENCE WPCD2 p.28
85.	Chalmers Continental (2006) <i>Improved rolling model and suggestions with design solutions for low noise tyres-Package WP C.1 Simulation and Evaluation.</i> European Commission 6th Framework priority 6- SILENCE WPC1, p.40

86.	Manfred Haider and Ulf Sandberg (2006) <i>Noise classification methods for urban road surfaces,</i> European Commission – DG Research – 6th Framework priority 6 SILENCE WPF4 Task F4.2, p.34
87.	E.U.Saemann (2007) <i>Vehicle-Tyre-Road Interaction,</i> Workshop 11 Silence project, p.28
88.	Manfred Haider (2007) <i>Improved systems for the maintenance of quieter surfaces,</i> Silence - Subproject F „Road Surfaces“ Work Package F3, p.20
89.	Oliver Ripke (2007) <i>New Production Technologies for Urban Low-Noise Road Surfaces,</i> Silence – Work Package F2 Federal Highway Research Institute (BAST) Germany, p.20
90.	Ulf Sandberg (2007) <i>New Production Technologies for Urban Low-Noise Road Surfaces,</i> Silence – Work Package F1, p.29
91.	E. Nijman (2007) <i>Road Vehicle Noise,</i> FPT/CRF SILENCE Seminar, p.31
92.	D. Hanson, R. James and C. Nesmith (2004) <i>Tire/Pavement noise study,</i> NCAT Report 04-02 National Center for Asphalt Technology, p.49
93.	Daniel H. Buffum and Donald R. Boldman (1987) <i>Unsteady Aerodynamics of an Oscillating Cascade in a Compressible Flow Field,</i> NASA Technical Memorandum 100219, p.22
94.	David C. Gibbs <i>et al.</i> (2004) <i>Quiet pavements - a scanning tour of denmark, the netherlands, france, italy and the united kingdom,</i> Federal highway administration international technology exchange program and American association of state highway and transportation officials, p.82

95.	P. Andren and A. Jolkin (2003) <i>Elastohydrodynamic aspects on the tyre-pavement contact at aquaplaning,</i> VTI Report 483A Swedish National Road & Transport Inst, p.46
96.	L.C. den Boer and A. Schrotten (2007) <i>Report - Traffic noise reduction in Europe,</i> Delft\ The Netherlands, p.70
97.	Hans G. Jonasson (2007) <i>Rolling Noise Emission of Tyres – A Market Survey,</i> Report Technical Research Inst. of Sweden, p.40
98.	I. Lopez (2010) <i>Influence of material damping on the prediction of road texture and tread pattern related rolling resistance,</i> Proceedings of ISMA, p.14
99.	Michael T. McNerney <i>et al.</i> (2000) <i>Comparative field measurements of tire/pavement noise of selected texas pavements,</i> Report No. FHWA/TX-7-2957-2, p.48
100.	L. Ingram <i>et al.</i> (2004) <i>Superior Materials, Advanced Test Methods and specifications in Europe,</i> Report FHWA-PL-04-007, p.140
101.	Thomas Cackler <i>et al.</i> (2006) <i>Evaluation of U.S. and European Concrete Pavement Noise Reduction Methods,</i> Federal Highway Administration (Project 15) Part 1, Task 2 - Concrete Pavement, p.101
102.	Ulf Sandberg (2003) “The road to quieter tires”, <i>journal VTI Tire technology international,</i> p.8
103.	James Sinnamon (1974) <i>Literature Survey of tire road experiments.</i> Highway safety research institute – Task 329180, p.153

