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Call 2018 Noise and Nuisance:

STEER Final Report

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CEDR Contractor Report 2022-07

STEER - STrenghtening the Effect of quieter tyres on European Roads

by

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PREFACE

Expert knowledge and practical knowledge meet for the better! The STEER project is based on the knowledge and experience of earlier projects; where three of the five partners were heavily involved in the NordTyre programme as well as in bilateral and national projects dealing with relevant subjects. Also, the other partners have vast experience on the subject. One of the partners provided substantial input to the Commission when the tyre noise labelling regulation was worked out. We decided to complement this strong scientific team with practical knowledge by incorporating a European tyre company as a full partner. This is absolutely crucial for such a project, as those who deal with the issues on a daily basis and also with economic and legal consequences may look at things quite differently than academic researchers. This together with the vast experience of the other partners make the STEER Consortium extremely strong and ensures that the solutions and recommendations worked out in this project lead to real improvements. This is with the overarching aim of strengthening the effects of quieter tyres on European roads.

The cooperation between all partners has worked excellently. In a few cases there have been different opinions on how to evaluate experimental data and proposals, always discussed respectfully, and in this final report all authors have reached a consensus. The participation by Nokian Tyres has greatly enhanced the work by sharing the experience and expert knowledge in the project team in an always friendly and open way.

Nokian Tyres has participated in the project STEER to give insight of tyre industry, tyre design and the complexity of tyre properties, also those not visible in current EU label. The views and opinions expressed in the final report are those of the authors and do not necessarily reflect the position of Nokian Tyres. It is not allowed to associate Nokian Tyres to this report and conclusions in it.

It was the intention of the STEER Consortium to conduct own measurement campaigns to undertake a targeted investigation into two important uncertainty sources of the current tyre labelling system: firstly, the effect of "tyre lines" in which not all tyres are tested, and, secondly, the effect of the ISO test track. This work was originally included in the project application to CEDR; unfortunately, then exceeding the budget that CEDR had available for the project. However, the STEER Consortium considered that these parts are absolutely crucial for the project, which also appeared to be the case when the project was finalized. Therefore, Consortium members applied for special projects dealing with these issues from the Swedish Transport Administration (STA) and the Polish-Norwegian research programme. We are grateful for this additional financial support and we are pleased to have received the assurance that the results may be used to improve the conclusions of STEER in this final report.

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Documents produced within the project

WP / Deliverable	Document Title
WP2, Task 2.1	Report of the background information and existing data
WP2, Task 2.2	Report of the a priori uncertainty analysis of the tyre labelling procedure
WP3, Task 3.1	Task Report on Temperature effects on tyre/road noise measurements
WP3, Deliverable 3 Reproducibility	**Improving reproducibility of tyre/road noise measurements on ISO test tracks**
WP4/Task 4.1	The influence of tyre inflation pressure and load on noise levels
WP4/Task 4.3.1	Report on the representativity of the ISO test track compared to common European road pavements
WP4, Deliverable 4, Representativity	**Recommendations for improved representativity of tyre labelling**
WP5, Task 5.4	Report on short term benefits
WP5, Task 5.5	Task 5.5 Constraints/impediments for tyre manufacturers to produce quieter tyres
WP5, Deliverable 5, Analysis and Scenarios	**Evaluation of strategies enhancing proliferation of quieter tyres and its implications for NRAs**
WP6: Final report	**STEER: Final report**

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Executive summary

Why are quieter tyres important?

Noise pollution is seen as one of the most important environmental causes of health problems in the EU as it can lead to annoyance, stress responses, sleep disturbances, poor mental health and well-being, impaired cognitive function in children, and negative effects on cardiovascular and metabolic systems. Low-noise tyres and road surfaces are two important solutions that have the potential to reduce noise levels on roads at the source and thus improve the quality of life for near-by residents. Many European countries have therefore, with considerable success, invested in the construction of low-noise road surfaces as an effective noise abatement measure for new and existing road infrastructures. From an economic and a health point of view, it is of utmost importance that the investments in noise abatement measures are not cancelled out by contrary developments on the vehicle side.

Not only road surfaces need to be subject of noise abatement; also tyres need to be improved for lowering the noise emission. One such measure is to encourage the use of low-noise tyres by means of labelling them with their noise level. However, in the past years it has been demonstrated in several studies that the labelling system has a number of problems, for example that the noise labels in general do not correspond well with noise levels measured on market tyres by independent organizations. To improve the noise part of the labelling system, therefore, CEDR sponsored this project named STEER (Strengthening The Effect of quieter tyres on European Roads).

Why have we done it?

The main purpose of STEER is to provide the basis for decision makers, such as EU institutions, national governments and NRA:s, allowing them to develop new guidelines and policies to enhance the impact of quieter tyres on European roads. The focus is thereby laid on the development of practical solutions that, firstly, improve the noise labelling for tyres with regard to its reproducibility and representativity, and, secondly, on measures that can be implemented by EU and national regulating bodies to create impact on European roads.

What we have done and how we did it

Over the past decades, extensive work has been carried out by various parties on the subject of quieter tyres. The STEER project builds upon a thorough evaluation of existing data to identify where the main weaknesses of the system lie and how one can reduce these weaknesses by proposals that can be implemented in new standards, guidelines and policies. But STEER did not have resources to conduct own measurements. Fortunately, two related projects allowed the STEER consortium to conduct supplementing measurement campaigns to undertake targeted investigations into two important uncertainty sources of the current tyre labelling system: firstly, the effect of measuring noise of only one or a few tyres in each tyre line and, secondly, the effect of variation in ISO test track properties. This work was originally included in the project application to CEDR but had to be removed from the project as CEDR required cuts in the budget. Therefore, Consortium members applied for special projects dealing with these issues from the Swedish Transport Administration (STA) and the Polish-Norwegian research programme ELANORE.

Conclusions

As intended, STEER was able to identify a number of serious flaws in the noise labelling procedure and suggested concrete improvements. The following section presents a list of the most important findings of STEER, separated into three main topics.

Regarding the current noise label:

- **The European tyre label** is an **important tool for consumers** to find their way through the broad field of tyres on the market and should unquestionably be continued but optimised. Many other countries have produced own tyre labels, essentially based on the European one, but not all of them include the noise parameter. STEER believes that the tyre label has the general effect of encouraging the use of higher quality tyres which is a win-win situation for society in terms of both safety and environment.
- **Noise is currently not a decisive purchase criterion for consumers**. More important is the purchase price, which has virtually no connection to the noise label value at present. Consumers and tyre dealers are not enough aware of the noise label and the advantages of acquiring quieter tyres.
- The STEER uncertainty analysis revealed a **standard uncertainty of between 1.4 and 2.0 dB** for the noise label values of both passenger car tyres (C1 tyres) and light commercial vehicle tyres (C2 tyres) and identified several issues that clearly showed why the **labelling procedure in its current form is far from optimal.** The largest uncertainty contributions were determined for the test track and the test tyres, shortly followed by the test vehicle and the measurement conditions.
- **Measurement uncertainty can be halved** if the improvements proposed by STEER are implemented now (see recommendations). This increases the value of the tyre labelling system substantially.

Regarding the impact of quieter tyres on European roads:

- **Efficiency for traffic noise reduction on European roads:** The good news from STEER is that the **potential of quieter tyres can be almost fully achieved on large parts of the European road network**. Only on roads with a rough-textured surface (MPD > 1.2 mm, as may be the case for asphalts with a maximum chipping size of 14 mm or larger and some cement concrete surfaces), the potential impact of quieter tyres of current design is not fully achieved.
- The **combination** of low noise tyres and low noise pavements **is the best solution.**

What to expect from quieter tyres in the future?

- **Potential of quieter tyres:** Quiet tyres could make traffic on European roads **up to 3 dB** quieter in the future, but only if their market share can be increased with suitable measures. However, STEER believes that there are significant possibilities to increase their market shares (see recommendations).

- **If no further measures are taken** at this stage to increase the market share of quiet tyres, their potential can hardly be further exploited. Nevertheless, there may be a marginal noise reduction in urban areas due to the shift of vehicles from ICE to electric drives which increases the effect of tyre/road noise reductions when the power unit noise contribution is substantially less.
- **Financial benefits:** In many European countries, **considerable benefits can be expected from the avoidance of external costs**. For example, in countries such as the Netherlands, an annual benefit of about 25 million Euros could be generated if measures were taken to promote quiet tyres.

What are the most promising scenarios to increase the market share of quieter tyres?

The tyre label provides a useful information tool that allows buyers to select tyres based on their performance in three relevant user aspects. The specific potential of the noise label could be used much more in the future to make European roads quieter. The scenario calculations in STEER showed that the following investigated scenarios, which aimed at increasing the market share of quiet tyres, had a significant impact:

- **Industry Agreement scenario:** Industry agreement between tyre sellers, implying that the average of the sum of all tyres sold shall not exceed a certain noise limit (similar to Regulation (EU) 2019/63 on maximum CO_2 emissions for passenger cars).
- **Consumer Incentives scenario:** This involves a change in consumer behaviour. The aim was to get the consumer to buy tyres of noise class A. Incentives (such as VAT exemption) are to be created for the purchase of these tyres.

Substantial noise reductions of up to 1.5 dB in 2030 and up to 2.5 dB in 2040 could be achieved by quiet tyres if their market share were promoted by the measures of "Industry agreement" or "Consumer incentives". The two following measures will produce a similar noise reduction, however, only on a local scale:

- **Additional Incentives scenario:** This involves that publicly controlled vehicle owners buy tyres of noise class A. This may be in the form of public procurement or admissions with regard to public vehicles or for transportation services which are under the control of public authorities. Our analysis has shown that such tyres are available for all tyre types, load and speed classes.
- **Restrictions scenario:** By using RFID technology one may detect tyres in traffic which are illegal in the season (when and where winter tyres are required) or in extra sensitive environmental areas (such as areas prohibiting the use of studded tyres).

Constraints of the project

Within this project it was not possible to carry out large measurement campaigns in which the entirety of tyres would be investigated in depth. Therefore, existing data had to be used as the main source for this project. As the previous studies mainly focused on passenger cars, the focus of this project was also on the passenger car tyres.

The proposals can be implemented quickly

Many of the proposed measures have already been outlined in relative detail (see section 9 *Overall conclusions and recommendations* with references to the corresponding sections in the report). With the involvement of technical expertise, the measures can be concretised and quickly implemented. For some of the measures, further research is required in order to arrive at a concrete implementation plan. The STEER consortium is happy to provide support in this regard.

The authors' concluding assessment

The STEER final report provides the essential basis for improving the tyre label. An action to improve the tyre noise label is not only necessary, but also fundamental to better exploit the great potential of quieter tyres in the future. If the tyre noise label is improved and the market share of quieter tyres can be increased, area-wide reductions in road traffic noise emissions of up to 3 dB are possible. The sooner the measures recommended by STEER can be implemented (individually or in combination), the greater the impact quiet tyres will have on European roads. Many of the EU's efforts on vehicle and tyre noise regulations are already moving in the right direction. Given the investments already made in low-noise road surfaces by national governments and given the fast-moving trend towards electrification of the vehicle fleet, it would be not only a pity but also costly to disregard the great potential of quieter tyres. It will be worthwhile to invest in measures, as the benefits of quieter tyres are likely to outperform their costs.

Recommendations

STEER recommends a number of measures to increase the efficiency of the tyre label, which are presented below, separated for four *target groups:*

EU Commission *(make additional requirements in 2020/740/EC)*	**Urgent need for improvements of the current noise labelling procedure** The STEER recommendations focus on measures that can be implemented by the European Commission as complementary requirements of the Directive 2020/740/EC which sets the requirements of the noise labelling procedure. The measures related to the measurement procedure are included in ECE Regulation 117 and should therefore either be implemented by the GRPB or be implemented as a special supplement to the 2020/740/EC. The measures are relatively simple and inexpensive to implement and would mean a major benefit in terms of improved reproducibility and representativity of the current labelling procedure. By doing so, the standard uncertainty can be halved from 1.95 to 0.93 dB. It is proposed to implement the following improvements to the current labelling procedure as soon as possible: ▪ Implement a **Reference Tyre Calibration procedure** as outlined in this report to compensate for the acoustic variability of ISO test tracks. ▪ Make it mandatory that **all tyre variants within a tyre line are labelled based on individual testing** and not only by testing one or a few of the tyres within a line. ▪ To simplify the testing requirements, STEER suggests **two options** where labelling is based on determining **differences between noise levels within a tyre line** in relation to one or more tyres measured in the current way. ▪ Such differences can be determined either by measurements with a laboratory drum method, or by simulation or modelling tyre noise differences, as suggested in this report. ▪ Implement **stricter requirements for test vehicles** (focus on ground clearance and wheelbase) to limit the vehicle influence on the label value as proposed in this report. ▪ **Improve the temperature correction procedure** according to the solution offered in this report. ▪ The noise label should have **three legal classes**, as it had before 2021. However, each class may have a range of 2 dB instead of 3. The labelled noise level shall still be stated, in addition to the class.

EU Commission *(invest in research)*	**Develop a new vision for an indoor labelling procedure** The improvements to the current labelling procedure are urgently needed to bring its standard uncertainty to acceptable levels. A residual uncertainty remains, however, which is related to the basic features of today's labelling procedure. In the long term, the focus should be on the further development of the noise labelling procedure into a more controllable indoor procedure with measurements on laboratory drums. The vision of STEER is outlined in this report. ▪ **Initiate development of a new indoor noise labelling method** to replace existing labelling procedure to further reduce uncertainty and to reduce workload for testing in the future. To have such a method implementable within a decade or so, one should initiate work soon.
NRA:s	**Choose the optimal standard pavement for your road network** Various existing studies, especially from Scandinavia, have shown that not all road surfaces have the same potential for reducing traffic noise due to quieter tyres. As STEER has demonstrated, the road surface macrotexture is responsible for this, since tyres are optimized for very low macrotextures. The higher the macrotexture is, the lower the impact potential of present quieter tyres is. ▪ **Consider choosing "smooth" to "medium" textured road surfaces** as a standard wearing course on the road network in order to benefit from quieter tyres and its future potential. Simultaneously, it will reduce rolling resistance. ▪ **Avoid "rough-textured" surfaces** (asphalts or surface dressings with aggregate sizes ≥14 mm or cement concrete with rough surface texture) on roads with high noise exposure

<table>
<tr>
<td>*NRA:s, environmental authorities, procurement authorities, national and local governments*</td>
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Raise awareness and inform the consumer about the benefits; use RFID systems

The tyre label constitutes an important information tool, helping consumers to find their way through the broad field of tyres on the market. However, it is important to ensure that the importance of the various parameters is actually taken into account by the consumer. The literature has shown that noise, for example, is not a decisive purchase criterion to many.

- **Raise awareness through information campaigns:** Labelling should be used as an information tool to support consumer decision-making. Inform consumers about available products and the benefits of buying quieter tyres
- **Raise awareness of the noise problem among the general public:** Encourage consumers to buy a quieter product.
- **When procuring road vehicles, consider requiring low-noise tyres:** This may be implemented by governmental authorities on the national, regional and even local levels, when they procure vehicles or when they have an influence over certain transportation services.
- **Use RFID systems to track vehicles with certain tyres:** Examples of this type of implementation is to give vehicles with quieter tyres certain favours when passing tolls, when parking or when accessing noise-sensitive areas. Also, non-desirable tyres may be detected in areas where such tyres are forbidden (studded tyres) or in seasons when summer tyres are not allowed.

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EU Commission, NRA:s, National, regional and local governments	**Do not miss the opportunity to implement the measures** Specific recommendations: ▪ **Further investigate, specify, and test the measures** of scenarios “Industry agreement” and “Consumer incentives” with regard to their practical feasibility and prepare implementation ▪ **Combine the scenarios with the mentioned additional incentives**, which will increase noise reduction. Especially one should not underestimate the effect that procurement policies may have on increasing the demand for quieter tyres, since vehicle fleets and transportation services controlled by public authorities are substantial. Furthermore, a showcase effect is triggered. ▪ **Benefits will likely offset the costs:** It is strongly recommended that countries with a high population density and many people exposed by noise invest in measures to promote quiet tyres, as the benefits will likely offset the costs in these states ▪ **Act now to benefit from market trends:** Due to the rapidly developing trend towards electric vehicles, tyre/road noise will become more and more dominant and therefore investments made today in the tyre noise label will pay off much more in the near future. The earlier the measures are taken, the greater effects can be expected. ▪ **Act now to avoid jeopardising the benefits of the new EU regulation** on vehicle noise emissions which is expected to come into force in 2024/2026[1]. The regulation will ensure quieter vehicles with quieter original equipment tyres from that date. The desired noise reduction on European roads can only be achieved if the industry's successes are not cancelled out by contrary trends in the secondary tyre market (when the vehicle is fitted with replacement summer or winter tyres by the consumer).

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[1] Regulation EU No 540/2014, [EU, 2014]

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1 Introduction

Noise pollution is seen as one of the most important environmental causes of health problems in the EU as it can lead to annoyance, stress responses, sleep disturbances, poor mental health and well-being, impaired cognitive function in children, and negative effects on cardiovascular and metabolic systems. Environmental noise causes approximately 16 600 cases of premature death in Europe each year, with nearly 32 million adults estimated to suffer from annoyance and over 13 million adults estimated to suffer from sleep disturbance [Blanes et al., 2017].

Low-noise tyres and road surfaces are two important solutions that have the potential to reduce noise levels on roads at the source and thus improve the quality of life for residents. Many European countries have therefore invested with considerable success in the construction of low-noise road surfaces as an effective noise abatement measure for new and existing road infrastructures.

From an economic and a health point of view, it is of utmost importance that the investments in noise abatement measures are not cancelled out by contrary developments on the vehicle side. Conversely, quiet tyres could significantly reduce noise emissions from roads and thus save on noise abatement costs elsewhere. Ideally, quiet tyres and low-noise road surfaces combined could lead to strong noise reductions, significantly improving the quality of life along European roads.

In order to simultaneously achieve a noise-reducing effect on the vehicle side, the EU introduced a tyre label for external noise just over a decade ago [EU, 2009], which allows consumers to select a tyre based on its noise emission in addition to two other important properties: wet grip and rolling resistance. The impact of the EU noise label for tyres on road traffic noise emissions has not yet been evaluated quantitively, but it is clear that it has substantially raised the interest in this environmental property of tyres.

To ensure that the noise reduction potential of low-noise tyres is fully realised, the following objectives should be met:

- (i) to understand the interaction between tyres and different road surfaces;
- (ii) to improve the tyre labelling system to better reflect this interaction, and;
- (iii) to identify the benefits that could be achieved by measures increasing the market share of low-noise tyres on European roads.

1.1 Project definition

The main objective of project STEER (Strengthening The Effect of quieter tyres on European Roads) is to provide the basis for decision makers allowing them to develop new guidelines and policies to enhance the impact of quieter tyres on European roads. The focus is thereby laid on the development of practical solutions that, firstly, improve the noise labelling for tyres with regard to its reproducibility and representativity, and, secondly, on measures that can be implemented by EU and national regulating bodies to create impact on European roads. Over the past decades, extensive work has been carried out by various parties on the subject of quieter tyres. The project STEER builds upon an evaluation of this existing data while ensuring that the valuable resources can be used for targeted work needed to develop solutions that can be used directly to implement new standards, guidelines and policies, namely:

1. STEER reviews the current labelling procedure and performs an uncertainty analysis from which the most important gaps that need improvement are identified.
2. STEER provides clear foundations and concrete recommendations for an improved noise labelling system for tyres.
3. STEER assesses the representativity of the tyre labelling for EU roads and provides recommendations for enhanced benefits.
4. STEER provides and evaluates a canvas of measures for EU and national regulating bodies to enhance the proliferations of quieter tyres and increase their impact on EU roads.
5. STEER ensures through its key persons that the findings are generalised and prepared in a way, that they directly address the most important target groups and thereby facilitate the implementation of the project’s main results.

No tyre noise labelling project would be complete without including analyses of how to optimize the many parameters and requirements that tyres on the market must meet without compromising some basic performance. Under the direction of our tyre partner, such analyses are carried out to find out how to reduce noise without compromising safety and rolling resistance. Besides a profound analysis of the available products on the tyre market is undertaken.

The following Figure 1-1 outlines the different work packages within STEER.

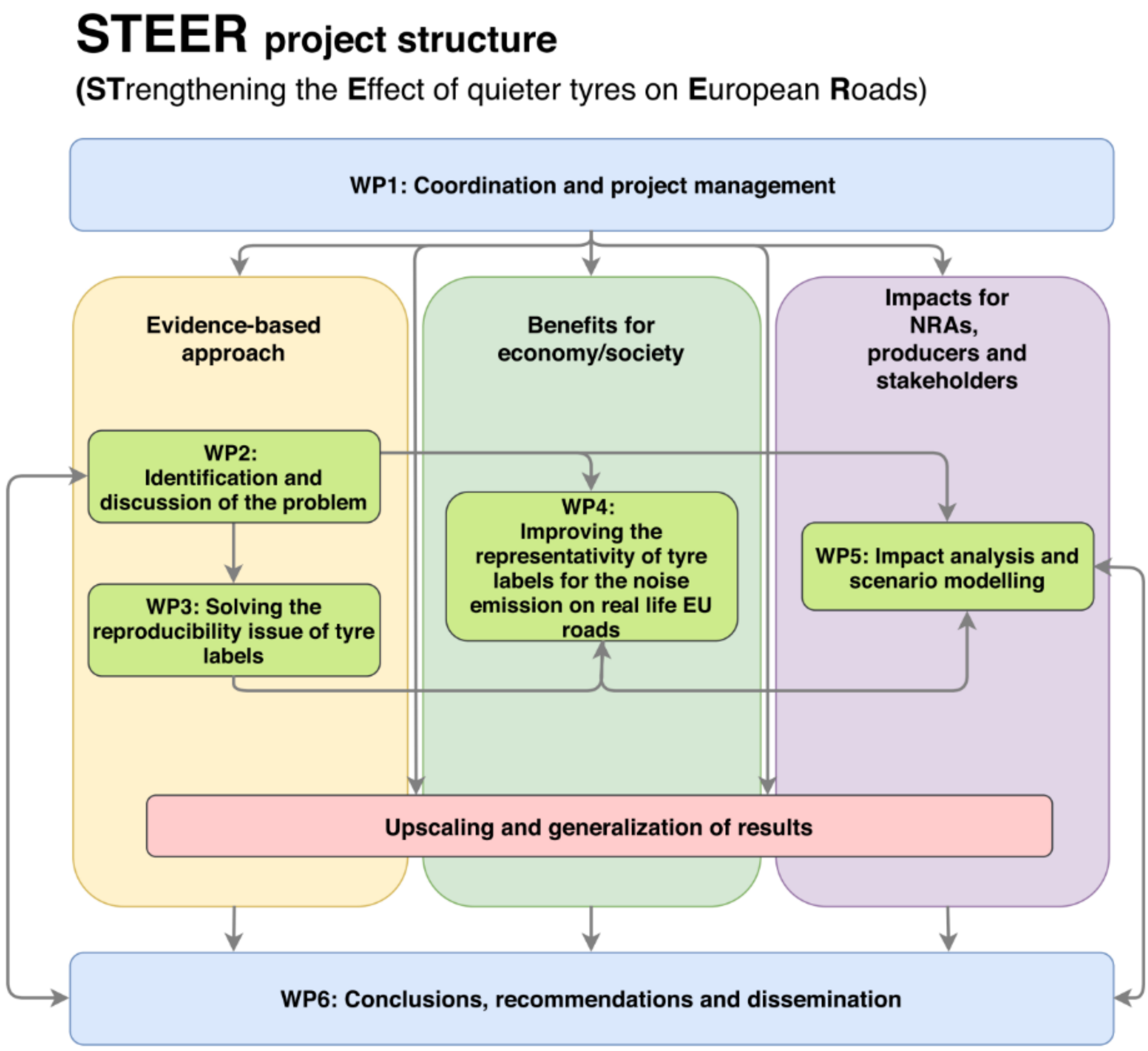

Figure 1-1: STEER project structure.

In the project STEER, the main focus was laid on passenger car tyres (C1 tyres), even though the contribution to noise from truck tyres should not be underestimated either. In this project, previous information has been incorporated, and it was already shown in [Kragh et al., 2013], that the labelled values vs. the measured values of truck tyres are better comparable. Accordingly, it was concluded, that the truck tyres are generally not very sensitive to surface texture. Consequently, the potential for optimization in terms of representativeness is smaller. Likewise, there are significantly fewer different tyre variants (speed index, load index, dimensions) for truck tyres than for passenger car tyres. Therefore, the field of the entire tyre range for passenger cars is much larger and so are the possible differences.

Within this study it was not possible to carry out large measurement campaigns in which the entirety of tyres would have been investigated in depth. Therefore, existing data had to be used as the main source for this project. As the previous studies mainly focused on passenger cars, the focus of this project was also on the passenger cars.

1.2 Consumer labels for tyres before the EU label

A Nordic Swan labelling system was organised under the Nordic Council of Ministers already in the 1990's, which established eco-labelling on a variety of products in all the five Nordic countries (Sweden, Denmark, Norway, Finland and Iceland), see [Sandberg, 2008]. After preparation work in the 1990's, tyres were added in 2002 as a product for which the label could be obtained. The product group included new and retreaded tyres of passenger vehicles and bus and truck vehicles for road use during summer and/or winter.

A few years later, the German Blue Angel system added tyres to their labelling system. But contrary to the Nordic Swan which included several tyres, the Blue Angel got only one tyre labelled and it was soon redrawn by the tyre company itself. The two labels are shown in Figure 1-2.

These two forerunners inspired work to prepare for introducing an international tyre labelling system.

Figure 1-2: The Nordic Swan environmental label in Swedish version (left) and the German Blue Angel label (right).

1.3 EU Tyre label

In the first decade of this century, an interest in labelling tyres with their rolling resistance properties evolved. The first official initiative was taken in 2003 by Russia, whose delegation at the ECE Working Party on Brakes and Running Gear (GRRF) proposed that limits on rolling resistance as well as a marking on tyres should be introduced. This was picked-up by the Commission which looked at a consumer label for C1 and C2 tyre classes as a strategy to make a significant contribution to the CO_2 reduction [European Commission, 2006]. Simultaneously, it was suggested in GRRF that if tyres are optimized for low rolling resistance there would be a risk of sacrificing wet friction, so the idea expanded to label tyres with both rolling resistance and “wet grip”. Therefore, in the beginning of the considerations, noise was not included as a parameter that should be part of such a consumer label.

However, at the time, FEHRL (the Forum of European National Highway Research Laboratories) was tasked by the Commission to suggest how tyre/road noise could be reduced in the future. In the final report for that project by FEHRL (in which VTI was a partner), it was proposed that a consumer label for noise should be included in a label system for rolling resistance and wet grip [FEHRL, 2006]. To strengthen this idea (which was not popular among the tyre industries), the European Federation for Transport and Environment (T&E) started to lobby for it and ordered a background study to be made by VTI. This report was published by

T&E in 2008 [Sandberg, 2008]. It received significant interest by the Commission, which at the end suggested that rolling resistance ("energy"), wet grip and noise should be included in a new Consumer Label for Tyres. This resulted in an EU regulation published in 2009 (Regulation (EC) No 1222/2009) [EU, 2009] and implemented from 2012. The mandatory label looked as illustrated in Figure 1-3.

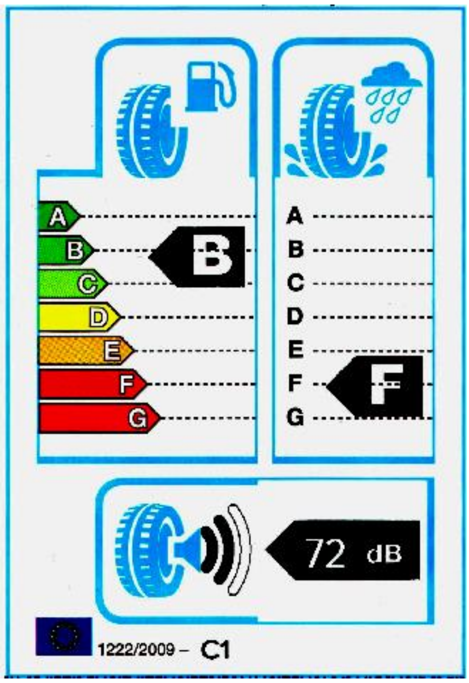

Figure 1-3 The EU tyre label used between 2012 and 2021.

The system has since been evaluated, although not with significant focus on noise; although in [Viegand Maagøe, 2016] a couple of future scenarios for tyre noise levels were outlined.

Between 2015 and 2018 a "Market Surveillance Project Tyres 2015 (MSTyr15)" took place which was designed to help deliver the intended economic and environment benefits of Regulation (EC) No 1222/2009 on the labelling of tyres by increasing the rates of product compliance with it (https://www.mstyr15.eu/index.php/en/). Between March 2016 and May 2018, monitoring, verification and enforcement activities related to tyres took place as part of the MSTyr15 project. In total, 11 899 tyre labels were checked as well as 761 technical documentations. These checks, however, did not include the noise label.

From 1 May 2021, the tyre regulation has been changed to a partly new one: Regulation (EU) 2020/740 [EU, 2020]. The main reason is that it is clear that wet grip of winter tyres has no relevance for grip on winter roads. To correct for this problem with the old label, the major change is that there is optional labelling of snow and ice friction of winter tyres. Also, the new rules are extended to mandatory cover bus and truck tyres, which was only voluntary before. There is another important change, which is that the three classes of noise emission have been changed to only two; one normal ("B") and one low noise ("A"). The previous class C is no longer legal for new tyres and tyres with noise above the limit are now (strangely) labelled as

Class B. It is also sad to see that the noise label has got a less prominent location and size in the new label. The new label is illustrated in Figure 1-4.

STEER recommends that the old Class C is re-instated and tyres previously in Class C should be moved back to C from Class B.

It is foreseen that the new labelling system shall be subject to an evaluation study in 2026. Currently, there are background studies going on to prepare for addition of tyre wear or "mileage" in the future; for example, project [LEON-T, 2021] (https://www.leont-project.eu/the-project/) This is important for classifying emission of particles into the air due to abrasion in the tyre/road contact patch but is also an important economic issue for consumers.

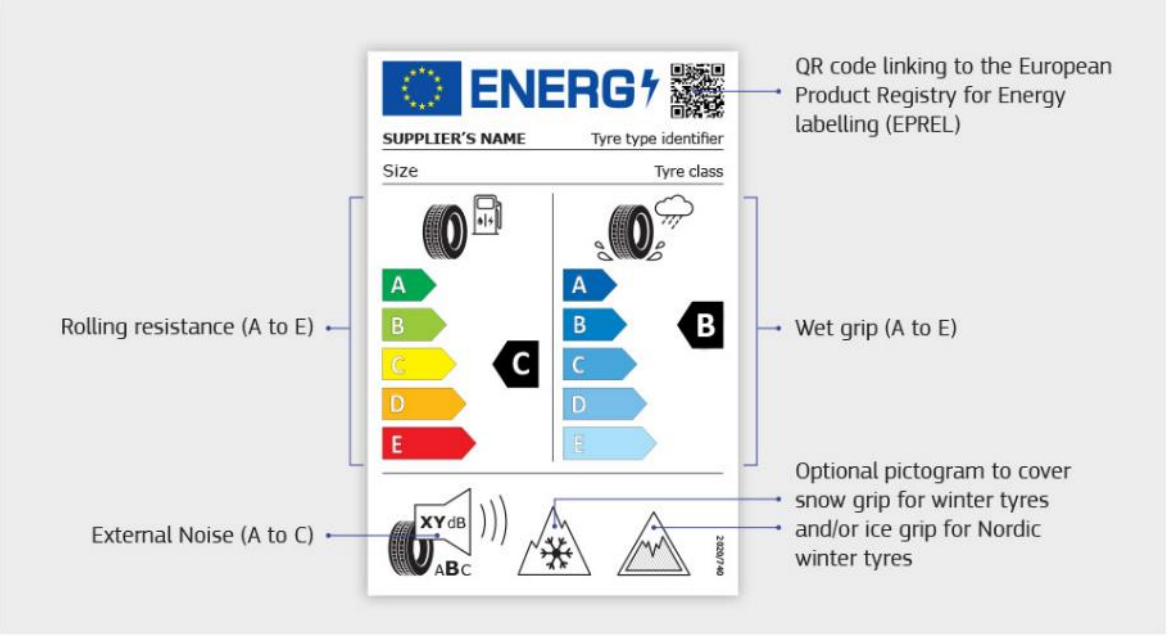

Figure 1-4: The EU tyre label valid from 1 May 2021 [EU, 2020].

1.4 Labels outside the EU

In **USA** it is required to include a quality marking called UTQG (Uniform Tire Quality Grading). This grading system, known as the Uniform Tire Quality Grading System (UTQGS), allows consumers to compare tyre treadwear, traction performance, and temperature resistance. The US federal government requires tyre manufacturers to grade their tyres in three subject areas and place the information on the sidewall. The system applies only to passenger car tyres (C1) and not to light truck (C2) or heavy truck tyres (C3). Furthermore, it is not required on winter tyres; although there is a symbol to distinguish between all-season and M+S (winter) tyres. The UTQGS includes the following three gradings:

- Treadwear (the resistance to wear of the tyre tread rubber; the higher the treadwear number is, the longer it should take for the tread to wear down). This marking has often popularly been referred to as "mileage" (i.e., the miles the tyre can be driven before it is worn-out).

- Traction (the tyre's ability to stop on wet pavement; in Europe the terms “wet grip”, "adhesion" or "skid resistance" are more common).
- Temperature (the possibility to endure sustained high temperatures; for example, driving long distances in hot weather).

The UTQG marking often appears also on tyres in Europe; especially in case they are also sold in North America. For a non-specialist, it is not easy to find this rating on the sidewall among several other sidewall markings. The usefulness for consumers is therefore arguable. Furthermore, the treadwear marking has been widely criticised as not being very representative.

It has been discussed several times to add a marking of rolling resistance (also referred to as fuel efficiency) but always with no resulting concrete action. In a very comprehensive study produced by a large group of experts [TRB, 2006], it was suggested:

“*Congress should authorize and make sufficient resources available to NHTSA to allow it to gather and report information on the influence of individual passenger tires on vehicle fuel consumption………. The effort should cover a large portion of the passenger tires sold in the United States and be comprehensive with regard to popular tire sizes, models, and types, both imported and domestic.*

NHTSA should consult with the U.S. Environmental Protection Agency on means of conveying the information and ensure that the information is made widely available in a timely manner and is easily understood by both buyers and sellers……”

Japan has applied its own independent labelling system since January 2010 and currently applies only to car tyres (C1). The qualities listed in the label system include rolling resistance and wet grip. See Figure 1-5.

Figure 1-5: The Japanese tyre label.

South Korea has applied a labelling system called Tire Efficiency Rating System since 2011 and (like Japan) currently applies it only to car tyres (C1). The qualities listed in the label system include rolling resistance and wet grip. See Figure 1-6.

Figure 1-6: The South Korean tyre label.

China has discussed a couple of optional tyre labels, with the aim to implement one of them voluntarily with a possibility to make it mandatory later. The most advanced one is the China Green Tyre Rating Assessment, which looks like a version of the European label. See Figure 1-7 (left). It has been active but voluntary since 2017 but has been used for certification of not so many tyres so far. However, while much of the layout and criteria remain the same as the EU tyre label, the main difference in the China Green Tyre Rating, apart from the language, is the addition of a tread wear rating as well as a QR code. The latter is a simple, but powerful feature which means that consumers can access further information about their tyres on the smartphones via the Internet. The tread wear label appears at the lower left.

China also has another tyre certification system, also voluntary, promoted by the China Rubber Industry Association and which already have several hundred of tyres certified. Its label is shown at the right in Figure 1-7.

There is a new Chinese standard which is corresponding to the recommended EU legislation, called GB/T 40718-2021 “Green product assessment - Tyres”. This document, to be implemented from 1 May 2022, specifies the product classification, evaluation requirements and evaluation judgments in the evaluation of green products for passenger car tyres and truck tyres. As far as the authors are aware, it is not a consumer label.

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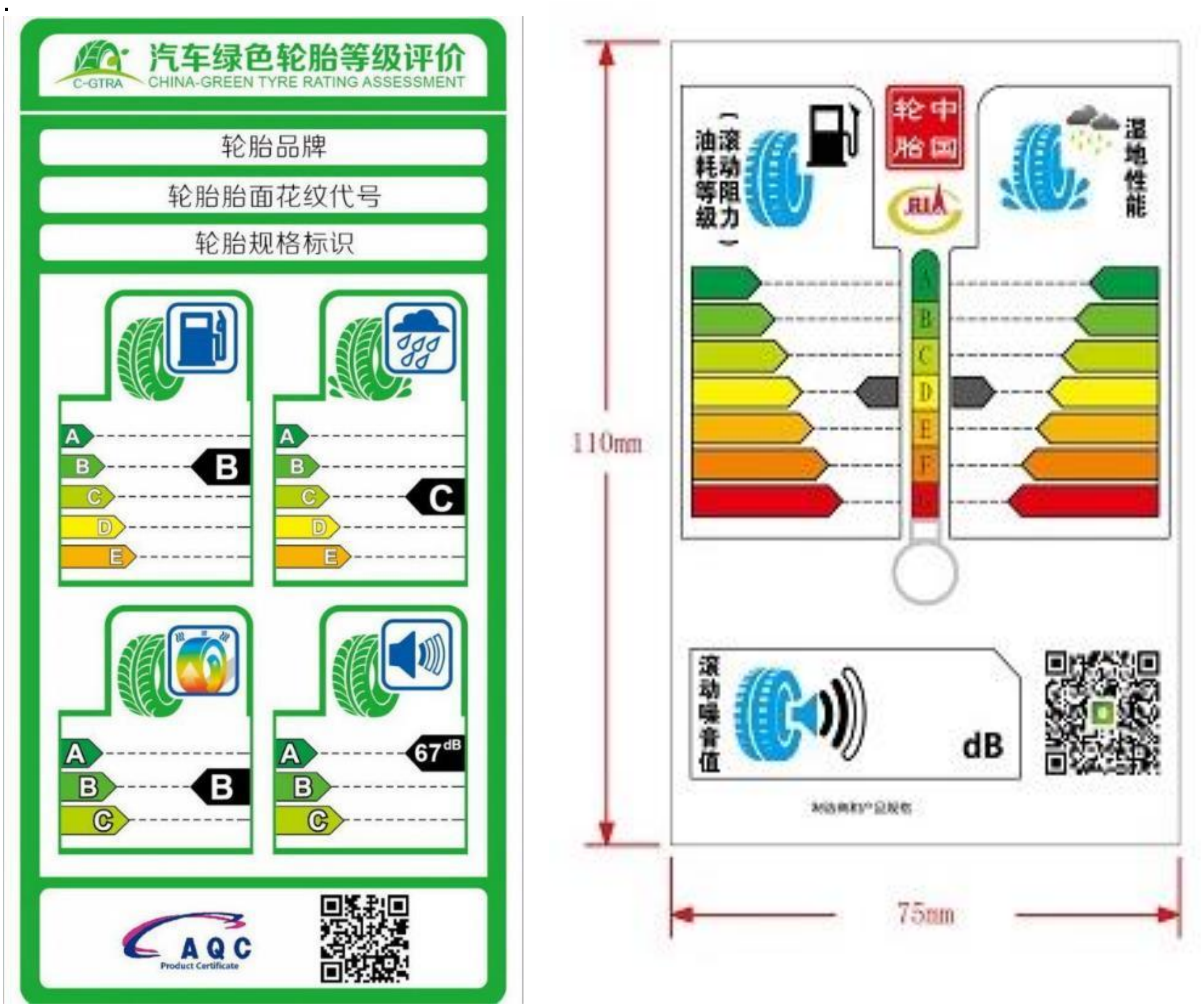


Figure 1-7: The Chinese (optional) tyre labels: Green Tyre Rating Assessment (left) and China Rubber Industry Association (right)

Brazil has introduced a new tyre label, in order to provide standardised information on three specific performances: fuel efficiency, wet grip and external tyre/road noise. See Figure 1-8. Essentially it is similar to the EU label. It is valid for C1 and C2 tyres.

It is interesting to note that China and Brazil are the only countries outside the EU which include a tyre noise label. The inclusion of a QR code seems to be a good idea that should be considered also in Europe. The very fact that consumers easily can access quite extensive tyre data as well as general information has a potential to increase public interest and awareness.

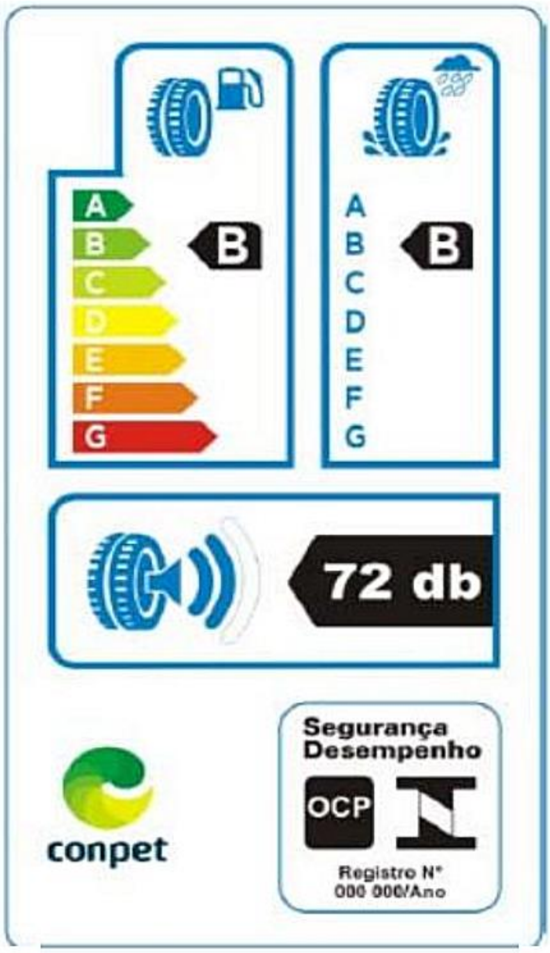


Figure 1-8: The Brazilian tyre label

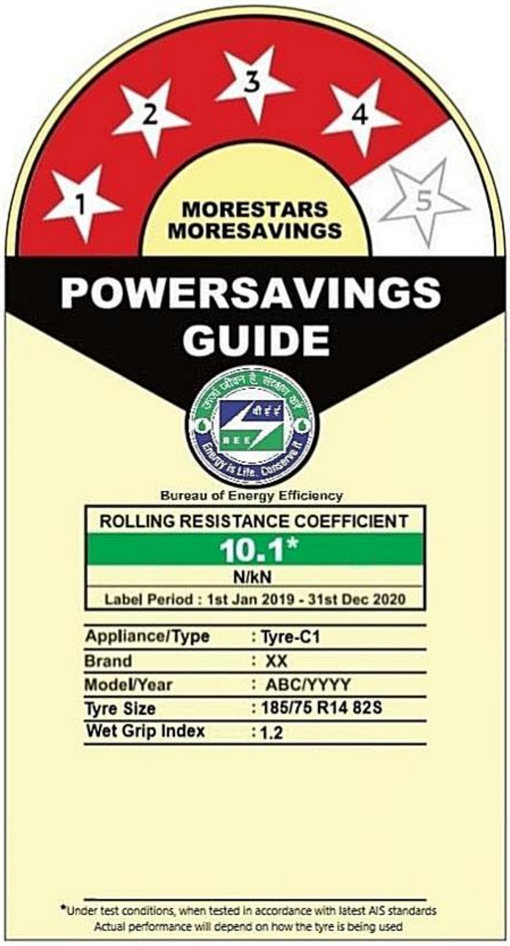


Figure 1-9: The proposed Star Rating in India

India has 41 tyre companies and 62 plants producing the largest variety of tyres in the world including bias and radial tyres. Like the Chinese market the Indian market is huge and rapidly expanding. The Bureau of Energy Efficiency (BEE), Bureau of Indian Standards (BIS), Ministry of Road Transport and Highways (MoRTH) and automobile testing agencies are planning to label tyres as per their rolling resistance and wet grip. There is also a proposal for a “Star Rating” of rolling resistance, see Figure 1-9. The label should be fixed to the sidewall or the tyre tread. However, bringing these reforms in tyre labelling will be a challenge for the agencies, as India does not have enough testing facilities. Thus, it has not yet been implemented other than voluntarily.

1.5 Potential reduction of road traffic noise through quieter tyres

Traffic noise is generated at two sources: The propulsion part coming from the engine and secondly at the tyre/road interface; the tyre/road noise part. The two shares behave differently with regard to various factors. The propulsion noise is mainly dependent on the engine load and engine speed (road gradient, speed, vehicle type) and the driving behaviour in general. The tyre/road noise depends on a variety of factors. The most important component is certainly the tyre-road interaction. Thus, it is very important, which kind of road surface is laid, and huge differences in terms of tyre/road noise can be detected. Furthermore, the driving speed is a key factor for tyre/road noise. Tyre/road noise increases with increasing driving speed. In the following Figure 1, the share of the rolling versus the propulsion noise is shown. The different shares are calculated using the Swiss traffic noise model sonROAD18, which differentiates between the different noise components rolling and engine noise [Heutschi et al., 2018].