104.	T. Bennet and D. Hanson (2004) <i>The Measurement of Pavement Noise on New Jersey Pavements Using the NCAT Noise Trailer - Demonstration Project</i> National Center for Asphalt Technology, final report, p.27
105.	Ron Blom (2004) <i>Report on tyre/road noise Generation mechanisms, influence of tyre parameters and experiment on belt resonances,</i> Technische Universiteit Eindhoven, p.43
106.	P. Morgan <i>et al.</i> (2006) <i>The Localisation, Quantification and Propagation of noise from a rolling tyre,</i> Transport Research Foundation, p.67
107.	W. van Keulen and Dr. ir. M . Duškov (2005) <i>Inventory study of basic knowledge on tyre/road noise,</i> Report DWW-2005-022 Delft, 2005, p.106
108.	G R Watts <i>et al.</i> (2004) <i>Tyre/road noise – assessment of the existing and proposed tyre noise limits,</i> TRL Limited, project report PPR 077, p.97
109.	Paul R Donovan and Dana Lodico, (2009) <i>Measuring tire-pavement noise at the source,</i> National cooperative highway research program No630, p. 47
110.	W. Schwanen and G.J. Blockland (2008) <i>Comparison of potential CPX tyres,</i> MB consulting engineers, Report No M+P.DWW07041, p.85
111.	Manuel Trevino and Terry Dossey (2006) <i>A research plan for measuring noise levels in highway pavements in Texas,</i> Technical report FHWA/TX-07/0-5185-1, p. 132
112.	Michael McNerney <i>et al.</i> (2000) <i>Comparative field measurements of tire/pavement noise of selected Texas pavements,</i> Technical report FHWA/TX-7-2957-2, p.48

113.	David Gibbs <i>et al.</i> (2005) <i>Quiet pavement systems in Europe</i> , Technical report FHWA/PL-05-011, p. 50
114.	P.A. Morgan <i>et al.</i> (2003) <i>Integrated assessment of noise reduction measures in the road transport section</i> , Technical report PRSE/652/03 ETD/FIF 20020051 European commission, p.116
115.	Karol Kowalski <i>et al.</i> (2010) <i>Identification of laboratory technique to optimize superpave HMA surface friction characteristics</i> , Technical report Purdue University, Iowa research board IHRB TR-450, p. 289
116.	Leo L. Beranek (1993) <i>Acoustics</i> , M.I.T Bolt Beranek and Newman Inc. Cambridge MA ISBN G-88318-494X first edition 1954, p.350
117.	Ioannis Zissimos (author of thesis) (2008) <i>Noise Control in Installations</i> , in Hellenic language, ISBN978-960-930626-3 1st edition, p.300
118.	<i>Directive 2001/43/ec of the european parliament and of the council of 27 June 2001</i> amending Council Directive 92/23/EEC relating to tyres for motor vehicles and their trailers and to their fitting, 2001, p.22
119.	<i>EU. Commision Enterprise Directorate General ENTR/F/5</i> (2003) Survey on motor vehivcle tyres & related aspects, prepared by TUV automotive, p.173
120.	Tyres for motor vehicles and their trailers and to their fitting, (2000) <i>Common position (ec) No 30/2000 adopted by the Council, with a view to adopting Directive 2000/EC of the European Parliament, relating to tyres for motor vehicles and their trailers and to their fitting</i> , p.25



121.	United nations - regulation no. 117 <i>Uniform provisions concerning the approval of tyres with regard to rolling sound emissions and to adhesion on wet surfaces</i> <i>E/ECE/TRANS/505, p.54</i>
122.	Regulation of the european parliament and of the council concerning type-approval requirements for the general safety of motor vehicles, (2008) <i>Commission of the European communities proposal COD100, p.34</i>
123.	Development of procedures for certifying noise testing equipment <i>project of the European Commission Silvia Project, Code - SILVIA-TUG-016-10-WP2-160104, p.117</i>
124.	Tyre/Road Noise (2006) <i>FEHRL Report - Study SI2.408210 Volume 1 : Final Report, p.119</i>
125.	Tyre/Road Noise (2006) <i>FEHRL Report - Study SI2.408210 Volume 2 : Appendices, p.155</i>
126.	Quieting Concrete Pavement Through Surface Texture Design and Modification (2006) <i>R&amp;T update ACPA, p.4</i>
127.	<i>Rules of Thumb on Pavement Noise</i> (2006) <i>R&amp;T update ACPA, p.8</i>
128.	Road Traffic Noise The Road Sector's Perspective (2004) <i>The European Union Road Federation, Position paper, p.6</i>
129.	Fact sheet tyre noise - Limit values proposals and measurements (2008) <i>The Netherlands Version 09; updated with IMCO proposal, p.22</i>
130.	Datasheet- noise of C2 and C3 tyres (2008) p.8
131.	Tyre data consumer tests (2008) VROM, p.16
132.	Tyre labelling - An EU Label to promote safe, fuel efficient and quiet tyres (2008) <i>COM(2008)0779 – COD 2008/0221 - European federation for Transport &amp; Environment, 2009, p.3</i>