As indicated in Figure 1, the share of the of tyre/road noise in relation to the total emitted noise is increasing with increasing driving speed. Even at low speeds, the tyre/road noise share is important and at a speed of 40 km/h, the tyre/road noise amounts already to 78.5 % of the total emitted noise.

- General discussion, what is typical range of noise (propulsion/tyre)
- Increasing importance due to shift to electric vehicles
- Present and historical relation to noise limits

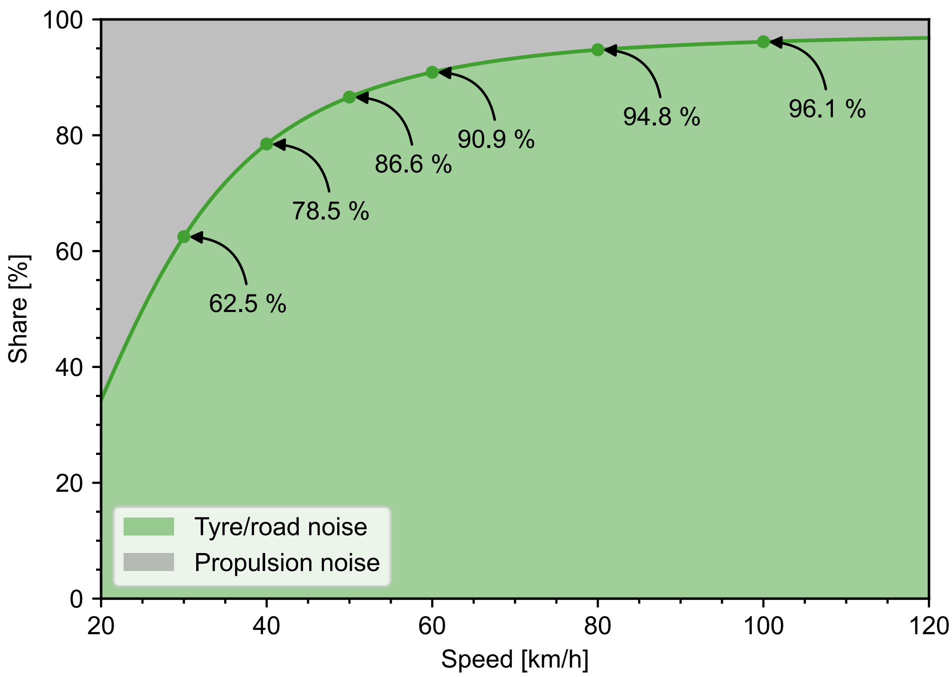


Figure 1-10: Distribution of tyre/road vs propulsion noise. Calculated using Switzerland's road noise calculation model sonROAD18 [Heutschi et al., 2018] for a typical traffic distribution with 8 % heavy vehicles.

2 Review of the current label

2.1 Labelling procedure

2.1.1 Overview of different noise testing procedures for vehicles

There are basically three testing procedures for external pass-by noise levels of vehicles:

- ISO 362-1 (External noise of M and N vehicles)
- ISO 362-3 (indoor testing of M and N vehicles)
- ISO 16254 (External noise of M and N vehicles at standstill or low speeds)

Ongoing and recent revisions of these standards are done within ISO/TC 43/SC 1/WG 42. For the STEER project the most relevant test procedure is ISO 362-1, as this is the basis of R51.03.

In this regulation there is an acceleration test and a constant speed test to define the type-approval level, L_{urban}. As an addition to the regulated test at a constant speed, a similar coast-by test (based on some of the test principles of R117, but at 50 km/h) shall be made, to define the tyre/road noise contribution to the overall level.

In the ISO standard, there is currently no correction for temperature or test track influence for this constant speed test. But, in a Working Document [GRBP, 2021a] for the 75th session of GRBP in February 2022 for amendments to R51.03 (Annex 3, Appendix 2). there is a proposal for a correction procedure for both temperature and test track influence, for the vehicle categories tested at constant speed (M_1, N_1 and M_2 < 3500 kg).

The tyre/road influence can either be measured during the type-approval (CASE 1) or as an independent test (CASE 2). Note that in this proposal, it is stated that if the measurements are made at an air temperature below 5 °C, the temperature correction (as proposed) can be applicable down to 0 °C.

The proposal also includes a temperature correction procedure for the full acceleration test, but this is not relevant for the content of the STEER project.

For CASE 2, there is a correction procedure for the influence of the test track since the tyres used for the type-approval may have been tested on a different test track. The following data is needed from the independent test:

- The tyre/road noise level at the reference temperature
- The reference vehicle speed
- The tyre/road noise level slope (speed vs noise)

By using the differences in the slope (and level at the reference speed) it is possible for compensation of differences between the two ISO tracks (if measured separately).

The flowchart below gives the principles for correction of temperature (CASE 1) (see Chapter 3.2) and for correction of both temperature and track influence (CASE 2).

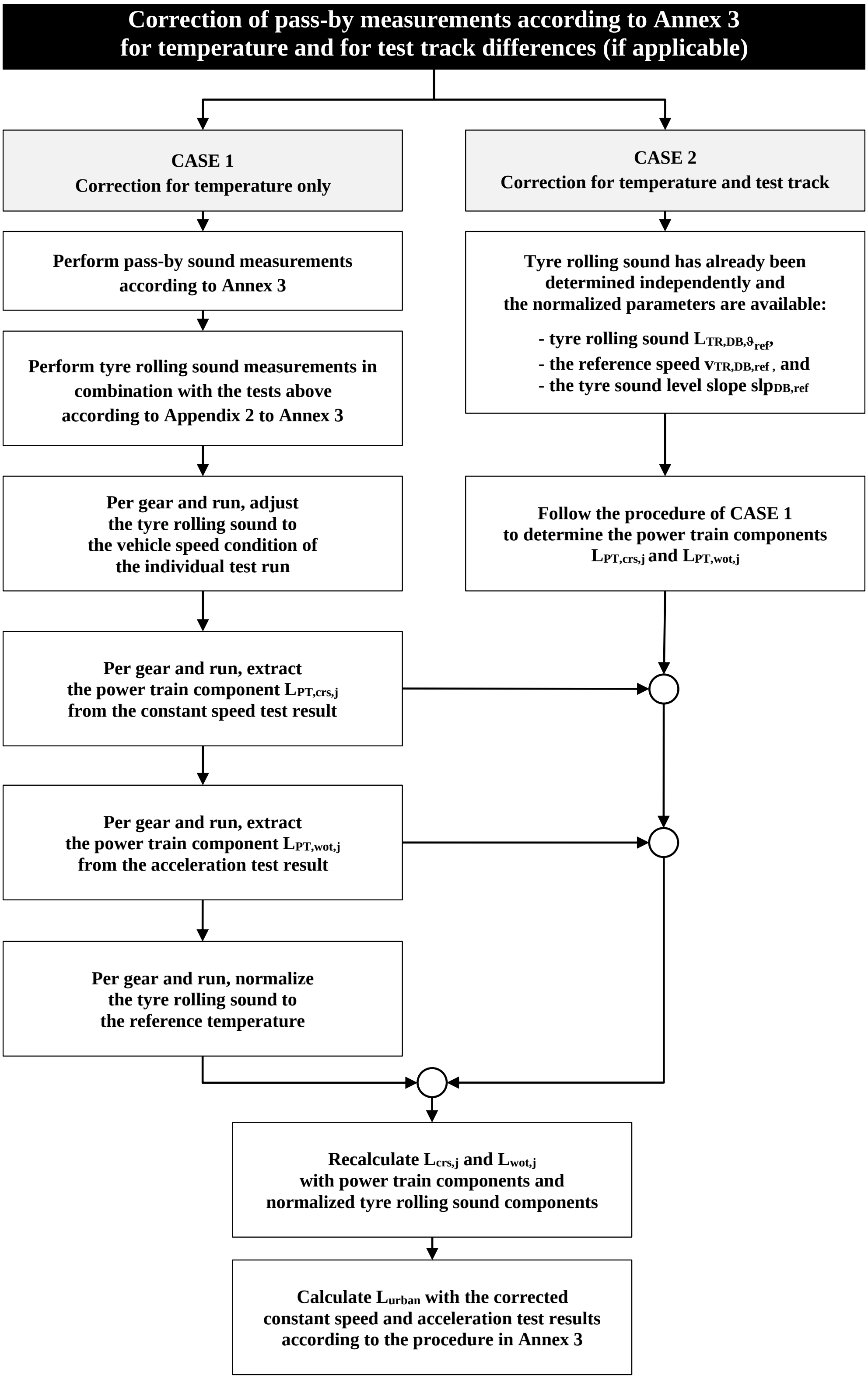


Figure 2-1: Flowchart for vehicles tested according to R51.03, Annex 3 – Correction of pass-by measurements for temperature and test track, if applicable. Flowchart from [GRBP, 2021a]

2.1.2 Regulation R117 and the GRBP Informal Working Group on Measurement Uncertainty

As will be presented in chapter 3.2, the correction procedure in R117 is based on ***road surface temperature***, with a reference temperature of 20 °C. In the GRBP Informal Working Group on Measurement Uncertainties (IWG MU), the different parameters influencing the measurement uncertainties have been studied with emphasis on the two regulations R51.03 (vehicles) and R117 (tyres).

The tyre industry [ETRTO, 2019] has shown that there are three main factors that have the highest contribution to the overall expanded uncertainties, in ranking order (standard uncertainty with 95 % confidence interval shown in parenthesis):

- Test track variation (± 1.8 dB)
- Vehicle influence (± 1.0 dB)
- Temperature influence (no correction applied: ± 0.6 dB)

Note that temperature correction applies only to C1 and C2 tyres. There is no correction for C3 tyres.

In Table 2-1, the estimated combined uncertainty with 95 % confidence is estimated for C1/C2 and C3 tyres:

Table 2-1: Estimated standard uncertainty with 95 % confidence interval. Source of table: [ETRTO, 2019].

Uncertainty source	C1/C2 tyres	C3 tyres
Excluding track influence	± 1.3 dB	± 1.5 dB
Excluding track and vehicle influence	± 0.9 dB	± 1.1 dB
Total	± 2.2 dB	± 2.3 dB

The table shows that the track influence is the most important source of uncertainty. It also shows that the C1/C2 uncertainty is lower, due to test track temperature correction. The uncertainty analysis is also discussed in the next chapter (2.3). IWG MU is expecting some input from the tyre industry/ETRTO regarding proposals for amendments to R117 for reduction of the expanded uncertainties, but it is not yet presented. It is not known if there will be some proposals to change the present temperature correction procedure in R117.

2.1.3 History of the ISO test track

The labelling of tyre noise levels is based on the test method described in R117, which again is based on ISO 13325. In 2009, when the labelling regulation was introduced, measurements according to R117 were based on the first edition of the ISO surface, ISO10844:1994. This ISO standard has been updated a few times (see 3.4.1). The latest version was published in December 2021 and is expected to be implemented in the near future in regulations. The main purpose of the updates has been to reduce the variability between ISO tracks, which in the first Round Robin Test of ISO tracks in 2005 [van Blokland et al., 2006] was found to be up to 9 dB. Later RRTs have revealed a spread in the range of 4-6 dB, which still is unacceptable. A full description of the history of the ISO test track is found in Chapter 6 of D3.1.

2.1.4 Test procedure for tyre noise labelling (R117)

Four sets of test tyres shall be mounted on a test vehicle with two axles. For C1 and C2 tyres a minimum of four coast-by measurements are made at equally spread speeds between 70 and 80 km/h, and four speeds between 80 and 90 km/h. C3 tyres are tested at 10 km/h lower speeds. A microphone at each side of the centre line of the test track is placed at a distance of 7.5 m at a height of 1.2 m.

For C1 and C2 tyres, the reference speed is 80 km/h, while for C3 tyres it is 70 km/h.

The A-weighted maximum sound level at the reference speed is established through a linear regression of the relationship between the speeds and the sound levels (see R117 for detailed calculation procedure). The final sound level is the average level of left and right sound levels.

2.1.5 Which tyres are tested?

First, it is mandatory only for new tyres sold in Europe (also if they are mounted on imported vehicles). Before 2021 only C1 and C2 tyres were required to be tested. For C3 tyres it was just voluntary, but from 2021 it is mandatory also for truck tyres.

Tyres not yet required to be tested are:

- Retread tyres
- Studded winter tyres

That retread tyres are not tested is a pity since for heavy vehicles, the retread tyres in Europe constitute approx. half the volume of transportation. The reason is that it is more complicated to define a retread tyre as it has an old carcass and new tread, and the carcass may be from many original tyres.

2.2 Uncertainty analysis of the current label

The labelling procedure, Regulation (EU) 2020/740 [EU, 2020] which refers to certain parts of UNECE Regulation R117[2] [UN/ECE, 2011], as outlined in chapter 1.3 (page 19) can be represented schematically as in Figure 2-2.

[2] UNECE, Regulation No 117 of the Economic Commission for Europe of the United Nations (UNECE) – Uniform provisions concerning the approval of tyres with regard to rolling sound emissions and/or adhesion on wet surfaces and/or rolling resistance of 12 August 2016 and in particular Annex 3 "Coast-by test method for measuring tyre-rolling sound emission" (2016)

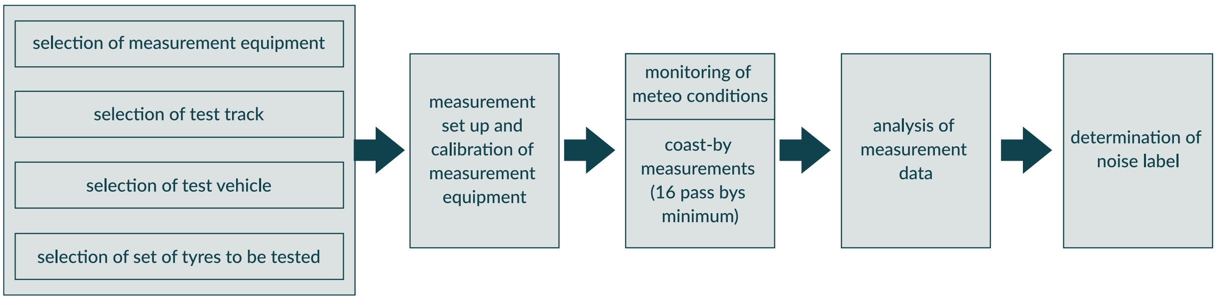


Figure 2-2: Schematic representation of the noise labelling procedure.

The procedure comprises several uncertainty sources, as already mentioned in chapter 0. The STEER consortium has made its own, independent uncertainty analysis, in order to avoid any bias as this is a crucial part of the project. Uncertainty sources yielding the highest uncertainty contributions were addressed with priority in the project. At the end of the project, the uncertainty analysis was repeated in order to see how much the recommendations of this project will improve the labelling system, if implemented (see chapter 7 on page 133).

The STEER consortium identified no less than 41 uncertainty sources in the tyre noise labelling procedure and all of them have been carefully evaluated following the concept of the measurement uncertainty according to ISO/IEC Guide 98-3-2008 (E) [ISO/IEC, 2008], based on the existing data for the tyre label. These uncertainty contributions can in certain cases be budgeted precisely, but in other cases one cannot do better than a rather rough estimate based on currently available expert knowledge.

The most important gaps/contradictions in the knowledge of the uncertainties were the following:

- **Air humidity:** the influence of the air humidity on the result is not completely clear, but it is our expert judgement that the effect is presumably small and even negligible.
- **Air temperature:** the contribution of the imperfect correction of tyre/road noise for the effect of air temperature, which is treated in a separate STEER report (see Deliverable D3.1).
- **Test vehicle:** for this uncertainty contribution, we could use the value extracted from a database from a tyre manufacturer, yielding a value of 0.60 dB, which is actually close to what is suggested by ETRTO (0.51 dB)[3] [ETRTO, 2019].
- **Test tyres:** the overall value for the tyre uncertainty from the data base of a tyre manufacturer was initially found to be 0.46 dB for measurements within the same tyre family, which is almost twice the value proposed by ETRTO, which is 0.26 [ETRTO, 2019]. But this was before data were available about the tyre line effect, i.e., the practice to measure only one type of tyre and assigning the result to all the tyres of the line (with different diameters, width, speed, load index…). According to chapter 4.2.5, from which the results were available in November 2021,this effect alone is responsible for an additional uncertainty between 0.59 and 1.1 dB.

[3] The referenced document mentions ±1 dB, but this is the 95 % confidence interval, whereas in this document the uncertainty in terms of the standard deviation is used. In order to obtain the standard deviation, one divides (half of) the width of the 95 % confidence interval by the covering factor k = 1.95, yielding 0.51 dB in this case

- **Test track:** based on an old round robin test on eight European ISO test tracks with four different tyres (slick, summer tyre, winter tyre and a van tyre) carried out in 2005 by M+P [van Blokland et al., 2006], a first estimation was made of 1 dB, which is in line with the expert view expressed in [Sandberg, 2017]. Recent measurements on 186 AC8[4] pavements in Switzerland by G+P yielded a standard deviation of 1.24 dB[5], which can be considered as an upper limit. ETRTO suggests an uncertainty contribution of 0.92 dB, quite close to the above estimations [ETRTO, 2019].

The analysis is carried out separately for C1 and C2 tyres, but the only difference in the calculation is the uncertainty contribution of the wheelbase: for C1 tyres this contribution is estimated to be only 0.21 dB and for C2 tyres 0.56 dB.

The outcome of the STEER uncertainty analysis is state-of-the-art, clearly illustrating why the label in its present form is not optimal. It indicates where the major challenges lie to have a label with an acceptable reproducibility.

For the sake of clarity, the 41 uncertainty sources were grouped in eight uncertainty classes/categories: equipment, experimental set up, measurement conditions, measurement, test vehicle, test tyres, test track and calculation.

The combined uncertainties per uncertainty group were calculated according to equation (10) in ISO/IEC Guide 98-3:2008 (E). The parameter u_c is the uncertainty - expressed as a standard deviation - of the measurand and according to the Central Limit Theorem, the measurand is normally distributed (at least in a good approximation even if not all of the constituents are normally distributed). To determine the confidence interval, the right coverage factor[6] must be selected, see Table G.1 in ISO/IEC Guide 98-3:2008 (E). The 95 % confidence interval can be obtained by multiplying u_c with the coverage factor k_p = 1.95.

The result of the calculation of the u_c with the lowest estimated and the highest estimated values, both for C1 and C2 tyres, are shown in Figure 2-3. Note that this is for the current situation, i.e., before any actions suggested by STEER are taken. The underlying analysis and determination of values are presented in STEER Task 2-2 Report [Goubert, 2020] but have been updated based on new information becoming known.

[4] AC8 pavements are relatively similar to ISO test track pavements
[5] Database evaluation of CPX Measurements by G+P
[6] number larger than one by which a combined standard measurement uncertainty is multiplied to obtain an expanded measurement uncertainty

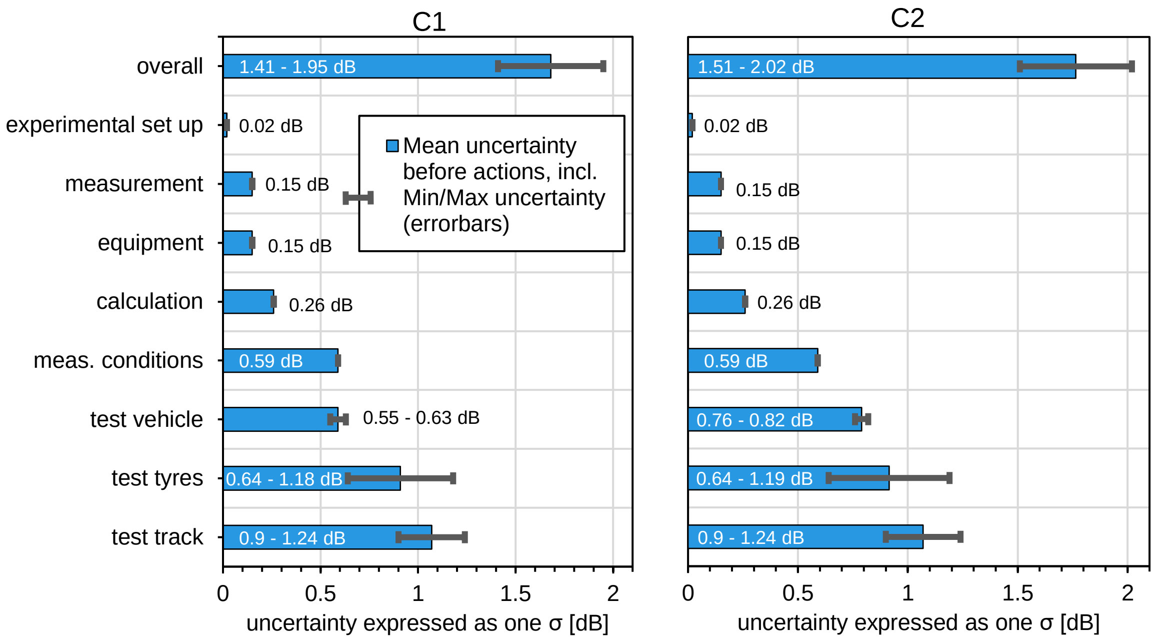


Figure 2-3: Uncertainty contributions per uncertainty group for the C1 (left) and C2 tyres (right) when labelled under the current tyre noise labelling procedure. Note that σ stands for standard deviation.

The test track and test tyres uncertainty appear to yield by far the main contributions, both for the mean and the pessimistic case (max) and for both C1 and C2 tyres. Therefore, these contributions should be given priority. The uncertainty contributions from the measurement conditions and the test vehicle appear to be comparable and share a third place. The latter is somewhat more important in the case of the C2 tyres. They have been addressed as well. Ranked on the fourth place, one finds the contribution from the tyres and this contribution could be underestimated, as the available data are not fully complete. The other sources contribute in a rather marginal way and could be ignored.

It can be concluded that the uncertainty on the tyre noise label for both C1 and C2 tyres is between 1.4 and 2.0 dB, expressed as standard deviations, which constitutes a substantial part of the entire noise level range.

2.3 Linking the uncertainty with empirical data

A high uncertainty of the tyre noise label has an adverse effect on the correlation between measured noise levels and labelled values. This makes it difficult to check the ranking of the tyre label values of a sample of tyres by means of coast-by or CPX noise measurements. This problem is illustrated by the STEER consortium with a Monte Carlo simulation. As a real-world example from an earlier project, the experimental correlation between the tyre noise label and close-proximity (CPX) measurements was considered. The noise label is not determined by means of CPX measurements, but the same principle would be valid for coast-by measurements.

The correlation depends on the actual range of the tyre label values in the sample (unknown but estimated here to be between 3 and 7 dB), the uncertainty of the CPX measurements (0.58 dB, known from actual tests) and the uncertainty of the label (between 1.41 and 1.95 dB for C1 tyres, according to the analysis in 2.2). Details of the simulation method are outlined in detail in the STEER Task Report 2-2 [Goubert, 2020]. The combination of a small range of tyre noise labels in the sample tested (3 dB) and the highest obtained uncertainty (u_c = 1.95 dB for C1 tyres) yields typically a correlation as shown in Figure 2-4, which resembles one of the most carefully measured correlations presented in literature (Figure 2-5). The uncertainties on the label and to a minor extent on the CPX measurements turns out to completely destroy the true and ideal correlation, which is consistent with the earlier experimental findings.

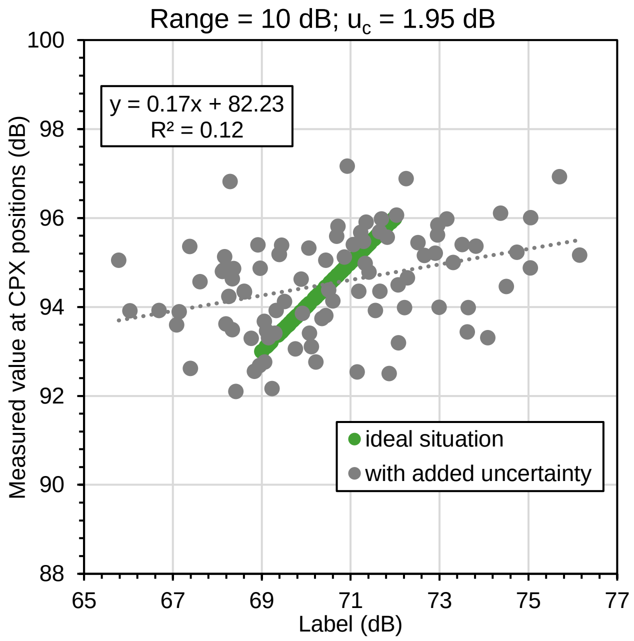


Figure 2-4: Illustration of the effect of adding uncertainties to true values using Monte Carlo simulation of correlation between a tyre label with the calculated uncertainties added to coast-by measurements (actual range of true label = 3 dB and uncertainty of label = 1.95 dB, uncertainty on CPX measurement = 0.58 dB, all expressed as standard deviations).

2.4 Conclusions and recommendations

In Section 2.2 (Uncertainty analysis of the current label) the uncertainty analysis of the current tyre noise labelling procedure is summarized, both for C1 and C2 tyres. The results for the C1 tyre are shown in Table 2-2, together with possible options to reduce them. The case of the C2 tyres is very similar with the exception that in this case the uncertainty contribution of the vehicle is a bit higher, due to wheelbase variations. For C2 tyres one could, in particular, consider measures to reduce this uncertainty contribution, i.e. narrowing the allowable wheelbase variations of the test vehicle.

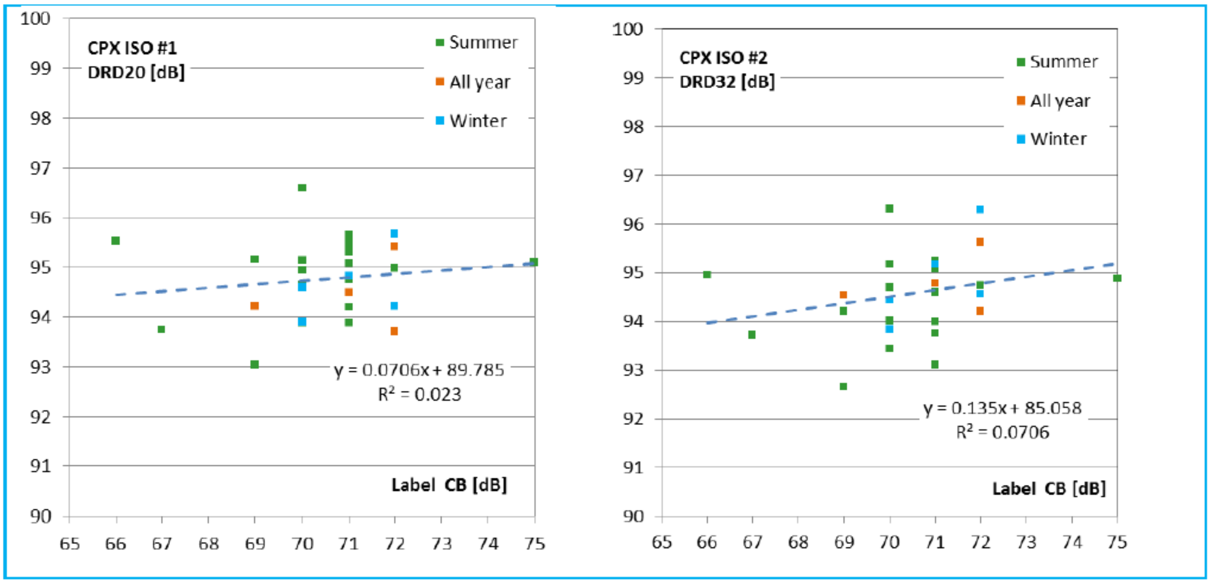


Figure 2-5: Measured CPX levels on two ISO test tracks as a function of the tyre label values issued by tyre manufacturers [Kragh et al., 2015].

Table 2-2: Uncertainties for the case of C1 tyres and possible actions to reduce them.

Uncertainty group	**Uncertainty contribution**	**Options for reduction of the uncertainty**	**Estimated improve-ment of uncertainty**	**Practical implications** The symbol (- -) indicates how serious the practical effect is
Test track	0.92 up to 1.30 dB	▪ Narrowing down specifications in ISO 10844 ▪ Acoustic calibration procedure of test track ▪ Second rough ISO 10844 test track	☆ ☆☆☆☆ ☆	Difficulties meeting requirements, increases costs of construction (- -) Repeated calibration measurements necessary (-) Increases costs for construction and tyre testing (- - -) and this tackles the problem of representativity, not reproducibility (see chapter 4.3)
Measurement conditions	0.59 dB	▪ Improved temperature correction procedure ▪ Update temperature corrections	☆ ☆	Possible changes to temperature measurement (-) Possible changes to temperature measurement (-)

Test vehicle	0.55 up to 0.63 dB	▪ Narrowing specifications of test vehicle (wheelbase and especially car underbody)	☆☆	Less number of vehicles useful for testing (-)
Calculation	0.26 dB	▪ Small contribution, no further reduction needed		
Test tyres	0.64 up to 1.18 dB	▪ Measurement of most variants within a tyre line	☆☆☆	Increase number of required tests and hence cost (- -)
Measurement	0.15 dB	▪ Small contribution, no further reduction needed		
Equipment	0.15 dB	▪ Small contribution, no further reduction needed		
Experimental setup	0.02 dB	▪ Small contribution, no further reduction needed		
Overall	1.41 up to 1.95 dB	All the above together		

3 Reproducibility of the tyre label

3.1 Uncertainty sources relevant to reproducibility

An analysis of uncertainty sources in the labelling system is described in the previous chapter. The essential outcome of that analysis of the present situation is illustrated in Figure 2-3. Note that the group named "meas. conditions" include the effects of wind and temperature, where temperature is the dominating contributor.

It appears that three groups (sources) of uncertainty dominate:

- Measuring conditions (wind and temperature)
- Test vehicle
- Test track

These sources will be analysed in this chapter.
Test vehicle influence on tyre/road noise

3.1.1 Description of the problem

The construction of the test vehicle (among vehicles on the market) always has some influence on the noise emission to the microphones during the tests. This is mainly due to partial screening of the noise emitted by the tyres of the vehicle body. As the noise source is near the tyre/road contact patch, the screening problem mainly influences the emission from the tyres on the opposite side of the vehicle in relation to the microphone. At high and some medium frequencies also the tyres on the closer side may at certain propagation angles somewhat screen noise from the tyres on the far side of the vehicle. The volume of the body surrounding the wheels will have certain resonance frequencies which may have a marginal effect also at the microphone locations.

The underbody of the vehicle will or may have openings or shapes that may "catch" some of the acoustic reflections that occur when noise is emitted from a tyre under the body to the other side, where there may be multiple reflections in the ground clearance between the road and the vehicle underbody. Finally, the distance between the tyres, the wheelbase, will influence whether the peak in the sound during coast-by from the front and rear tyres will mix into one single peak or if there may one peak from the front and another from the rear tyres, or (more normal for C1 tyres) two peaks so close in time and space that they will combine into a somewhat reduced and widened peak. Therefore, ground clearance, vehicle underbody, wheelhouses and wheelbase will be critical parameters.

It is a trend that tyres tend to be more and more covered by body parts (for air resistance and design purposes) which may create more resonant spaces around the tyres (in wheelhouses) and thus give increased vehicle influence; furthermore, with increasing popularity of SUV:s and more off-road applications, ground clearance seems to be more varied than previously.

Since most tyre manufacturers have so many tyres of widely different dimensions and load capacity, it is a challenge to find just a few test vehicles to accommodate all dimensions and loads in the product range; especially in the C1 tyre class. The R117 has restrictions on vehicle construction (listed in Deliverable 3.1). Nevertheless, there is a certain playroom for the selection of actual test vehicles.

In Deliverable 3.1, some studies of the problem are mentioned. The result seems to be that vehicle influence may be somewhere between 0.5 and 1.0 dB, which is reflected in the estimations of uncertainty contributions between 0.5 to 0.8 dB in Figure 2-3.

3.1.2 Suggested improvement

As shown in Figure 2-3, the contribution of vehicles to the overall uncertainty is the third highest and the contribution to the uncertainty of the test tyres and test surface are currently clearly higher. This may be a reason for why this uncertainty source has not been addressed more in depth; for example, by defining special test vehicles. However, if the test tyre and test track influences are reduced, as proposed here, the vehicle influence will be relatively more important and should receive more attention.

So far, the present requirements are valid for coast-by testing of tyre/road noise. Ideally, one would like to use the same special test vehicle worldwide for a certain and defined range of tyres. To cover all tyre dimensions and their loads, probably three different sizes of cars/SUV:s for C1 tyres, one or two small-to-medium trucks for C2 tyres and two sizes of trucks for C3 tyres would be needed. Obviously, to define such standard test vehicles or produce special or modified vehicles that can be available worldwide and required in the regulation may increase costs and may be difficult to agree on (would US and Chinese manufacturers accept, for example a German vehicle, or vice versa?). Tyre manufacturers already have their own special test vehicles for such purposes, probably more than mentioned above, but they are generally market vehicles that can be used also for other purposes.

However, it would absolutely be technically possible to decide on standard test vehicles, adapted for minimum effect on tyre/road noise, in which case one could eliminate almost all the uncertainty contributions of the test vehicles in the testing procedure. If it is politically possible is another matter, as it is unlikely that a defined vehicle brand and type will be accepted to be part of an international regulation.

It is noted that the principle of defining special test vehicles is already implemented in standards for measuring the noise properties of road surfaces (ISO 11819-2 and ISO/TS 11819-3).

As is shown later in this report, if and when our proposals have been implemented, the test vehicle uncertainty contribution will be the second largest, and therefore should be addressed in the future.

Too little research on the test vehicle influence and how more uniform vehicles should be constructed is available, so this is something that is needed quite urgently. Therefore, here we propose that research is initiated with the aim to propose more uniform or, if possible, consider standardized vehicles for use during tyre/road noise testing.

The “ultimate solution” will be if and when the present measurements can be made indoors on individual tyres rolling on a drum covered with a standard replica of a road surface. In such a case the test vehicle influence will disappear and possibly be replaced by a (much smaller and much easier to standardize) influence of the tyre setup.

In the meantime, it is proposed to somewhat limit the wheelbase requirements for vehicles testing C2 and C3 tyres. Also, the test vehicle ground clearance for C1 tyres should be restricted since it is currently not specified.

3.2 Temperature effects on tyre/road noise measurements

3.2.1 Description of the problem

As already described in a project report of STEER Task Report 3.1, the influence of temperature at the tyre type approval and label noise measurements may influence the measurements by up to 2 dB. Figure 2-3 also indicates that temperature (dominant in the "measurement conditions") is one of the four major sources of uncertainty.

Fortunately, some of the temperature influence is possible to compensate for by correction procedures. ECE R117 already includes a temperature correction; however, we think that a better correction procedure is possible. For example, a matter of controversy is whether ambient air or test track surface temperatures should be used for the correction. The findings of STEER and other actors are reported in Deliverable D3.1, ending with recommendations for improved corrections by STEER. The most important issues are treated in the following subchapters.

3.2.2 The ISO/TS 13471-2 Draft Technical Specification

The working group ISO/TC 43/SC 1/WG 27 has the task to produce two Technical Specifications for correction of noise levels for the influence of temperature. The work was first published in 2017 as ISO/TS 13471-1 (ISO/TS 13471-1, 2017) and then it was only valid for the two reference tyres used in the CPX standard. The concept was widened to also include coast-by or cruise-by methods (but cases where tyre/road noise was not significantly "obscured" by power-unit noise), and was intended for tyres in general, in the work to produce ISO/TS 13471-2. This is or should become the relevant standard document for corrections to measurements of the type made in R117. At this moment, the document is a Draft Technical Specification (DTS) (ISO/TS 13471-2, 2021). The latest version is influenced in parts by the work presented in the STEER Deliverable D3.1.

In the draft for ISO/TS 13471-2, at first, it is determined that the most relevant temperature for the corrections is the ambient air temperature, with a reference of 20 °C. This is justified in the STEER Deliverable D3.1. In summary, the correction procedure is then as follows (copied from ISO/DTS 13471-2:2021 and adapted for coast-by measurements as required in R117):

Temperature correction shall be applied as follows. Each measured noise level, $L_{\mathrm{A,max}}$ shall be corrected by adding the term $C_{T,\mathrm{t}}$, using Formula (1):

$$C_{T,t} = -\gamma_t (T - T_{\mathrm{ref}}) \quad (1)$$

where

$C_{T,\mathrm{t}}$ is the noise level L_{Amax} correction for temperature (T) for tyre class (t), in dB, to be added to the measured noise level;

γ_t is the temperature coefficient for tyre class t (either C1, C2, or C3), in dB/°C;

T is the air temperature (T) during the noise measurement, in °C;

T_{ref} is the reference air temperature = 20.0 °C.

The γ_t (temperature coefficient) values are indicated in Table 3.1, where it should be noted that ISO 10844 test tracks would belong to road surface category “Dense asphaltic surfaces”:

Table 3-1: Compilation of temperature coefficients (excerpt from ISO/DTS 13471-2:2021).

Tyre class (t) → **Road surface category ↓**	**C1**	**C2**	**C3**
Dense asphaltic surfaces	-0.10	-0.07	-0.06
Cement concrete surfaces	-0.07	-0.06	-0.06
Porous asphalt surfaces	-0.05	-0.04	-0.04
Other surfaces	See Note 2 and/or Appendix A in ISO/DTS 13471-2		

This DTS will be subject to a final ballot during the first months of 2022. Since it was approved already in the previous version, there is no reason to suspect that it will not be approved again as the new version has been revised to take most of the ballot comments into consideration.

The DTS includes an optional Annex in which conversion between correction systems based on air (as in the DTS) versus road surface temperatures (as in ECE R117) is discussed. This is treated further in the next sub-chapter.

3.2.3 Review of the temperature correction in ECE R117

In R117 it is mandatory to measure both air and surface temperature. The air temperature shall be within 5–40 °C or the surface temperature shall be within 5–50 °C. Regarding the temperature correction required in R117, a procedure for normalizing the results to a reference temperature of 20 °C is provided for tyres belonging to classes C1 and C2 only. The temperature correction is carried out by applying the following Equation, which is written in a bit different way than Equation (1), but in practice is similar:

$$L_R(\vartheta_{ref}) = L_R(\vartheta) + K(\vartheta_{ref} - \vartheta) \quad (2)$$

where ϑ is the measured test surface temperature, and ϑ_{ref} is the reference temperature of 20 °C. The coefficient K is defined according to the tyre class and the difference between measured surface temperature and the reference temperature, as shown in Table 3-1. The speed ranges and reference speeds for each tyre class are also shown in the same table. The procedure is illustrated in Figure 3-1.

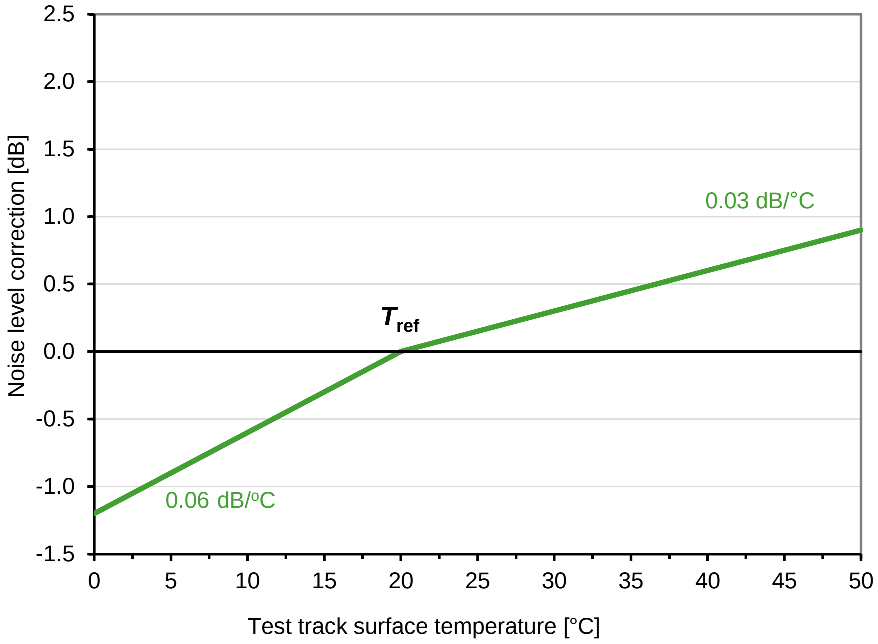


Figure 3-1: The noise-temperature relation that is used for car (C1) tyres in a number of EU and ECE regulations (see the text).

Table 3-2: Temperature correction coefficient according to ECE R117 and some test requirements. Note that the Regulation still uses the unit dB(A), which is not allowed according to ISO terminology standards. The unit shall be dB and not dB(A).

Tyre class	Speed range	Reference speed	Road temperature ϑ	Correction coefficient K
C1	70–90 km/h	80 km/h	$> \vartheta_{ref}$	-0.03 dB(A)/°C
			$< \vartheta_{ref}$	-0.06 dB(A)/°C
C2			-	-0.02 dB(A)/°C
C3	60–80 km/h	70 km/h	-	-

The R117 temperature correction has been implemented also in ISO 13325, which uses a similar method for tyre/road noise measurement.

3.2.4 Brief summary of most recently obtained data, as reported in Deliverable 3.1

In Deliverable D3.1 as well as in STEER Technical Report 3.1, a number of new sources of information which are crucial for this report are presented. These are summarized here.

Japanese data on road versus air temperatures:

First, a very comprehensive database by Nissan Motor Company of air and road surface temperatures (and some other meteorological data) were made available to STEER by [Shirahashi, 2020], The data shows how the air temperature changes simultaneously with the road temperature, which was measured with a sensor located 40 mm below the ISO road surface. The result is presented in Figure 3-2. It appears that the relation is linear between approx. 5 and 25 °C but has nonlinearities outside these ranges. The average slope is 1.36.

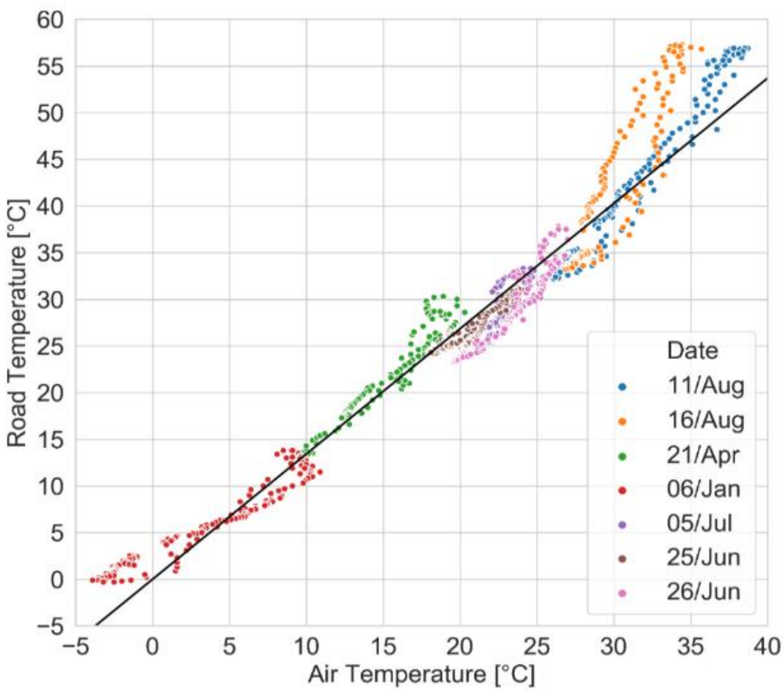


Figure 3-2: Air and road temperature in linear regression with zero intercept. Based on information from [Shirahashi, 2020] but data processed by the authors.

Qatar study in high temperatures:

Secondly, in a recently published article, measurements of temperature influence on tyre/road noise were made at very high temperatures, in Qatar [Sirin et al., 2021]. It means that temperatures ranged from 20 to 43 °C (air) and 20 to 65 °C (road surface), which is interesting due to the focus on very high temperatures. Only one tyre was used, namely the tyre P1 (16" SRTT) in ISO/TS 11819-3, which was tested with the OBSI method, which is the American version of the CPX method. The tests were run on four dense asphalt surfaces having MTD values from 0.65 to 2.9 mm (MTD = Mean Texture Depth, which is numerically close to MPD values).

The relation between road and air temperatures was linear with a K factor (slope) of 1.94. This slope is much higher than the 1.36 in the Japanese data, but for the higher temperature range it would fit rather well with the Japanese data. The correction factor for air temperature was -0.14 dB/°C, for the smooth-textured surface which was closer to ISO 10844 (which had an MTD within the range allowed in ISO 10844). If one would convert the air temperature coefficient for this road surface (-0.14) to a road temperature coefficient, the latter would be -0.14/1.94 which is approx. -0.07. This coefficient happens to be similar to our proposal later in Chapter 3.3.

Re-evaluations of comprehensive Swiss data:

In a recent paper, presented at Inter-Noise 2021 in Washington [Bühlmann et al., 2021] temperature effects on noise emission have been re-evaluated. In the paper, the influence of the different temperatures on the generation of tyre/road noise is highlighted. The basic underlying assumption was that tyre/road noise is basically generated in the tyre, as it is assumed that noise is not directly emitted from the road surface; at least not to a substantial amount. Thus, it was assumed that the noise emission must depend on the temperatures in or on the tyre. Accordingly, the most relevant temperature should be the tyre temperature. Nevertheless, both air and road surface temperatures have an influence on the tyre temperature, as the thermal system tyre/road/air is connected.