133.	Tyre noise simulation & tread design - PC software <i>Quantum Age Tech Solutions Ltd-Silentroll- www.qagetech.com</i>
134.	Anechoic Room Tyres test International - PC software Akustec – Munster – Germany
135.	<i>The process of T-mode in tire development</i> (2002) <i>Technical Service Department Japan TOYO TIRE TALK No.02-015 (TTT-136), p.4</i>
136.	TIRE/ROAD NOISE - Part (1) Prologue (2003) <i>Technical Service Department Japan TOYO TIRE TALK No.03 - 016 (TTT - 154), p.3</i>
137.	Noise reduction in Tyres. (White Noise) (2004) <i>Technical Service Department Japan TOYO TIRE TALK No.05-003 (TTT-171), p.2</i>
138.	Impact assessment study on possible energy labelling of tyres, (2006) <i>Annexes to the European commission-General transport and energy, contract, TREN/D3/375, p. 96</i>
139.	U.S. patent number: 2,808,867 Date of patent: Oct. 8 1957 <i>Noiseless tire tread construction</i>
140.	U.S. patent number: 4,727,501 Date of patent: Feb.23 1988 <i>Method of stimulating tire tread noise and apparatus</i>
141.	U.S. patent number: 5,295,087 Date of patent: Mar. 15 1994 <i>Method of stimulating tire tread noise and stimulator therefore</i>

142.	U.S. patent number: 5,314,551 Date of patent: May 24 1994 <i>Tire pitch sequencing for reduced tire tread noise</i>
143.	U.S. patent number: 5,371,685 Date of patent: Dec. 6 1994 <i>Low noise sequence of tread elements for vehicle tires and related generation method</i>
144.	U.S. patent number:5,394,916 Date of patent: Mar. 7 1995 <i>Multiple tread geometries for reduced tire tread noise</i>
145.	U.S. patent number: 5,746,848 Date of patent: May 5 1998 <i>Profiled vehicle tire and method for dimensioning the optimum phase offset between adjacent tread portions</i>
146.	U.S. patent number: 5,759,311 Date of patent: Jun 2 1998 <i>Low noise tire tread</i>
147.	U.S. patent number: 5,769,990 Date of patent: Jun. 23 1998 <i>Method of making tire with tire tread pitch bands</i>
148.	U.S. patent number: 5,865,921 Date of patent: Feb. 2 1999 <i>Tire noise treatment</i>
149.	U.S. patent number: 6,112,167 Date of patent: Aug.29 2000 <i>Tire tread noise treatment</i>
150.	U.S. patent number: US 6,415,835 B1 Date of patent: Jul. 9 2002 <i>Pneumatic tire tread having groove with peaks and valleys</i>
151.	BS EN ISO 11819-1:2001 Acoustics- Measurement of the influence of road surfaces on traffic noise- Part1 Statistical Pass-By method