In the paper, different datasets collected in different projects in Switzerland have been re-evaluated, with the perspective to determine the temperature effects for the three respective temperatures *air, road* and *tyre*. In the following Figure 3-3, data from a study [Bühlmann et al., 2011] in late summer 2010 is re-evaluated. In this study, the highly varying temperatures during this time of the year are used to continuously repeat measurements on the same road sections over the course of the day, from the minimum (around 06:00) to the maximum air temperatures (around 17:00)). In Figure 3-3 the (squared correlation coefficient) R^2 of the spectral linear regression model of the respective temperature versus the acoustic measurement value is shown as a function of frequency.

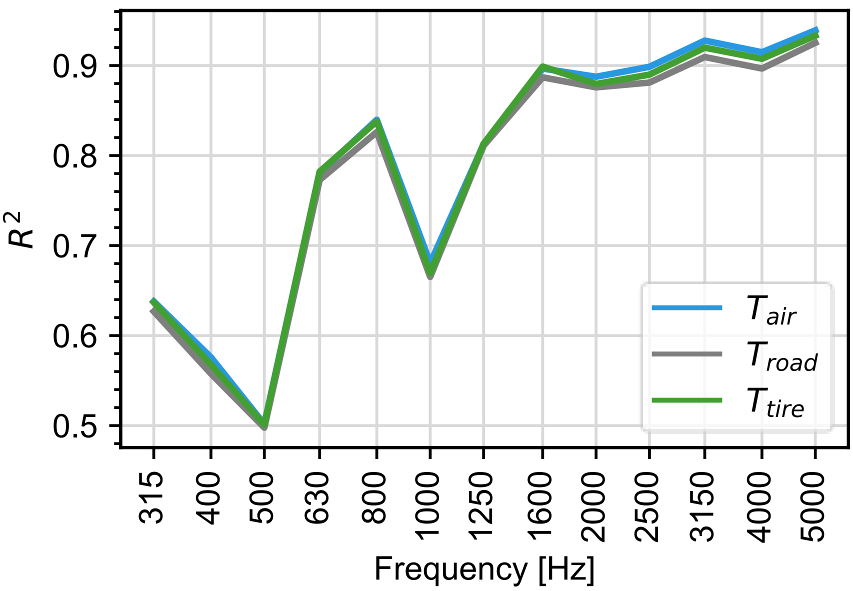


Figure 3-3: Average R2 between temperatures and tyre/road noise in third-octave-band spectra (left) and residual error of the slope for the linear regression models (based on 28 tyre/pavement combinations at reference speed 50 km/h)

The figure suggests that all the temperatures (Air, Road and Tyre) can explain the temperature effects over a large band of the noise frequency spectrum; albeit not so well at the crucial frequency of 1000 Hz.

The respective temperatures, measured during this study are shown in the Figure 3-4 below. An important information from this figure, is that the different temperatures behave differently over the course of the day. The impact of solar radiation on T_{tyre} through heating-up of the pavement becomes clearly visible, as the offset of T_{tyre} from T_{air} starts to gradually increase after the sun rises at around 06:40. In the early morning, T_{tyre} is 9 °C warmer than T_{air}, increasing to 15 °C in the afternoon, when the maximum offset is reached at 15:00. These observations support the assumption that it might be difficult to determine the temperature effects solely on for instance air or road temperatures, under the assumption that tyre temperatures are the most relevant for noise generation.

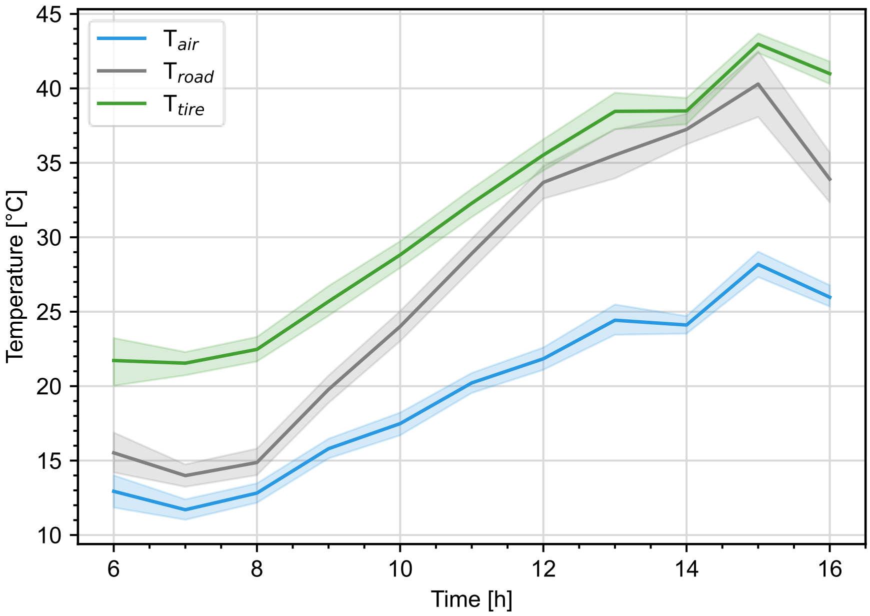


Figure 3-4: Average temperature profiles during a 9-day measurement campaign (with 95 % confidence intervals)

Furthermore, in the paper, an extensive dataset with millions of combined temperature measurements has been evaluated. The dataset has been collected during various projects between the years 2010 and 2020 in different regions in Switzerland. The data is collected at a speed of 50 km/h and covers a measurement distance of over 50 000 km. In Figure 3-5, the interdependence of the air to tyre temperatures is shown in the upper part, and the relation between the road and tyre temperatures are shown in the lower part. All the data has been separately evaluated for daytime (left graphic) and for night-time (right graphic).

The relations between the different temperatures have been investigated with different models and the *goodness of fit* (GOF) indicate that the linear model represents the data best. Between all the different temperatures, statistically significant different slopes could be found. For instance, between T_{air} and T_{tyre} higher slopes can be found for daytime than for night-time. The same, but to a lower degree, was observed for the temperature relations between T_{road} and T_{tyre}. The reason for the different behaviour of the slopes might be depending on the prevalence of solar radiation having a different impact on the heating of the road.

Accordingly, any correction approach based on T_{air} alone, would result in a certain error if measurements over both day and night are performed, as the impact of solar radiation on tyre temperature cannot be fully accounted for. A similar effect would be expected for cloudy vs. sunny days (though not tested here).

An important result emerging from the analysis in Figure 3-5 is that the tyre temperatures seem to be somewhat more closely related to road surface than to air temperatures, as the R^2 values are somewhat higher for road than for air temperatures. Then one shall note that these measurements were made at the speed of 50 km/h, and that at (say) 80 km/h (at which the tyre noise label is determined) the relation could be different since at 80 km/h the air turbulence which cools or heats the tyre will be about 2.5 times higher than at 50 km/h.

In the paper, the following recommendations were made:

- Using air temperature or road surface temperature as a single variable in correction procedures are not the ideal solution for International Standards that require valid temperature correction mechanisms for all climatic regions around the world.
- A promising solution is to include <u>both</u> variables to account for the different influences they have on the tyre temperature.
- An alternative is to directly integrate the tyre temperature in the correction approach. However, tyre temperatures vary due to location and time in a very complicated matter, so before introducing tyre temperatures for the correction more research is needed
- Furthermore, it was again consistently shown, that not solely the A-weighted SPL should be corrected, but also the different frequency spectra, as the behaviour of the sound generation is different at different frequencies. However, to actually do so, more research is needed.

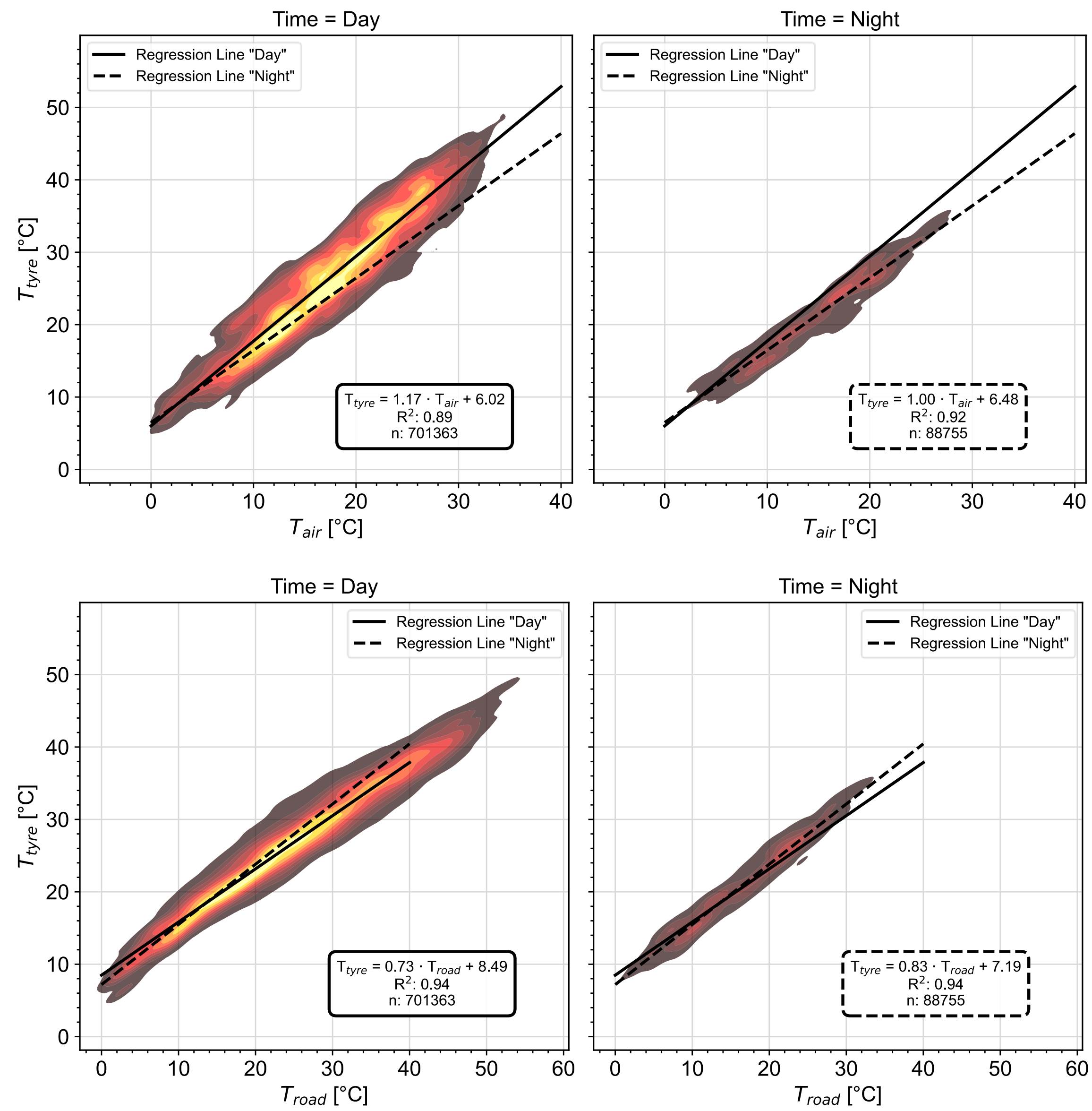


Figure 3-5: Relationships between T_{tyre} and T_{air} (upper part), and T_{road} (lower part) during daytime with varying amount of solar radiation (left) and during night-time, i.e., without solar radiation (right).

Analyses of uncertainty sources in an International Working Group under GRBP of UN/ECE:

Figure 3-6 shows the temperature correction for the R117 which contains the relevant measurement method for the tyre noise label. Currently, in the vehicle noise regulation R51.03, there is no correction for temperature, even though tyre/road noise is a substantial part of vehicle noise.

The GRBP informal working group IWG MU has the task to analyse the uncertainty of tyre and vehicle noise measurements in ECE Regulations R117 (tyres) and R51.03 (vehicles). It is chaired by one of the members of STEER (Berge). IWG MU has proposed several documents on how to handle uncertainty in general (Document of Reference, [GRBP, 2021b] and amendments to R51.03 concerning vehicle and tyre preparations prior to testing, [GRBP, 2021a]. One of the uncertainty sources of concern is the temperature influence. Although, this is not entirely relevant to the tyre noise labelling, the considerations of the IWG MU are interesting as it relates to mainly tyre/road noise.

In R51.03 (type approval of sound levels of M and N categories of vehicles) there is a constant speed test (for M1, N1 and M2 < 3500 kg) in addition to the full throttle test. For most cases, the reference speed will be 50 km/h for the constant speed test. The IWG MU has proposed to include a temperature correction procedure for the measurement of the tyre/road noise contribution to the constant speed test [GRBP, 2021c].

The temperature correction is based on ***air temperature*** and is a non-linear correction as shown in equation (3) and illustrated in Figure 3-6.

For each individual test run (gear, speed and vehicle side), a tyre/road noise reference shall be calculated for the applicable air temperature $\vartheta_{crs,j}$.:

$$L_{TR,crs,j,\vartheta crs} = L_{TR,crs,j,\vartheta_{ref}} + K_1 \times \lg\left(\frac{\vartheta_{ref} + K_2}{\vartheta_{crs,j} + K_2}\right) \qquad (3)$$

- Where ϑ_{ref} = 20 °C and
- K_1 = 3.4 for C1 and C2 tyres and
- K_2 = 3.0 for C1 tyres 15.0 for C2 tyres.

In this proposal it is stated that the correction can be applied down to an air temperature of 0 °C. If measurements below 0 °C are made, the correction at 0 °C shall be applied, see Figure 3-6. For R117, however, measurements with an air or road surface temperature below 5 °C are not acceptable.

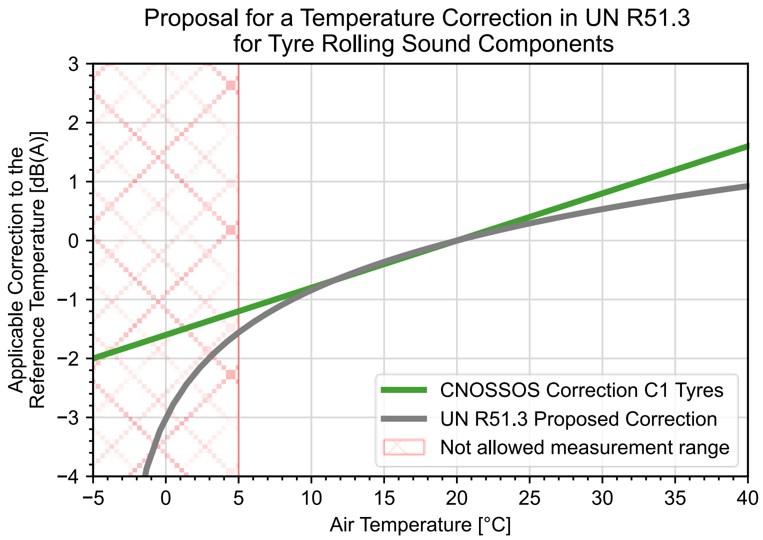


Figure 3-6: Proposed temperature correction for R51.03, compared with the present correction for C1 tyres in CNOSSOS-EU. The figure is from [OICA, 2021] but has been edited by the authors without changing any data.

The very non-linear shape of the R51.03 proposed correction is very different from all data collected in the ISO work and when transferred to road temperatures it also becomes different from that in R117. There are no references given in the document presented to IWG MU [OICA, 2021], but assumably, the proposal is based on measurements the vehicle industry has performed during type approval or COP testing.

For regulations R117 and R51.03 there are mainly the following differences:

- different reference speed (80 km/h for R117 and 50 km/h for R51.03)
- different test conditions regarding tyre inflation pressure and tyre load
- different temperature correction procedures (road surface vs. air temperature)
- different relations between noise and temperatures (both slope and non-linearity)

It should be noted that R117 is a homologation procedure for tyres, while the constant speed test in R51.03 defines the tyre/road noise contribution for a specific tyre used on the test vehicle to the overall vehicle sound level during vehicle type approval.

To align test procedures, STEER thinks that a first step should be to agree on a common temperature correction procedure. In the short-term it should be based on air temperature influence, as this is normally more stable during testing and not so influenced by sunshine/clouds etc, but in a long-term perspective it should be based on both air and road temperatures.

3.2.5 Conversion between temperature coefficients based on road and air temperatures

Since ISO and the vehicle industry (through its influence in IWG MU) suggest the use of air temperatures and the tyre industry wants to keep the use of road temperature in R117, it is useful to be able to convert between those systems. Therefore, in Deliverable D3.1 a procedure to convert between air and road temperatures is discussed and a proposal is made. The background is a great number of studies of the relations between air and road temperatures, also considering what has been reported above. STEER proposes a model that uses the two K factors (slope coefficient) 1.44 and 2.0, where K = 1.44 is used below 20 °C and K = 2.0 is used above 20 °C. For a linear air temperature-based model, as suggested by ISO and STEER, converted to road temperature-based, the latter will be piecewise linear (two linear regressions with different slopes) which actually quite well fits the existing R117 model, but has higher slopes, i.e., correction coefficients. See further the conclusions.

3.2.6 Linear or non-linear noise-temperature relation?

Based on all the work with data collection in ISO, STEER suggests that the air temperature-based model shall be linear over the appropriate range, which is from 5 to 35 °C. For an optional road temperature-based model (not preferred but corresponding to that existing in R117) STEER suggests a piecewise linear model with two linear regression lines of different slopes and connected at the reference temperature 20 °C.

3.2.7 Suggested temperature correction to noise levels

As the preferred short-term option, STEER suggests that the air temperature-based model presented in Table 3-3 and in graphical form in Figure 3-7 is applied. The decision to use air temperature is motivated in Deliverable 3.1. One of the reasons is that studies indicate that at the relatively high speed of 80 km/h, tyre temperature is somewhat more influenced by air than by road temperature, i.e., that air convection around the tyre has a larger effect than heat conduction in the tyre/road contact patch.

Table 3-3: Temperature coefficients suggested by STEER, based on air temperatures (will be introduced into ISO/DTS 13471-2:2021).

Tyre class (t) → **Road surface category ↓**	**C1**	**C2**	**C3**
Dense asphaltic surfaces	-0.10	-0.06	-0.04
Cement concrete surfaces	-0.07	-0.04	-0.03
Porous asphalt surfaces	-0.05	-0.03	-0.02
Other surfaces	See Note 2 and/or Appendix A in ISO/DTS 13471-2		

The reference surface specified in ISO 10844 belongs to the category dense asphaltic surfaces.

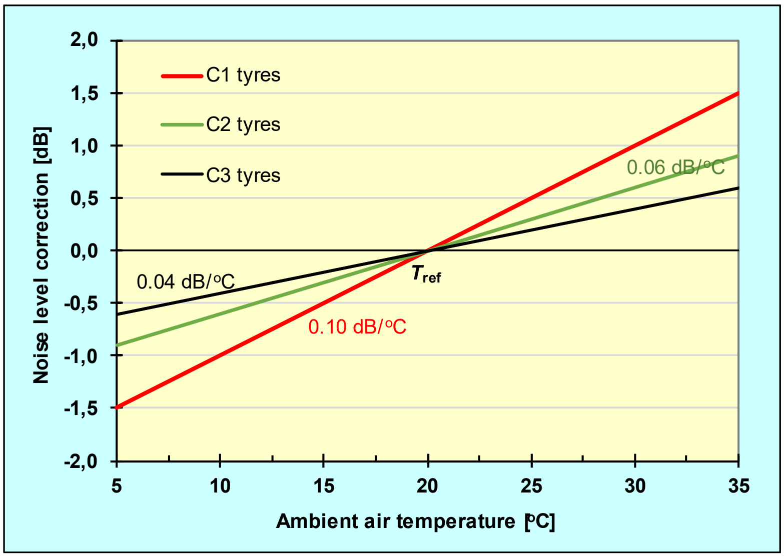


Figure 3-7: Illustration of the temperature correction model. In this case the data for dense asphaltic surfaces are used for the three tyre categories C1, C2 and C3. Coefficients for other road surface types are listed in Table 3-3.

Applying the conversion factors between air and road surface temperatures, the proposal by STEER is presented in Table 3-4 and in Figure 3-8. The latter illustrates only the case for C1 tyres.

Table 3-4: Temperature coefficients suggested by STEER, based on conversion from air to road temperatures. The reference temperature is 20 °C.

Tyre class (t) → Road surface category ↓	C1	C2	C3
For temperatures ≤ 20 °C	-0.07	-0.04	-0.03
For temperatures ≥ 20 °C	-0.05	-0.03	-0.02

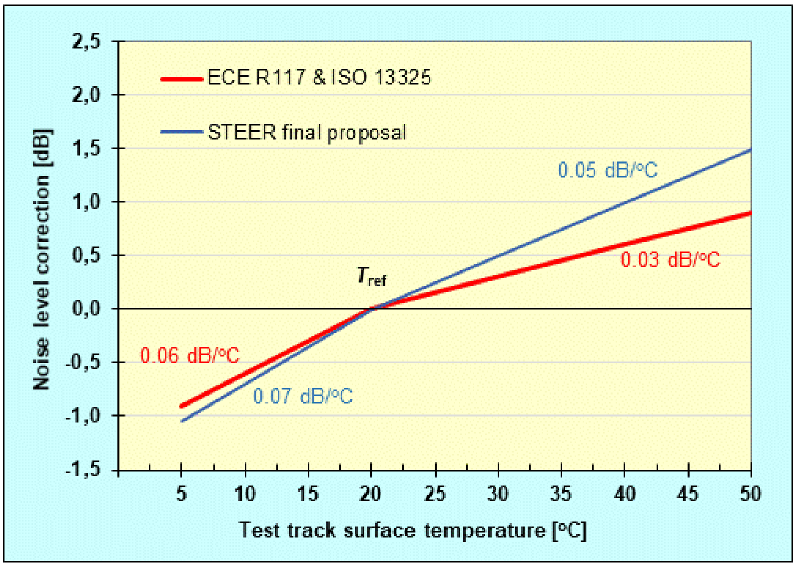


Figure 3-8: Illustration of an alternative temperature correction model for measurements of tyre category C1, in accordance with R117 and ISO 13325. In this case the road surface is the reference surface specified in ISO 10844.

If the correction proposed by OICA (Figure 3-6) is converted into the same diagram (Figure 3-8), using the same air-to-road temperature conversion factors, that correction will be closer to STEER in the range 5-10 °C but closer to R117 at other temperatures. But it will be a complicated non-linear relation which will need to be calculated in two equations.

Under the assumption that the real temperature influence on noise is closest to the STEER proposal in Figure 3-8, as STEER believes, the implication is that using the R117 or the OICA proposals (both) will result in corrected noise levels lower than they should be with a more accurate correction; especially the OICA proposal at temperatures above 20 °C would be very favourable for achieving low tyre noise levels after correction.

STEER has also identified several topics for further research. Most important is to develop a new correction model which is based on both air and road temperatures combined. Both temperatures are already measured, so it means no extra efforts by the industry, but research is needed to determine how the model shall be constructed. Research is also needed to determine whether speed should be a factor in such a model and how one shall consider the frequency spectrum.

Like for vehicle and test track influence, the ultimate solution to the temperature influence would be to go indoors with the measurements, i.e., to make them on a drum facility in a temperature that can be controlled to be close to 20 °C.

3.3 ISO 10844 test tracks

3.3.1 Introduction

When testing noise emission of road vehicles or tyres, such as for type approval or determination of tyre noise labels, the measurements are required to be conducted on the test track reference surface specified in ISO 10844. This reference surface is used in most, if not all, legal requirements for such measurements, such as ECE R117.

The historic background is treated in detail in Deliverable 3.1. Only a few important issues are mentioned below.

When the work to develop ISO 10844, as a reference test track surface during vehicle noise measurements, was started the intention was that tyre/road noise on this surface would have a minimum influence on the overall vehicle noise emitted during constant speed and acceleration at speeds around 40-60 km/h according to the vehicle noise regulations at that time. See Figure 3-9. The first ISO 10844 standard was published in 1994 and met the initial intention. It was intended only for vehicle noise measurements, but lacking another reference surface specification, soon it was selected to be used also for tyre/road noise regulations.

> This International Standard does not take into account the influence on tyre/road noise of purely tyre-related parameters such as tyre construction, tread pattern, inflation pressure and tyre loading. It follows that since the surface is not intended to produce significant tyre/road noise levels, it is not particularly designed for the testing and comparison of tyre/road noise.

Figure 3-9: Statement in ISO 10844:1994, under the heading “Scope”.

Thus, the ISO surface was never intended to be representative of common asphalt surfaces; instead, it was intended to give the lowest possible tyre/road noise, but without using a porous surface that could give sound absorption since the latter could reduce not only tyre/road noise but also power unit noise.

Since the original standard was published, a number of revisions or updates have been published. The following is a list of the different editions of ISO 10844 so far:

- ISO 10844:1994. This was the original version, not intended for tyre/road noise measurements.
- ISO 10844:2011. This was the first revision of the original version.
- ISO 10844:2014. This is still the latest published edition.

- ISO 10844:2021. This is the version which was published in December 2021 and is expected to be implemented in regulations in the near future.
- The 2014 edition is the currently implemented version and has been made mandatory to use in the following UN ECE regulations:
- ECE Reg.51.03 (revision 3, amendment 5)
- ECE Reg.117 (revision 4)
- ECE Reg.138 (revision 2, amendment 2)

It is stated in the standard text that the 2014 version:

- produces consistent levels of tyre or road sound emission under a wide range of operating conditions including those appropriate to vehicle sound testing,
- minimizes inter-site variation,
- provides minor absorption of the vehicle sound sources, and
- is consistent with road-building practice.

Note that it is not stated that it produces typical or representative levels of tyre noise. That it is *consistent with road-building practice* is arguable, as no such pavement has been paved on actual roads. This subject is treated in detail in the STEER Report for Task 2.2.

3.3.2 Round Robin Tests of ISO 10844 test tracks

To determine how the various test tracks influence tyre/road noise measurements, a number of experiments have been made to reproduce tyre/road noise measurements on different test tracks; so-called Round Robin Tests (RRT). The tests for which STEER has had access to results are five, two made many years ago and three made quite recently:

- RRT made by M+P in 2005, in Europe (7+2 test tracks)
- RRT made by JSAE in 2006, in Japan (8 test tracks)
- RRT made by VDA in 2016, in Europe (13 test tracks)
- RRT made by ETRTO for ISO/TC 31/WG 11 in 2018 (?), in Europe (4 test tracks)
- RRT made within the project ELANORE in 2021, in Europe (3 test tracks)

These are briefly summarized below. A more detailed presentation of the results appears in Deliverable 3.1.

RRT by M+P in 2005: Dutch consultant company M+P performed several coast-by and accelerated pass-by measurements with a test vehicle on nine different surfaces using four different tyres as part of a Round Robin Test (RRT) for test tracks constructed according to ISO 10844:1994 [Van Blokland et al., 2006]. Seven of the nine surfaces were supposed to comply with ISO 10844 and were designated ISO1, ISO2, …ISO7. The other two surfaces were SMA surfaces, designated SMA1 and SMA2. Four car tyre sets were used in the tests, of which one was a slick tyre (thus not a legal tyre), one was a summer tyre, one was a winter tyre and the fourth was an off-road tyre. The tested surfaces were located in north-western Europe (BeNeLux, France and Germany). In Figure 3-10, the coast-by levels (at 7.5 m) for a speed of 80 km/h are shown for the four sets of tyres on the nine test sections.

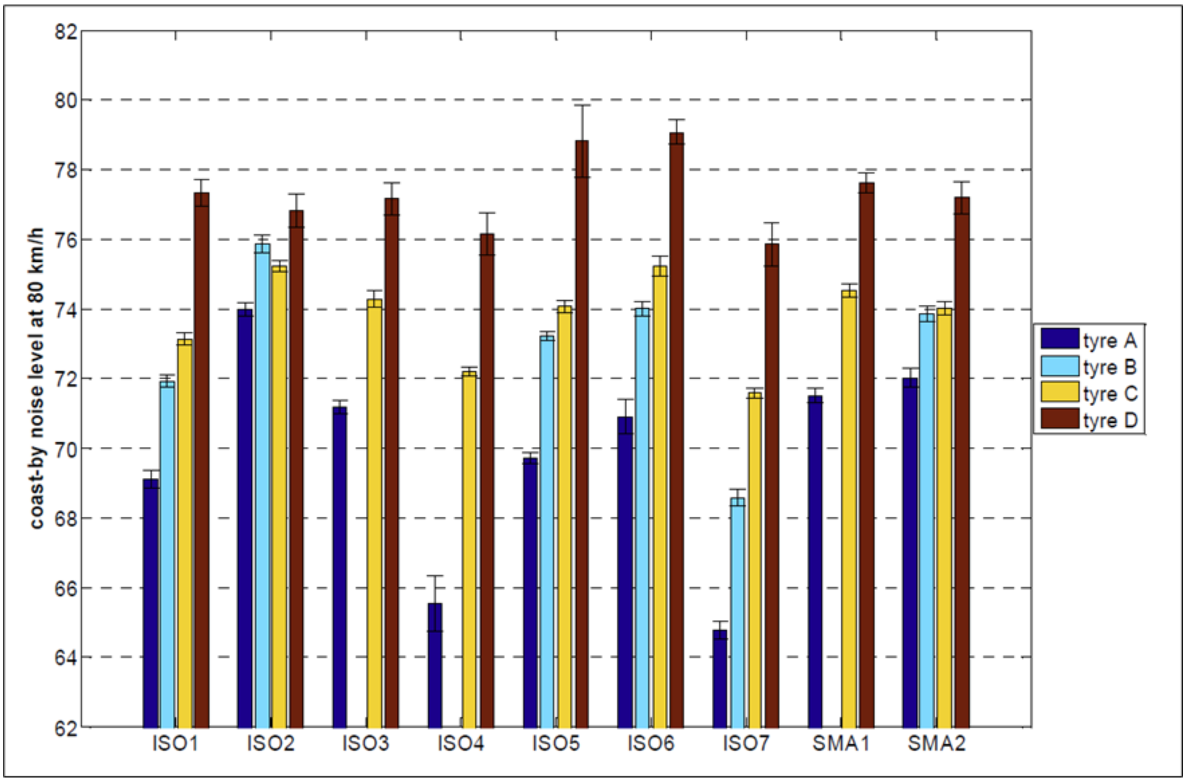


Figure 3-10: Coast-by levels at 80 km/h for all tyres at each test track; error bars show 95 % confidence intervals.

Excluding the two SMA surfaces and two test track surfaces which appeared to have higher sound absorption than accepted and, the maximum difference between the remaining five test tracks in noise levels for the four tyre sets were:

- Tyre A (slick tread): 4.9 dB
- Tyre B (summer tyre): 4.0 dB (NB, not measured on ISO3 and ISO4)
- Tyre C (winter tyre): 2.0 dB
- Tyre D (off-road tyre): 1.9 dB

If all seven ISO test tracks are included, tyre A showed a difference of 9.2 dB, tyre B a difference of 7.5 dB, tyre C a difference of 3.5 dB and tyre D a difference of 3.2 dB. Note that Tyre A is a slick non-patterned tyre.

RRT by JSAE in 2006: To supplement the European RRT described above, eight ISO test tracks were tested in 2006 by Japan Society of Automotive Engineers [JSAE, 2006]. As test tyres they used the tyres B and C from the European study, supplemented with two Japanese summer tyres. The test vehicle was a Japanese car used on all test tracks. Noise measurements according to the R117 test procedure were made at the speeds of 50 and 80 km/h (except missing one test track at 80 km/h).

The spread of the noise results is shown in Figure 3-11. It appears that among the seven or eight Japanese ISO tracks the spread in tyre/road noise levels were 1.7 to 3.3 dB at 50 km/h and 2.0 to 3.6 dB, which is lower than in the European tests.

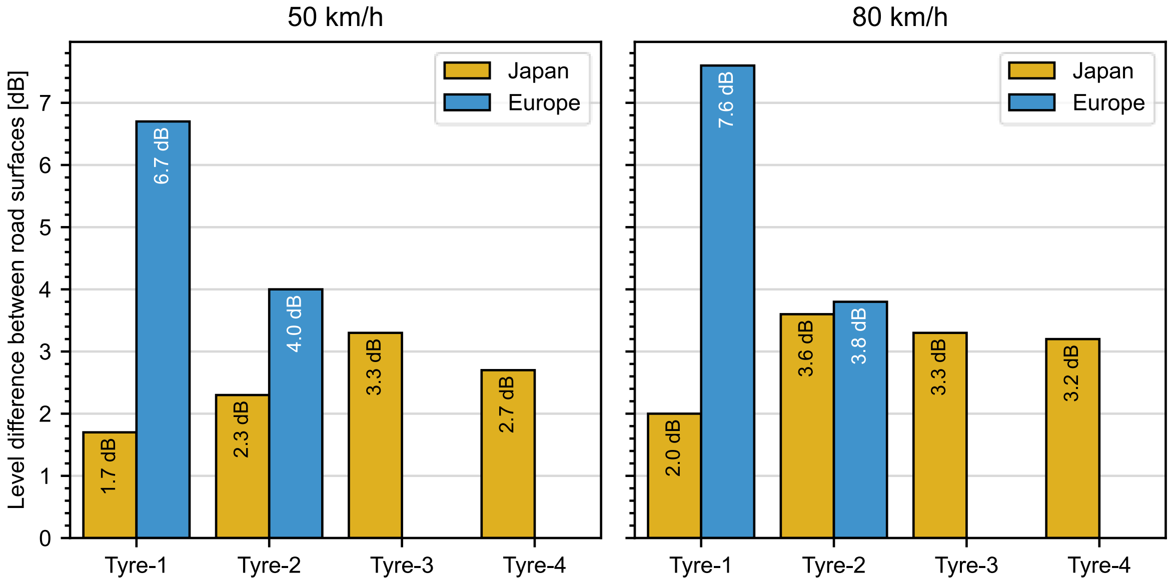


Figure 3-11: Spread of coast-by tyre/road noise levels at 50 km/h (left) and at 80 km/h (right) between the test tracks for the four tyres in Japan in yellow and the European tyres B and C in blue. Graphics by the authors, data from [JSAE, 2006].

RRT made by VDA in 2016: In this investigation, made by the German Association of the Automotive Industry (VDA), pass-by measurements (coast-by, cruise-by and acceleration) were made on 13 different ISO tracks in Europe in 2016. All test surfaces were constructed according to ISO 10844:2014 probably around or just after 2014. Thus, they were relatively new at the time of the RRT.

An electric vehicle (VW e-Golf) was used for testing. The following tyre sets were used:

- Four different typical summer tyre sets by different tyre manufacturers, size 205/55R16
- One typical summer tyre set, size 245/40R18
- One slick tyre set (without negative profile), size 205/55R16
- One SRTT tyre set, size 225/60R16

Driving conditions included a number of cruise-by at speeds in the range 10-80 km/h and pass-by at 2 m/s^2 acceleration, and 50 km/h. All were made with the engine switched-on.

The basic results were presented in [Richartz et al., 2019]. There is no official report containing all measured data available, only the summary of some of the results that were presented at this meeting. Figure 3-12 shows the results from cruising at 50 km/h for the 13 test tracks. The red dots in the figure (R06) are values for the SRTT tyre and the green dots (R02) are values for the slick tyre. The grey line shows the average levels for the tyres (excluding the slick tyre) on each test track.

The main conclusions from this figure (excluding tyres R02 and R06 from the analysis) were:

- The sound level **spread** among the test tracks for **tyres** with tread pattern is approx. **5.0-5.9 dB** depending on tyre.
- Without the SRTT tyre, the spread among test tracks remains nearly unchanged with a range from **5.0-5.7 dB** depending on tyre.
- If test tracks S09 and S12 are not counted, due to their measured sound absorption (although they were originally certified), the spread is reduced to approx. **2.6-3.2 dB**, depending on tyre.

Note that an analysis of the absorption data revealed that S09 and S12 appeared not to meet the requirements of ISO 10844:2014, although they were produced to do so.

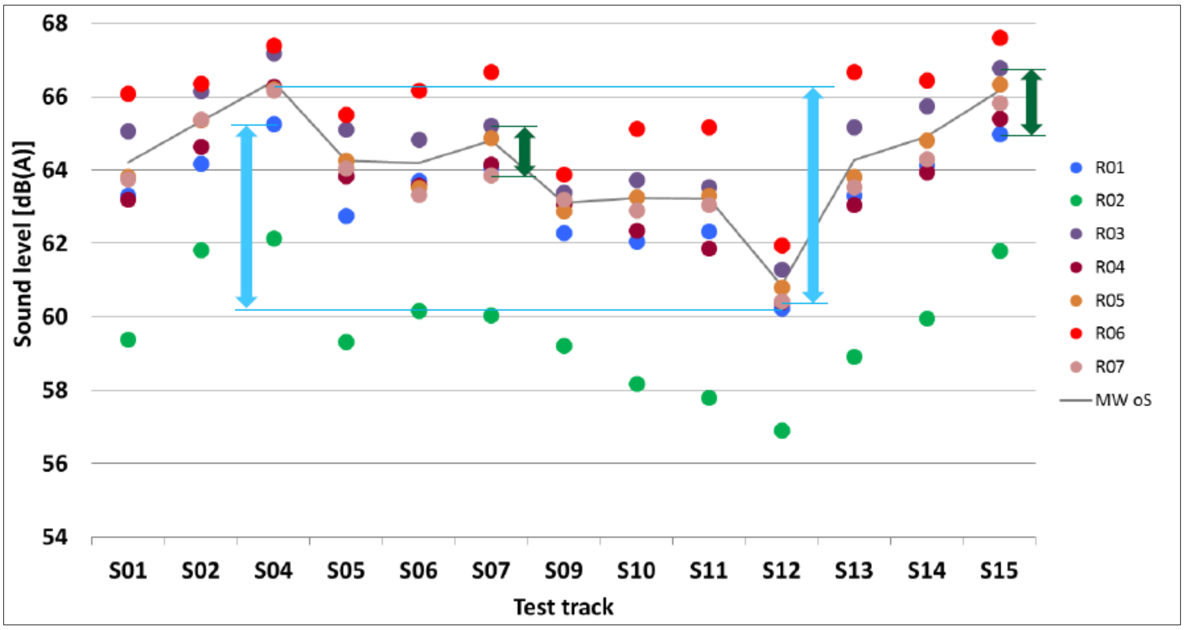


Figure 3-12: Cruise-by levels at 50 km/h, for seven tyres on 13 different ISO test tracks [Richartz et al., 2019]. See the text for further information.

RRT made for ISO/TC 31/WG 11 by ETRTO in 2018 (?): The main results of this RRT were presented by ETRTO in 2019 [ETRTO, 2019].

This RRT involved five different tyres (both summer and winter, 16" and 18") and four different ISO test tracks. In this case, all measurements were conducted at the speed 80 km/h, to meet the requirements of R117. Figure 3-13 shows the results.

Their main conclusions were that these results, with a spread of 1.3 to 2.4 dB depending on tyre, were in line with the findings in the VDA RRT. Then it shall be noted that this study included only four test tracks while the VGA study included 13 test tracks. Of course, it is natural that differences increase when more test tracks are added to the sample, or vice versa.

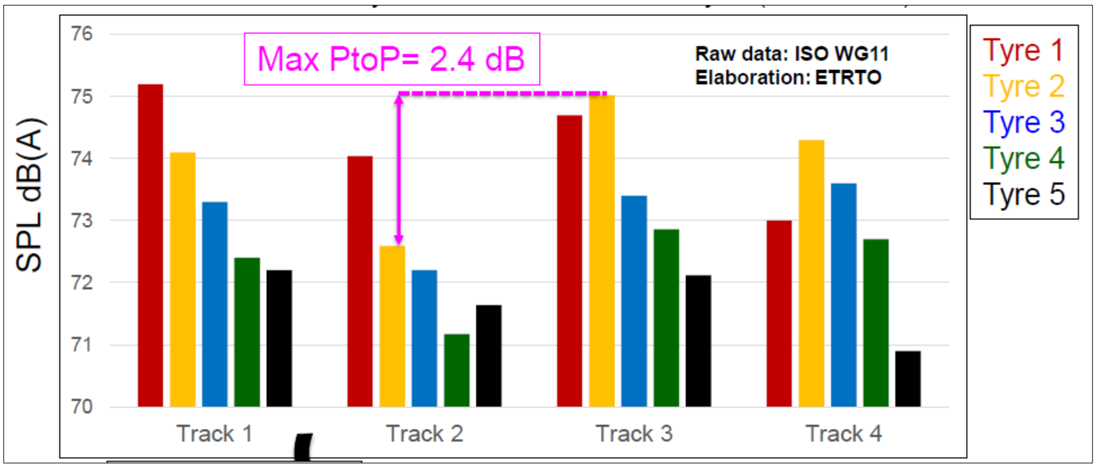


Figure 3-13: Results of the RRT by ISO/TC 31/WG 11, elaborated by ETRTO. Results show track-to-track sound level variation at 80 km/h [ETRTO, 2019].

ETRTO did also get access to the raw data from the VDA study and presented the track-to-track variation at 80 km/h. These results are shown in Figure 3-14. They are more relevant to the STEER project than the results presented in Figure 3-12 as those measurements were made according to R117. The slick tyre is excluded from the comparison.

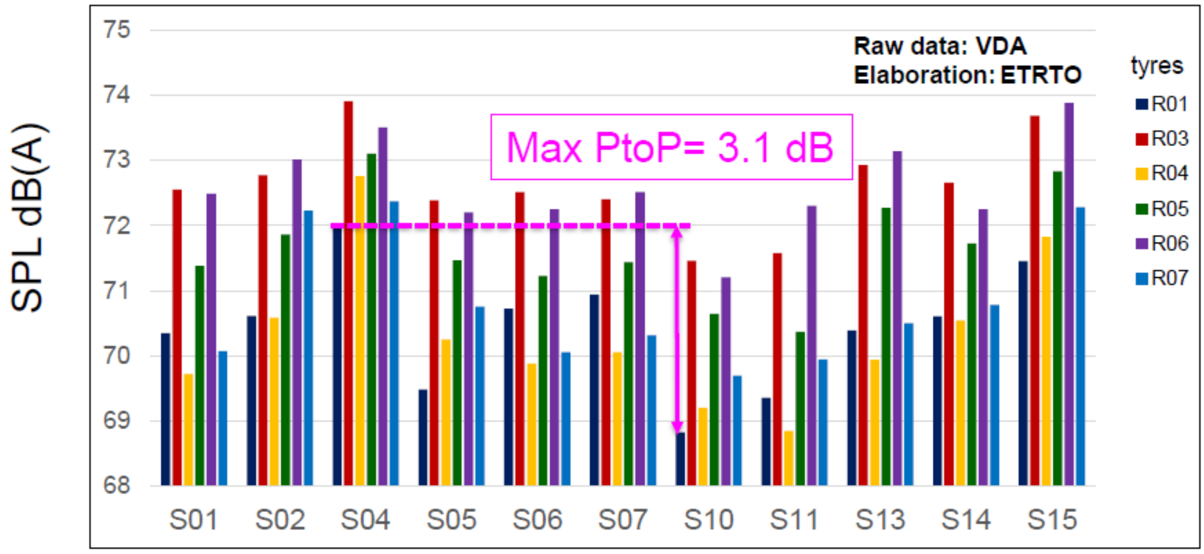


Figure 3-14: The VDA RRT results elaborated by ETRTO showing track-to-track variations at 80 km/h [ETRTO, 2019].

In the VDA study, for 80 km/h as reported by ETRTO in Figure 3-14, the spread in tyre/road noise levels between the tracks seems to be 2.3 to 3.9 dB, depending on the tyre set.

RRT made within the ELANORE project in 2021: In the Polish-Norwegian EEA-project ELANORE[7], the main objective is the improvements of the labelling of tyres, both for noise and rolling resistance. In this project, an RRT on ISO tracks, as well as on normal trafficked roads are planned. In 2021, the first part of the RRT was conducted on three ISO tracks in northern-central Europe.

The measurements consisted of coast-by measurements using a test vehicle with five different C1 tyre sets (summer, winter, all season), including a set of SRTT tyres, The measurements were made according to R117 regarding the tyre load, tyre inflation pressure and test speeds (70 to 90 km/h). Additionally, tests speeds of 40, 50 and 60 km/h were used.

A second subsets of tests were made where the inflation pressure was increased by 15 %, while the load was reduced by 15 %. These were designated as “ModR117” test. These test conditions correspond to typical tyre load and inflation pressure values for the test vehicle operated in typical daily conditions.

In addition, 11 sets of C1 tyres were measured with the CPX trailer of Gdansk University of Technology, including the two reference tyres (P1 and H1) of the CPX ISO standard (ISO/TS 11819-3). Test speeds were 50 and 80 km/h. Due to bad weather (rain) on two of the ISO tracks, only part of the test program was completed.

At the time of this report, only minor results from one of the ISO tracks are available, regarding the influence of changes in load and tyre inflation pressure and these results are presented in Deliverable D3.1, see also Sub-chapter 4.1. The full planned test program for the ELANORE RRT is expected to be completed in 2022.