152.	DRAFT BS ISO 11819-2 “Acoustics – Method for measuring the influence of road surfaces on traffic noise – Part 2: Close Proximity Method” - 03 Jan-2013
153.	BS ISO 10844:1994 & 2011 Acoustics- Specification of test trucks for the purpose of measuring noise emitted by road vehicles
154.	ISO 13472-1 /2002 Acoustics — Measurement of sound absorption properties of road surfaces <i>insitu</i> Part 1: Extended surface method
155.	Draft BS ISO 13472-2 Acoustics Measurement of sound absorption properties of road surfaces in situ Part 2: Spot method for reflective surfaces 22 March 2007
156.	EN 13036-1, Road and airfield surface characteristics — Test methods — Part 1: Measurement of pavement surface macrotexture depth using a volumetric patch technique
157.	CEN/TS 13036-2, Road and airfield surface characteristics — Test methods — Part 2: Assessment of the skid resistance of a road pavement surface by the use of dynamic measuring systems
158.	EN 13036-3, Road and airfield surface characteristics — Test methods — Part 3: Measurement of pavement surface horizontal drainability
159.	EN 13036-4, Road and airfield surface characteristics — Test methods — Part 4: Method for measurement of slip/skid resistance of a surface — The pendulum test

160.	prEN 13036-5, Road and airfield surface characteristics — Test methods — Part 5: Determination of longitudinal unevenness indices
161.	EN 13036-6, Road and airfield surface characteristics — Test methods — Part 6: Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges
162.	EN 13036-7, Road and airfield surface characteristics — Test methods — Part 7: Irregularity measurement of pavement courses: the straightedge test
163.	EN 13036-8, Road and airfield surface characteristics — Test methods — Part 8: Determination of transverse unevenness indices
164.	Draft ISO 3747 Acoustics- Determination of sound power levels and sound energy levels of noise sources using sound pressure- Engineering/survey methods for use in situ in a reverberant environment Date: 25 September 2007
165.	BS ISO 3911:2004 Wheels and rims for pneumatic tyres - Vocabulary designation and marking
166.	BS ISO 4000-1:2007 Passenger car tyres and rims- Part 1: tyres
167.	BS ISO 4000-2:2007 Passenger car tyres and rims- Part 2: Rims
168.	BS ISO 5130:2007 Acoustics- Measurements of sound pressure level emitted by stationary road vehicles
169.	BS ISO TR 5168:1998 Measurement of fluid flow- Evaluation of uncertainties

170.	BS ISO 8349:2002 Road vehicles- Measurement of road surface friction
171.	BS ISO 9112:2008 Truck and bus tyres- Methods of measuring tyre rolling circumference – Loaded new tyres
172.	EN 12697-16 July 2004 Bituminous mixtures - Test methods for hot mix asphalt - Part16: Abrasion by studded tyres
173.	BS EN 13108-7:2006 Bituminous mixtures- Material specifications- Part 7 : Porous Asphalt
174.	BS EN ISO 13473-1:2004 Characterization of pavement texture by use of surface profiles. Part 1: Determination of mean profile depth
175.	BS ISO 13473-2:2002 Characterization of pavement texture by use of surface profiles. Part 2: Terminology and basic requirements related to pavement texture profile analysis
176.	BS ISO 13473-3:2002 Characterization of pavement texture by use of surface profiles. Part 3: Specification and classification of profilometers
177.	DD ISO/TS 13473-4:2008 Characterization of pavement texture by use of surface profiles. Part 4: Spectral analysis of surface profiles
178.	Draft ISO 15086-3 4Dec.2006 Hydraulic fluid power - Determination of the fluid-borne noise characteristics of compressors and systems. Part 3: Measurement of hydraulic impedance