3.3.3 Discussion and conclusions

Discussion: At hindsight, the RRT:s in Europe and Japan in 2005-2006 did not present so alarming spread in tyre/road noise levels as we would expect today from the original ISO 10844 edition. It appeared to be a spread from 2.0 to 4.0 dB between test tracks, depending on which tyre was considered. This is actually not worse than what the VDA and ETRTO studies arrived at more than a decade later. Yet, it is too much.

It appears that the spread between the 13 test tracks in the VDA study (for cruise-by at 50 km/h) is surprisingly high (almost 6 dB); in fact, not lower than in the RRT made in 2005, before ISO 10844:2014 was published. In the VDA study for 80 km/h, as reported by ETRTO in Figure 3-14, the spread in tyre/road noise levels between the tracks seems to be 2.3 to 3.9 dB, depending on the tyre set. However, ETRTO left out tracks S09 and S12, and if they had been included, the spread would have been substantially higher. The reason why ETRTO left out S09 and S12 was that they had too high sound absorption and thus were not meeting the specifications of ISO 10844:2014. But even if they did not meet the 2014 standard, they may have been used for type approval test and for labelling of tyres. Therefore, it may be sensible to include such test tracks as an indication about the <u>actual</u> spread between test tracks.

Unfortunately, the ISO test tracks tested recently in these RRT:s are located only in western and middle Europe. Can one rely on test tracks in (say) eastern Europe, China, India, or

[7] NCBR Contract No. NOR/POLNOR/ELANORE/0001/2019-00

Indonesia being of equally high quality? Finally, it should be mentioned that the noise properties of ISO test tracks change with time, just as road surfaces with little traffic do. The test tracks included in these measurements were of quite similar age.

Conclusions:

The Round Robin Tests reported here seem to suggest that there is a stunning difference in noise levels between the test tracks of up to 6 dB if all test tracks are included. If test tracks such as S09 and S12, which were found not to fully comply with ISO 10844:2014, could be detected before they start operating for legal testing purposes, the spread in noise levels would be up to 4 dB.

Whether the real spread is 4 or 6 dB, it is too much. The variation between the ISO test tracks must be reduced substantially.

Another conclusion is that it seems that an original certification of a test track is not sufficient. Maybe the certification should be made twice, and the track must pass both times. At least part of the certification should be repeated after one or two years (presently it is required to be repeated after four years).

Finally, it should be noted that the STEER proposal originally included conducting an own advanced RRT. However, this part of the project was cut away by budget restrictions imposed by the sponsor.

3.4 Improving sound absorption measurements on ISO 10844 surfaces

The previous section showed one highly undesirable problem, namely that surfaces which are supposed to meet the sound absorption requirements are not actually doing it when tested again. The reason for this is unclear, but what is clear is that the sound absorption measurements are difficult to make. Therefore, a revision of the method has recently been made in ISO. The new version is ISO 13472-2:2021.

The main improvement in the method is to add one more microphone in the measuring tube. Testing made by, among others, one of the STEER partners (VTI) has shown that the new method is much better than the old one. Therefore, STEER proposes that the revised method is implemented as soon as possible. This will reduce the risk of a repetition of the mentioned problem.

3.5 Possibilities to reduce the site-to-site variation of ISO 10844 surfaces

Attempts to reduce the variation in noise properties of ISO 10844 surfaces have been made by using the main physical properties, macrotexture, air voids and sound absorption, to try to explain the measured noise differences. The 2014 version of ISO 10844 includes an informative Annex specifying a method to calculate the expected differences in noise levels between various test tracks, called END_T ("Expected pass-by Noise level Difference from Texture level variation”). However, the latter has not been very successful, so in the latest version (2021) it has been replaced by calculation of texture skewness, shape factor (g-factor), and texture spectrum.

The options currently under consideration are as follows:

1. **Modelling of test track noise properties:** Very tight requirements on road surface texture, including MPD (Mean Profile Depth) according to ISO 13473-1, skewness according to ISO 13473-2 and texture spectrum according to ISO/TS 13473-4, also the German-derived g-factor or skewness.
2. **Round Robin Tests (RRT):** RRT:s may be performed at regular time intervals to determine how the track noise properties differ between each other or to a defined reference. Thereafter a correction may be made to normalize all tracks to a similar and defined reference. Very limited RRT:s have been conducted in the past. It would be impractical and too expensive to perform on most (hundreds of) ISO test tracks worldwide.
3. **Calibration by using reference tyres:** By selecting reference tyres with very stable tyre/road noise properties and measuring noise emission from them at regular time intervals on every ISO test track, the method can provide a relatively accurate measure of the test track noise properties. These can then be used to normalize the surface to a defined reference.
4. **3D-printed reference surface**: A durable and accurately copied hard surface from a defined ISO test surface can be applied in the wheel tracks of the test track using 3D-printing[8]. It can be used to produce replicas of a reference surface (the same for all users worldwide) applicable and virtually identical on all test tracks. Most of the deviations in noise properties can be eliminated if this method is used. Although 3D-printing is already possible, in principle, it is not yet tried to lay such pavement replicas on an actual test track, but it is technically possible.

The 3D-printing option will likely be implemented in the future; although it may be in a future indoor method using a laboratory drum covered with the 3D-printed pavement replica. Discussions about the implementation of drum measurements are currently taking place in various working groups.

Options 1 and 3 are considered as the currently most promising alternatives for calibrating ISO test tracks with respect to their noise properties while still being reasonably practical to implement. These are therefore discussed below.

3.6 Modelling of test track noise properties

3.6.1 The END_T procedure

The END_T procedure was used in the 2011 and 2014 editions of ISO 10844 but is deleted in the 2021 version. It is a complicated calculation procedure based on texture spectra of the surface

[8] Known technically as *Additive Manufacturing (https://www.twi-global.com/technical-knowledge/faqs/what-is-additive-manufacturing)*

profile which is compared to a reference spectrum. The result is a predicted difference in noise level compared to the reference surface texture.

The procedure has the disadvantage of missing the sound absorption properties and the asymmetry of the surface profile. Neither does it consider stick-slip or stick-snap motions in the tyre/road interface.

It is not considered further here as it would probably be inferior to the Müller-BBM procedure described below and that success stories do not exist.

3.6.2 The Müller-BBM procedure (as used in the RRT by VDA)

This method appears to be suggested by the consultant company Müller-BBM and used in the VDA study reported in Section 3.3.2.

Based on the measured surface parameters VDA developed an equation for estimation of a pass-by level at 50 km/h as shown below:

$$L_{crs} = 60.3 + 27.7 * MPD^{1.5} - 143 \cdot \left(\frac{g \cdot MPD}{(100 \cdot 0.97)}\right)^{4.3} - 36 * \alpha^{0.9} \; [dB] \qquad (4)$$

where

MPD = Mean profile depth in mm

g = g-factor, a factor between 0 and 1.

α = sound absorption factor, between 0 and 1

Figure 3-15 shows a comparison between calculated values from equation (4) and measured levels. It is assumed that the measured levels are the average of all seven tyres. The differences between the measured and calculated data suggest an uncertainty (95 % coverage) of only (±) 0.5 dB. Such an uncertainty, if achieved generally for coast-by at 80 km/h and not just in the VDA study for cruise-by at 50 km/h, would potentially be useful to normalize the ISO test tracks to within an expanded uncertainty of less than 1.0 dB, which would be a great progress.

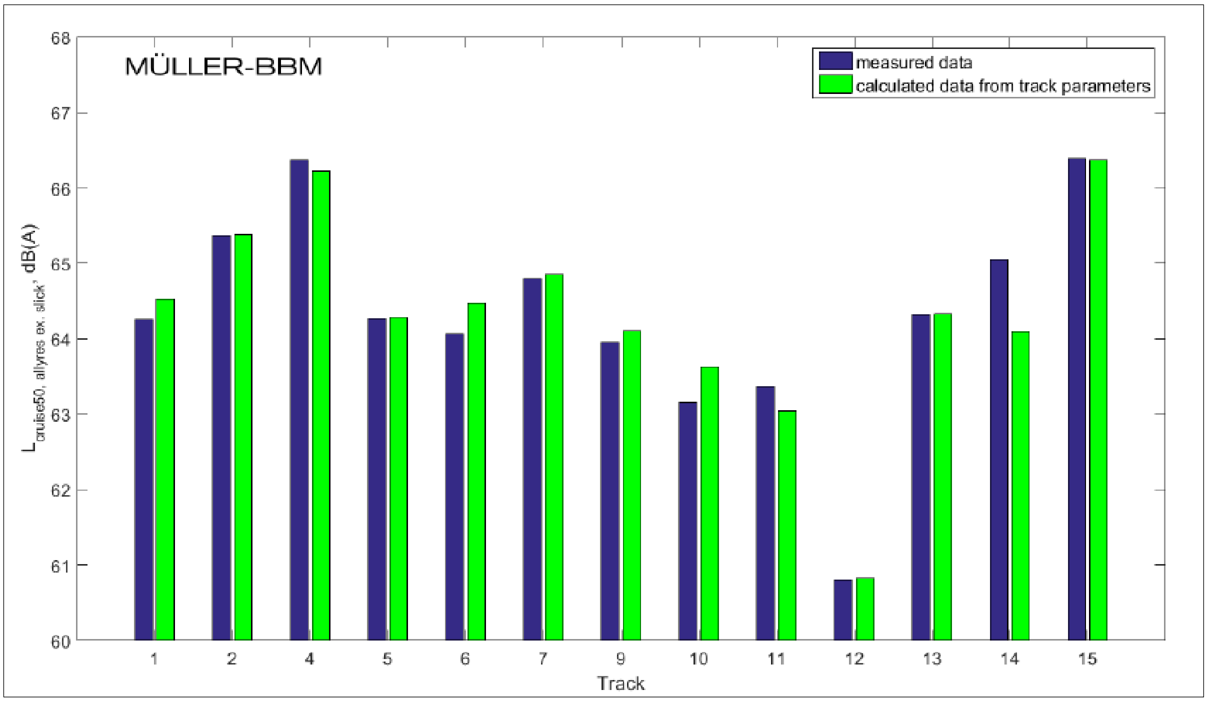


Figure 3-15: Comparison of calculated levels (green bars) according to equation (4) and measured cruise-by sound levels at 50 km/h [Richartz et al., 2019].

3.7 Calibration of ISO test tracks by means of reference tyres

3.7.1 The principle

It is suggested that the solution to the reproducibility problem is to introduce a calibration procedure. Such a calibration procedure has become possible recently, after a number of other ISO standards have been completed and published. Briefly, it is suggested to include:

1. Using a set of reference tyres of the SRTT 16" type, specified in ISO/TS 11819-3,
2. mounted on a relatively well-defined vehicle,
3. conducting tyre/road noise measurements according to the method in R117,
4. normalizing the resulting noise level to a reference temperature using ISO/TS 13471-1,
5. and then normalizing the final result to some defined ISO 10844 reference level.

Then the tested ISO test track will be normalized to a common reference level, reducing the spread between results on different test tracks to a significantly lower level.

3.7.2 Reference tyres

The reference tyres must be produced to the highest possible standards and be available for a long time. As reference tyre, the 16" SRTT (Standard Reference Test Tyre) defined in ASTM F2493:20 and in ISO/TS 11819-3:2017 is suggested. The noise properties of the 16" SRTT has been demonstrated to have good correlation with noise properties of other passenger car tyres and with light traffic as a whole.

See further details about the reference tyre in Deliverable 3.1.

In order to average out a major part of the unavoidable tyre-to-tyre noise differences, due to tolerances in the production, it is suggested that eight tyres are used for the calibration, i.e., two sets of four tyres. These eight tyres should not be from the same production batch; ideally, they should be from different production batches. Tyres shall be loaded and inflated according to requirements in R117. Run-in and warm-up shall be according to ISO/TS 11819-3. The latter also specifies how the tyres shall be stored. It is suggested that these tyres are set aside to be used solely for this purpose, to avoid wear.

The tyres shall be checked for their rubber hardness before use, observing the method in ISO/TS 11819-3, at a temperature close to 20 °C and the result shall be within the specifications in ASTM F2493:20. If hardness has increased due to aging or use, they can be used even if hardness exceeds the maximum in the ASTM standard by up to three units, but then a correction for increased noise properties shall be done according to ISO/TS 11819-3. An investment in eight SRTT:s for 8-10 years would not be a significant burden compared to other test track costs.

3.7.3 The test vehicle and the noise measurement procedure

The test vehicle shall be a four-wheel passenger car on which the tyres fit and can be loaded to the same load on all tyres. The vehicle shall meet the requirements and be driven as specified in R117; i.e. at coast-by. This includes the wheel alignment.

Ideally, the vehicle and tyre industries should agree on a particular car to be used worldwide for this purpose. A less preferred alternative is to use one car from each continent (one European, one Asian and one American) which are assumed to influence noise emission and propagation in the same way. Preferably, it should be checked if such “continent-selected” cars would give different tyre/road noise, to minimize the vehicle influence on noise measurements. Note that, as eight reference tyres are used, they need to be tested in two sets of four tyres, mounted on the same test vehicle. The direction of the driving shall be the same as normally is used for R117 testing.

Noise tests should be made in full accordance with R117 for the range 70-90 km/h. In case the test track is also used for vehicle noise tests, measurements should also be made for the reference speed of 50 km/h; in this case with the same number of runs as in R117 and within the speed range 45-65 km/h.

3.7.4 Temperature corrections

In ISO/TS 13471-1:2017 a quite robust procedure for temperature corrections for noise measurements on the SRTT is presented. It is based on air temperature and expressed as a “temperature coefficient” (γ) in dB per °C, and for the SRTT and a dense asphaltic surface such as the ISO 10844, the coefficients will be:

- γ = -0.11 dB/°C at 50 km/h
- γ = -0.09 dB/°C at 80 km/h

To reduce as much as possible the uncertainty in the temperature correction, the aim should always be to measure during a season when air temperatures are the closest to 20 °C. In no case, the range 10-30 °C (air) should be exceeded.

3.7.5 Reported ISO 10844 Calibration Level

The average of all measured tyre/road noise levels, by means of regression read at the nominal speeds 80 or 50 km/h, normalized to the reference air temperature of 20 °C, should be the reported value, here named "**Calibration Level**". This represents the tyre/road noise property of the ISO surface on the test track. Measured values shall not be truncated to integers and no subtraction of 1 dB shall be made.

3.7.6 Global Average Level and Test Track Correction constant (TTC)

After a large number of test tracks of varying ages have been calibrated by this procedure, one can calculate a "global average" of them all. The nearest integer dB value to this average should be selected as the "**Global Average Level**". Then a "**Test Track Correction constant (TTC)**" may be assigned to the particular test track which is the difference between the Global Average and the Calibration Level. The TTC may be updated at time periods according to the results of the most recent global calibrations.

3.7.7 Frequency of calibration procedures

Since it is well-known that surface properties change with time, especially the first years, it is suggested that calibrations according to this proposal are conducted at times after laying of the surface, as follows:

- First time, when the surface is 3-6 months old
- 2nd time, when the surface is 12-18 months old
- and so on, each 3rd year if the surface is still in good condition.

It is expected that the TTC will change significantly during the three first years; depending on ageing and the traffic on the test track. The calibration procedure will reduce most of the effect of such changes.

3.7.8 Implementation in project STEER of the Reference Tyre Calibration procedure

To check the effect of implementing the Reference Tyre Calibration procedure, data of the most comprehensive RRT we know about is used, namely the VDA study reported in 3.3.2. The values presented in Figure 3-12 have been used to produce a Calibration. The average values of the tyres (the grey curve in the are used (named "All tyres"), but excluding the slick tyre, for the 13 test tracks. Then the values for the SRTT tyre (the red dots) are used for the calibration. The difference between each SRTT value and the average of all SRTT values are then used to correct the "All tyres" data, i.e., subtracting the SRTT difference values from the "All tyres" values. After this correction, a Calibrated result is achieved.

The result is shown in Figure 3-16. Remember that the slick tyre data is excluded since it is not a legal tyre. The result is a dramatic reduction of test track noise differences. Table 3-5 shows some core data. It appears that the spread in noise levels among test tracks is substantially reduced.

A comparison of the grey (SRTT) and blue (market tyres) curves in Figure 3-16 shows that the shape of the curves are similar. This means that the SRTT is fairly representative of the market tyres in terms of noise properties of the ISO surfaces, even though it is of a much older design. The same has also been found for classification of road surfaces for high-speed (car) traffic noise in general [Kragh et al., 2015].

In principle, one can find market tyres that would have similar properties as the SRTT in this respect. But market tyres are available only for a few years. Furthermore, they are rarely the same over the time period when they are available, as small improvements are often made from one year to another, even though the trade name stays the same. There is no guarantee that they are sufficiently stable in time as one would expect for reference tyres, which are subject to more rigorous production and intended to be stable and available for a long time.

For the label values to be comparable over many years, the ISO test track surface must be stable over time regarding its noise properties. A noise measurement in (say) 2030 should give the same value as a measurement in (say) 2022 for the same tyre. The use of market tyres cannot guarantee that. Actually, over the period when the ISO 10844 has existed (27 years), a firm aim with all modifications has been that the latest ISO surface specification would also be acceptable according to the older specifications; in this way at least in principle preserving the comparability over time.

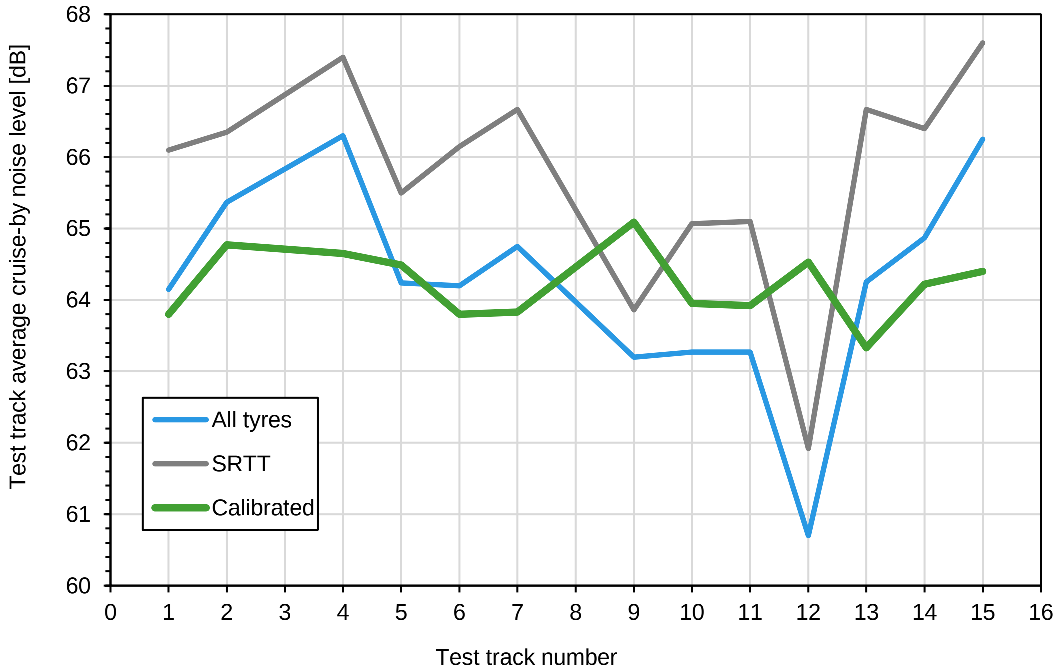


Figure 3-16: Comparison of measured cruise-by sound levels at 50 km/h for each test track (average for all tyres excl. the slick tyre in red) and the corresponding sound level for each test track after implementing the Reference Tyre

Calibration procedure (calibrated data in green). The data for the SRTT tyre is shown in the background in light grey colour. See text for further explanations.

Table 3-5: The result of implementing the Reference Tyre Calibration, in summary. Note that even if it reads "All tyres" the slick tyre is excluded.

	Average noise level [dB]	Noise level difference max - min [dB]	Standard deviation of noise levels [dB]
All tyres on all test tracks	64.22	5.55	1.46
SRTT on all test tracks	65.75	5.68	1.53
All tyres on all tracks after calibration	64.21	1.44	0.49
Influence of test track on noise levels after/before calibration, in %		26 %	34 %

3.8 Discussion of improvement of ISO test track reproducibility

3.8.1 Tightening of the ISO 10844 test surface requirements

Practical experience with laying of test tracks in the past 5-10 years have indicated that it is difficult to construct a pavement with closer tolerances than today at such low texture levels. Part of the problem is that the required texture is so low. The problems are illustrated by the practical examples of laying that are included in the present edition of ISO 10844, which are deleted in the edition of 2021 with the motivation "Avoided conflicts and confusion in interpretation of the technical requirements in the standard" (ISO 10844:2021).

Nevertheless, it would be better and easy to move the lower limit of MPD from 0.3 to 0.4 mm.

3.8.2 Homogeneity of the texture

The coast-by, cruise-by and accelerated pass-by are all methods relying on measuring a transient noise signal. Several issues make the time and spatial location of the peak A-weighted level a complicated matter:

1. Inhomogeneity of the texture is a well-known and unavoidable feature of pavement surfaces
2. Directionality of the noise emission is a variable depending on the tyre and the surface
3. Screening of noise propagation paths continuously change during a pass-by, due to the vehicle body and wheelhouse resonances, and also the tyres may give some screening
4. Additionally, multiple sound reflections between the vehicle underbody and the road surface is another problem influencing the noise propagating under the body from the tyres on the other side than the microphone; especially in the presence of a small patches having sound absorption.
5. Finally, a contributing factor is the distance the noise travels to the microphones when the maximum noise level is reached. It is not always when the vehicle is at the closest position

that the maximum noise occurs. This factor also depends on the homogeneity of the surface texture.

An example of how noise emission may vary during a vehicle noise passage is illustrated in Figure 3-17 which is a recording of time history per 10 m of five pass-bys made with a CPX trailer using the SRTT with the microphones close to the tyre and moving with the vehicle. Note the big difference between the wheel tracks and the variation between 10 m segments. The difference between the five curves within a wheel track is an effect of not driving exactly in the same lateral position each time. It is clear that homogeneity is a problem both longitudinally and laterally. The variations may be caused not only by surface texture inhomogeneity but also because of small vertical vibrations ("jumping") of the vehicle when it passes over a joint between the drive lane surface and the run-in surface.

This problem is one of the reasons why reproducibility and even repeatability of ISO test track measurements of maximum sound levels are far from ideal. It means that spot measurements of noise and texture and sound absorption features are not ideal and continuous measurements over the test track length are preferred. The best would be if the surface properties near the expected position of maximum noise levels are weighted higher than the data further away from that position.

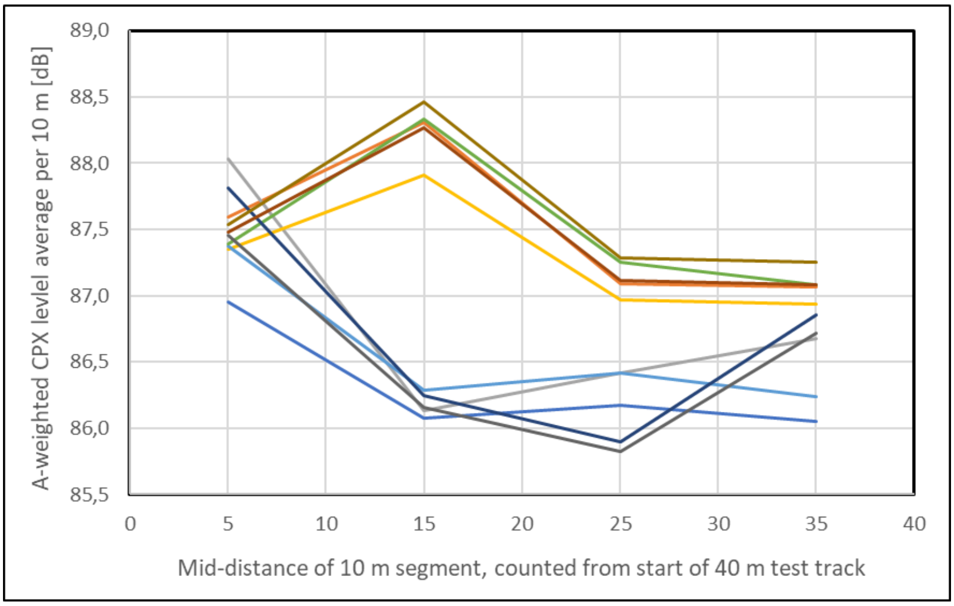


Figure 3-17: A-weighted CPX levels as a function of distance from start of drive lane (average per 10 m distance). The upper five curves are for the eastern wheel track and the five lower curves are for the western wheel track. The measurements were made on a two-month-old ISO test track laid 2020 near Skövde in Sweden.

3.8.3 The Müller-BBM procedure

At first sight of the results in Figure 3-15 the Müller-BBM procedure looks like a great success. One disadvantage of the Müller-BBM procedure is that it misses the noise generation mechanisms stick-slip or stick-snap in the tyre/road interface, the contributions of which are unknown, except that they do exist. Another and much more significant disadvantage is that there are three parameters in the equation and all of them are subject to significant uncertainties. Especially the MPD parameter has a very high sensitivity to the uncertainty of its measurement at the low MPD values that most ISO test tracks have (0.3 – 0.5 mm).

It is difficult to make a sensitivity analysis, but it can be mentioned that only the MPD determination has an uncertainty (95 % coverage) given in ISO 13473-1 of (±) 0.08 mm. If the measured MPD is 0.40 mm (for example), it will mean that MPD uncertainty limits would be from 0.32 to 0.48 mm, which will give a spread in dB values in Equation (4) of up to 4.2 dB. And this is without the uncertainties of the g-factor, the sound absorption and, not the least, the shortcomings of the model itself.

Therefore, the Müller-BBM procedure has a potential to give so high uncertainties, potentially amounting to several dB, which would limit or even disqualify the general use of the method.

Despite this, the differences between the measured and calculated data in Figure 3-15 suggest an uncertainty (95 % coverage) of only (±) 0.5 dB according to the author's calculations. If this model would be used to normalize the 13 test tracks in the VDA study to a common reference with the mentioned uncertainty, this would really look like a great success. But then one must realize that the model is optimized for exactly the measured values and conditions in this particular experiment. Such optimization can be done well if sufficiently many parameters are selected, and the same equipment and the same operators are used for all test tracks. But it may not work at all for another set of data, collected with different equipment and operators on different test tracks.

3.8.4 The Reference Tyre Calibration procedure

The advantage with this procedure is three-fold:

- All tyre/road noise mechanisms are covered, not only those which are causing influence by surface texture, profile asymmetry and sound absorption
- No extra test instruments are needed
- Uncertainties are low and there is no large sensitivity to any uncertainty factor varying regionally

The basic assumption is that the SRTT tyre is sensitive to ISO test track surface properties in the same way as normal tyres. That this is the case has been demonstrated in many studies related to characterization of road surfaces, for example in [Kragh et al., 2015] and [Donavan et al., 2011], and is even the justification for selecting this tyre as a reference to represent light vehicle tyres in traffic. Nevertheless, it is unavoidable that some tyres are special and will always fall outside the general picture. It is simply impossible to produce test tracks which will rank all tyres in the same way on any of the tracks.

The Calibration procedure suggested here would be easy to implement worldwide and requires only tyre/road noise measurements, including temperature correction (plus checking the rubber hardness). Unlike the Müller-BBM procedure, it does not require any advanced surface measurements; instead requires investment in eight SRTT tyres. As the tyres will be used rarely, they and even the test vehicle can be shared by test track owners located within reasonable distances and for a quite long time.

The uncertainties include the following sources:

- Variation in noise levels between SRTT tyres
- Uncertainty in the temperature correction
- Influence of test vehicle
- Uncertainty of the noise measurement, if not negligible compared to the above sources

The variation between SRTT tyres was studied by Donavan [Donavan et al., 2011]. He found an average standard deviation of 0.24 dB between individual tyres. Approximately the same estimation has been made in the uncertainty estimations of the SRTT in ISO/TS 11819-3. For an average of eight such tyres, standard deviation would shrink to below 0.10 dB.

The uncertainty in temperature correction could amount to max. ± 0.2 dB, assuming that the temperature coefficient may be in error by 20 % and temperatures would differ 10 °C from the reference 20 °C.

The vehicle influence should be low if a decision can be reached as to what vehicle to use. However, with the assumption that it is possible only to agree on one car in Japan, one in Europe and one in America, and if these are as similar as practical, the influence should be possible to reduce to less than ± 0.2 dB. It should be possible to select them to be similar in terms of ground clearance, tyre/wheel screening, wheelbase, etc.

The average of all noise measurements from all the runs (and two sides) should have a statistical uncertainty of much less than 0.2 dB.

Overall, this should sum up to an uncertainty (with 95 % coverage) of maximum 0.5 dB. As this procedure is general and not optimized to fit measured data in any particular RRT, this procedure would be independent on where in the world and by whom the calibration is made.

The implementation example showed excellent performance of the procedure. The spread in noise levels between the test tracks was reduced to only one-third of the non-calibrated data. In Figure 3-15 the standard deviation between the predicted (by Müller-BBM) and measured values is appr. 0.34 dB. This is lower than the 0.49 dB by the Reference Tyre Calibration procedure. However, it is not a fair comparison, since the Müller-BBM calculations are based on a model optimized using the same data as it is implemented for and with three surface variables. The same model will give far from so good results for other RRT:s; especially when the texture and sound absorption values are measured by other devices, as it is extremely sensitive to measurement uncertainties of texture and sound absorption. In contrast, the Reference Tyre Calibration procedure uses a general model which will be the same for all similar RRT:s. Of course, more implementations should be tested to give a statistically robust value, but the example based on the VDA noise measurement results was indeed very promising. It will also be possible to check the procedure (for three ISO test tracks) when the ELANORE project is resumed in 2022.

3.8.5 Conclusion and recommendations

First, it should be noted that the STEER proposal originally included conducting an own advanced RRT, which would be used for testing the implementation of the Calibration procedure. However, this part of the project was cut away by budget restrictions imposed by the sponsor.

It does not seem that the specification about how the ISO surface shall be constructed can be tightened significantly, with the aim to reduce spread in noise levels between test tracks, compared to the present situation. The exception is that the lower MPD limit should be moved from 0.3 to 0.4 mm. This would reduce the MPD variation (lowest to highest) from 133 % to 75 %. Simultaneously, test track surfaces that would be considered unsafe on highways due to wet friction concerns would not be used for noise testing. Some countries do not accept MPD values of less than 0.5 mm on highways.

The inhomogeneity of ISO test tracks should be addressed more than presently. However, it may be practically difficult to improve homogeneity substantially compared to now, since it is such an extreme surface. Instead, it may be worth considering the use of time averaging (like SEL, but over only the length of the ISO drive lane surface) to avoid the sensitivity to the noise peak. The present dependency on a noise peak that is influenced by surface inhomogeneity is unlucky. It is actually a similar situation as for noise characterization of road surfaces, where SPB measurements rely on noise peaks, but CPX measurements are preferred as they do not depend on spot-wise noise properties.

STEER proposes to introduce the new and improved sound absorption measurement method ISO 13472-2:2021, which should reduce the risk of test tracks being approved for sound absorption in error.

The Müller-BBM procedure for predicting the noise performance of ISO tracks seems to have been a success in the VDA study. However, it is because the procedure has been optimized based on the data in that study, something which is not likely to hold well in other studies. Most of all, it is extremely sensitive to uncertainties in the MPD determination; especially for the low MPD values (0.3 to 0.5). It therefore has a potentially low reproducibility.

The Reference Tyre Calibration procedure would be more generally applicable since it is not optimized for any particular set of data and is not sensitive to uncertain surface parameters. It still has uncertainties, but an estimation suggests that the method’s uncertainty may be limited to around 0.25 dB (expressed as standard uncertainty). Additional to this is the uncertainty of the model (that the SRTT represents the ISO test track influence on noise measurements) which may be taken as a conservative value of 0.49 dB according to Table 3-5. Then the overall standard uncertainty would be around 0.55 dB, which would substantially reduce the present spread in noise levels from different test tracks around the world. This procedure is therefore suggested to be used for normalization of noise properties of ISO test tracks.

4 Representativity of the tyre label

4.1 Influence of abnormally low inflation and load on noise levels

In R117 the test load and tyre inflation pressure are depending on the load index of the tyre. In general, the test load shall be 50 to 90 % of the reference load, defined by the load index, but the average test load for all tyres shall be 75 ± 5 % of the reference load. For C1 tyres, the reference tyre inflation pressure is 250 kPa.

For typical C1 tyres, the tyre inflation pressure according to this definition can often be in the range of 150 to 200 kPa, depending on the load index. This is somewhat lower than recommended for passenger cars, which normally is the range of 220-260 kPa, depending on the recommended inflation pressure recommended by the vehicle manufacturer. When the tyre inflation pressure is low (but above the minimum of 150 kPa for C1 tyres), the contact area can be enlarged compared with the contact area with a higher inflation pressure. This could lead to a higher noise level and this relationship was part of this small investigation.

One of the tasks in the STEER project was to investigate if the test conditions according to R117 for these parameters could explain some of the lack of correlation between measured noise levels and labelled values.

4.1.1 Influence of deviating tyre pressure

The influence of the tyre inflation pressure on the noise levels was performed by the Gdansk University of Technology (GUT) at their drum facilities.

A total of six C1 tyres (four summer, one winter and one all-season) was tested at 50 km/h with an inflation pressure of 150 kPa and at 80 km/h where the inflation pressure varied from 180 to 240 kPa. Each of the tyres had a fixed load defined by their load index. The main results appear in Figure 4-1.

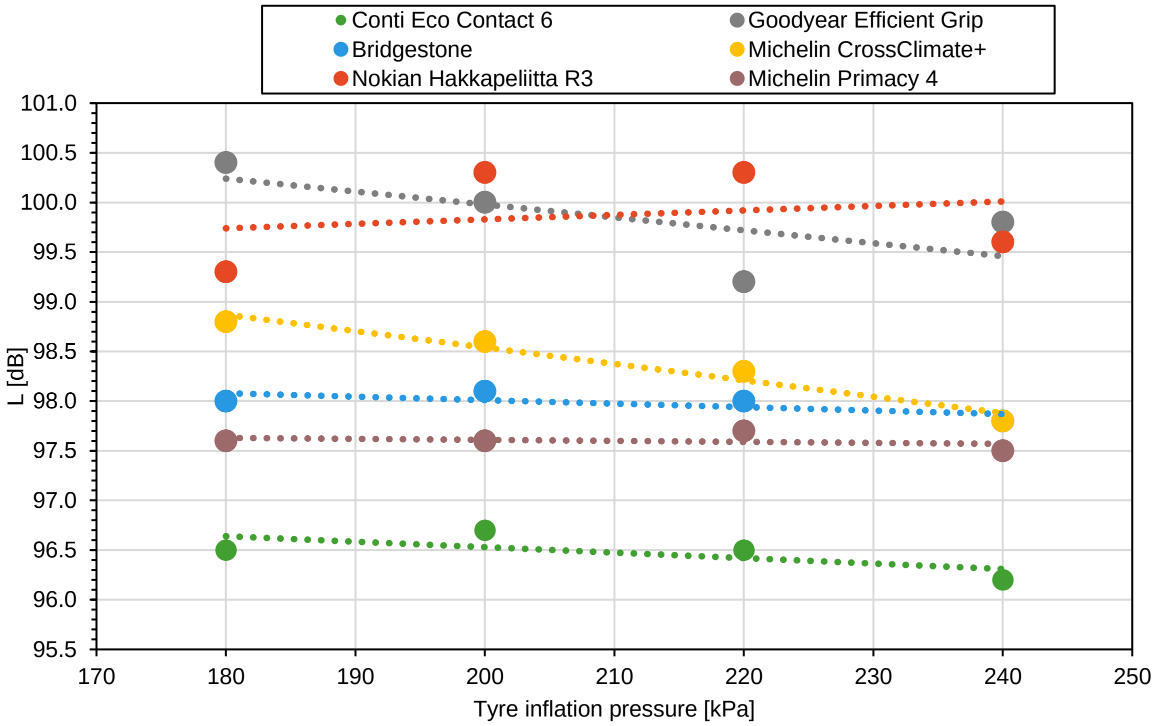


Figure 4-1: Tyre inflation pressure influence on measured noise levels for six C1 tyres.

The main findings were that three of the six tyres showed an influence of the tyre inflation pressure, with an ***increase*** of the noise levels of around 1 dB when the inflation pressure was ***reduced*** from 240 kPa to 180-190 kPa. Other tyres did not show any sensitivity to changes in the tyre inflation pressure.

Even if there is no firm conclusion, STEER proposes that the tyre inflation pressure should be as recommended by the vehicle manufacturer. Thus, this will be in line with the proposed amendments of R51.03 for the coast-by procedure to measure the tyre/road part. See STEER Project report WP4/ Task 4.1 for more details.

4.1.2 Influence of deviating tyre load

The influence of the tyre load was originally planned to be a part of the RRT that was taken out of the STEER project. Thus, the influence of tyre load must be based on previous studies, such as the LEO project [Berge et al., 2016b].

In this project, measurements were made with a CPX trailer, so it is deviating from the test conditions in Reg.117. From measurements on two Polish SMA 8 surfaces (similar max. chipping size as the ISO surface), the main conclusion was:

Some influence of the load was found. An increase in load in the range of 10-15 % gives an increase in noise levels around 0.4-0.5 dB on these SMA 8 road surfaces.

The influence of load has also been studied and summarised by Sandberg [Sandberg et al., 2002].

The main conclusions by Sandberg are:

1. Tyre/road noise is sensitive to tyre load for most but not for all tyres.

2. The load influence is much higher at low speeds than at high speeds.
3. Doubling of load can give an increase in noise level of approx.2 dB.
4. The influence of the tyre inflation pressure is highly sensitive to the road surface. On a rougher surface, drum measurements at GUT found a decrease of 0.2 dB if the tyre inflation pressure was increased by 10 %. On a smooth "ISO" surface, the effect was opposite, with an increase in the range of 0-0.3 dB.

Based on the available data on the load influence it is not recommended to do any changes in R117 on the test load conditions.

4.2 Representativity of one or a few tyres within a tyre line

4.2.1 Introduction

The term "**tyre line**" refers to tyres that share the same trade description or product name but may have different dimensions, load index or speed rating. For example, *Michelin Primacy 4* and *Goodyear EfficientGrip Performance 2* are two such tyre lines. Within a popular tyre line there may be 50-100 variants having different dimensions, load index, and speed ratings. But they share the same basic construction and tread pattern, although adapted to the variant. Another variation may be that when a tyre line is selling well and is produced over a long time, some minor changes may be made with regard to materials (such as the tread compound) from year to year, with the purpose to improve the performance or maybe to adapt to availability of the materials. Such minor changes are generally not indicated for the consumers.

Since the labelling regulation does not require that all variants of tyres within a certain tyre line are tested, it is common that tyre manufacturers save money by testing only the noisiest tyre(s) within such a line, and then giving the other tyres the same label. It is also common that a few tyre variants are chosen to represent all variants in a certain range within a tyre line.

To measure only the (estimated) noisiest tyre in a line is perfectly legal, and practical and economical as well, since the measurements for labelling are allowed to be the same as the measurements for type approval. Type approval intends to make sure that a certain noise level is not exceeded. The label will then show a noise level which is conservative for most of the tyre variants, but as the real noise level (at labelling conditions) would only be better than or equal to the labelled value, one cannot say that the system is violated from a legal aspect.

This simplification in the measuring system unfortunately means that when consumers select tyres, they will not have the full potential of the labelling system to select the quietest tyres. When such a simplified procedure is implemented, the consumers might in the best case only be able to compare the noisiest tyres in tyre lines, which seriously limits the value of the labelling system.

This problem was originally included in the project application to CEDR. However, CEDR required cuts in the project and this particular part was then cut away from STEER, so it was not part of the final project plan. However, VTI considered that this part is crucial for the project and, therefore, applied for a special project dealing with this issue from the Swedish Transport Administration (STA). This was granted to VTI by STA under a special contract with the title (in English translation) ”*Tyre labelling – Effects of noise measurements made only on a small part of the tyres*”. The intention was that the results shall be used in STEER despite the work is made in a separate project.

4.2.2 Test method and test surface

Since the measurements in this case require an exceptional repeatability, in order to distinguish between tyres that are of quite similar construction, it is impossible to do this in the standard way by coast-by measurements on a car, both for reasons of uncertainty and for project budget. Instead, it was decided to do this in the laboratory of the Gdansk University of Technology (GUT) in Poland, where they have a suitable drum facility with replica road surfaces and where temperature variation and other uncertainty factors can be minimal; see Figure 4-2. More illustrations are found in Deliverable D4.1. The measurement method is similar to the CPX method (ISO 11819-2:2017) but adapted for indoor drum measurements. Loading and inflating tyres was according to requirements in R117 for each tyre variant.

It turned out that GUT had removed its old ISO replica surface from the drum facility. Therefore, VTI produced a replica of a newly laid ISO 10844 surface near Skövde in Sweden, which had been approved to meet the ISO requirements. This replica was in plastic which then was transported to Poland where a copy in epoxy was made and fitted on the laboratory drum surface. This is so far the conventional way to reproduce a test track surface on a drum. It turned out that the final replica looks very good and similar to the original test track surface (although in another colour). An illustration appears in Deliverable D4.1. Its texture will be measured and compared to the texture on the test track. The MPD value of the original surface on the test track was 0.40 mm.

The noise measurements were made as time averages over 32 s at each of the speeds of 70, 73, 76, 79, 81, 84, 87, 90 km/h, It means that at each test speed measurements were taken over 100 to 125 drum rotations. Ambient temperatures were within 19.0 and 21.0 °C. Average tyre tread temperatures were within the range 31.0 to 36.5 °C. Tyres were warmed up before any measurements took place.

Figure 4-2: The laboratory drum facility at the GUT in Gdansk. The drum diameter is 2.0 m. An overview above and a zoom-in on the tyre/drum contact area below. Note the position of the microphones.

GUT had already before these tests made experiments about the repeatability of their drum measurements. The maximum actual speed deviation was within ± 0.2 km/h from the set speed. With a normal noise-speed relation, this corresponds to a maximum noise effect of ± 0.03 dB (expressed as standard deviation it means approx. 0.015 dB). The results indicated that single measurements at a specific speed were repeatable with a standard deviation of 0.03 dB. If the speed uncertainty and the noise measurement uncertainty are added, the standard deviation becomes less than 0.04 dB and when averaging over eight speeds, the overall standard deviation will be less than 0.02 dB. This is important since we want to compare noise of tyres with an uncertainty of repeatability of less than 0.1 dB and this was obviously achieved. Although not really needed, the results were corrected for deviations in ambient air temperature from the reference 20 °C by using 0.1 dB per km/h (as per ISO/DTS 13471-2:2020).

4.2.3 Test tyres

As test objects in the project, a major criterion was that the line should include many variants covering a wide range of dimensions, loads and speeds, and yet being labelled with the same noise level. The project budget allowed a maximum purchase of around 50 tyres. VTI finally selected and purchased 53 car tyres of very different dimensions (e.g., test loads vary from 270 to 670 kg). Three tyre lines were chosen after careful considerations:

- Pirelli Cinturato P1 Verde: representing a European (and international) quality brand

- Yokohama BluEarth-ES (ES32): representing an international (non-European) quality brand
- LingLong Greenmax HP010: representing an Asian (and international) budget brand

A picture of the test tyres, stored in the VTI lab before they were transported to Poland for measurements appears in Figure 4-3.

Figure 4-3: The test tyres stored before measurements.

For each of the selected test objects (tyres) the label values were noted in a table, along with all dimensional data and capacity in terms of speed and load ratings, but also the week of production. Some data about the test tyres are presented in Table 4-1 in condensed form. Attempts were made to obtain as wide ranges within each tyre line as possible (and available).

Table 4-1: Selected condensed data about the test tyres.

Tyre line	Number of tyres	Rim range [inches]	Width range [mm]	Profile ratio range [%]	Test load range [kg]	Max speed range [km/h]
Pirelli Cinturato P1 Verde	22	14 - 17	165 - 215	50 - 70	294 - 524	190 - 240
Yokohama BluEarth-ES (ES32)	16	13 - 18	145 - 245	40 - 70	270 - 570	190 - 270
LingLong Greenmax HP010	15	14 - 17	185 - 235	50 - 65	361 - 665	210 - 240

Labelled values were first noted from the two large tyre on-line shops, www.dackonline.se and www.dack365.se, from which most of the tyres were purchased. When the tyres arrived, it appeared that a few of them did not have a label fixed on them, which is mandatory, and for a couple of tyres the labels fixed on the tyres did not match the label values given on the web sites. In case of such discrepancy, always what was fixed on the tyre was used in our tables and analyses.

For at least one dimension for each of the tyre lines, four tyres of identical construction were purchased. The intention with this was to get an idea of how much the measured values for these nominally identical tyres will differ (to study tolerances and uncertainties). In several cases, tyres were selected in pairs where the pair had the same dimension but differed in terms of load index, or in speed rating (and sometimes also in labelled values). This will give, as a bonus effect, an idea of how much these slight tyre modifications will influence tyre/road noise emission.

Before testing, the tyres were run-in according to R117 by the crew in the GUT lab during the spring of 2021. Noise testing was made in June-August 2021 in the range 70-90 km/h as required in R117.

4.2.4 Observations when selecting test tyres

The three selected tyre lines demonstrate different policies in terms of noise testing. Here are some observations from the analysis of the labelled values:

- Despite the extremely wide range of tyre dimensions, the Yokohama tyres are all labelled with the same noise level (68 dB). The same applies to the energy label, which is C for all the tyres. For the safety label, however, the smaller tyres are labelled C while the medium and larger are labelled B.
- All the LingLong tyres are labelled the same, i.e., 71 dB for noise, C for energy and B for safety. However, there is one exemption, namely one of the reinforced tyres, which is labelled 72 dB. The range in dimensions for the LingLong tyres is not as wide as that of the Yokohama tyres.
- The Pirelli tyres are labelled with two noise levels: 17 tyres are labelled 69 dB, while 5 are labelled 70 dB. The latter include one small tyre and four large tyres. Energy and safety labels vary.

When looking at other tyre lines, the picture is more mixed: some have different (noise) label values, while some (the majority it seems to us) have the same label for the entire line or maybe two levels for two parts of the line (the latter similar to our Pirelli line used here).

4.2.5 Measurement results

The noise measurement results are summarized in Table 4-2 and Figure 4-4. The noise levels measured by the two microphones at each speed are averaged to represent an average speed of 80 km/h. Third-octave band frequency spectra were also measured but are not reported here. A more comprehensive data compilation will be produced in the beginning of 2022.

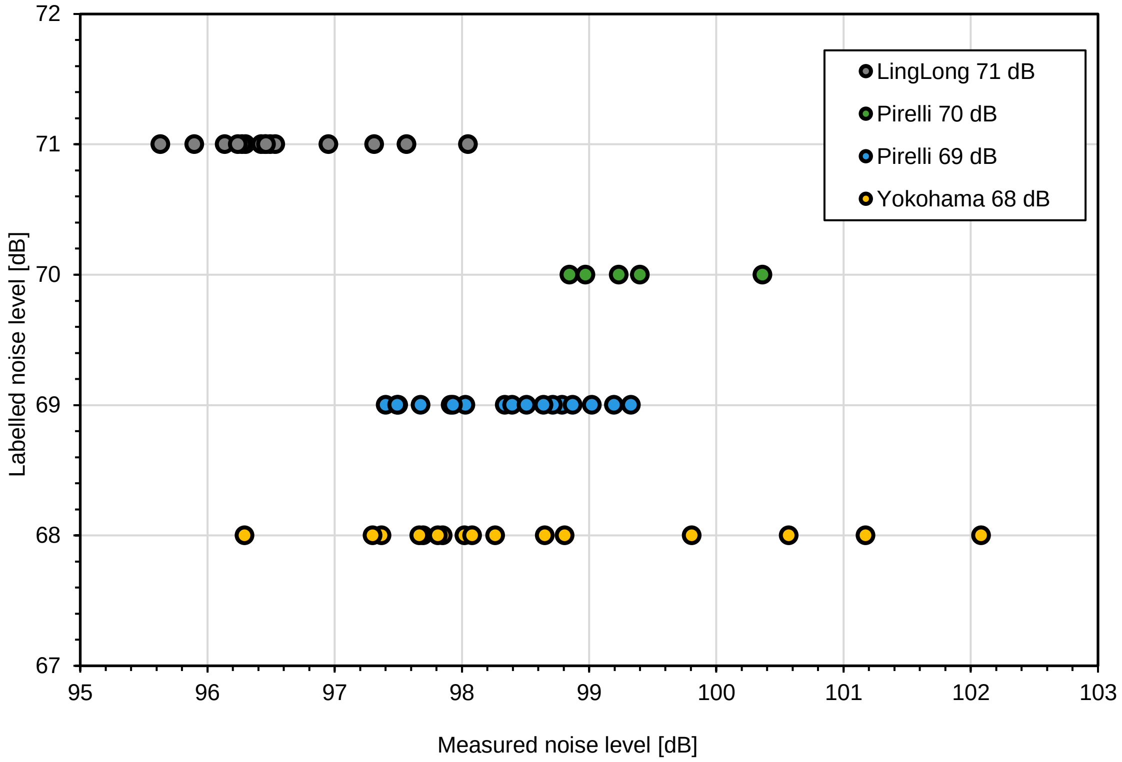


Figure 4-4: Distribution of measured noise levels for each of the tyre selections (with each tyre's label level on the ordinate). One symbol for each tyre. The two Pirelli selections are for the same tyre line but separated for the labels 69 and 70 dB.

Table 4-2: Summary of labelled and measured noise levels for the selected tyres. The speed range is 70-90 km/h but the level represents the "average" at 80 km/h. The noise level range is the difference between the maximum and minimum noise levels for the selected tyres.

Tyre	No. of tyres	Labelled noise level [dB]	Noise level measured on drum		
			Average [dB]	Stand. dev. [dB]	Range [dB]
LingLong Greenmax HP010	15	71	96.6	**0.64**	**2.4**
Pirelli Cinturato P1 Verde	5	70	99.4	**0.60**	**1.5**
Pirelli Cinturato P1 Verde	17	69	98.3	**0.62**	**1.9**
Yokohama BluEarth-ES (ES32)	16	68	98.6	**1.55**	**5.8**

As mentioned above for each tyre line, one variant was tested with four tyre samples; the reason being to study how large the spread in noise levels between different tyres of nominally identical construction and performance would be. The results are presented in Table 4-3. Note that uncertainty according to the section about test method is less than 0.10 dB.

Table 4-3: Results of noise measurements on four tyre samples nominally identical, for each of the three tyre brands. Within each tyre brand/line all tyres were produced the same week, except for the Pirelli tyres which were produced eight weeks apart.

Tyre code	Tyre brand/line designation	Dimension, load and speed index	Label value	Measured noise level	Notes
L7	LingLong Greenmax HP010	205/50 R16 87 V	71	96.14	
L8	LingLong Greenmax HP010	205/50 R16 87 V	71	96.24	
L9	LingLong Greenmax HP010	205/50 R16 87 V	71	96.53	
L10	LingLong Greenmax HP010	205/50 R16 87 V	71	96.45	
		Average level:		**96.34**	
		Standard deviation:		**0.18**	
		Range (max – min)		**0.39**	
P10	Pirelli Cinturato P1 Verde	195/65 R15 91 V	69	99.02	Produced 5118
P11	Pirelli Cinturato P1 Verde	195/65 R15 91 V	69	98.51	Produced 5118
P12	Pirelli Cinturato P1 Verde	195/65 R15 91 V	69	98.03	Produced 0719
P13	Pirelli Cinturato P1 Verde	195/65 R15 91 V	69	98.64	Produced 0719
		Average level:		**98.55**	
		Standard deviation:		**0.41**	
		Range (max – min)		**0.99**	
Y8	Yokohama BluEarth-ES (ES32)	205/55 R16 91 V	68	98.02	
Y9	Yokohama BluEarth-ES (ES32)	205/55 R16 91 V	68	97.81	
Y10	Yokohama BluEarth-ES (ES32)	205/55 R16 91 V	68	98.08	
Y11	Yokohama BluEarth-ES (ES32)	205/55 R16 91 V	68	98.65	
		Average level:		**98.14**	

		Standard deviation:	**0.36**	
		Range (max – min)	**0.84**	
	Average standard deviation:		**0.32**	
	Average range (max-min):		**0.74**	

It appears that for the LingLong tyre the standard deviation was only 0.18 dB, for the Pirelli tyre it was 0.41 dB and for Yokohama it was 0.36 dB. For the Pirelli tyre it appears that the tyres were from two different batches (years), with about 0.5 dB between each one, and had all four tyres been from the same batch it is probable that the standard deviation would have been less than 0.3 dB. For the Yokohama tyre, it is one of the tyres which is 0.5 dB noisier than the other three, despite being produced in the same week. However, it may still be from a different batch.

The results suggest that for tyres produced in the same week, the standard deviation between tyre samples is around 0.3 dB, but for different batches, larger differences may occur. These results are in-line with estimations from ETRTO which suggest that the standard deviation due to tyre sample differences is around 0.26 dB.

4.2.6 Observations and discussion

Each measurement, at the eight speeds 70-90 km/h, took 25-30 minutes. The time from start until 70 km/h has been reached is additional and is estimated at 1-2 minutes. Extra warm-up time is 15-20 minutes. The time required for tyre change is 10-15 minutes. Thus, each tyre can be measured in a total time of 60 minutes.

Some notes about a few of the extreme noise levels:

- The four noisiest Yokohama tyres have widths 225-245 mm, rim diameters 16-18 inches, and load indices of 91 to 98. The quietest Yokohama tyre has the dimension 145/65 R15 and load index 72.
- The noisiest Pirelli tyre has the dimension 215/50 R17 and load index 95. It is the largest of the Pirelli tyres both in width and rim.
- It is interesting that it seems that the five Pirelli tyres labelled at 70 dB are about 1 dB noisier than the ones labelled at 69 dB; especially for the noisiest for each label level.
- The noisiest LingLong tyre has the dimension 225/65 R17 and load index 102. It is the second largest of the LingLong tyres both in width and load index, and the largest in rim size.

Consequently, as one could expect; the larger tyres give the higher noise levels. It appears that the tyres labelled with the lowest level (68) actually are two dB noisier than the ones with the highest label (Yokohama vs LingLong). The noisiest ones in each group actually differ as much as 4 dB, while their labels differ by 3 dB; however, in the opposite way. How this can be explained is impossible for the authors to know. But the previous chapter showed that ISO test tracks may differ by at least up to 4 dB, and it may also be that the label values for LingLong have been determined in a very conservative way. Whatever the reason is there is nothing illegal in it.

It may be interesting to know that the purchase cost for these tyres (as paid by the project) were as follows per average tyre of each line:

- Pirelli Cinturato P1 Verde: 868 SEK per tyre
- Yokohama BluEarth-ES (ES32): 985 SEK per tyre
- LingLong Greenmax HP010: 565 SEK per tyre

To convert to EUR just divide by 10. Note that the Swedish costs include 25 % VAT.

Thus, for the lowest average cost per tyre we got the quietest tyres. This is of course somewhat biased by the differences in tyre dimensions between the three lines.

A priori, one must consider that the type-approval and tyre labelling regulations are using the principle of reporting results to truncate the measured noise level, i.e., to skip the decimal. This immediately gives a reporting uncertainty of between 0.1 and 0.9 dB under the assumption that reporting results with one decimal would be the preferred case. Additionally, there will be an inevitable uncertainty in the measurements. Assuming that it would be normal to test all tyres within the line on the same test track, the measurement uncertainty within the tyre line, expressed as max-min deviation, should be less than 0.5 dB. It follows that up to 1.4 dB of difference within a tyre line could be due to measurement and reporting uncertainty alone. Our results shall be considered with that in mind.

4.2.7 Conclusions

Results show that the measured noise levels within all three tyre lines differ more than the 1.4 dB which is considered as “normal” according to the discussion in the previous section, despite they are labelled with the same level. The Pirelli tyres labelled with 70 dB are a border case. The Yokohama tyres are an extreme case with almost 6 dB difference between tyres labelled with the same level. The overestimation of the noise label within a tyre line due to considering only the noisiest tyre is then 2 dB or more, with the exception of the 70 dB Pirellis. This seriously limits the value of the labelling system as consumer information since the consumers will not be able to identify the quietest tyres, unless all tyres within a tyre line have been measured for noise. Therefore, the conclusion is that the present way of labelling is not acceptable and needs to be changed.

To make the noise label values as appropriate and correct as practical and possible, this means that it is not enough to rely on just the type approval value for the tyre line. Most tyre variants must be measured and labelled individually. How to do this in a practical way is discussed in the next section.

4.2.8 Test methods to make noise measurements of all tyre variants: three options

To eliminate the problem identified in the previous sections, three options are suggested:

1. Measure and report the noise levels of all tyre variants within a tyre line, using the method of R117 (coast-by on ISO test track). Note that this may already be implemented by some tyre manufacturers for some tyre lines.
2. Use a simplified laboratory measuring method to determine differences between tyre variants within a tyre line and use this difference to assign noise labels to all tyre variants, with the type approval level as a reference, and (optionally) with a few more tyres tested by the coast-by method as additional noise references.
3. Use a noise modelling procedure to determine differences between tyre variants within a tyre line and use this difference to assign noise labels to all (or at least most) tyre variants with really measured tyres as references (using the coast-by procedure). This procedure should be limited to labelling tyres which are only slightly different in dimension or materials to the closest measured tyre(s).

In the first option, the workload to produce the noise labels will be high or very high compared to the present situation (needs four test tyres, a test vehicle, driver, access to ISO test track and proper weather), depending on to what extent this option is already implemented. It may be difficult to have access to test tracks for such extensive measurements.

In the second option, a significantly simplified procedure to measure many more tyres than presently will have to be defined. If this is made reasonably practical, the extra work may be very limited. Therefore, a much more practical method is proposed, namely measurements indoor in a laboratory, utilizing a drum with appropriate surface and with microphones close to the tyre/drum contact patch.

The third option has the potential to reduce the measurement workload substantially compared to the first option.

Whichever, option is used, it must be indicated on the label with some kind of mark or symbol which option was used to label the tyre in question.

4.2.9 Laboratory drum method

Method according to ISO/DIS 20908

A drum method for measurement of tyre/road noise is already under development in the ISO tyre committee ISO/TC 31; currently available as a draft international standard ISO/DIS 20908 [ISO, 2021]. Discussion about a similar method is also ongoing in a WG of the ISO noise committee (ISO/TC 43/SC 1/WG 42). The concept is similar to the coast-by method in R117 but taken indoors. To reduce the size of the laboratory facility, a full 4-wheel test vehicle is not used, instead only one tyre, mounted on a rig is tested. See Figure 4-5. To simulate a coast-by, instead of moving the tyre (the vehicle in R117), the microphone is moving to simulate the relative motion between the test vehicle and the microphone(s). The microphone movement is replaced by instead of having a moving microphone, a number of microphones situated along the microphone path are read and averaged. In this way, the directivity of the noise emission during a coast-by is simulated in a way which rather closely corresponds to an actual coast-by. Another simplification is that instead of having microphones 7.5 m from the centre of the test vehicle path, that distance is reduced to be at least 1.75 m. The reasons for this is that it dramatically reduces the required size of the test room and also increases signal-to-noise ratio.

The 20908 method needs a drum facility, located in an acoustically verified test room lined with sound absorbing material, using several microphones at a distance of around 1.75 to 5 m from the tyre centre. The drum surface shall be covered by a replica ISO 10844 surface (however, currently under discussion). Figure 4-54-5 shows one of the possible set-ups according to the ISO/DIS 20908.

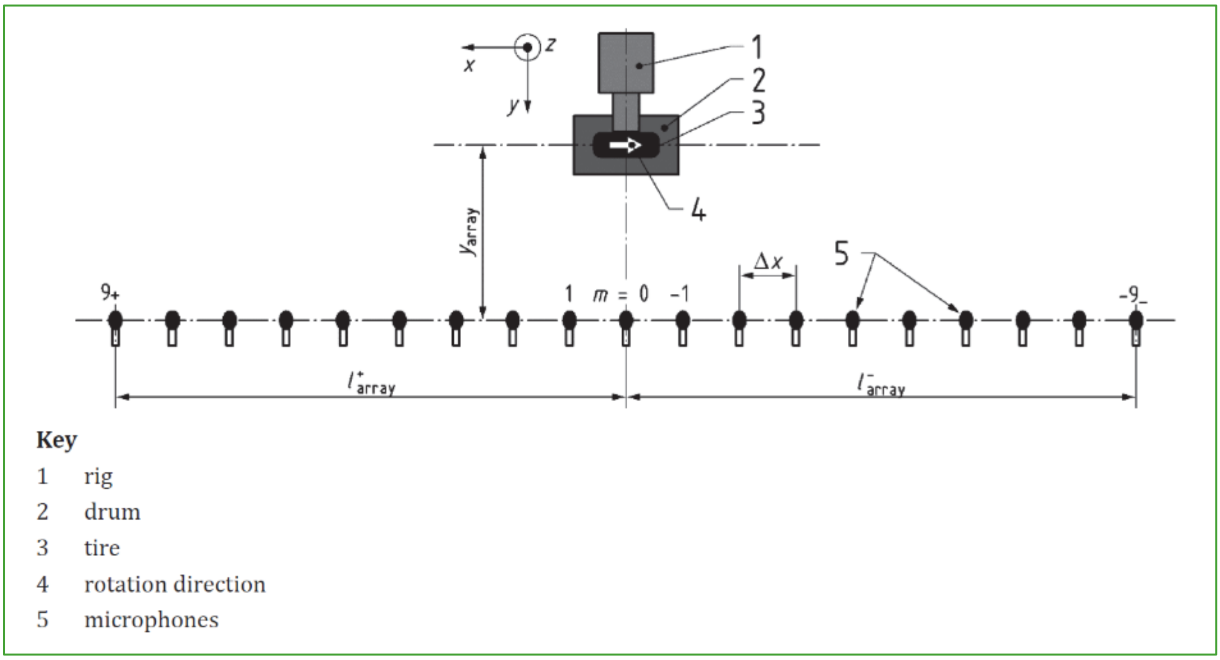


Figure 4-5: Set-up of measurements according to ISO/DIS 20908. The *Yarray* distance is assumed to be at least 1.75 m.

Differential tyre noise laboratory drum method, as designed by STEER

If the tyre manufacturer has access to such a facility as needed for ISO 20908, it is excellent, and the measurements suggested here can be made on this facility. However, the authors think that the 20908 method is too complicated and resourceful. A simpler method is possible to apply in this particular application, using the tyre manufacturer's already existing laboratory drum facilities and with less stringent room requirements. However, a strict requirement is that the drum must be equipped with a replica ISO 10844 surface if it is not already having such a surface. The setup is similar to the so-called CPX method (CPX = Close-ProXimity), adapted from trailer to laboratory drum conditions. The method, but applied on a measurement trailer, is standardized in ISO 11819-2 [ISO, 2017a]. This option is described in some detail below.

First, it shall be noted that such a drum facility, especially the simpler variant that we propose, cannot fully simulate the noise level valid for the method in R117; i.e. for coast-by running at 7.5 m microphone distance. There are two significant problems:

1. The microphone is located much closer to the tyre(s) which will of course mean that noise levels will be much higher, but also the frequency spectra may be somewhat influenced by the change in distance from the source.

2. The tyre/drum contact patch will not be plain, as a tyre/road contact patch, but will be curved, depending on the drum diameter.

Despite these problems, the method can enough well measure noise emission differences between tyres within the same tyre line. If the tyres are within the same line, they will have similar basic construction and materials. Thus, the idea here is to select the tyre which is used for type approval as a reference in this drum method and just measure the difference in noise level against the other tyre variants in that tyre line. Such differences would hardly exceed 6 dB and when measuring such limited differences for tyres of the same line (having rather similar physical properties) the uncertainty should be much less than 0.5 dB. The difference in noise level compared to the type approved tyre would be used to calculate what the noise label for each tyre variant would be.

It is necessary to use a replica of an ISO 10844 test track surface on the drum, since just plain steel or sandpaper will not give representative noise emission. Such surfaces may be produced in the way described above, but in the future, it is better to produce such a surface by 3D printing, based on a 3D digitization of a real ISO 10844 surface. ISO/DIS 20908 mentions this option. Once a digitized surface profile is obtained, this surface may be used for 3D printing of all drum surfaces worldwide.

Replica drum surfaces made with the 3D printing procedure have already been produced. At the FKA in Aachen, Germany, such a surface is already in place [Bachmann, 2021]. There may be more which are not known to STEER members.

The STEER simplified method is described below in a condensed way:

- A drum facility having a drum with a diameter of at least 1.7 m shall be used (for C1 tyres). Ideally, the diameter should be 2 m or more even för C1 tyres, but for C2 and C3 tyres, 2 m would be a minimum.
- The drum shall be covered with a replica of an ISO 10844 surface
- At least two microphones shall be used, at positions relative to the test tyre as described in ISO 11819-2; i.e., at 0.2 - 0.3 m from the tyre contact patch. More of the positions specified in 11819-2 may be used but are not required. Noise levels of the microphones shall be averaged to get one final result
- The drum surroundings should be properly noise controlled to avoid acoustic reflections and unwanted noise that may in fluence the noise measured by the microphones (should require rather modest actions)
- Drum circumferential speed during measurements shall be in the range 70-90 km/h for C1 and C2 tyres, and 10 km/h lower for C3 tyres.
- The tentative name of the method is proposed to be “Differential tyre noise test on laboratory drum”.
- The quality of the measurements should be assured by the Type Approval Authority as already foreseen in chapters 3.3 to 3.5 of R117 (2016/1350).

Most tyre manufacturers already have such a facility (except maybe for the replica ISO surface and with different microphone positions) and they most probably already test their tyres (all variants in the line) in the development process; thus, the extra labour and time consumption for this task will be limited. It may even mean less labour and costs for some, since they will not need to test so many tyres on the outdoor test track. Instead, they can rely on this differential noise testing method.

4.2.10 Differential tyre noise simulation method ("virtual testing")

Recent interviews with experts from major tyre industries, consistently report that the tyre manufacturers are increasingly using simulations to predict performance of wet grip and rolling resistance of their tyre prototypes and they seem to be quite happy with this [Tire Technology International, 2021b],[Tada et al, 2021]. Tyre/road noise is admittedly more difficult to simulate and predict, but small differences between tyres within a line can probably be quite well predicted based on their models.

Therefore, an alternative to making drum or coast-by measurements, would be "virtual testing"; i.e., to label (some) tyres by using a noise prediction model. This may be used in cases where there is a measured noise level (by the official coast-by method) for a specific tyre when one can predict the noise difference for tyres which are not very different in dimension, or which differ only in load or in speed rating, in relation to the specific tyre.

For example, probably (at least the major) tyre manufacturers can predict the effect on noise of different speed rating for an identical tyre dimension within an uncertainty of (say) ±0.3 dB, and the same when they increase the load rating by some strengthening measure for the same dimension. Probably they can do similar predictions when changing dimension from (say) 195/55 R16 to 185/55 R16 or to 205/55 R16 and further to 215/55 R16. The same could be considered when playing with the rim diameter instead of width. In such an example, they only need to measure noise of the middle size and the somewhat smaller and the somewhat bigger sizes may be predicted as a difference level. Then the difference noise level will be used to adjust the labels by such simulations.

Such virtual testing may reduce the actual measurement effort to maybe less than ¼ of the option of testing all tyres in coast-by on test track, as many measurements would be replaced by computations. With better models, more measurements may be replaced by computations.

Such simulation tools should be either (1) certified by an independent organization or (2) one may use the principle of self-certification. In the latter case, it would mean that the label values may be subject to spot-checks by an independent organization and if the label value is measured to be more than X dB (say 1.5 dB?) different from the expected level based on the difference between the label and the type approval level, there will be penalties to the manufacturer.

4.2.11 Recommendations

It is recommended that the tyre labelling regulation is changed as follows and as soon as possible:

It shall be clarified that within a tyre line it is not enough to measure the noise level of not only tyres that are measured for type approval, but all tyre variants within each tyre line shall be separately measured and labelled.

In order not to increase the testing efforts too much, it is allowed to use a much simpler test method than the coast-by method in R117, namely an indoor laboratory drum method with a drum surface which is a replica of an ISO 10844 surface. This replica could preferably use the same original test track surface worldwide, and it could be made by means of 3D printing (but also the traditional replication method is acceptable).

The laboratory drum method can be the method currently worked-out as ISO/DIS 20908.

However, if the mentioned ISO/DIS 20908 method or its equipment is not available, a much simpler method is advised by STEER (see a previous section) which does not require so much space and not such an acoustically advanced environment thanks to using much closer microphone positions.

Another option is to use “virtual testing”; i.e. a noise modelling procedure to determine differences between tyre variants within a tyre line and use this difference to assign noise labels to all (or at least most) tyre variants with a really measured tyre as a reference (using the coast-by procedure).

To be able to assign the noise label values the following procedure is advised:

For each tyre line, at least one tyre variant TYR_{ref} (with unique dimension, load index and speed rating) is measured according to the coast-by method in R117. This may be the same tyre as is used for type approval. The obtained noise level (with one decimal) is set as a reference level (L_{CBref}) for that particular tyre line (and the corresponding label value is determined).

The drum method is used (only) to measure the differences in noise levels between tyre variants within a tyre line (with a resolution of one decimal and using same speeds, loads and inflation as in R117).

The tyre TYR_{ref} is measured with the laboratory drum method and thus assigned a noise level L_{DRref}. It is recommended that this is made for at least four tyre samples (the same tyres as in the coast-by method) and the averaged noise level used, since this reference level is important as it influences all other labels within the tyre line.

For each tyre variant (with unique dimension, load index and speed rating) the noise level is measured with the laboratory drum method (for one tyre sample) and the resulting difference to the L_{DRref} is calculated. This difference is subtracted from or added to (whichever is applicable) to the L_{CBref} to get the label value L_{CB} for the tyre variant.

The same differential procedure is used when applying the simulation/modelling option. However, this procedure should be limited to labelling tyres which are only slightly different to the nearest measured tyre(s).

4.2.12 Comments to the recommendations

As a very different measuring method is used to determine the noise differences between tyre variants it may be feared to give non-representative end results. However, as only tyres within the same tyre line are compared in this way, the drum method should give approx. the same differences as the coast-by method would do. The laboratory drum method is superior to the coast-by method in terms of repeatability and lack of meteorological influences. Another advantage is that in principle the whole world could use the same replica test track surface.

It may at first look like a substantially increased testing effort is suggested. However, the laboratory drum method is fast to use, as each (C1) tyre variant may be measured in one hour or less, and most tyre manufacturers already have such drums, or will have to get them anyway since it is a clear future aim to go indoors with the noise measurements. Such drums are necessary for development or verification of new tyres and this differential noise measurement could be part of that.

In fact, the proposed methods may reduce the outdoor measurement efforts, since labelling for a full tyre line may be made outdoors for only one set of tyres (as for type approval). Tyre companies which today measure several tyre variants within a tyre line for the label values, will save a lot of outdoor test track time.

4.3 Representativity of the tyre label regarding real-world conditions

4.3.1 Description of ISO 10844 standard reference surface and commonly used pavements on EU road networks

A reference surface specification was developed in the early 1990s to harmonize measurements of vehicle noise emissions. This work was done in ISO and resulted in the standard ISO 10844:1994, which was later revised in 2014, and a new revision is ongoing. ISO 10844:2014 is the standard surface in the current EU tyre noise labelling procedure and in the R117, which sets limit to noise emission of tyres.

The first ISO 10844 standard describing the properties of a test track was issued in 1994 and was designed to generate minimal tyre/road noise and minimum variance. It was originally not intended to measure tyre/road noise on it but nevertheless, the standard has been used since for tyre/road noise regulations and directives.

In the first version of the standard (1994), one finds the requirements for the following parameters relevant for the acoustic qualities of the driving area of the test track:

- The basic pavement type shall be a dense asphalt concrete
- Maximum chipping size and sieving curve are specified
- Maximum void content is specified
- There are limitations for the Mean Texture Depth (MTD)

- For the driving and the propagation surfaces: there are limitations for the acoustic absorption factor per third octave band: average of maximum reached in the area 400 – 800 Hz and in the area 800 – 1600 Hz.

In 2014 the standard was revised in an attempt was to reduce the large variance of the acoustic properties of the existing test tracks, which was demonstrated in a round robin test. In the 2014 standard, similar parameters were used to describe the acoustic behaviour of the test track, with the exception of MTD, which was replaced by the closely related but more accurately measured “Mean Profile Depth” (MPD). The absorption coefficient of the third octave bands in the range 315 Hz up to 1600 Hz are limited. Moreover, in the revised version (2014), no limits are imposed on the void content, as absorption due to a high void content is avoided by the limitation of the absorption coefficient. The requirements imposed to the mentioned parameters are summarized in Table 4-4. The sieving curve of the 1994 version of the standard has been altered slightly in the 2014 version.

Since the 2014 version of ISO 10844 was published, work has continued in ISO/TC 43/SC 1/WG 42 and its subgroup TT, to further try to reduce site-to-site variability in noise measurements. When this is written a DIS for a new version is published and balloting is ongoing.

Table 4-4: Requirements for parameters with acoustic relevance in the two versions of the ISO 10844 standards

Parameter	ISO 10844:1994	ISO 10844:2014
Maximum chipping size	8 mm with allowable limits [6.3-10 mm]	8 mm with allowable limits [6.3-10 mm]
Maximum void content	Average of cores ≤ 8 %; no core > 10 %	-
Macrotexture (MTD or MPD)	MTD ≥ 0.4 mm	MPD = 0.5 mm ± 0.2 mm
Absorption coefficient α	α < 10 % for average of maximum reached in the area 400 – 800 Hz and in the area 800 – 1600 Hz	α < 8 % for any third octave band between 315 and 1600 Hz for driving lane; α < 10 % for propagation area

Texture is the determining parameter for the acoustic properties of an ISO test surface and even in the new version of the standard the problems remain the MPD is not a good descriptor for the acoustic quality (correlation with SPB or CPX levels is generally poor) and the allowed range is still far too wide, allowing very smooth to medium textured surfaces (see Figure 4-6).

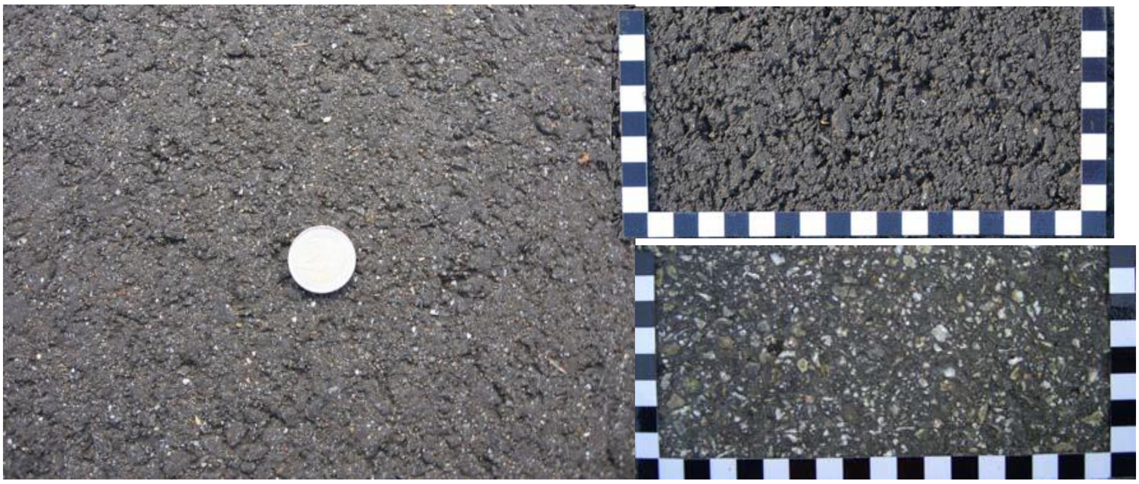


Figure 4-6: Surface pictures of three different ISO test tracks.

4.3.2 Commonly used pavements on EU road networks

One of the main challenges to the representativity of the EU tyre label is that the predominant road surface types and their surface characteristics can vary largely between climatic regions, member states and road categories. Of importance regarding representativity is the predominance of rough surfaces on the road network.

It is important to distinguish between surfaces with little texture (rather smooth) and surfaces with a lot of texture (rather rough). The STEER consortium proposes a roughness classification of road surfaces, based on the Mean Profile Depth (MPD) as follows:

Smooth:	Below 0.7 mm (in practice this covers a range of 0.2 - 0.7 mm, hence with a width of 0.5 mm)
Medium:	0.7 – 1.2 mm (this covers a range of 0.7-1.2 mm; width = 0.5 mm)
Rough:	Above 1.2 mm (in practice this covers a range of 1.2 - 1.7 mm; width = 0.5 mm, if we forget very rough surface dressings, which are uncommon on roads with significant traffic volume)

It is important to notice that on high-speed roads a minimum texture is necessary for safety reasons. During heavy rainfall a minimum ETD of 0.5 mm is required to avoid the risk of aquaplaning, where ETD ≈ MTD ≈ 1.1 * MPD.

The STEER consortium made a (non-exhaustive) survey of the texture on the European road networks, with emphasis on the road networks of the countries funding STEER. These are the main findings (for full details, see STEER Task Report 4.3.1 *Report on the representativity of the ISO test track compared to common European road pavements*)

Denmark

The absence of studded tyres allows Denmark to use pavements with smaller chipping sizes, yielding less noisy surfaces with less rolling resistance. About 75 % of the pavements on the Danish main road network concern SMA or DAC with a maximum aggregate size of 11 mm. For about 20 %, the maximum chipping size is 8 mm and for 5 % of the Danish main road network it is only 5 mm (data from 2011), [Berge, 2012].

On the secondary road network often smooth pavement types are used with the purpose of reducing noise and rolling resistance.

The ROSANNE measurements carried out on Danish roads show that the majority high speed roads have a texture in the medium texture class Figure 4-7, top). Few measurements were carried out on local roads, but the small sample shows that most of these roads have a smooth texture, which is consistent with the considerations above (Figure 4-7, bottom).

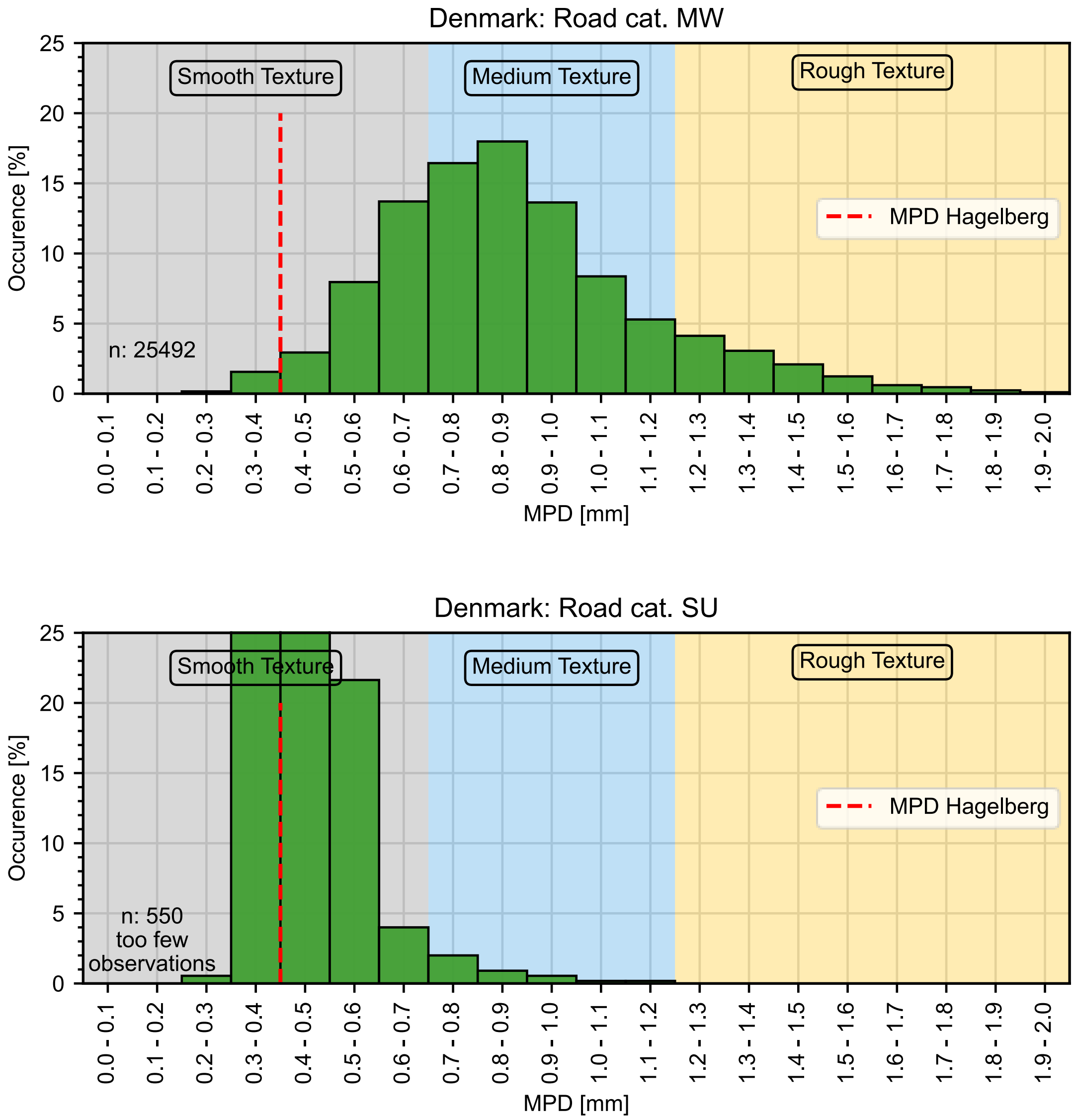


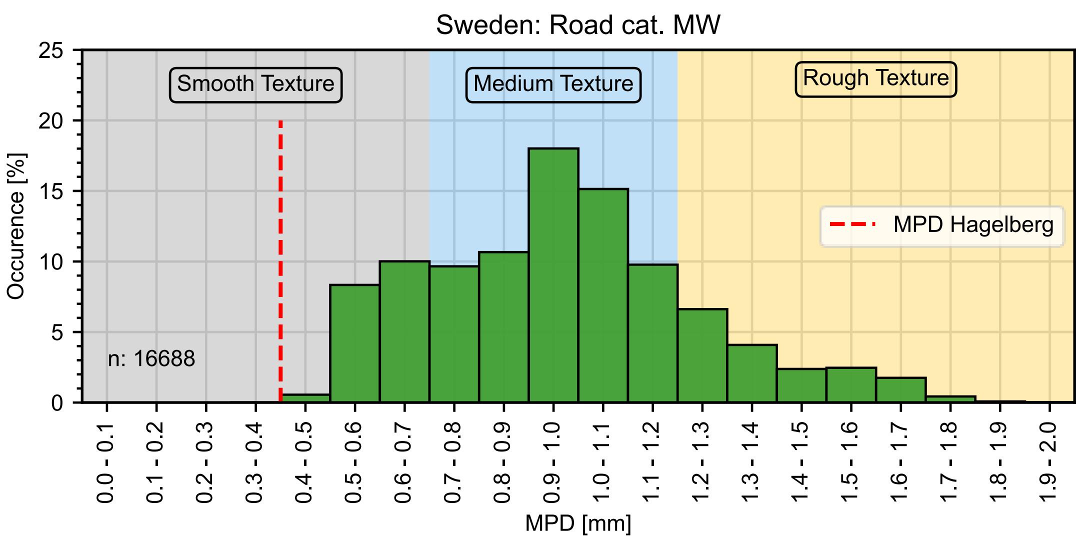
Figure 4-7: Distribution of MPD values in Denmark on highways (top) and on local roads (bottom). Red line is the MPD value of the Swedish ISO test track.

Sweden

The Swedish national highway network is almost entirely using SMA 16, or remixes based on SMA 16. A few motorways are paved with EACC 0/16, with an MPD of around 1.2 mm. However, some regional highways serving relatively low traffic are paved with surface dressings; usually with 11 mm maximum aggregate size. Communal (urban) streets have a more varied mix of pavements; however, even there the most common one is SMA 16 or its remixes. Nevertheless, a significant portion of streets is covered by SMA 11, especially in or close to residential areas. There are also some DAC 11 and DAC 16 pavements on local streets with posted speeds 50 or lower. The paving contractors often use special versions of the mentioned standard pavements, that may have slightly modified gradations and some modified binders, but from a texture point of view they are similar to the standard pavements mentioned above.

There are a few motorways paved with cement concrete (less than 500 km); usually of the exposed aggregate type and with maximum aggregate size 16 mm. The reason for the dominance of the large aggregate size (16 mm) is their better wear resistance, as the use of studded tyres is widespread in Sweden during wintertime. It can be concluded that most of the high-speed roads are in the medium texture class, as well as the local roads, although a significant fraction of the latter has a smooth texture.

A recent survey of the texture carried out on roads in - among other countries – Sweden [Sjögren et al., 2016] confirms the generally rough texture on Swedish roads. Figure 4-8 (top) shows the distribution of the MPD on Swedish highways and Figure 4-8 (bottom) shows MPD values measured on local roads. The distribution of MPD on secondary roads is like that on highways. On the figures the MPD value of the Swedish ISO test track in Hagelberg is shown, which can be considered as typical (see discussion in chapter 4.3.1, page 86).



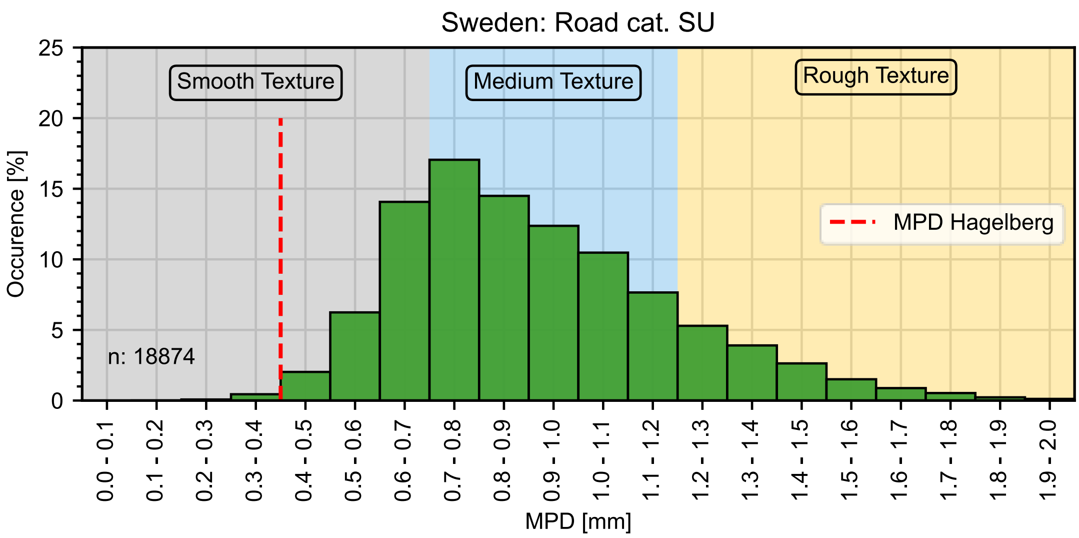


Figure 4-8: Distribution of MPD values in Sweden on highways (top) and on local roads (bottom). Red line is the MPD value of the ISO test track.

Norway

In Norway, pavements on the main road network, including highways and the secondary roads consist mainly of DAC and SMA, about 2/3 with a maximum chipping size of 11 mm and 1/3 with a maximum chipping size of 16 mm. A few percentages use maximum chipping size 8 mm. At least this was the situation in 2010 and based on only two Road Administration districts (Middle and East). [Berge, 2012]

The use of studded tyres is also widespread in Norway. Measurements show that studded tyres sometimes smoothen and sometimes roughen the pavements. The Norwegian pavements on main roads can be considered as medium to rough textured: typical values for SMA 0/16 range between 1 and 1.5 mm and for SMA 0/11 between 0.8 and 1.5 mm [Storeheier, 2011].

Netherlands

In the Netherlands, porous asphalt (PA, mostly single layered) is the default road surface on highways, for environmental reasons (noise abatement). Test tracks representing a large variety of pavements have been built in 2005 on an abandoned section of a highway in Kloosterzande, in the South of the Netherlands. BRRC measured the MPD on those pavements unexposed to traffic in May 2009. The Kloosterzande collection comprised a wide selection of Thin Surface Layers (TSL), Porous asphalt (PA), dense asphalt concrete (DAC, including an ISO test track) and Stone Mastic Asphalt (SMA). MPD values varied a lot, even between sections of the same type as they are sensitive to slight variations of the asphalt mix and on the degree of compaction; the typical MPD values for PA 4/8, PA 0/11 and PA 0/16 range between 1.0 and 1.5 mm. For PA 4/6 and PA 2/4 MPD is in the range of 0.4 up to 0.6 mm. TSL yielded MPD values between 0.3 and 0.6, as did the DAC 0/16.

Based on the this, the consortium concluded that in the Netherlands both on high speed and on local roads smooth, medium and rough textured pavements occur, presumably with a majority of medium textured pavements on the high-speed roads and smooth and medium textured pavements on the local road network.

Belgium

In Belgium (as in Germany and Austria) SMA road surfaces are common, but a significant part of the main road network is covered with durable cement concrete pavements on which a surface treatment, such as burlapping, brooming, grinding or chemically “washing” (yielding exposed aggregate cement concrete, EACC), has been applied. Measurement on EACC 0/7 in Belgium yielded MPD values between 0.56 and 1.00 mm, which is consistent with the results measured on German highways and motorways. Rougher types of EACC, such as EACC 0/20 occur as well. Standard specifications in Flanders require a minimum MPD value of 0.7 mm for two layered EACC (with 0/7 mm aggregate in the top layer) and 0.8 mm for single layered EACC (typically with 0/14 or even 0/20 mm aggregate). Most high-speed roads are presumably in the medium texture class. The consortium did not find data on local and secondary roads, but from an expert assessment one could say that local roads are in the smooth or medium texture class and the secondary roads in the medium texture class.