179.	Draft BS ISO 17089-1 4 Nov. 2008 Measurement of fluid flow in closed conduits - Ultrasonic meters for gas Part 1: Meters for custody transfer and allocation measurements
180.	BS ISO 18164:2005 Passenger car, truck, bus and motorcycle tyres — Methods of measuring rolling resistance
181.	BS ISO 19003:2006 Rubber and rubber products — Guidance on the application of statistics to physical testing
182.	Draft BS ISO 28580 3 June 2008 Passenger car, truck and bus tyres - Methods of measuring rolling resistance – Single point test and correlation of measurement results
183.	CEN/TS 15901-1, Road and airfield surface characteristics — Part 1: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal fixed slip ratio (LFCS): RoadSTAR
184.	CEN/TS 15901-2, Road and airfield surface characteristics — Part 2: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal controlled slip (LFCRNL): ROAR (Road Analyser and Recorder of Norsemeter)
185.	CEN/TS 15901-3, Road and airfield surface characteristics — Part 3: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal controlled slip (LFCA): The ADHERA
186.	CEN/TS 15901-4, Road and airfield surface characteristics — Part 4: Procedure for determining the skid resistance of pavements using a device with longitudinal controlled slip (LFCT): Tatra Runway Tester (TRT)
187.	CEN/TS 15901-5, Road and airfield surface characteristics — Part 5: Procedure for determining the skid resistance of a

	pavement surface using a device with longitudinal controlled slip (LFCRDK): ROAR (Road Analyser and Recorder of Norsemeter)
188.	CEN/TS 15901-6, Road and airfield surface characteristics – Part 6: Procedure for determining the skid resistance of a pavement surface by measurement of the sideway force coefficient (SFCS): SCRIM®
189.	CEN/TS 15901-7, Road and airfield surface characteristics – Part 7: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal fixed slip ratio (LFCG): the GripTester®
190.	CEN/TS 15901-8, Road and airfield surface characteristics – Part 8: Procedure for determining the skid resistance of a pavement surface by measurement of the sideway-force coefficient (SFCD): SKM
191.	CEN/TS 15901-9, Road and airfield surface characteristics – Part 9: Procedure for determining the skid resistance of a pavement surface by measurement of the longitudinal friction coefficient (LFCD): DWWNL skid resistance trailer
192.	<a href="http://www.highways.gov.uk/aboutus/10895.htm">http://www.highways.gov.uk/aboutus/10895.htm</a> (accessed 2009)
193.	<a href="http://international.fhwa.dot.gov/quiet_pav/chapter_two_d.cfm">http://international.fhwa.dot.gov/quiet_pav/chapter_two_d.cfm</a> (accessed 2009)
194.	<a href="http://www.cedex.es/ingles/presentacion/datos/instalaciones/cet_re.html">http://www.cedex.es/ingles/presentacion/datos/instalaciones/cet_re.html</a> (accessed 2009)
195.	<a href="http://www.mp.nl/leaflets/leaflets.php?langID=2&amp;page=CPX">http://www.mp.nl/leaflets/leaflets.php?langID=2&amp;page=CPX</a> (accessed 2009)
196.	<a href="http://www.silentroads.nl/index.php?section=research&amp;subject=robustcpx">http://www.silentroads.nl/index.php?section=research&amp;subject=robustcpx</a> (accessed 2009)



197.	<a href="http://www.silentroads.nl/index.php?section=research&amp;subject=cpx_validation&amp;page=cpxval_participants">http://www.silentroads.nl/index.php?section=research&amp;subject=cpx_validation&amp;page=cpxval_participants</a> (accessed 2009)
198.	<a href="http://www.highfrictionroads.com/index.php?q=node/18">http://www.highfrictionroads.com/index.php?q=node/18</a> (accessed 2009)
199.	<a href="http://enr.construction.com/news/transportation/archives/040202b.asp">http://enr.construction.com/news/transportation/archives/040202b.asp</a> (accessed 2009)
200.	<a href="http://www.fhwa.dot.gov/publications/publicroads/10julaug/01.cfm">http://www.fhwa.dot.gov/publications/publicroads/10julaug/01.cfm</a> (accessed 2009)
201.	<a href="http://tireguides.com/TireTips/TireDocument">http://tireguides.com/TireTips/TireDocument</a> (accessed 2009)
202.	<a href="http://www.sensorprod.com">http://www.sensorprod.com</a> (accessed 2009)
203.	<a href="http://www.vibrationandshock.com/glossary.htm">http://www.vibrationandshock.com/glossary.htm</a> (accessed 2008)
204.	<a href="http://maps.google.com">http://maps.google.com</a> (accessed 2011)

End of thesis