United Kingdom

The consortium only got data for England[9] hence not of the other parts of the UK. For England the preferred surfacing material is a Thin Surface Course System (TSCS) which makes up around 65 % of the surfaces, HRA is around 30 % and other surface types, e.g. concrete and high friction surfacing is around 5 %.

TSCS is the name assigned in the Highway England specification. TSCS's can be produced under the following EN 13108 families; Part 1- Asphalt Concrete or Part 5 - Stone Mastic Asphalt, providing they meet the English specification requirements (deformation resistance, air voids, binder content etc.). The requirements for texture are shown in Table 4-5.

The Highway England network is predominantly high speed and surfaced with 14 and/or 10 mm size aggregate.

The conclusion is that in England, high speed and secondary roads are medium to rough textured. No information is received about the texture on local roads.

Table 4-5: Requirements for initial texture depths for trunk roads (including motorways) for TSCS's in England. High-speed roads are those with a posted speed limit ≥ 50 miles/hour (80 km/h); lower speed roads are those with a posted speed limit ≤ 40 miles/hour (65 km/h)

Road Type	Surfacing Type	Average per 1000 m section, mm		Average for a set of 10 measurements, mm (minimum)
		Minimum	Maximum	
High-speed roads	Upper (D) aggregate size of 14 mm	1.3	1.8	1.0
	Upper (D) aggregate size of 10 mm	1.1	1.6	0.9
	Upper (D) aggregate size of 14 mm	1.0	1.5	0.9
Lower speed roads	Upper (D) aggregate size of 10 mm	1.0	1.5	0.9
Roundabouts on high-speed roads	Upper (D) aggregate size of 10 mm	1.1	1.6	0.9
Roundabouts on lower speed roads	Upper (D) aggregate size of 10 mm	1.0	1.5	0.9
	Upper (D) aggregate size of 6 mm	1.0	1.5	0.9

High Speed Roads are those with a posted speed limit >= 50 mph (80km/h)

Lower Speed Roads are those with a posted speed limit <= 40 mph (65 km/h)

[9] Hudson-Griffiths, R. (2021) Personal communication from Robin Hudson-Griffiths, Highways England, Birmingham, United Kingdom

Ireland

An annual survey is carried out on the main road network in Ireland by Transport Infrastructure Ireland and the MPD is one of the pavement indicators. In 2020 6457.3 lane km were measured and the MPD values were averaged per 100 m[10]. A histogram showing the distribution is given in Figure 4-9. The overall average MPD value is 1.51 mm and the standard deviation is 0.50 mm. The Irish trunk roads are rather rough textured and hence poorly represented by the ISO test track.

Other European countries

The STEER consortium reported as well about the texture of road networks in a few other European countries: for Germany and Austria one can draw more or less the same conclusions as for Belgium. The texture on the roads in Finland is comparable to that in Sweden. In Poland high speed and secondary roads appear to have medium textured pavements and local roads mainly smooth pavements.

Conclusions regarding the texture of pavements in the funding countries (and in other European countries)

The conclusion is that the pavement specified in ISO 10844 is far from having a common pavement macrotexture which one can find on the roads of the funding and other European countries. The ISO surfaces having MPD values at or below 0.4 mm can be considered as very uncommon for real roads, while the range of 0.50 to 0.70 mm exists to a significant degree when considering rather narrow low speed urban or suburban roads. Such roads do not generally carry such a high load of traffic that noise emission becomes a significant nuisance.

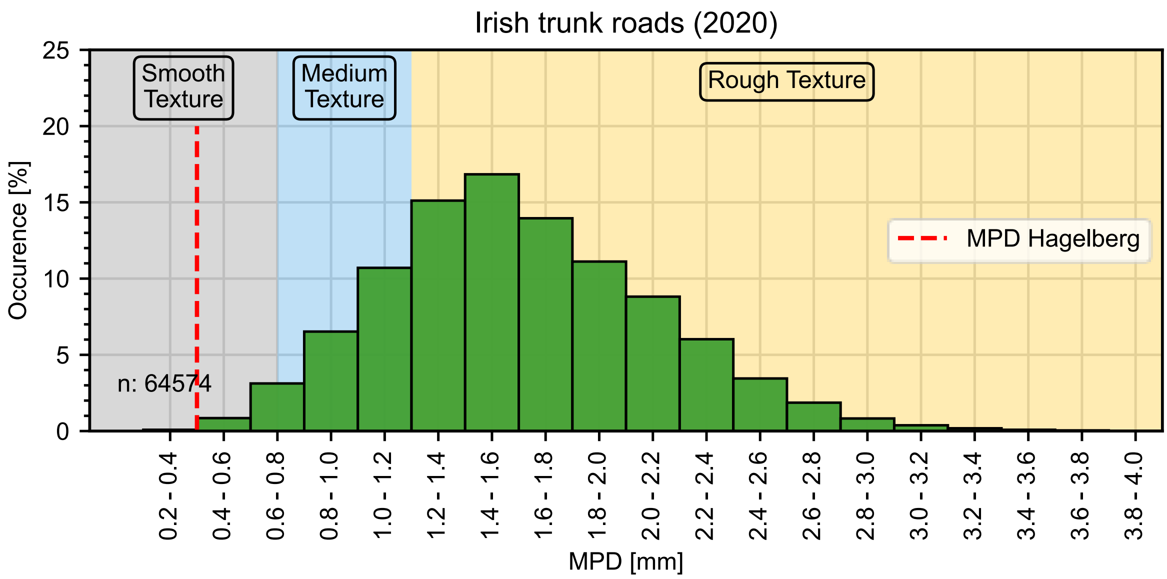


Figure 4-9: Histogram of MPD values measured in the 2020 measurement campaign on the Irish trunk roads.

[10] Byrne, S. (2021) Personal communication from Stephen Byrne, Environmental Policy and Compliance Section,Transport Infrastructure, Dublin, Ireland

4.3.3 Comparing noise emission of tyres on ISO test tracks on common pavement types

Several studies have been conducted to check whether the acoustic ranking of a tyre population obtained on ISO 10844 test tracks is the same as on the main road network in Europe.

Early measurements carried out in Norway and the Netherlands

In a joint project between SINTEF and M+P (NL), in 2003-2004, a total of 20 passenger car tyres were measured on selected road surfaces in the Netherlands and in Norway [Berge, 2005]. The test surfaces in the Netherlands included an ISO test track and a two-layer porous surface. In Norway, 13 of the tyres were tested on SMA 11 and SMA 14 road surfaces (trafficked roads).

"Labelled" noise values and measured values on a normal trafficked road surface were compared. The "label" values have been calculated for this report and are not the ones provided by the tyre manufacturer.

In Figure 4-10, the regression analysis between the "EU label values" and the measured noise levels on the SMA 11 surfaces is shown. The vehicle speed is 80 km/h. The correlation coefficient is very low, around 0.2. The correlation is similar for SMA 14 surfaces.

This is a strong indication of the lack of representativity of the ISO surface compared to rough surfaces, as found in Norway and in many other European countries.

A similar analysis was made between the ISO results and the results on the two-layer porous surface (2LPA). The correlation is much higher, and the slope is close to 1, which means that 1 dB reduction on the ISO track gives almost 1 dB reduction on the porous surface. It seems that the EU labelling procedure works much better for low noise road surfaces, than for rather rough surfaces, as mainly – but not exclusively – found in the Nordic countries.

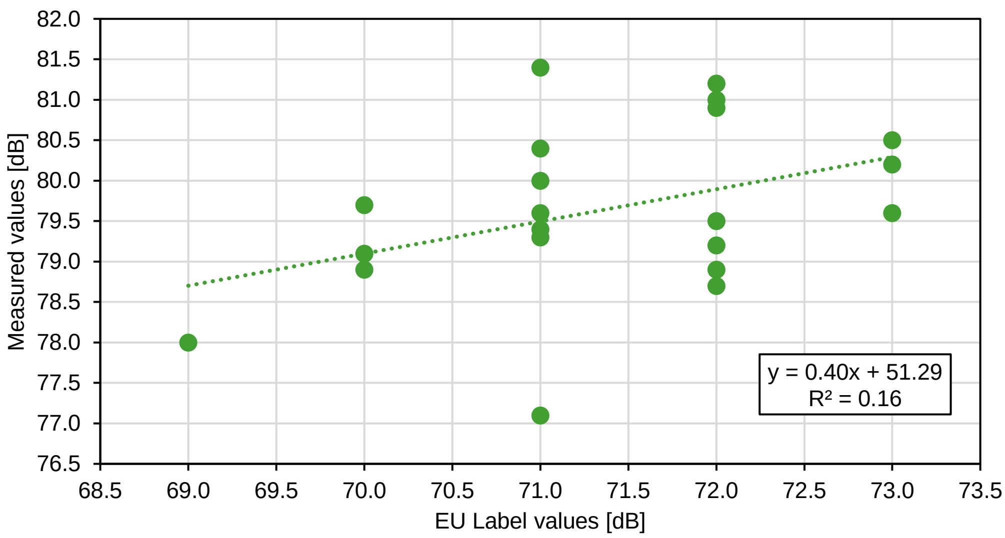


Figure 4-10: Regression analysis of "EU label" values and measured noise levels on the SMA 11 road surface. Graphics by the authors with data from [Berge, 2005].

Measurements on the Kloosterzande test area

In 2009, SINTEF carried out CPX measurements of a total of 22 summer tyres (C1) on 23 different road surfaces at the Kloosterzande test area in the Netherlands [Berge et al., 2011].

All measurements were made at two speeds, 50 and 80 km/h. The tyre dimensions were from 175/70R14 to 225/60R16. Four identical Michelin Energy Saver tyres, two identical SRTT tyres and two identical Avon AV4 tyres were part of the 22 tyres.

As one of the road surfaces was an ISO surface (built according to the 1994 edition), the correlation and ranking of the noise of the tyres on the other surfaces, compared to the ISO surface was investigated. This ISO surface at Kloosterzande was as a very smooth surface (M+P measured an MPD = 0.36 mm).

SINTEF found out that the correlation with the measured levels on the ISO surface were in general higher for all these surfaces, than found during the experiments in Norway and at Lelystad (see above) and in the NordTyre project (see below). For the smooth surfaces, such as the two thin layers and the SMA 6, the slope is also close to 1. The reason for the higher correlations may be that none of the test sections were exposed to regular traffic (and compaction and wear); something which had been identified earlier as giving poor relation to measurements on in-service roads [Sandberg et al., 2002]

The thin layer 2/6 and SMA 6 both had an MPD value very close to the ISO surface, and both these surfaces seemed to rank the tyres very close to the ranking on the ISO track. However, for both the SMA 11 and the SMA 16, the ranking of the tyres was quite different than on the ISO track. This is another clear indication that the ISO surface is not representative for the noise behaviour of tyres on the commonly used road surfaces, such as SMA 11 and SMA 16.

The NordTyre project

The NordTyre project (2012-2016) was intended to investigate the potential noise reducing effect of the EU tyre regulation on labelling of tyres, for the Nordic countries. The project was split into three parts:

- Part 1: State-of-the-art review [Berge, 2012]
- Part 2: Passenger car tyres [Kragh et al., 2015]
- Part 3: Truck tyres [Kragh et al., 2017]

One of the aims of the NordTyre project was to establish a relationship between the label values and measured noise level on the most used road surfaces in the Nordic countries. For passenger car tyres, all measurements were performed using a trailer (CPX method). Unfortunately, the load and tyre inflation pressure were not adjusted according to the specifications in R117. Thus, the regression analysis between the labelled and measured values on different road surfaces seemed of limited use, as the variation in noise levels is of the magnitude of expected influence of the ISO test track variations. The follow-up project LEO, carried out by TU Gdansk and SINTEF, demonstrated however that the main reason for the lack of correlation between the CPX levels and the tyre noise labels was NOT deviating tyre pressures [Berge et al., 2016b, 2016a]. The conclusions of the NordTyre project can hence be considered as valuable.

In Part 2 of the NordTyre project, 31 car tyres (C1) were measured on 30 road surfaces in Denmark, Sweden and Norway, using the CPX method.

The car tyres were all summer tyres, ranging from 175 to 225 mm tyre widths. For the car tyres, poor correlation was found between the measured values and the EU Tyre label values, independent on the type of surface, see Figure 4-11.

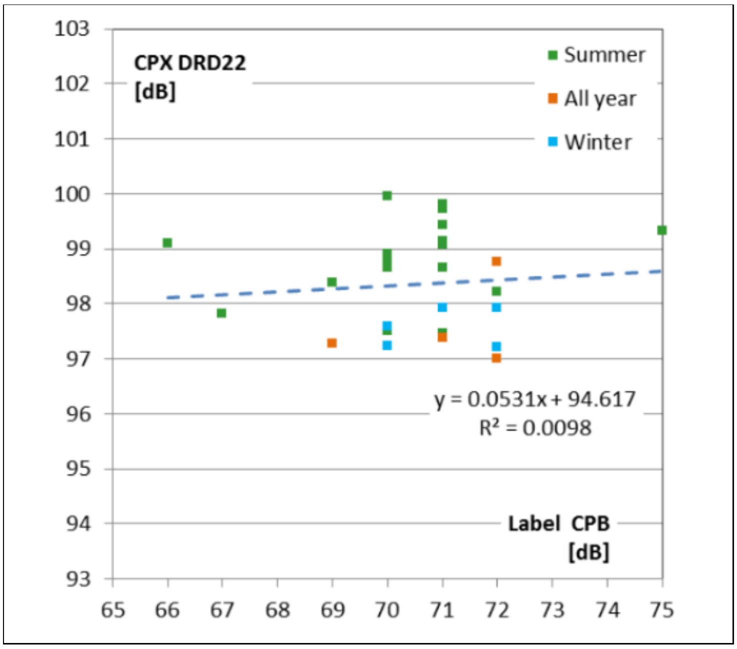


Figure 4-11: Measured CPX levels on SMA 11 road surface as a function of tyre label values issued by the tyre manufacturer. Figure copied from [Kragh et al., 2015].

In Part 3, 20 truck tyres (C3) were tested using a heavy-duty truck and the coast-by method as described in R117. These measurements were conducted on five different road surfaces on a closed test area in the Netherlands (Twente Proving Ground). One of the test surfaces was laid according to ISO 10844 and one surface was SMA 11, like a commonly used surface in the Nordic countries (but in non-trafficked condition).

Figure 4-12 shows correlations between coast-by measurement results on the ISO surface results and on a smooth "real-world" surfaces DAC 16. The correlation coefficient is high and the slope of the regression line about 45°, meaning that a 1 dB reduction measured on the ISO surface corresponds to a 1 dB reduction on the smooth real-world surfaces.

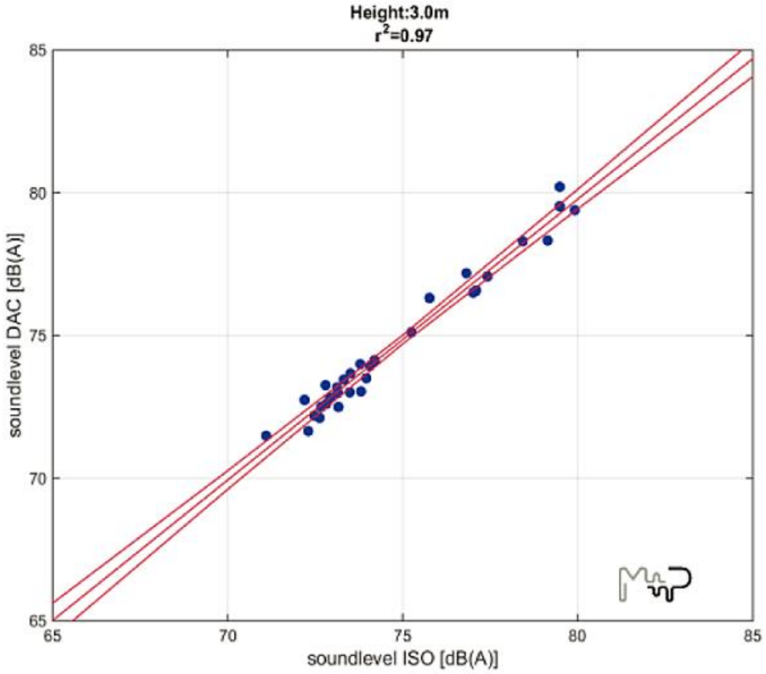


Figure 4-12: Measured coast by noise levels of truck tyres on the ISO test track versus noise levels measured on DAC 16 [Blokland et al., 2015].

Recent Swiss results

In 2017 a study [Hammer et al., 2018], carried out in Switzerland with the dedicated goal to investigate how much noise could be potentially reduced by choosing quieter tyres on typical Swiss road surfaces. For this goal, 14 representative tyre types were selected, together with the two reference tyres (SRTT and Avon AV4). The tyres were mounted on a closed CPX trailer, which has been modified and provided with extra mass, to meet the Regulation 117 requirements for load on the tested tyres (75 % ± 5 % of the load index of the respective tyre). A set of 11 common asphaltic road surfaces of the dense asphalt concrete (DAC), the semi-dense asphalt (SDA), the surface dressing (SD) and the SMA type were selected. The goal of the study was to evaluate the noise reduction potential of “silent tyres” on the most common road surfaces in Switzerland and elsewhere in Europe. However, interesting conclusions can be drawn after re-analysing the raw data set with these goals in mind. Figure 4-13 shows the adapted CPX levels of the respective tyres measured on the surface dressing (SD 6) pavement as a function of the tyre noise labels.

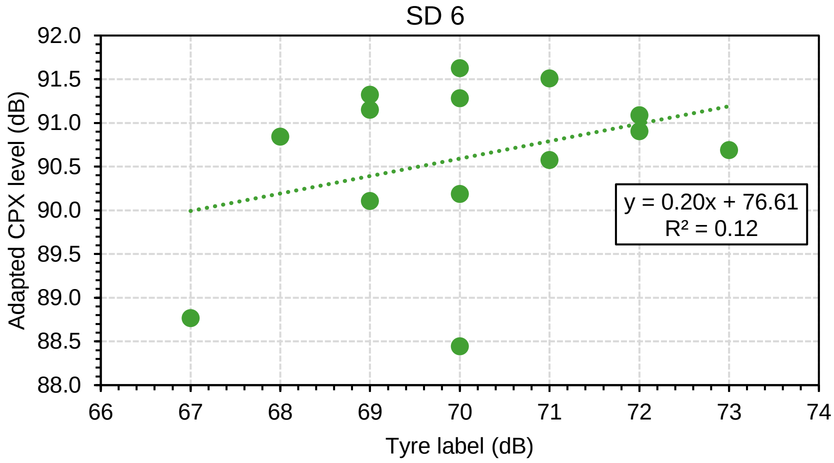


Figure 4-13: Adapted CPX levels on 6 mm surface dressing (SD 6) as a function of the tyre (noise) label [Hammer et al., 2018]

The correlation is very poor. Further investigation showed that the correlation is bad for ALL tested surfaces. The lack of correlation of the tyre noise label with adapted CPX levels measured on any surface (smooth or more textured) cannot be explained by a lack of *representativity* of the ISO surface but must be attributed to the lack of *reproducibility* of the tyre noise label. This aspect is treated in chapter 3 of this report.

This is particularly evident when the different tyres are normalised to a reference surface using the CPX method. This shows that the correlation between the quiet tyres (on the reference surface, vs. the test surface) is quite good.

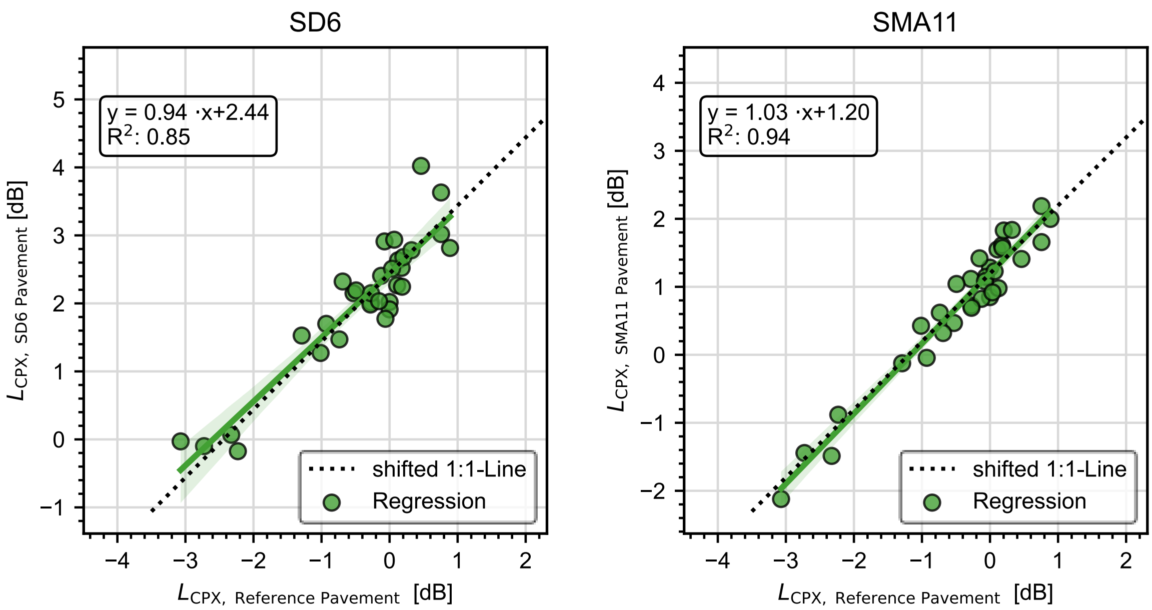


Figure 4-14: Regression analysis between tyre CPX levels measured on the reference surface vs. the test surfaces. (Left: SD6, Right SMA 11). (Normalized values)

4.4 Retread tyres

One very important part of the tyre market is exempt from the limiting and labelling system, namely the retreaded tyres. For the C1 class they constitute a rather small part of the tyres in traffic, but for C3 tyres they constitute about half of all tyres in service on European roads. Therefore, this is a serious lack of representativity and efficiency of the labelling system, as a substantial part of the tyres in service are not labelled.

It is interesting to note that when a consumer label for tyres was introduced in the five Nordic countries in 2002 ("The Nordic Swan environment label"), the retread companies were most interested to have their tyres labelled, which happened to a large extent [Sandberg, 2008]. By January 2008, three tyre retread companies held licences for car and truck tyres, covering several tread patterns, dimensions and speed classes: both for normal ("summer") and winter ("M+S") tyres. Figure 4-15 is a proof of this.

It is more complicated to label retreaded tyres than new tyres, since each new tread may be fitted to different carcasses and the definition of the tyre becomes a problem. The label will essentially depend on the performance of the (new) tread, and the carcass will have a negligible effect on (exterior) noise and wet grip. It may have a significant effect on rolling resistance, but the tread will still be the most important part. Therefore, it is acceptable to define the tyre by the tread and by the retread company. Consequently, one will have to accept that different carcasses may cause an extra uncertainty in the label, which will probably be negligible for noise and wet grip but have a marginal effect on rolling resistance. It may be necessary to introduce some (reasonable) limits for the carcasses in order to limit the (small) effect it may have on rolling resistance. This should be studied in new research.

Figure 4-15: The first licences for tyres in the Nordic Swan environmental label are awarded in 2002: Representatives of the retread companies Fighter, Green Diamond, MacRipper, AGI and Galaxie show their licences. From [Sandberg, 2008].

4.5 Winter tyres

4.5.1 The problem with testing versus operating temperatures

A major problem for the labelling system is that winter and normal tyres (the latter referred to here as “summer tyres”) are optimized for operation in very different seasons but are tested and labelled for noise under summer or at least not winter conditions; ideally and usually around or above 20 °C, and with temperature corrections applied. This is acceptable for summer tyres. However, summer tyres are often used at temperatures around or not far above 0 °C. Also, winter tyres are often used also in summer. Even though there is a temperature correction, at such extreme temperatures, the correction has a significant uncertainty.

Also, winter tyres are tested and labelled (for noise) under summer or at least not winter conditions; ideally and usually around or above 20 °C. But they are mostly used at temperatures in the range -20 to +10 °C. For lower temperatures than 5 °C there is no correction to noise. It may well be that winter tyres (which may include such different types as all-season tyres, winter tyres optimized for mid-European conditions and winter tyres optimized for Nordic winter conditions) emit quite different noise emission at freezing temperatures than they are labelled for. Therefore, the noise labelling, if done at temperatures above (say) 15 °C may be unfair to winter tyres when they operate in the range they are developed for. The classification and ranking of them for their normal operating temperature range may be different than at common testing temperatures around 20 °C.

When comparing the use of summer tyres at low temperatures and winter tyres at high temperatures, the noise emission may be very different from what they are labelled for. In general, probably, summer tyres are noisier than winter tyres at low temperatures while winter tyres perhaps are noisier than summer tyres at high temperatures. This problem is accentuated when the present trend of producing more and more advanced all-season tyres instead of optimizing the tyres for the main season. Consequently, the tyres should be tested in the temperature range for which they are optimized. At the present time it is arguable if the noise limits and labelling are representative of actual winter conditions and is fair in the ranking for winter tyres.

Unfortunately, we expect that this problem is much worse for rolling resistance, but this parameter is not part of this project.

4.5.2 Noise limits for winter versus summer tyres

In the EU regulation (EC) 661/2009, limits for noise emission at type approval are specified. The measurements according to type approval are also used for determining the tyre noise label value. For C1, C2 and C3 tyres, an extra dB is allowed for “snow tyres” (what we here call winter tyres). An exception is for C2 tyres of “traction” type which are allowed 2 extra dB instead of the 1 dB for all other “snow” tyres.

The reason for this extra allowance may be the situation until about 50 years ago when it was common that winter tyres had very aggressive tread patterns which caused excessive noise. This is no longer the case. For example, measurements on approx. one hundred C1 tyres about

20 years ago, presented in [Sandberg et al., 2002] did not indicate that winter tyres were noisier than summer tyres. The common technology to provide winter treads with plenty of sipes, and to avoid too wide tyres, while also using softer rubber are all very favourable measures for noise reduction, as is shown in for example Figure 6-3. However, data presented in Fig. 8-4, compared to Fig 2-2 in Deliverable D5.1, suggest that winter tyres on average are labelled with 0.7 dB higher values than summer tyres (levels weighted by the number of tyres having that level). This of course is no surprise as the limit values are 1 dB higher; yet it is interesting that it is less than the 1 dB allowance. Nevertheless, it is not time to delete the extra allowance, as too many winter tyres would fall above the limit value if it is done now.

The authors are uncertain about what applies to all-season tyres which are becoming more and more popular. Tyre companies are currently devoting substantial resources to development of such tyres. As EU Regulation 661/2009 does not mention all-season tyres, we assume that they are considered to be “normal tyres”; i.e., “summer tyres” in our terminology, and should not be given an extra dB of allowance.

4.5.3 Recommendations regarding winter tyres

It should be clarified that all-season tyres are considered to be “normal tyres” (or “summer tyres”) as they are generally used less in winter than in summer seasons. They should not be allowed the extra 1 dB as is allowed for winter tyres.

When it comes to testing in a more representative and fair way for winter tyres, it is difficult to make realistic recommendations; except that research is needed. One would need to make experiments to determine the performance of tyres in summer temperatures versus winter temperatures and how such performance may differ among tyres. Testing at low temperatures could be made in conjunction with ordinary winter tests in northern Europe if an ISO 10844 surface would be paved there and kept free from snow or ice. Such testing may much easier be made in a laboratory setting, with a drum covered by a replica of an ISO surface and where temperature may be varied.

Regarding the extra noise limit (1 dB) allowed for winter tyres compared to summer tyres, at least for C1 tyres this allowance should be removed as the technical justification for it is lacking. However, it cannot be made immediately, but should be planned in future updates of the limit values.

4.6 Conclusions and recommendations

4.6.1 Conclusions

Regional distribution of surfaces and their representation by the ISO track:

- Secondary and local roads and streets in European countries with a “moderate” climate generally have pavements with a relatively “smooth” macrotexture, at least in their new state. Smooth-textured pavements are useful for lowering tyre/road noise and rolling resistance compared to rough pavements and the ISO test track represents them quite well.
- Pavements used on the highway network of these countries with a moderate climate (such as SMA 11, SMA 14 or exposed aggregate cement concrete pavements) usually have at least a “medium” texture for safety reasons, i.e. in order to ensure good grip at high speed under rainy conditions. In Nordic countries, studded tyres are used in wintertime, and therefore pavements with larger aggregate sizes are common for a better wear resistance. All secondary and high-speed roads belong to the medium or even the rough texture class. The smooth ISO 10844 surface has no resemblance to the medium- or rough-textured highways in the north European climatic zone.
- Road authorities should be aware that the use of very rough-textured surfaces on the road network, such as SMA 14, SMA 16 and HRA and exposed aggregate cement concrete with large aggregates, will reduce the effect of quiet tyres (compared to using smooth-textured surfaces) while at the same time causing excessive rolling resistance and thus CO2 emission and air pollution.
- The extremely large range (MPD of 0.70 mm is no less than 2.3 times 0.30 mm) allowed in the ISO 10844 is a problem in itself as it means that noise measurements on surfaces having MPD near the lower limit may give quite different results than on surfaces near the higher limit. It contributes to the uncertainty of such noise measurements.

Performance of tyre labels on different surfaces:

- The smooth-textured ISO surface ranks tyres in a similar way as on local roads and streets in service but this is not the case for the ranking of the C1 tyres on the medium or rough textured surfaces, used on the main road network. Truck tyres C3 seem to be less sensitive to the texture hence a better correlation between labelled values and normal road surfaces, also the more roughly textured, such as SMA 11.

Differences between tyre variants within a tyre line:

- It appeared that the common practice to measure only one or a few tyre variants within a tyre line (such as for type approval) may assign tyre noise labels which are grossly incorrect. The few examples STEER were able to study, showed that for one tyre line, tyre variants differed almost by 6 dB despite they were all labelled with the same level. This makes it impossible in general for tyre consumers to select quieter tyres which should be the purpose with the tyre label.

Retreaded tyres:

- Retreaded tyres are used in a large part of the European road traffic (for C3 tyres they are about as common as new tyres) but are not included in the tyre labelling program.

4.6.2 Recommended actions

- To investigate the representativity of the tyre labels in future studies, regional differences in predominance of rough pavements should be considered. Regions could be defined based on their climate, e.g., based on the Köppen Climate Classification System [Kottek et al., 2006]. Evaluation regarding representativity of tyre labels should only be made taking into account the predominance of a certain pavement in a European context.
- A second reference surface for noise labelling of tyres with a higher texture should be considered to increase the representativity of tyre labelling in countries with predominantly rough road surfaces. One possible second reference pavement, actually considered in the ISO work 20 years ago, may be the SMA 11 which now is part of the virtual reference pavement in the common European traffic noise prediction model CNOSSOS-EU, as it is considered as a common pavement used (more or less) in all European countries, and also was proposed in the ROSANNE project. However, this pavement type must be more precisely defined if it shall be standardized for noise-measuring purposes. It must be recognized that introducing a second ISO test surface, will double the number of required measurements per tyre, although the workload is largely influenced by all preparations of tyres and test vehicles which are needed irrespective of number of test surfaces. If a second test surface is located as an extension of the present ISO test surface, the extra workload is very small as the measurements on both surfaces can be made in the same runs.
- Moreover, the range of macrotexture in the existing ISO 10844 should be reduced from the current MPD range of 0.30-0.70 mm to 0.40-0.70 mm, in order to reduce the acoustic variability of the ISO test tracks.
- NRA:s should, if possible, avoid using rough-textured road surfaces (such as SMA 14, SMA 16, HRAs and some exposed aggregate cement concrete surfaces with large aggregates, as they generally give higher noise levels and smaller noise differences between present tyres running on such surfaces; resulting in lower noise-reducing effect of quieter tyres (see chapter 4.3.3).
- Tyre noise labelling should be made based on noise measurements for each tyre variant within a tyre line and not only for the noisiest tyre or a few tyres, as often is made currently.
- To avoid too much extra testing efforts, STEER proposes to use a simplified laboratory drum method for determining the tyre noise differences between the tyre variants within a tyre line, which then is used to set the noise label compared to one selected reference variant (which could be the type approved one). In this way one may save a lot of outdoor test track measurements, by going indoors. See the proposal in more detail in section 4.2.11.

- In a long-term perspective, the extra 1 dB of allowance for winter tyres, should be removed, since there are no clear technical reasons for it. But it cannot be made soon, as too many winter tyres might fall above the present limit then.
- It is suggested that retread tyres are becoming part of the labelling system. It is disturbing that about one half of all C3 tyres in service on European roads are not subject to the labelling. Therefore, the work that was made earlier for this purpose should be resumed. Since it is more complicated to define retread tyres as they may have the same tread on a number of carcasses, one may have to accept certain sacrifices in the system, but in principle they shall be labelled too.
- To increase the efficiency of the tyre labelling system, it is time to include labelling also for retreaded tyres. It is more complicated than for new tyres, but it is possible. As the label will essentially apply to the (new) tread, one will have to accept that different carcasses may cause an extra uncertainty in the label.

5 Scenarios and business cases

5.1 Consumers' choices

In 2016, a study performed by [Viegand Maagøe, 2016] investigated the end-users' awareness of the tyre labelling system and to what extent it influences their tyre purchasing behaviour. The survey was conducted between 2012 and 2016 with 1000 private car owners in each of six EU countries (Italy, Sweden, France, UK, Finland, Germany), after the (first) label had been introduced in 2012. In Figure 5-1, the importance of the information on the label for the end-users (consumers) is shown. The data is taken from [Viegand Maagøe, 2016].

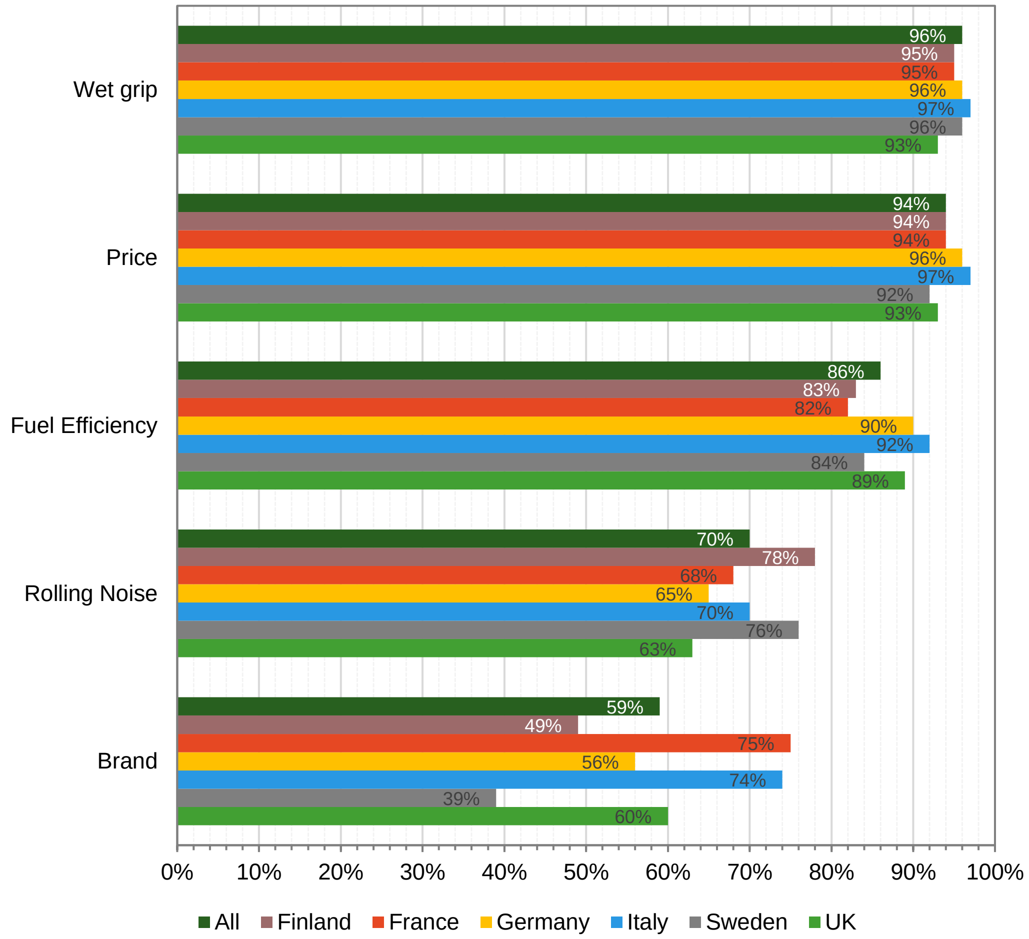


Figure 5-1: Importance of the information on the label for each performance parameter on the label (proportion of consumers who answered *very important* or *important*).
Source of data: [Viegand Maagøe, 2016]*, graphic by the authors.*

Hence it was shown, that for the consumers (end-users) the safety aspect (wet grip) was most important, followed by the price and then fuel efficiency. The tyre/road noise was only the 4th most important item. The fact that wet grip is a key performance parameter is also mentionned in other studies [Sandberg, 2008].

Investigations regarding the dependency of the tyre price with the noise labels performed by different authors have shown, that the price is not necessarily related to the noise level [Dittrich et al., 2015; Sandberg, 2008]. Therefore, it can be assumed that, for the time being, the choice of quiet tyres is not necessarily associated with higher financial costs for the consumer. The combination of these aspects leads to the conclusion that the introduction of low-noise tyres (from today's point of view) should not have a major financial impact on the consumer. This means that the consumer should already be able to choose a low-noise product, regardless of the purchase price. The study by [Sandberg, 2008] shows, however, that certain consumers would be willing to pay a higher price for tyres if they could buy a more environmentally friendly (quieter) product. However, the study also showed that about 1/3 of the people would not be willing to pay more for a quiet tyre, so it is a very individual choice.

5.2 Noise awareness in public

Noise is omnipresent in our society. It has been shown several times that excessive noise exposure leads to adverse health effects. As consumers, we must, therefore, focus more on the noise pollution that each individual generates, especially when it comes to the road traffic noise problem. In the sense of a service to society, the exposure of each individual should be minimised by his or her own behaviour. Buying a quiet tyre can, therefore, reduce the impact on other people. It has also been shown that quieter tyres tend to be quieter inside the vehicle, although there is not a very high correlation. Consequently, the use of quieter tyres can be a service to the general public as well as to one's own well-being (less noise pollution in the vehicle).

Consumer organisations can play an important role in communicating and advancing these arguments. An example of such an organisation is for instance QUIETMARK[11]. National Touring clubs have also an impact and perform tests on tyres as well[12].

5.3 Business cases for national road administrations

The purpose of this section is to illustrate the potential benefits of quieter tyres and their influence on the noise abatement strategies of National Road Administrations (NRA). The focus was laid on the evaluation of possible benefits regarding noise reduction strategies by the proliferation of quieter tyres in the different EU Member States.

As a basis for the calculations, the European Noise Directive (END) data published in [European Environment Agency, 2020] has been used, in which the assessment of the population exposed to high levels of environmental noise is calculated. This data is necessary to evaluate the effect of the different scenarios. The European parliament has decreed in the

[11] https://www.quietmark.com/
[12] https://www.tcs.ch/de/testberichte-ratgeber/tests/reifentests/

EU Directive 2002/49/EC, that the noise pollution must be recorded collectively for all the EU member states every five years. It is defined in the directive that municipalities over 100'000 inhabitants are obliged to report their noise pollution. In this analysis, only the inhabitants around major roads inside these END-agglomerations are considered, but still covering ~70% of the exposed population.

5.3.1 Scenario definition

The scenarios examined all aim to make the utilized tyres quieter. There are various possible courses of action for this, which are briefly outlined in the scenarios. Table 5-1 lists the different evaluated scenarios. For all the scenarios, the reference scenario (status quo, business as usual) is always included and thus, the enforcement of the directive 2009/661/EC is taken into account in all the scenarios calculated. This also makes it possible to compare the individual scenarios directly with each other and the consequences of the implementations can be studied while everything being equal.

Table 5-1: Scenarios for calculating the impact of tyres

Scenario Name	**Short description**
Reference (Status quo)	Defined in 2009/661/EC, status quo, business as usual
Scenario 1, Baseline ECE Proposal	ECE Proposal 2022
Scenario 2, Industry agreement	Output-oriented noise levels average for tyres
Scenario 3, Subsidies for tyre manufacturers	Subsidies for tyre manufacturers to produce tyres with LV-3 (LV = noise limit value)
Scenario 4, Consumer incentives	Potential incentives to consumers buying class A tyre (LV-3 tyre)

Scenario 1, Baseline ECE Proposal:

The *scenario 1, ECE Proposal* comprises of the proposal of the Netherlands[13]. The *ECE Proposal* foresees a reduction of all three different types of tyres C1-C3 as specified in Table 5-2.

Table 5-2: Reduction of noise limits according the ECE Proposal.

Year	Tyre type C1	Tyre type C2	Tyre type C3
2022	1 dB	1 dB	-
2024	-	-	2 dB
2032	3 dB	2 dB	
2034	-	-	4 dB

Scenario 2, Industry agreement:

[13] Informal document GRB-62-11-Rev.1, 64th GRB, 5-7 September 2016, agenda item 7

The scenario, *Industry Agreement* requires tyre manufacturers and tyre dealers to sign a letter of in-tent. The basic idea is that quiet tyres are already available on the market and only consumer buying behaviour needs to change. This is to be achieved with an industry agreement so that the sum of all tyres sold does not exceed a certain threshold level of noise. This measure is comparable to other areas. For example, the EU regulation 2019/63 sets the maximum CO_2 emissions for passenger cars and light commercial vehicles in Europe. Put simply, this system works in such a way that vehicle manufacturers have to comply with a certain limit value for CO_2 emissions (weighted according to vehicle weight). In case of non-compliance, the manufacturer is fined for exceeding the limit. With regard to noise limits, a similar system would be conceivable.

Scenario 3, Subsidies for tyre manufacturers

This scenario should encourage the development of quiet tyres by tyre manufacturers. This development, especially of quiet tyres, should be financially supported or rewarded. However, this scenario is problematic with regard to European legislation. For example, no subsidies to private manufacturers are possible. Similarly, subsidising European tyres would have a significant impact on the global market economy. For this reason, it was decided within the STEER consortium not to pursue this scenario any further.

Scenario 4, Consumer incentives

With this scenario, a change in consumer behaviour is desired. This change should be rewarded with financial incentives for the purchase or installation of especially quiet tyres and thus be promoted. This scenario is based on the fact that quiet tyres are already available on the market, but that end users have not yet focused enough on the noise factor. A possible driving factor could be that the quiet tyres could be exempt from the VAT.

5.3.2 Scenario impacts

Since the scenarios all aim at a change in tyre/road noise, a model must be chosen for the modelling of the acoustic influence that differentiates between the engine and tyre/road noise. Thus, the Model TRANECAM has been selected to calculate the impact of the scenarios [Pardo & Steven, 2010]. The results of the modelling are compared with the country-specific noise exposure curves as shown in Figure 5-2. The results of the modelling are compared with the country-specific noise exposure curves. In this case, the original distribution represents the calculation according to the status quo.

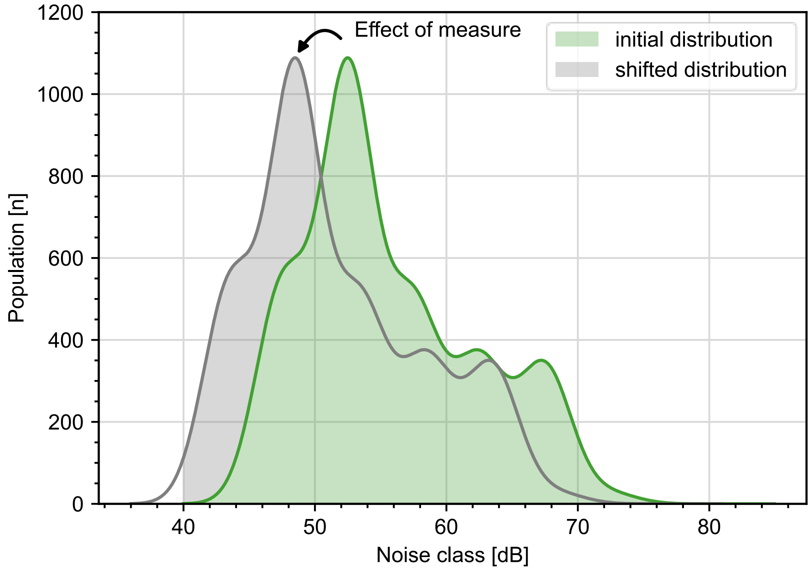


Figure 5-2: Illustration of interpolated and refined END Data and the effect of a potential measure resulting in a shifted distribution (green moves to grey).

With the calculation using the END data set [European Environment Agency, 2020], it was thus possible to make region-specific predictions for the individual sub-regions (agglomeration definition according to the END definition). This methodology was applied to all the END Agglomerations reported in 2017. In total, this results in 528 different noise-population densities for the European Union. In this final report, only country specific results are shown. For more details, consider Deliverable D5.

The applied methodology assumes that the exposure curve remains constant and has the same shape when a noise abatement measure is introduced. This is a simplification, as the shape of the noise exposure curve might shift as well when a noise abatement measure is introduced.

The potential financial benefits by the reduction of the noise burden is estimated using Figure 5-3 as presented in [European Commission, 2019]. Using these interpolated environmental costs combined with the calculated noise reductions from the scenarios yielded the total financial benefits of the different scenarios.

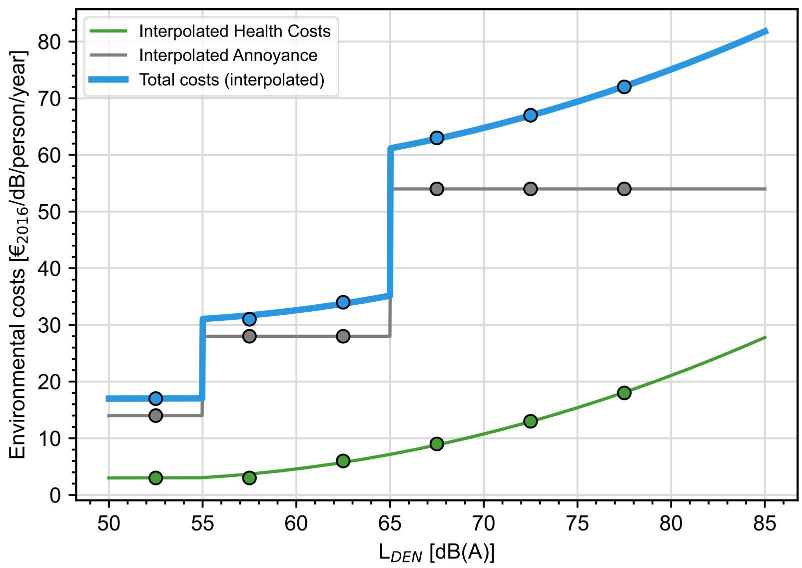


Figure 5-3: Interpolated environmental costs (health & annoyance). The blue line indicates the parameterized total environmental costs.
Source: data from [European Commission, 2019]*, calculation and illustration by the authors.*

5.3.3 Possible reduction per scenario

The different scenarios show different reductions in noise emission levels as depicted in the following Figure 5-4. The expected emission levels are strongly dependent on the general driving speed, as the influence of the tyres tends to be greater at higher driving speeds, as already illustrated and discussed in Figure 2-1. Consequently, the greatest influence is also to be found for the road category "Motorway". The smallest effect is found for the category "Urban Road". However, an effect of between 0.7 and 1.1 dB can still be expected, compared to the reference condition (status quo).

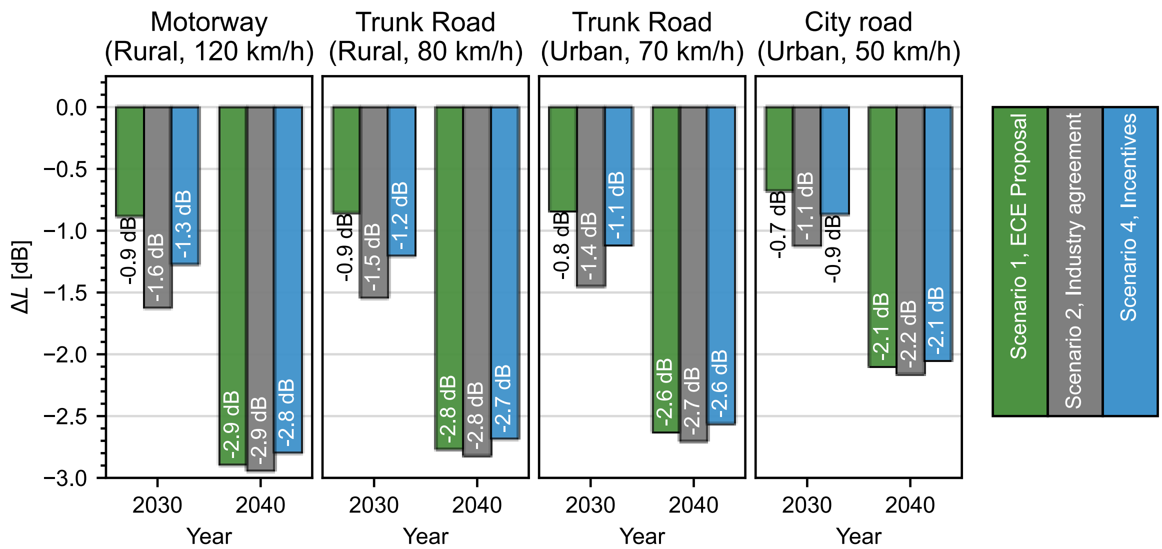


Figure 5-4: Average noise reduction (Δ) per scenario

In general, the tightening of the limit values (Scenario 1) tends to have the lowest effect as indicated in Figure 5-4. This is a result based on the assumption that by the enforcement of a stricter limit value scheme, only the noisiest tyres will disappear from the market. As a result, the improvement only occurs by cutting away the segment of the noisiest tyres. The rest of the categories remain unchanged, and thus there is only a minor shift in the overall noise impact of the tyre fleet.

The other scenarios (*Industry agreement* and *Consumer Incentives*) have a slightly different approach as they approach the problem more holistically by focusing on effective noise protection based on the population and the community, respectively. Thus, in this approach, it is assumed that the improvement is not only based on the noisiest tyres, but that an improvement can be achieved across a broader category of tyres.

Furthermore, it can be seen that the reductions in 2040 are very similar, when compared amongst each other. The final stage of the *ECE proposal* (See Table 5-2), which is to be implemented between 2032 and 2035, will have a major impact and leads to a convergence of these scenarios. Nevertheless, it is very important to bear in mind that, up to this period, there is the possibility that a very large part of the vehicle fleet will be electrified by then. Therefore, the noise problem of road traffic noise will mainly relate to tyres (compare with the following chapter). But this shows all the more that the use of quiet tyres is an urgent need.

5.3.4 Country specific benefits

The following Figure 5-5 shows the influence of the different scenarios on the fraction of the heavily exposed population in the agglomerations for the reference year 2030 for selected countries. The figure shows that the *status quo* is the worst performer overall. It can also be observed that the scenarios lead to a significant improvement. It would be difficult to achieve the same effect, for example, by building noise barriers.

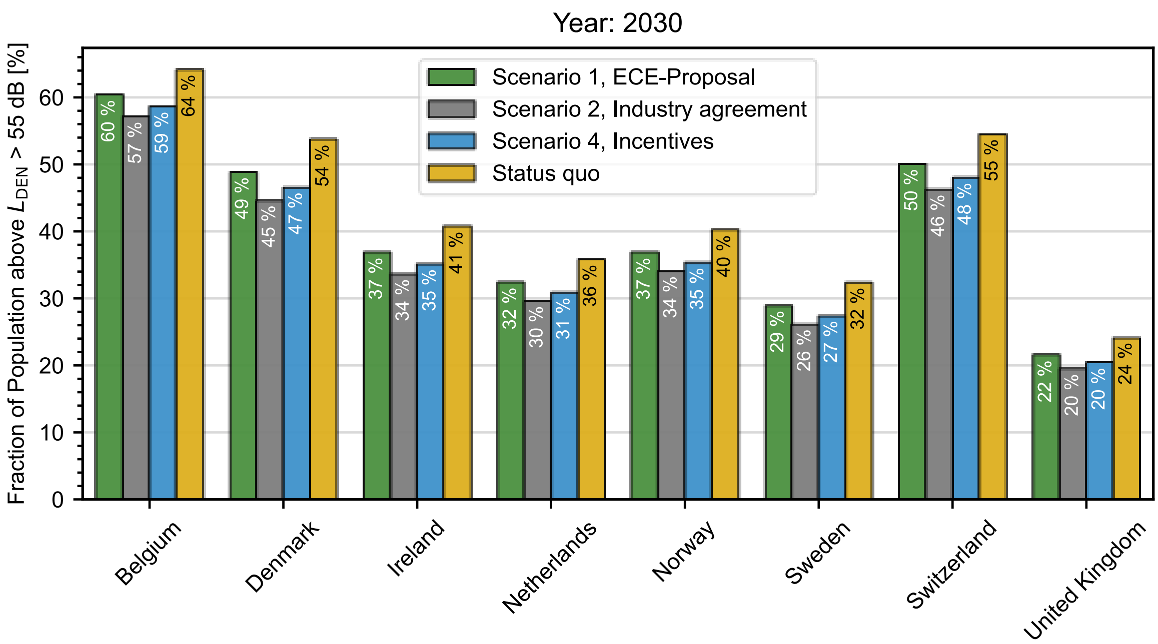


Figure 5-5: Fraction of the population exposed to a L_{DEN} > 55 dB for a selected number of countries (STEER – Founding countries including Switzerland) for the reference year 2030.

The environmental financial benefits through avoidance of external costs from the different scenarios is presented in Figure 5-6. The figure illustrates the total annual benefits in €, which range from 0.5 € up to 2.8 € (costs are in € per person and year). Interestingly, Scenario 1 with the *ECE Proposal* leads to the lowest annual benefits for the year 2030. However, with the adapted limits for stage 4 of the proposal, applicable in 2032 (see scenario definitions in Table 5-1), the scenarios result in comparable annual benefits. It has to be considered, that these costs only involve the health as well as annoyance costs, therefore it is assumed that the total macroeconomic benefit might be even higher as the cost of depreciation of buildings and properties in the noise-exposed area is not included in this type of calculation.

The annual benefits also show that the measure of quieter tyres could offer an interesting perspective on the noise problem, especially for countries with a high population density. Quiet tyres represent a measure at the source, whose cost-benefit is very well demonstrated in densely populated areas. This is because this noise protection measure does not require any structural intervention, and thus no (valuable) space has to be expended. In densely populated areas, a measure quickly affects a larger number of inhabitants. Similarly, the noise problem tends to be smaller in sparsely populated areas. Therefore, the benefit is higher in more densely populated areas. It appears that the annual benefits tend to be greater in countries with a high population density.

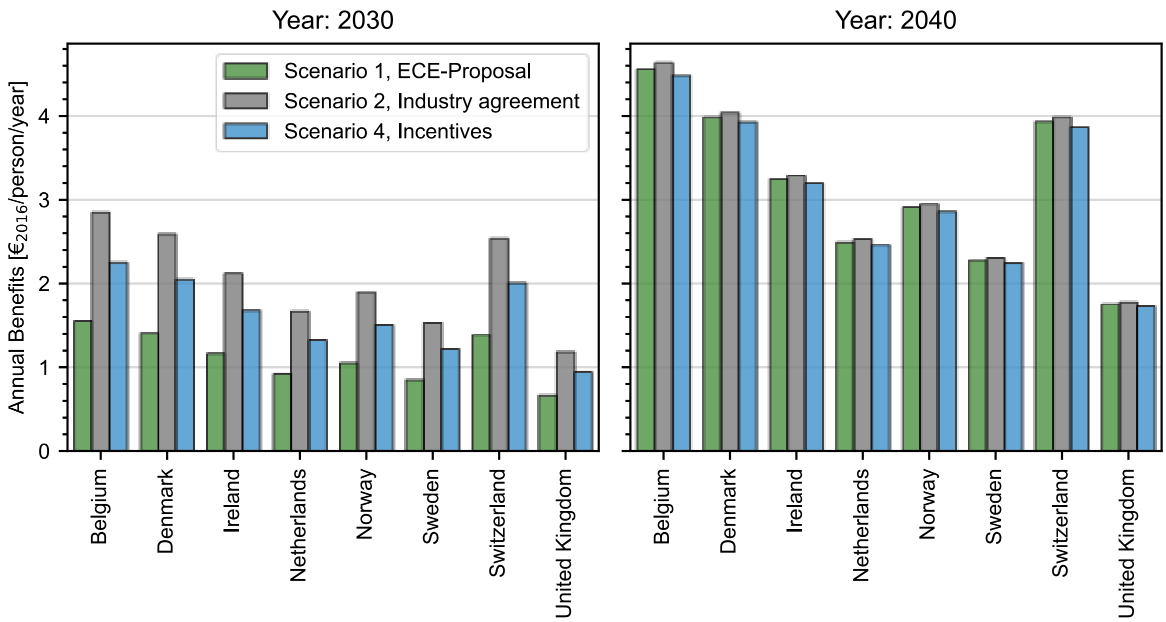


Figure 5-6: Resulting benefits from avoided external costs (health and annoyance) for the different scenarios relative to the *status quo* of the respective year. Basis for the calculation are the environmental costs as specified in [European Commission, 2019] and depicted in Figure 5-3.

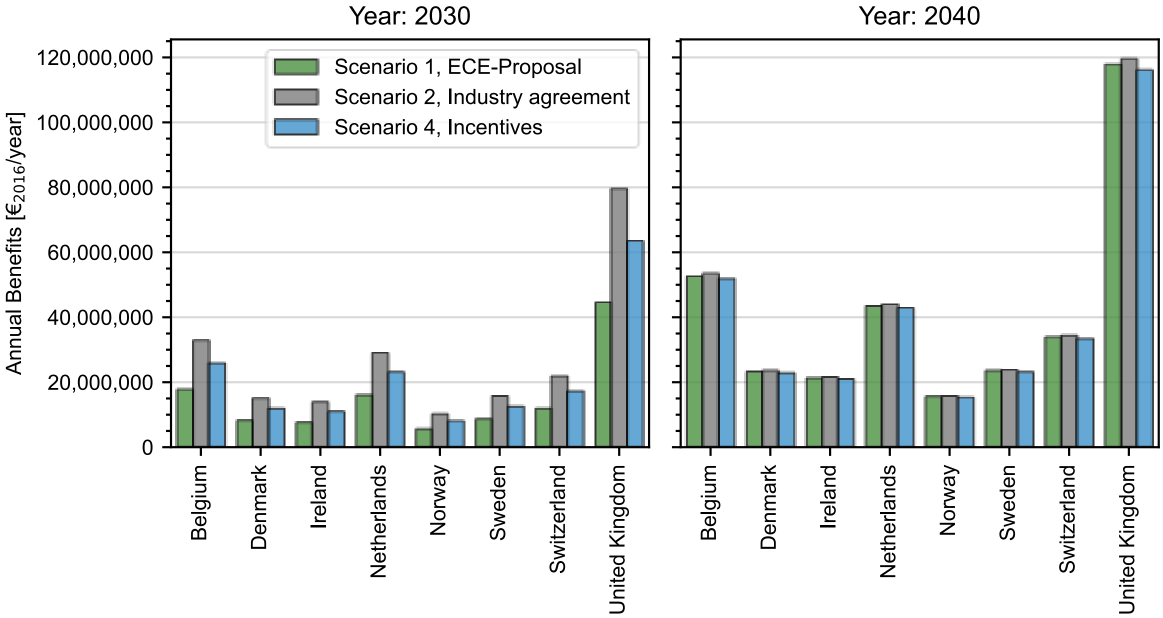


Figure 5-7: Resulting total annual benefits from avoided external costs (health and annoyance) for the different scenarios relative to the *status quo* of the respective year. Basis for the calculation are the environmental costs as specified in [European Commission, 2019] and depicted in Figure 5-3. Basis for the calculation: Multiplication of relative benefits from Figure 5-6 by the total number of inhabitants.

In Table 5-3 the main stakeholders are listed and the respective costs are estimated on a qualitative basis. All the costs are compared to the *status quo* option, for which, no additional costs emerge.

Table 5-3: Qualitative illustration of costs and benefits for different scenarios and stakeholders. (-- for highest expected costs, + for highest expected benefits, and 0 indicates a neutral option, compared to the *status quo*)

Stakeholder	Measure	Status quo	Scenario 1, ECE proposal	Scenario 2, Industry agreement	Scenario 4, Consumer incentives
Public authority	Costs for enforcement	0	nearly 0 Changing of technical documents, update enforcement procedure	- New enforcement, checking for contractual requirements regarding fleet average	- National enforcement
	Funding	0	0	0	- Reduced VAT revenue
Tyre industry	R&D Investment & Testing	0	- Product replacement, costs for the replacement or development of new products	+/- Some manufacturers will profit, some will have to pay fines or develop new products	0
Consumer	Additional tyre cost	0	0	0	+ Consumers can opt to buy VAT-exempted tyres

5.3.5 Discussion of the scenarios

The modelling has shown that all the scenarios result in a better noise pollution situation throughout all countries involved. Concerning the exposure assessment, all scenarios have shown a high reduction potential in the percentage of the population exposed to high noise levels (L_{DEN} > 55 dB). Compared to the respective *status quo* situation, which includes tightening limits according to regulation EU 540/2014 of vehicle noise, the scenarios could reduce the percentage of people with L_{DEN} above 55 dB by about 10 %.

The proliferation of quiet tyres has benefits in terms of avoided external costs (health and annoyance) compared to the *status quo*. Estimating the avoided health and annoyance costs of a noise abatement measure is subject to high uncertainty, and most costs are also not directly attributable, as they are external and are also likely to occur with a time lag; i.e., medical expenses, rent losses, etc.

However, as outlined in this report, all measures have significant benefits in terms of avoided external health and annoyance costs. The benefits range in the selected STEER-funding countries from 0.5 €/per person/year in the year 2030 to up to 2.8 €/per person/year. Note that by “person” here is meant each person in the entire country population and not just the noise-exposed ones.

A recently completed EU Project *Assessment of Potential HEalth Benefits of NOise AbateMENt MeAsures in the EU* (PHENOMENA) has investigated the effectiveness of different noise abatement scenarios in the EU [Salomons et al., 2021]. Besides other transportation noise sources, different abatement solutions for road transportation noise have been studied and compared amongst each other. The study showed that the use of quiet tyres as a noise abatement measure has a very high cost-benefit ratio. The modelling in the PHENOMENA project was carried out with a reduction in tyre/road noise in the range of 3-5 dB. With that input parameters, an overall reduction of highly annoyed persons of approx. 14 % was reported. These reductions are therefore somewhat higher than the values calculated in the STEER project. This is a consequence of the assumed reductions in tyre/road noise. Accordingly, the analysis of future scenarios and the resulting benefits is strongly dependent on the input parameters used for the simulation. What was revealed, however, regardless of the assumed reductions in tyre/road noise, was the consensus that a reduction in the area of the tyre/road noise leads to a significant improvement in noise pollution.

In our case, the only varying input parameters were the expected reduction in the tyre/road noise part, which is given by the proliferation of quieter tyres. Since the tyre/road noise contribution is dominant to the overall traffic noise, even at lower speeds, the effect of the proliferation of quieter tyres is drastic (see Figure 1).

5.3.6 Other measures to increase the market share of quieter tyres

An important opportunity to increase the use of low noise tyres is through the public procurement system. Public authorities (national, regional, communal, city departments) have influence over several types of procurement, for example:

- Procurement of vehicles and their tyres owned by the public authorities
- Procuring transportation services through private companies
- Accepting/allowing transportation services which need some kind of authority approval; for example, taxi services (where appropriate)

When considering those examples, it is obvious that the number of vehicles and tyres which are under some kind of authority control affect a substantial part of all vehicles on the market. Authorities can require that such procurement or acceptance be conditional, by requiring that tyres shall be of low noise type (or even further meet certain energy and wet grip criteria). Furthermore, when admitting tax deductions for the use of private vehicles in businesses (where appropriate), in principle, a condition might be that the vehicle is environmentally friendly (for example an EV) and equipped with low noise tyres.

The above is in-line with the Green Public Procurement (GPP) system. The European Commission has just published a revised version of the EU GPP criteria for road transport, updating the previous criteria published in 2019[14]. The revised criteria are fully consistent with the revised Clean Vehicles Directive (Directive 2019/1161/EU) and provide contracting authorities with the necessary guidance to procure clean and environmentally responsible road vehicles and services. They address five categories:

- purchase, lease or rental of cars, light commercial vehicles (LCVs) and L Category vehicles

[14] https://ec.europa.eu/environment/gpp/index_en.htm (20 October 2021)

- mobility services
- purchase or lease of heavy-duty vehicles
- outsourcing of road transport services, and
- post, courier and moving services

In Section 6.1.4 the possibilities of using RFID systems are discussed. RFID technology allows a wide range of useful applications, such as to include a kind of consumers' digital label. The tyre label values or classes can be included in the RFID chip (along with for example week of production) and then read from a distance; some chips allow it even for moving vehicles. This can be in toll passages, at parking areas, along a street or at the entrance to environmentally protected zones. A low-noise tyre label may give access to a certain zone, and the opposite for tyres with higher levels. When winter tyres are mandatory to use, the RFID can provide information about this, and other tyres can be stopped. Studded tyres may be detected easily by RFID technology and register unlawful driving in a zone where such tyres are not permitted. Unlawful combination of different tyres can be easily detected. Tolls could be favourable to high-performance tyres, and so on—there are numerous applications for the RFID technology in the near future. All these options have a potential to encourage consumers to purchase and use tyres that are favourable in such detection systems.

Note that the above possibilities to increase the market shares of low noise tyres are possible to implement nationally and even locally in some cases. It is entirely up to the actions of the relevant authorities, of course given that they are legal on all relevant levels.

Finally, it is worth mentioning that the vehicle manufacturers put pressure on the tyre manufacturers to supply *Original Equipment* (OE) tyres with favourable noise performance to them. The present *Internal Combustion Engine* (ICE)-driven vehicles must meet noise criteria which sometimes are difficult to meet. The overall noise limit that the vehicle shall pass includes both a test where power unit noise dominates and one where tyre/road noise dominates. If tyre/road noise is low there may be more allowance for power unit noise—something loved by car manufacturers of sport or other high-performance vehicles where a certain sound is desired. This is one reason why many wide tyres are fairly quiet despite they are wide. Since stricter vehicle noise limits are planned for introduction in 2024/2026 [EU, 2014], this may put even higher pressure on manufacturers of OE tyres.

However, from 2035, all new ICE vehicles should be replaced by electric vehicles (or other fossil-free vehicles) and then power unit noise should not be heard (except the AVAS[15] sounds and perhaps some whistle from electric motors). Thus, the vehicle and tyre noise limits will, or at least, should converge. How this will be implemented in noise regulations is still under discussion.

A potential problem is the AVAS sounds, which will create strange sounds in urban centres when the EV:s will be common and power unit noise will disappear (especially from the heavy

[15] AVAS = Acoustic Vehicle Alerting System

diesel vehicles). It is uncertain what will happen with AVAS then, as tyre/road noise in low-speed locations will be much easier to hear when it is not masked by power unit noise. Will AVAS sounds be increased, decreased or removed, or possibly be just optional? According to the authors, these sounds have no significant function. At most, they may have a political function as they may allow vehicle manufacturers to produce artificial engine noise as their AVAS, emphasizing the vehicle brand's sound signature.

5.4 Practical considerations and scenarios

As indicated in the previous chapter, the benefits of a scenario do not come without some costs. In this project, the costs are solely estimated on a qualitative basis and compared to the 0-Option (*status quo*). We estimated that in most of the scenarios, the public authority has to bear some costs, which always involves the enforcement costs of the scenario and additional checking of the requirements and administrative effort. For scenarios 1 & 2, additional costs might possibly emerge, as some of the tyres (the noisiest tyres) will be banned and thus the industry has to replace their products, which possibly could involve new research and development.

The implementation of stricter tyre noise limits (Scenario 1) will require a Europe-wide legislation change and have to be approved by its member states. Scenario 2, *Industry agreement* requires some international cooperation as well, as all the manufacturers (EU-Wide, and also non-EU (Imports)) have to be involved. The only scenario, that could be implemented on a national level (at least to a certain degree) would be Scenario 4, *Consumer incentives*.

5.5 Conclusions and recommendations

It is known that, with increasing speed, the importance of the tyre/road noise is increasing. Especially on high-speed roads, the share of the tyre/road noise is clearly dominating. With increasing share of EV:s in the future, the focus will be even more on tyre/road noise, as power unit noise will most likely decrease.

The analysis and the scenarios have shown that the consumer is aware of a tyre label. But the most important factor for the decision which tyre is equipped on a vehicle is still safety and the price of the tyre. Noise is generally only mentioned in 4th or 5th place of the decision criteria. Further analysis within the project STEER has shown, that there are (at least for summer tyres) possibilities to equip a vehicle with tyres performing equally well for all the labelled parameters (for example, labels AAA or BB on wet grip, rolling resistance and noise), see section 6.3.

Therefore, consumer awareness of these opportunities needs to be raised. This is because the analyses have shown that a simple tightening of the limits leads to an improvement for the noisiest tyres. But only the noisiest tyres are affected, and with other measures, consumers with already quieter tyres can be persuaded to fit even quieter tyres. This effect is shown in the analysis of the scenarios, where the scenarios other than limit values adaption shows larger improvements.

Accordingly, the authors suggest that NRA:s act on raising the awareness and the proliferation of quieter tyres. This can be achieved in several ways:

- It is important to act as early as possible, as the influence of tyres will become more important in the future due to the increased share of electromobility and the associated shift of the noise problem towards the tyre/road noise.
- The scenarios within this project have shown that it is important to act. The scenarios *industry agreement* and *consumer incentives* are preferable in contrast to a pure adjustment of limit values (*ECE proposal*). The other scenarios, than scenario 1 are more preferable, as they favour the improvement of noise characteristics of the whole tyre fleet and not just the loudest tyres, as it would be done with a change in tyre noise limit values.
- Information campaign for promoting quiet tyres. This can involve a simple awareness campaign in favour of the tyre label. Within this campaign it is of special importance to involve different stakeholders such as tyre dealers and garage owners as well, as they have a great influence on the decision-making process as well as on consumer opinion. It is important that the issue of the tyre label is included holistically, i.e., also in relation to the other parameters (wet grip and rolling resistance).
- Consider the support of consumer organisations that can promote the use of quiet tyres.
- Address tyre dealers and tyre workshops, to promote AAA tyres (maybe with financial benefits).
- Investigate and test the measures for a possible implementation of a scenario according to *Financial incentives* for the consumer to buy AAA tyres.
- Implement the proposed procurement requirements for tyres
- Implement the use of RFID systems to detect and encourage the use of low noise tyres in the traffic.

6 Consideration of future trends

6.1 Market and other time trends

6.1.1 Vehicle trends

A trend which has during the last decade worried the scientific community dealing with climate change, is that “normal” passenger cars lose market shares to the significantly heavier and larger SUV:s. They are also commonly more powerful than the vehicles in the passenger car sector that they replace. For example, in just over 10 years SUV:s went from a peripheral 10 % of sales to nearly half of all car sales in Europe today (45 %) [Transport & Environment, 2021]. These SUV:s generally require larger tyres, which together with the increased load may give an increase in tyre/road noise.

The trend in Europe for the increased market share of electric vehicles of the M class (essentially passenger cars and SUV:s) versus vehicles with internal combustion engines (ICE) is very clear. For example, in Europe the sales of electric vehicles (EV:s) increased by 168 % from 2020 to the first half of 2021 [EV-Volumes, 2021].By 2035 no new CO_2-emitting cars are supposed to be sold in Europe, instead electric or hydrogen cars should have the full market share. This potentially has an impact on the tyre dimensions, since the EV:s in general need low rolling resistance tyres in order to have a driving range which is desired by the owners. Further, the electric vehicles (so far) are a little heavier than their ICE counterparts due to the battery weights. Due to the high torque provided by electric motors at low revolutions, the accelerations from standstill are expected to be higher for an average EV than an average ICE car. The higher load (also increased by heavier tyres) and the higher torque will mean a marginal increase in tyre/road noise emission.

Considering all effects mentioned, it is probable that the vehicle market trends will have only a marginally increasing effect on tyre/road noise. Opposite to this, we will have a decreasing effect of power unit noise, which will disappear at low speeds when the electric vehicles take over the market.

With regard to the expectations of future autonomous driving and vehicles driving in platoons, it is impossible to estimate the effect on noise emission of these future trends, but the authors think that these effects will be only marginal, if any at all. However, if these autonomous technologies can be used to divert traffic from roads with noise exposed areas to areas not suffering from noise exposure, the trend may be clearly positive.

6.1.2 Tyre dimensions

For the cars, both the trend towards more SUV:s and electric vehicles point towards larger tyres, both in terms of larger rim diameters and larger tyre widths. For a while it looked like the electric vehicles would break the trend of wider tyres, as lower rolling resistance could be achieved with narrower (and larger diameter) tyres, but the sportier appearance of the wider tyres seems to have a larger impact on sales or at least on the marketing departments. As mentioned above, the trends are likely to have a marginally increasing effect on tyre/road noise due to the combined effect of tyre width, load and higher torque for the electric vehicles.

For truck tyres, the trend is more complicated. It has been a trend for many years that the very common dual tyre mounting (two tyres of same size mounted together on the same axle on each side of the heavy vehicle) has been gradually exchanged to using either so-called super wide singles, or two-three tyres on one or two extra axles. Generally, this is nowadays implemented almost entirely on semitrailers (unless exceptional load capacity is needed), but it appears now and then also on some trailers for 24 m articulated trucks. An example of the former appears in Figure 6-1.

The tyre configuration for the truck in Figure 6-1 is single tyres on the steering axle, dual tyres on the driving axle and single tyres in the three trailer axles. The drive axle has 4 tyres of dimension 12 R 22.5 (which is common) and the trailer axles have 385/65 R 22.5 (also very common). The 6 trailer tyres can altogether carry a load of up to 27 000 kg. In earlier days this load would more commonly be carried by two axles with dual tyres of size 315/80 R 22.5. So, which is the quietest of these: 8 tyres in dual mounting of 315/80 R 22.5 or 6 tyres in single mounting of 385/65 R 22.5? Unfortunately, such (reliable) measured data have not been published. Furthermore, it is known that tyre width is a factor influencing noise emission, mainly because of the so-called horn effect. Then the question is: what is best of a width of 385 mm or two widths of 315 mm with 50-100 mm spacing between? The answer is not available. However, from a legal point of view, each of these tyres are allowed to emit 73 dB (in single mounting at 70 km/h on ISO surface), which means that the six 385 mm wide tyres may (legally) emit a total sound energy which is 1.2 dB less than that of the eight 315 mm tyres. Nevertheless, it is unclear if the trend with fewer but wider tyres (meeting the same noise limit) is actually an advantage in terms of noise exposure which occurs in reality.

Figure 6-1: Typical truck with semitrailer from middle Europe.

6.1.3 Speed

With the introduction of EV:s, there is a quite clear trend that the majority of the normal EV:s (excluding extreme sports cars) have a speed limit of 150 km/h rather than the quite common speed limiters set at 170-250 km/h for “traditional” fossil-fuel-driven cars. This opens up for tyres optimized for lower top speeds than today. Vehicles limited to 150 km/h need tyres with speed rating of only T (190 km/h). Maybe speed rating R (170 km/h) would be enough for these EV:s, although car tyres are normally not (yet) available for this rating. If tyres need not be optimized for extreme speed performance, they could more easily be optimized for better environmental performance instead (noise and rolling resistance). Of course, if fewer vehicles than presently will drive above 150 km/h (illegally) this means an advantage for noise exposure in addition to potentially quieter tyres.

Another trend is that speed limits on roads are lowered, both for increased safety and for reduction of energy consumption and CO_2 emissions. In some countries, speed limits on highways and motorways have been and might be further reduced for these reasons and/or speed limits in urban and suburban areas are reduced. That is mainly for reasons of increased traffic safety and for limiting the use of private transportation. For ICE-driven vehicles, lowering speeds to below 50 km/h has very limited or no benefits for fuel consumption, but for EV:s this is an important way to reduce energy consumption and thus increase range, but also for reducing noise emissions.

Electric vehicles run smoother at low speeds than ICE vehicles which may give a trend of lower speeds in urban areas and make it easier to comply with speed limits of 30 and 40 km/h.

A special but very important case is the German free speed on certain motorways (Autobahn). On most motorways the speed limits are nowadays 130 km/h and even on those without a limit, there is a recommendation to keep a maximum speed of about 130 km/h. On those free speed motorways, it happens often that some cars are driven well above 200 km/h. Germany is the only developed country having some roads without speed limit; all other countries have maximum limits in the range 100-130 km/h. Many premium passenger cars are designed to be driven at maximum speeds of up to 250 km/h just because of this which means that tyres must be produced for driving at speeds up to at least 250 km/h (there are even some for higher speeds). An effect is that optimizations for other parameters, such as noise and rolling resistance, need to be compromised, compared to if maximum speeds were (say) 130 km/h. Thus, the German free speed policy is detrimental to the rest of the world in terms of optimization of tyres for reasonable speeds, not to mention the negative environmental and safety effects it has inside Germany.

Recently, there was a general election to the German Parliament (Bundestag). In the election campaign some parties suggested an end to the free speeds on German motorways. Those parties were successful in the election and set up a new government. Very sadly for the rest of the world, the promises for removing the free speed policy do not seem to be realised.

Despite the persisting free speed on (some) German motorways, the speed-related trends are consistently favourable for reducing noise exposure.

6.1.4 RFID chips

Radio frequency identification (RFID) systems uses electromagnetic fields to automatically identify and track chips in tags attached to objects. An RFID system consists of a radio transponder, receiver and transmitter. When triggered by an electromagnetic pulse from a nearby RFID reader, the tag transmits digital data stored in the chip back to the reader. Much more information about RFID is included in Deliverable D5.1.

RFID tags are already standard in credit cards and passports – also used in burglary alarm systems. A common use is to protect products from theft in shops. RFID systems have become popular in electronic toll systems for highways and are used in many countries in Europe and worldwide. Examples are given in Deliverable D5.1.

"*RFID is the hottest topic in the tyre industry right now*" is a statement recently posted by an automotive-focused journalist [Tangeman, 2019]. Yes, RFID are already mounted into several tyres and are expected to be introduced in most tyres within the next few years. They are presently being standardized and are thus likely to provide useful data such as dimension and production week. It is a kind of embedded tyre label with digital information.

The purpose is generally to make it possible to follow the production, distribution and potentially even use of the tyres to get feedback on performance and quality. Another reason is to help trucking companies improve maintenance, as the tyres on their fleet provide data on running distances and inflation pressure and possibly some other parameters. The chips will also be useful in future autonomous driving systems.

For example, Michelin has announced plans to equip all its new car tyres with RFID chips by 2024. The latest tags developed in cooperation with a company Murata have a dimension of 6x1x1 mm and already are embedded in four million Michelin tyres. A Michelin spokesperson said that "An embedded tag is the only way to identify tires, from the cradle to the grave" [Tire Technology International, 2021]

Another tyre tag measuring 43 x 2 x 2 mm, is supplied by the company Avery Dennison, which can be read from a range of up to 11 m depending on its mounting position and the tyre type it is attached to. It is fitted to the tyre side during the vulcanization procedure. China is planning to make the technology mandatory [Tire Technology International, 2021a].

It is perfectly clear that the tyre industry has acknowledged the potential benefits and is moving quickly to adopt the technology. To enable standardization, ISO/TC 31, has a WG 10 which is working on a universal standard for RFID in tyres. This committee has already produced four standards; see Deliverable D5.1.

It is obvious that RFID technology allows a wide range of useful applications, not only for tyre companies and truck operators to trace tyres "from the cradle to the grave", but also to include a kind of consumers' digital label. The tyre label values or classes can be included (along with for example week of production) and then read from a distance. This can be in toll passages, at parking areas, along a street or at the entrance to environmentally protected zones. A low-noise tyre label may give access to a certain zone, and the opposite for tyres with higher levels. When winter tyres are mandatory to use, the RFID can provide information about this, and other tyres can be stopped. Studded tyres may be detected easily by RFID technology and register unlawful driving in a zone where such tyres are not permitted. Unlawful combination of different tyres can be easily detected. Tolls could be favourable to high-performance tyres, and so on—there are numerous applications for the RFID technology in the near future.

6.2 Constructing a future noise-optimized tyre: an example

In this chapter the impediments for a tyre manufacturer to create a new quieter than average tyre is shortly outlined. Details to the process can be found in Task report 5.4. Generally, there are several products of different tyre manufacturers on the market, which are marketed to be particularly well performing regarding the pass-by noise performance. This is an indication that it would be possible for the tyre manufacturers to produce tyres which are quieter that the average tyre sold on the tyre market.

6.2.1 Prototype for noise optimized tyre

Within the project STEER, a special prototype for a noise optimized tyre has been produced. The process of the noise optimised tyre was done following a two-step approach. First of all, a noise-favourable tread pattern was selected and in a second step, two additional and incremental improvements by increasing the amount of vibration damping using redesigned rubber components in the tyre structure, were done. The first of these two additional modifications were done on the tread component by increasing the mass of the tread uniformly across the width of the tyre. The second improvement, additional to the first, was a modification done on the sidewall component of the tyre, increasing the thickness of the component substantially. Thus, in total, three prototypes as described in the following Table 6-1 have been produced.

Table 6-1: Tyre characterization chart

Description	Short name	Tyre weight (kg)	Notes
Reference tyre	REF	13.3	Normal producibility
Prototype tyre 1	PRT-1	13.3	Normal producibility
Prototype tyre 2	PRT-2	15.4	Producibility on upper limit of component manufacturing, normal tyre buildability
Prototype tyre 3	PRT-3	17.6	Producibility beyond upper limit of component manufacturing, extremely compromised tyre buildability

6.2.2 Performance of noise optimized tyres

In the following Table 6-2, the evaluated tyre performance measures are displayed. The values indicate a normalized test value with 100 to be the reference index. A higher value indicates better performance, while lower values indicate worse performance. As indicated in the table, not all the performance measures were tested. This was because PRT-2 and PRT-3 are differing too much from the production specification of the base product and there would have been too many manufacturing rounds needed to be able to produce valid protype specimens to be used in tests such as high-speed handling without risking the safety of the test driver.

Table 6-2: Test result summary for the three prototypes. The values indicate a normalized test result (larger values indicate better performance). However, the indices cannot be compared amongst different categories, as the scaling between the different tests is different.

Tyre ID	Dry Road Handling (<120 km/h)	Vehicle Cabin noise	Pass-By Noise (R117)	Rolling Resistance (R117)	Wet Braking (R117)	Aquaplaning (Long)	Aquaplaning (Lateral)	High Speed Handling
REF	100	100	100	100	100	100	100	100
PRT-1	107.7	101.1	103.0	106.0	97.5	100.3	99.9	108
PRT-2	96.2	100.2	103.8	96.2				
PRT-3	103.8	99.4	104.0	83.4				

From Table 6-2 it is obvious that the introduction of the noise optimized tread pattern (PRT-1) had a disruptive effect on the noise parameters (increase by 3 Index points). It is also noticeable that the other performance measures did not change too negatively. Only the wet braking behaviour has changed negatively.

Regarding the PRT-2, with added damping material in the tyre structure, noise emissions have further decreased. But only pass-by noise. This effect even increased with more damping material in PRT-3. The most drastic changes of PRT-2 and PRT-3 can be observed in the rolling resistance measurements, with large decreases observed in the performance measure.

From a manufacturing point of view, there are no impediments in manufacturing tyres with the tread pattern design of the prototype tyres in this experiment. However, due to the increased damping material, raw material costs of a tyre go up by 16 % with modifications used on PRT-2 and 34 % with PRT-3. At a time when resource utilisation is becoming more and more important, the additional use of more resources is unlikely to achieve its goals.

According to this experiment, the best compromise would be the redesigned tread pattern, and according to this experiment, a quieter tyre is technically possible. The only drawback of the noise-reducing tread pattern design is a negative effect on wet grip performance. Further tyre/road noise performance improvements by structural modifications have a drastic negative influence on many of the key characteristics of tyre performance.

Most complicated and also the most effective way of introducing improvements comes in a form of tread pattern design modifications. Tread pattern design dictates many of the characteristics of a tyre and gives the visual look for the tyre. However, making tyre moulds is a very complicated and slow process. Likewise, changes in the tyre moulds after production are hardly possible. But it is precisely these small changes that should be important, because that is where the (last) potential for improvement is to be found.

6.3 Challenges for tyre manufacturers

The tyre optimization has revealed that the optimization in terms of noise has effects on other tyre performance measures. This aspect is illustrated in the following Figure 6-2. This triangle consists of three main characteristics of tyre performance parameters. These performance parameters are connected in a way that by altering one of the parameters it has an effect on the other parameters as well. The limiting factor is the area of the triangle which is constant.

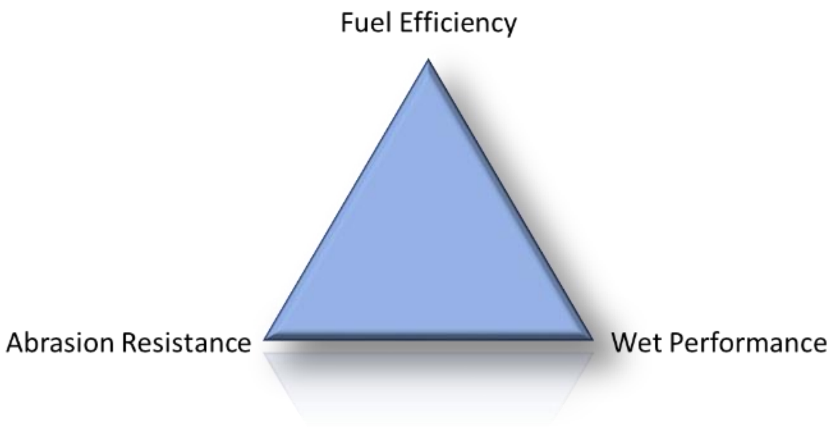


Figure 6-2: The tyre performance “Magic Triangle”, consisting of abrasion resistance, wet grip performance and fuel efficiency. Noise is an additional parameter which has to be considered, which may have an impact on the other parameters.

The experiments have shown some of the interactions of the parameters illustrated in Figure 6-2. A very illustrative example of interactions and challenges to find the optimum balance between the parameters appears in Figure 6-3.

The European Automobile Manufacturers Association has performed a study on the tyre performance [OICA, 2019; Scorianz, 2021]. The study comprehensively investigated 16 different tyres regarding different performance measures and performed some statistical analysis on the interrelation of the parameters. The main finding of this report was that the two performance measures safety (wet grip index) vs. noise (tyre/road noise according to R117) showed an antagonistic behaviour. Therefore, an increase in safety (wet grip behaviour) increased the measured noise level. It was stated that ‘*Obtaining a low level of rolling sound performance without a compromise regarding other parameters essential for vehicle safety and CO2 emission reduction could not be proven as feasible by this study’*.

Similarly the European Tyre and Rim Technical Organisation (ETRTO) presented at the 73rd GRBP Meeting in 2021 [ETRTO, 2021] a study with 10 different tyres including some winter tyres and two plain tread tyres with the findings that “*Rolling Sound performance is in trade-off with Wet Safety performances at least on the study sample*.” And “*These performances are in opposition; good rolling sound performances implies less good wet safety performances*”. Furthermore, it was claimed that some existing tyres are already close to the physical limits of the tyre/road noise emission and a further reduction of tyre/road noise will irremediably impact other tyre performances.

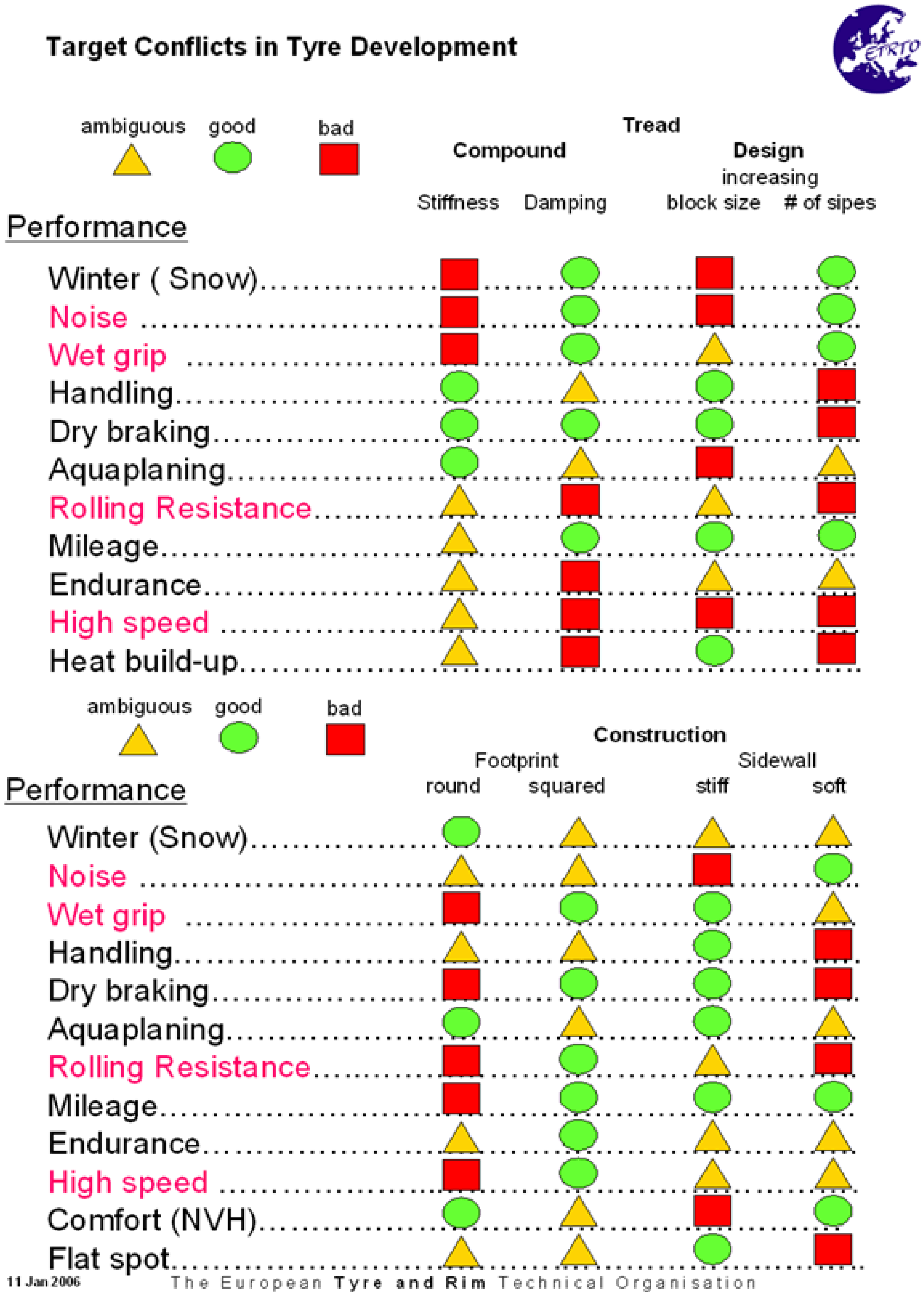


Figure 6-3: Qualitative effect on tyre performance of changing tread parameters (above) or tyre construction (below). Figure submitted by ETRTO to FEHRL, published in [FEHRL, 2006].

The two statements above by the industries are not supported by the label values presented for several thousands of tyres in Figure 6-4. In general, the low noise tyres are labelled with good ratings also for wet grip (green and yellow colours) and definitely there is not a significant opposite trend. Furthermore, in a study including about 100 tyres in Sweden, there was no correlation between noise and wet friction [Sandberg et al., 2002]. It may be that if only a small set of tyres is selected one may find undesirable correlations, but when looking at very large number of tyres, findings do not support the claims by the industry that low noise tyres would have poor wet grip.

Nevertheless, the industry is right that in development work, when optimizing tyre performance, there are always sacrifices between the parameters as it is increasingly challenging to give good ratings in all three labels simultaneously. In this respect there is always a problem to satisfy low noise and good wet grip (as for other parameters). Nevertheless, when it comes to tyres released on the market, there seems not to be any undesirable sacrifice of wet grip for low noise tyres, in general. Recently, it has been reported by experts in the tyre industry that progress in material research has made it possible to expand the area of the “Magic Triangle” in all directions [Sarkawi et al, 2021][Abney et al, 2021].

In 2019, the Netherlands presented a Working Document to the 69th session of GRB [GRB, 2019] with a proposal for new sound limits (R117) for Stage 3 and Stage 4. For Stage 3, the noise limits were reduced by 1 dB, compared to Stage 2 from 2016. The dates for Stage 3 were set to 1 Nov. 2022 for C1/C2 tyres and 1 Nov. 2024 for C3 tyres. This proposal was never adopted by GRB/GRBP as it was referred to an ongoing discussion within the European Union on this issue and that it would be premature to modify the limits now. It was recommended to come back to this proposal at a later stage. So far, no further discussions on this proposal have been promoted.

In EC 540/2014 there is a phase 3 table with noise limits for vehicles. For the category M1 vehicles, the sound limit is 68 dB. Phase 3 is applicable for new vehicle type from July 1, 2024, and for first registration from July 1, 2026. Similar limits and dates are found in R51.03.

The VDA study from 2016 [Richartz et al., 2019] showed that the tyre/road noise (using an electric car) at 50 km/h can vary from 62 to 68 dB, depending on tyre tread and ISO track. With the maximum sound level of 68 dB for M1 vehicles based on a combination of a constant speed and acceleration test, it is obvious that the vehicle manufacturers may require special low noise OE tyres for homologation of vehicles, to meet the limit of 68 dB. It may be that this sound limit may have a stronger impact on the development of more quiet tyres, than the proposed limits for Stage 3 in R117.

Furthermore, the requirements for tyres are likely to increase further in the future, which could pose some challenges for tyre manufacturers. For example, as part of sustainability discussion, the careful use of resources is always under discussion. The main component of tyres is still rubber (natural or synthetic) and thus consists largely of non-renewable resources as crude oil. Likewise, the demand on the durability of the tyres is likely to increase. The introduction of such a class on the label could accelerate this process. This is also connected with the careful handling of additives in the tyres, because the abrasion issue will also become more important in the near future.

With increasing electromobility, the focus of various interest groups will be directed even more towards tyres, anyway. With the elimination of the power unit noise component of the ICE vehicles, a large part of the noise emissions will consequently come from the tyre/road interaction. Similarly, the discussion of the range of electric vehicles is currently still strongly linked to the rolling resistance component of the tyres. In addition to the higher requirements regarding the rolling resistance components, EV:s generally can accelerate with a higher torque (which, however, easily may be limited electronically), which has to be transmitted to the road using tyres.

Another issue which is important is the expected focus on tyre wear (and particle and microplastics emissions) in the near future [LEON-T, 2021]. When an additional labelling of tyre wear ("mileage") will be introduced, tyre manufacturers will have to put higher weight on that parameter which increases the challenges they face.

6.4 Potential compromises in the current market situation?

Since market data on tyres is regarded as business secrets by the industry and therefore difficult to obtain, alternative data sources were looked for to provide a better picture of the current landscape of market tyres. With permission from the Swiss Federal Office for the Environment FOEN, a product database comprising of all C1 tyre products approved for selling in Switzerland including complete information on their tyre label and performance dimensions was further analysed for this purpose[16].

The results of the multidimensional tyre analysis are shown in Figure 6-4 (summer tyres) in the form of pie/sector diagrams. In the figure, from left to right, on a hypothetical x-axis, the tyre widths are shown with the categories C1A (narrow tyre) to C1E (wide tyre). From top to bottom on a hypothetical y-axis, the tyre noise is indicated with 75 dB (= loud) to 66 dB (= quiet). The coloured pie charts visualise the values of the respective tyre category in terms of wet grip (WG index) and rolling resistance (RR index). These two parameters were combined into a single parameter in accordance with the coloured evaluation matrix (top right) and categorised by means of colour codes (green = favourable values, red = unfavourable values). This combination reduces the data by one dimension, which makes it easier to present.

The numbers in black on white in the middle of the pie charts provide information on the number of tyres per tyre width and noise category, where the percentage number refers to the percentage of the respective tyre width. The M+S and XL tyres are not included in the percentages.

- Example: C1B & 68 dB → 154 tyres, which correspond to 8.4 % of all C1B tyres.

With this figure, it is now possible to assess the tyres approved in Switzerland with regard to the three parameters mentioned. In addition, it can be investigated whether a shift in the noise limits would result in changes for the end user and whether there might be restrictions on the "best" tyres.

[16] Excerpt from the database: https://www.tcs.ch/de/testberichte-ratgeber/tests/reifentests/

As indicated in Figure 6-4, a large proportion of the available tyres are close to the tyre noise limits (30-40 %). This can be seen from the high percentages of the diagrams within the grey, solid rectangles. If the tyre noise limits were to be tightened, these tyres on the market would disappear, and thus a large proportion of tyres were not allowed anymore. However, this would not lead to an obvious deterioration in tyre quality in terms of wet grip and rolling resistance rating. Although fewer tyres would be available, the proportion of the best-rated tyres would tend to increase (shift from yellow/orange to green with lower tyre noise limits. This applies to practically all tyre widths. There are still enough tyres on the market that are good in terms of driving safety, energy efficiency and acoustics. This circumstance is particularly true in the case of summer tyres.

It is important to note that this type of analysis is limited to the four parameters noise, wet braking behaviour, rolling resistance and tyre width. The parameters considered, therefore contain all the information that the consumer can find on the old tyre label (compare Figure 1-3). On the new tyre label (from 2021), pictograms for snow/ice grip will be added as an option (see Figure 1-4).

In this analysis, only the three performance parameters tyre noise, wet grip and rolling resistance were examined. However, when evaluating tyres, other factors must also be taken into account, such as durability, wear, vehicle dynamics performance, resource use, etc. Likewise, it is not possible to draw conclusions regarding the price of the tyres from the illustration as the consortium did not have access to this data.

Summer Tyres

Figure 6-4: Rating of C1 **summer tyres** (Switzerland 2021), sorted according to their tyre width (hypothetical X axis, rated A-E according to EC 661/2009). On the hypothetical Y axis, the noise limits are depicted. The colours indicate the related Wet grip / Rolling resistance Index as defined by the matrix.[17].

6.5 Conclusions and recommendations

6.5.1 Conclusions

The project included an attempt to analyse the difficulty to develop a quiet tyre. Simultaneously, also time trends were discussed.

Tyre prototypes: Three prototypes were developed and tested with the aim to achieve substantially lower noise than an “average” tyre. As expected, this showed that optimizing for low noise gave trade-offs in either wet grip or rolling resistance. This illustrates the challenges tyre manufacturers face to develop tyres without sacrificing too much of one or a few of the important properties. This is the common case in all product development and tyres are no exception.

Trade-off between low noise and high wet grip: Studies by vehicle and tyre industry organizations both showed that for the (few) tyres they had selected, the tyres with low noise had a trade-off in wet grip. This is contradicted by two independent studies made based on a large amount of car tyres on the market which showed no significant trade-off between low noise and wet grip; neither between noise and rolling resistance. An analysis of labels of available summer tyres in Switzerland showed that, in principle, products with good properties for noise, wet grip and rolling resistance are available in all tyre widths. This means that it is basically possible to choose a tyre product that is listed as very good for all label parameters.

Tyre wear: Apart from the present three label parameters, in the future the challenge may increase as also wear will have to receive increased focus as a potential new label may be introduced, something which is motivated by increased awareness of emission of particles and microplastics, possibly worsened by the higher tyre torque available in electric vehicles.

Time trends: An analysis of time trends for vehicles and tyres showed that the shift from ICE-driven to electric-driven vehicles is happened already at a fast rate. This is favourable for noise emission in urban driving situations but the popularity of the heavier SUV:s as well as the increased weight of electric vehicles needing larger tyres may increase tyre/road noise.

RFID systems: Perhaps the fastest time trend currently in the tyre business is the introduction of RFID systems in tyres. Some of these systems allow reading the information stored in the RFID chips several meters from the driving lane, just as already is implemented in toll gates for vehicle drivers to swiftly pay for passing the gate. RFID systems has a great potential for implementation for making it possible to encourage the use of high-quality tyres in traffic or by limiting access for vehicles in certain areas if they have tyres not allowed due to season or environmental limitations.

[17] *Source of data: Touring Club Switzerland, Illustration and evaluation by the authors, financed by the Swiss Federal Office of the Environment FOEN* https://www.bafu.admin.ch/bafu/en/home.html

Scenarios for the proliferation of quieter tyres: The analyses of the scenarios have shown that with the introduction of different scenarios, the overall exposure of the population to noise can be significantly reduced. According to the scenario calculations, significant noise reductions of up to 1.5 dB in 2030 and up to 2.5 dB in 2040 could be achieved by quiet tyres if their market share were promoted through the measures *industry agreement* or *consumer incentives*. In order to be able to use the great noise reduction potential of quieter tyres in the future, these two measures should be further specified and tested for their practical feasibility as soon as possible.

6.5.2 Recommendations

We have the following recommendations for action:

High tyre torque: Authorities should ask for or require the introduction of torque limiters in electric vehicles, to avoid too much wear on road surfaces and tyres. This is easy to do in electric vehicles and is already implemented in a few of them.

RFID opportunities: Authorities should also observe the great potential of reading tyre data in RFID systems from the roadside and at periodical vehicle testing. This can be used to give tyres with desirable performance (for example low noise) advantages either economical (such as tax, toll or parking relief) or for access to a certain area. One may also limit access for tyres not allowed in sensitive areas or during certain times or seasons. For example, winter tyres may be required in wintertime or studded winter tyres may not be allowed in certain areas. Also aged tyres may be identified, as well as worn-out tyres if the RFID system is supplemented by some tread depth sensors. All this may substantially favour the use of higher quality tyres.

Benefit from quieter tyres: It is recommended, to further investigate, specify and test the measures *Industry agreement* and *Consumer Incentives* with regard to their practical feasibility and possible implementation strategies. Early action is of great importance because market trends point to a rapid rise in electric mobility, which will increase the focus on tyre/road noise.

7 Updated uncertainty analysis of the tyre noise label

The following actions are recommended for reducing the uncertainty of the tyre noise label:

- **Test track:** an acoustic calibration of the ISO test tracks by means of coast-by measurements with SRTT reference tyres, as described in section 3.7. The calibration measurements would yield an overall value for the noisiness of the test track, which can be compared to the one of a virtual ISO track (average of a large number of ISO test tracks) from which the correction term can be deducted to be added to each measurement obtained on the considered ISO test track. This procedure would considerably reduce the uncertainty contribution of the test track. The tyre-to-tyre variance for the SRTT tyre is only 0.15 dB, as specified in [ISO, 2017b]. Uncertainty contribution from the test track before introduction of the acoustic calibration was estimated to be between 0.92 and 1.24 dB. After calibration and taking into account the actions below, the uncertainty contribution from the test track would reduce to 0.55 dB, both for C1 tyres and the C2 tyres (see section 3.8.5).
- **Temperature influence:** C1 tyres and C2 tyres improved temperature correction procedure: a better temperature correction might cut the uncertainty on the measurement conditions from 0.58 dB to 0.31 dB.
- **Test vehicle #1:** reducing the range of the wheelbase and a more restrictive description of the rim could only yield a marginal reduction for the C1 tyres, but a significant one for the C2 tyres: stricter limitations of the wheelbase range of the test vehicle could reduce the uncertainty to 0.21 dB.
- **Test vehicle #2:** a better description of the car underbody – ground clearance would be worthwhile and might reduce the total vehicle contribution from 0.63 to 0.45 dB.
- **Testing all variants in a tyre line:** reduction/annihilation of the “tyre line effect” by doing simplified tyre/road noise measurements on a drum facility for every member of the tyre family (line) could reduce this important uncertainty contribution (from 0.59 up to 1.2 dB) to a much lower value. An uncertainty of 0.25 dB (standard deviation between tyres due to tolerances in the production) can be assumed if one tyre is tested on a drum. If four tyres are tested the uncertainty on the average is reduced to $0.25/\sqrt{4} = 0.13$ dB.

A detailed calculation of the enhanced uncertainty after application of the measures suggested by the STEER consortium is shown in Annex A.

The results of these proposals on the tyre noise label calculations are shown in Figure 7-1, both for the C1 and C2 tyres. The conclusion is that for both tyre categories C1 and C2, the uncertainty on the noise label result can be reduced with an amount ranging from about 30 up to 50 %, significantly enhancing the quality.

What are the consequences of the improved accuracy of the tyre noise label? A rough estimation can be made as follows: the range of tyre noise labels is about 10 dB for the C1 tyres [GRB, 2014]. Figure 7-2 shows Monte Carlo simulations how the relations between noise label values and measured values (CPX) would look like before and after application of the STEER measures for reducing the uncertainty on the noise label. The correlation is improved by the reduction of the uncertainty, and the slope increased with an amount of about 0.2. About 70 %

of the car users are willing to choose for quieter tyres, see 5.1 and if they choose for tyres with a 5 dB lower noise label, the gain could be estimated to be 0.70 x 0.2 x 5 dB = 0.7 dB, solely due to the reduction of the uncertainty on the tyre noise label.

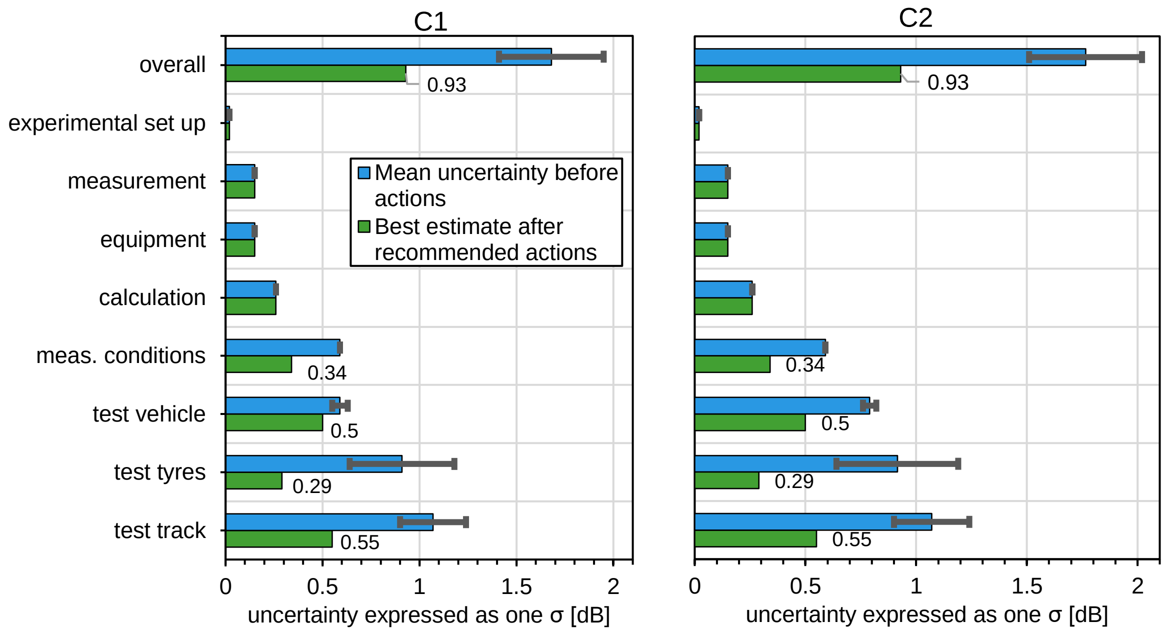


Figure 7-1: Uncertainty contributions per uncertainty group – expressed as standard deviations – for the current tyre noise label procedure (minimum and maximum estimation) and for the situation after implementation of the STEER actions in the procedure; calculation for the C1 tyres (left) and for the C2 tyres (right)

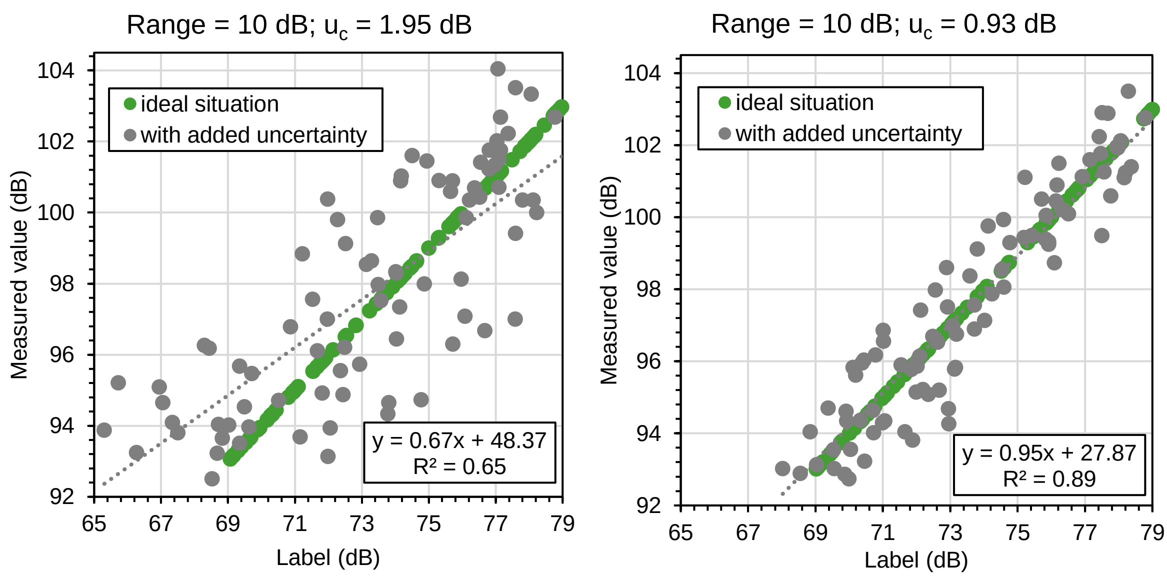


Figure 7-2: Demonstration of the effect of the reduced uncertainty before (left graph) after implementing (right graph) the STEER proposals by Monte Carlo simulation of the relation between the noise label and CPX measurements.

8 The STEER vision for the future tyre label

Road vehicle tyres are the most important component of the vehicles, having high impact on safety, environment, human health and economy. When consumers purchase or rent/lease a vehicle they may be looking at the performance of the vehicle, but they shall be aware that much of that performance depends on what tyres the vehicle has.

The STEER project thinks that the tyre label system is a valuable tool for consumer information. It stimulates interest in tyre performance and encourages consumers to purchase tyres of high quality. It serves as a tool for spreading information about the most important functional properties of tyres, showing consumers that it is performance rather than price, size and appearance that they shall base their tyre selections on.

The three major properties included in the tyre label today shall remain in the label but be supplemented by a parameter representing tyre wear. In addition, winter performance shall be indicated as currently, or preferably with quality classes. Due to development towards lower rolling resistance a new class A+ or AA shall be introduced. The noise label shall have four classes, A+ (or AA), A, B and C, with B being for noise levels 0-2 dB lower than the limit value, A for 2-4 dB lower than the limit and A+ or AA for noise levels more than 4 dB lower than the limit value. C shall continue to be used for the noise levels in the previous labelling regulation. Simultaneously, the noise level in its dB value shall be presented on the label.

In a long-term perspective STEER has the vision of a system that, for measurement of noise (like currently for rolling resistance), is based on measurements in a laboratory, using drums large enough to make the tyre/drum contact patch enough flat to simulate the tyre/road contact. The drum surface should preferably have two replicas of road surfaces: one similar to an ISO 10844 surface but with an MPD value of around 0.50 mm and another similar to an SMA 11 or SMA 14 surface, with an MPD value around 1.0 mm. These replicas can be made from 3D digital representations of texture of the mentioned surfaces; the same digital reference for all drum surfaces worldwide. The drum surfaces may be produced by means of moulds, like a tyre tread mould, but it may be more practical to make them by 3D printing. Some kind of quality assurance should be introduced. This quality assurance also should cover some kind of acoustic assessment of the drum (i.e Round – Robin Test).

Tyres shall be tested for noise at temperatures within the range they are intended to operate. This could be 20 or 25 °C for summer tyres, 0 °C for winter tyres and (say) 10 °C for all-season tyres.

The new measurement procedure will eliminate two of the most serious uncertainty sources we have today, namely the influence of outdoor climate and weather and the problems to get test track surfaces that give the same results. When the two replica surfaces have the suggested textures (one smooth and one rougher), the representativity problem of the noise test on only the present ISO 10844 test surface will disappear.

To avoid the present problem of not all tyres in a product line being tested, in the future all tyre variants shall be tested, possibly with exception of certain minor differences which are assumed not to influence the labelled properties.

Going indoors with noise measurements will require some investments in additional resources, but STEER thinks that the advantages of indoor testing balance out such investments, The main advantage is that the labelled noise levels will be much more accurate and fairer than currently.

With the gradual phase-out of ICE-driven vehicles and their replacement by electric-driven vehicles (EV) in the period from now until 2050, vehicle noise testing will more and more measure only tyre/road noise. Without significant power unit noise, EV:s need to be tested only for tyre/road noise and can therefore just rely on measurements of tyre/road noise which then should be made at both 50 and 80 km/h nominal speeds (in practice a range from 40 to 90 km/h for C1 tyres). Possibly, also a test for tyres under torque representing accelerating vehicles will be needed, which can also be made on a drum. The label value can be a weighted average of those tests to avoid too many values on the label. It would mean that the present noise measurements by vehicle manufacturers will be unnecessary (at least for EV:s) and instead tyre manufacturers would be responsible for both. It is logical that the noise measurements of tyres are made by tyre manufacturers since they would have to do such testing, anyway, during the production.

To be effective, the tyre label shall include all tyres used on road vehicles. It means, that in the STEER vision, also retreaded tyres are tested. Yet, there will be a remaining representativity problem, namely that only tyres in new condition are tested. How long during a tyre’s lifetime, are the label values representative? In the STEER vision, in a long-term perspective, the labels shall represent the tyre both in new condition and in a used condition. The “used condition” may be for example approximately when the tyre has worn away 50 or 60 % of its tread. The tyre could also be artificially aged by exposure to hot temperatures in an oven. This will require much more testing but will encourage the production and purchase of tyres that work well over their entire lifetime.

The above is the long-term vision of the tyre label system according to STEER. However, few of the proposals to achieve this are possible to do in the present decade. In the meantime, STEER offers the proposals in the next Chapter to increase the quality of the label in the short-term perspective.

9 Overall conclusions and recommendations

The STEER project investigated several key issues in connection with the tyre noise label. The most important findings and the priority need for action are explained in this chapter. The focus is on measures that can be implemented and by the indicated target groups and – according to the findings of STEER – will lead to a significant improvement in the impact of quieter tyres on European roads. The proposed measures can be implemented individually or, better, in combination to maximise the potential of quiet tyres for lowering road traffic noise emissions in the future.

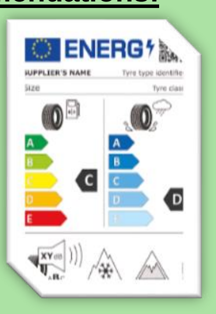
Is the tyre noise label generally useful?

The analysis of the literature has shown that the tyre label can be an important aid for consumers to find their way through the broad field of tyres on the market. However, it is important to ensure that the importance of the various parameters is actually taken into account by the consumer. The literature has shown that noise, for example, is not a decisive purchase criterion to many. Much more important is the purchase price, which, according to earlier analyses, has no (or only a very slight) connection to the noise label value.

Conclusion: **The tyre label is a useful information tool and should unquestionably be continued, but …**	▪ Consumers and tyre dealers are not enough aware of the noise label and the advantages of acquiring quieter tyres. ▪ Noise currently is not a decisive purchase criterion.
Recommendations:  **Of high priority** ***Target groups: NRAs, environmental authorities, procurement authorities and national governments, the EU Commission***	▪ Raise awareness through information campaigns: Labelling should be used as an information tool to support consumer decision-making. Inform consumers about available products the benefits of buying quieter tyres (see section 5.1) ▪ Raise awareness of the noise problem among the general public. Encourage consumers to buy a quieter product (section 5.2) ▪ The noise label shall have three legal classes, as it had before 2021. However, each class may have a range of 2 dB instead of 3. The labelled noise level shall still be printed (section 1.3). ▪ In the latest version of the labelling regulation, old tyres in the previous noise Class C have now been merged with Class B. This is confusing and the old Class C shall be reinstated.

Urgent need for improvements of the current noise labelling procedure

The present overarching recommendations focus on measures that can be implemented by the European Commission as complementary requirements of the Directive 2020/740/EC which sets the requirements of the noise labelling procedure. The measures are relatively simple and inexpensive to implement and achieve a major benefit in terms of improving the reproducibility and representativity of the current labelling procedure (the improvements regarding the respective uncertainty contributions are also indicated here). In addition to the recommendations here, the STEER consortium makes a number of secondary recommendations to the responsible standardisation bodies, with further possibilities for improvement of the underlying standard R117 and less potential impact regarding the improvement of the overall standard uncertainty that are not addressed in this section.

Conclusion: **Uncertainty is high, noise labelling procedure in its current form is far from optimal**	▪ The STEER uncertainty analysis revealed a standard uncertainty of between 1.4 and 2.0 dB for both C1 and C2 tyres and identified several issues that clearly showed why labelling procedure in its current form is far from optimal (section 2.2) ▪ The largest uncertainty contributions were determined for the test track and the test tyres, shortly followed by the test vehicle and the measurement conditions.
Recommendations:  **Of high priority** ***Target group: EU Commission (make additional requirements in 2020/740/EC)***	▪ Implement a Reference Tyre Calibration procedure as outlined in section 3.7 to account for the acoustic variability of ISO test tracks (uncertainty contribution from *test track* can be approximately halved, down to 0.55 dB). ▪ Implement a testing procedure for testing of entire tyre lines according to section 4.2.8 on laboratory drum or by simulation/modelling (uncertainty contribution can be significantly reduced: currently the contribution is between 0.59 and 1.2 dB, but the STEER proposal would reduce that to only 0.13 dB). ▪ Implement stricter requirements for test vehicles (focus on ground clearance and wheelbase) to limit the vehicle influence on the label value as proposed in section 3.1.2 (uncertainty contribution from ground clearance and wheelbase can be reduced to 0.45 and 0.21 dB respectively) ▪ Improve the temperature correction procedure according to section 3.2.7 (uncertainty contribution

	from measurement condition can be reduced by 0.27 dB, leading to a remaining uncertainty contribution of 0.31 dB).

Improvements following the implementation of the proposals by STEER

In the case the improvements from the previous section are implemented, the overall measurement uncertainty can be halved from 1.95 to 0.93 dB. However, a residual uncertainty remains, which is related to the basic features of today's labelling procedure. In the long term, the focus should be on the further development of the noise labelling procedure into a more controllable indoor procedure with measurements on laboratory drums. The vision of STEER is outlined in the previous Chapter.

<u>Conclusion:</u> **Measurement uncertainty can be halved if improvements are made now.**	▪ Uncertainty of current labelling procedure can be halved from 1.95 to 0.93 dB in case suggested improvements by STEER to the current noise labelling procedure are implemented.
<u>Recommendations:</u>  **Of high priority** ***Target group: EU Commission***	▪ Implement improvements to current labelling procedure and benefit from the improved reproducibility (see recommendations above) ▪ To realize the vision of STEER outlined in Chapter 9, initiate development of a new indoor noise labelling method to replace existing labelling procedure to further reduce uncertainty and to reduce workload for testing in the long run. To have such a method implementable within a decade or so, one should initiate work soon.

Do quieter tyres produce an impact on European roads?

Various existing studies, especially from Scandinavia, have shown that not all road surfaces have the same potential for reducing traffic noise due to quiet tyres. As STEER has demonstrated, the road surface texture is responsible for this since tyres are optimized for very low surface textures. The more decisive the contribution of the road texture is to the excitation of the tyre treads, the lower the impact potential of present quiet tyres is. That does not say that quiet tyres cannot be produced also for rough textures. The good news from STEER is that the full potential of quieter tyres can be achieved on road surfaces with “smooth” to “medium” textures. Since inner-city roads are mostly “smooth” to “medium” textured, and even SMA 11 (a common standard surface on national roads) falls into this category, the impact potential of quiet tyres can be almost fully achieved on large parts of the European road network. Only on roads with a rough surface (MPD > 1.2 mm, as may be the case for asphalts with a maximum chipping size of 14 mm or larger and cement concrete surfaces), the potential impact of quieter tyres of current design is not fully achieved.

Conclusion: **Quieter tyres can unfold their potential on large parts of the European road network.**	▪ Quieter tyres unfold their potential on “smooth” to “medium” textured roads (as is typical for asphalt pavements with max. aggregate size <14 mm) ▪ The combination of low noise tyres and low noise pavements is best ▪ The full potential impact of quieter tyres will not be achieved on “rough” textured road surfaces.
Recommendations:  **Of high priority** ***Target group: NRAs***	▪ Consider choosing “smooth” to “medium” textured road surfaces as a standard road surface on the road network in order to benefit from quieter tyres and its future potential. Also, with benefits for rolling resistance. ▪ Avoid “rough” surfaces (asphalts or surface dressings with aggregate sizes ≥14 mm or cement concrete with rough surface texture) on roads with high noise exposure (section 4.6)

How can quieter tyres further reduce noise levels on European roads?

With the tyre label, a useful information tool was created that allows buyers to select tyres based on their performance in three relevant user aspects. The specific potential of the noise label could be used much more in the future to make European roads quieter. The scenario calculations in STEER have shown that two of the three scenarios investigated to increase the market share of quiet tyres have resulted in a large impact:

- **Industry Agreement:** Industry agreement between tyre sellers that the sum of all tyres sold does not exceed a certain noise limit (similar to Regulation (EU) 2019/63 on maximum CO2 emissions for passenger cars).
- **Consumer Incentives scenario:** This scenario involved a change in consumer behaviour. The aim was to get the consumer to buy tyres of noise class A. Incentives (such as VAT exemption) are to be created for the purchase of these tyres.
- **Additional Incentives scenario:** This scenario involves a change in authorities’ behaviour. The aim is to get the publicly controlled vehicle owners to buy tyres of noise class A. This may be in the form of public procurement or admissions with regard to public vehicles or for transportation services which are under the control of public authorities. Another form of incentives may be enabled by using RFID technology to identify quiet tyres in traffic, in which case the vehicle/tyre owners may be given tax exemptions, waived tolls or parking fees, etc.

- **Restrictions:** By using RFID technology one may detect tyres in traffic which are illegal in the season (when and where winter tyres are required) or in extra sensitive environmental areas (such as prohibiting the use of studded tyres). In some extra noise exposed areas, one may even prohibit the use of tyres labelled with C or require their vehicles to be driven at reduced speed.

Substantial noise reductions of up to 1.5 dB in 2030 and up to 2.5 dB in 2040 could be achieved by quiet tyres if their market share were promoted by the measures "Industry agreement" or "Consumer incentives". In order to be able to benefit from the great noise reduction potential of quieter tyres in the future, these two measures should be further specified as soon as possible and tested with regard to their practical feasibility. The third scenario - a further tightening of the permissible noise label values as once planned for 2022 - resulted in effects of approx. 0.8 dB by the end of 2030.

Combining the scenarios with the mentioned additional incentives, the effects on noise reduction will increase; especially one should not underestimate the effect that procurement policies may have on increasing the demand for quieter tyres, since vehicles and transportation services controlled by public authorities are substantial.

Conclusion: **Quiet tyres could make European roads up to 3 dB quieter in the future, but only if their market share can be increased with suitable measures.**	▪ If quiet tyres can be promoted in the future through the two measures "Industry agreement" and/or "Incentives", noise reductions of up to 3 dB could be achieved. ▪ If no further measures are taken at this stage to increase the market share of quiet tyres, their potential can hardly be further exploited. ▪ Nevertheless, there may be a marginal noise reduction due to the shift of vehicles from ICE to electric drives which increases the effect of tyre/road noise reductions when the power unit noise contribution disappears. ▪ In many European countries, considerable benefits can be expected from the avoidance of external costs. For example, in countries such as the Netherlands, an annual benefit of about 25 million Euros could be generated if measures were taken to promote quiet tyres (section 5.3.4).
Recommendations: 	▪ Further investigate, specify, and test measures “Industry agreement” and “Consumer incentives” regarding their practical feasibility and prepare implementation (section 5.3.1) ▪ It is strongly recommended that countries with a

Of high priority ***Target group: EU Commission, NRAs, National, regional and local governments***	high population density and many people affected by noise invest in measures to promote quiet tyres, as the benefits will likely offset the costs in these states (section 5.3.4) ▪ Act now to benefit from market trends: Due to the rapidly developing trend towards electric vehicles, tyre/road noise will become more and more dominant and therefore investments made today in the tyre noise label will pay off much more in the near future. The earlier the measures are taken, the greater effects can be expected (section 6.1) ▪ Act now to avoid jeopardising the benefits of the new EU regulation on vehicle noise emissions which is expected to come into force in the future, by the introduction of the Phase III limits of EU Reg 540/2014 [EU, 2014]. The regulation will ensure quieter vehicles with quieter original equipment tyres from that date. The desired noise reduction on European roads can only be achieved if the industry's successes are not cancelled out by contrary trends in the secondary tyre market (when the vehicle is fitted with replacement summer or winter tyres by the consumer) (section 6.1) ▪ First measures to promote quiet tyres could be implemented immediately by national governments: tyres of the best noise class could be prescribed in the context of public tenders of vehicle fleets. Our analysis has shown that such tyres are available for all tyre types, load and speed classes (section 5.3.6)

STEER has identified the following needs for research and development:

The further need for research, identified by STEER is grouped in three main areas, as listed below. The research and development has been divided into three different time horizons:.

1. In the short-term (as soon as possible)
2. In the mid-term (starting within 2-5 years)
3. In the long-term (starting within 6+ years)

Improvements of the current noise labelling procedure	**Time horizon**
▪ Collect more data regarding the relation between tyre/road noise and ambient air and road surface temperature	1
▪ Study if the temperature correction may be improved if frequency spectra are used	1
▪ Develop the temperature correction to be based on both ambient air and road surface temperatures (update ISO 13471-2)	1
▪ Study the effect of various test vehicles (with variations in wheelbase, ground clearance, underbody construction and wheel screening) on tyre/road noise	1
▪ Make more round robin tests between various test tracks, also outside western and southern Europe, and then also check the effect of the calibration procedure	1
▪ Check if the calibration of ISO test tracks proposed by STEER may be improved if frequency spectra are used	1
▪ Specify in terms of a standard procedure the method proposed by STEER for calibration of ISO test tracks and correction for noise differences between them (perhaps later to become an Annex in ISO 10844)	1
▪ Specify in terms of a standard procedure the methods proposed by STEER for simple measurement of noise differences between tyres from the same tyre line (to become an ISO/TS)	1
▪ Consider if it is fair that tyres intended for use at temperatures between -20 to +5 °C are tested and labelled at temperatures around or above 20 °C: Study the effect of testing and ranking winter tyres at near-zero temperatures compared to the range 20-25 °C, also the ranking of summer tyres at temperatures 5-10 °C versus at 25-30 °C.	1

Development of new indoor noise labelling method	Time horizon
▪ Develop and test the laboratory drum test procedure for tyre/road noise measurement, to replace the present outdoor procedure for determining the noise level of the noisiest tyre(s) in a tyre line	1-2
▪ Develop a suitable technology to produce replica surfaces from original road surfaces by using the 3D printing technique, including selection of optimum materials, primarily to be used on laboratory drums. This should be supplemented with a kind of quality assurance, such as checking the reproduced texture against the original one or some kind of acoustic calibration as described in chapter 3.7.	1-2
▪ Study the effect of drum curvature on tyre/noise emission, compared to makingeasurements on flat tracks with the same surface, with the purpose to determine a minimum diameter of drums for noise testing (for both C1 and C3 tyres).	2
▪ Determine two suitable reference surfaces (as replicas on drum) for future tyre/road noise testing (one with smooth and one with medium-rough texture)	3
▪ Compare the tyre/road noise levels of the drum method with those of the present coast-by method, to determine how noise limits should be transformed from the old to the new system	3

Policy changes & strategies	Time horizon
▪ Predict the overall effect of changing pavements with 14 mm or larger maximum aggregate sizes to 12 mm or lower in noise-exposed areas, considering environment (noise reduction, rolling resistance, CO_2, and particle emissions) and economy (pavement LCA cost, vehicle energy consumption).	1
▪ Further investigate, specify, and test scenarios “Industry agreement” and “Consumer incentives” regarding their practical feasibility and prepare implementation. This should include public procurement	1

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In 2020, the ELANORE project (Norwegian-Polish Project) was launched. The first RRT measurements, which were made available to the project consortium, provided initial information about the test tracks. The measurements planned for the future will certainly yield further informative findings.

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ANNEX

A. Uncertainties analysis after implementation of STEER proposals – for C1 and C2 tyres

Group #	Uncertainty group	Source of uncertainty	Concerned § in Annex 3 of Reg. 117	Nature	Estimand	Probab. distrib.	Uncert. Contrib. c_i u_i	Uncert. contrib. for N = 16	See § in ISO/IEC Guide 98-3:2008	Remarks
1	equipment	calibration	1,10	syst.	0,00	normal	0,10	0,10		tolerance for calibration
1	equipment	SPL meter accuracy	1.1	syst.	0,00	normal	0,10	0,10		intrinsic accuracy of Class I of IEC 61672-1:2002 is present standard; in Reg 1222/2009 referred to IEC 60651:1979/A1:1993; systematic error
1	equipment	tachometer accuracy	1.2	syst.	0,00	normal	0,05	0,05		+/- 1 km/h on 80 km/h leads to +/- 0,16 dB
1	equipment	thermometer accuracy	1.3	syst.	0,00	normal	0,03	0,03		
1	equipment	anemometer accuracy	1.4	syst.	0,00	normal	0,00	0,00		anemometer tolerance is +/- 1 m/s
2	experimental set up	vertical position of microphone	1.1.3	syst.	0,00	normal	0,00	0,00		height 1,2 m +/- 0,02 m
2	experimental set up	horizontal position of microphone	1.1.3	syst.	0,00	normal	0,02	0,02	4.3.9. NOTE 1	distance 7,5 m +/- 0,05 m
3	meas. conditions	temperature influence: correction error	2.2 and 4	syst.	0,00	rectangular	0,31	0,31	4.3.8 eq. (8)	See discussion in section 3.2.7
3	meas. conditions	temperature influence: representativity of method	2.2 and 4	syst.	0,00	rectangular	0,00	0,00		
3	meas. conditions	humidity influence (incl possible water remaining in voids)	2.1	syst.		half-normal	0,00	0,00	F.2.4.4	not specified in Annex 3, except that surface must be "dry" and "clean"; presumably influence on "dry" road surface is negligible; asymmetric probability distribution as can only lead to increase of SPL
3	meas. conditions	wind speed influence	2.2	syst.		half-normal	0,00	0,00	F.2.4.4	wind speed < 5 m/s ; potentially high influence, even with windscreen; asymmetric probability distribution as can only lead to increase of SPL; possibly exponential distribution (input from B&K pending)
3	meas. conditions	wind direction influence		syst.	0,00	normal	0,00	0,00		presumably insignificant @ such small distance (7,5 m)
3	meas. conditions	ambient noise	2.3.1	syst.	0,11	half-normal	0,14	0,14	F.2.4.4	ambient noise must be at least 10 dB lower than L_{Amax}, for the case it is exact 10 dB lower it biases Lamax with 0,41 dB
3	meas. conditions	disturbing noise events	2.3.2	syst.	0,00	half-normal	0,00	0,00	F.2.4.4	all measurement influenced by an external noise event shall be discarded
4	measurement	random fluctuations of LAFmax measurements		random	0,00	normal	0,17	0,04		roughly estimated to be between 0,3 up to 0,5 dB (could be determined by repeated measurements of L_{Amax} with controlled source in controlled environment) (possibility to carry out experiment if B&K cannot provide this info)
4	measurement	drift of SLM during measurement	1.1.1	syst.	0,00	rectangular	0,14	0,14	4.3.7.	0,5 dB deviation allowed between calibrations before and after measurements
4	measurement	deviation of vehicle from "perfect" straight line during coast by		random	0,00	normal	0,04	0,01		deviation of straight line with +/- 10 cm leads to deviation of +/- 0,12 dB; 10 cm might be an appropriate estimation
4	measurement	vehicle speed		random	0,00	normal	0,05	0,01		presumed that the driver keeps the speed +/- 1 km/h

		deviations								
5	test vehicle	car underbody-ground clearance		syst.	0,48	normal	0,45	0,45		uncertainty according to ETRTO analysis: 0,51 dB; comprises detailed contribution of category "test vehicle". From a tyre manufacturer database, we derived the value 0,60 dB, which is pretty consistent. A better standardization of the test vehicle should lead to a lower uncertainty, here conservatively estimated 0,45 dB
5	test vehicle	car engine and transmission contribution		syst.	0,00	half-normal	0,00	0,00	F.2.4.4	for pass-by measurements: DRD graph: @80 km/h: engine contr. = 67 dB and car contr. = 74 dB; for coast by measurements: engine is switched off: contribution is 0
5	test vehicle	mechanical contributions from car (rattling etc)	2.4.4.2	syst.	0,00	half-normal	0,00	0,00	F.2.4.4	presumably negligible taking into account precautions prescribed in cited §
5	test vehicle	car aerodynamical contributions	2.4.4.2	syst.	0,00	half-normal	0,00	0,00	F.2.4.4	presumably low @ 80 km/h
5	test vehicle	wheel housing	2.4.4.1 d)	syst.	0,00	half-normal	0,00	0,00		no additional sound absorbing material to be mounted in wheelhouse or under car body, but absorbing character of wheel causing can differ from vehicle to vehicle and hence add uncertainty to the result; dimension and shape of wheel housing might differ from vehicle to vehicle, leading to differences in reverberation field and hence noise emission
5	test vehicle	wheel alignment	2.4.4.1 c)	syst.	0,00	half-normal	0,00	0,00		wheel alignment should be in accordance with vehicle manufacturers specifications, but on there are tolerances on the wheel alignment angles (toe in, camber, caster) which may influence the result.
5	test vehicle	wheelbase	2.4.3	syst.	0,17	rectangular	0,21	0,21	4.3.8 eq. (8)	This was originally the only difference between the uncertainty analysis of C1- and C2-tyres: for C1 tyres wheelbase should be lower than 3,5 m. For C2 tyres lower than 5 m. Difference in L_{Amax} between 2,5 and 3,5 m can be estimated to be 0,72 dB. A limitation of the allowable range of the wheelbase of the test vehicle, especially for the testing of C2 tyres should reduce this contribution to 0,21 dB, the same as originally for C1 tyres.
5	test vehicle	Influence of the width and material of selected test rim		syst.	0,00	normal	0,00	0,00		contribution presumably small. Possibly later new input.
6	test track	influence of texture (macro- and mega-)		syst.	0,00	half-normal	0.55	0.55		ETRTO analysis estimates uncertainty contribution of 0.92 dB. A round robin test on eight European ISO test tracks with four different tyres (slick, summer tyre, winter tyre and a van tyre) was carried out in 2005 by M+P. Most relevant are the results obtained with the summer and winter tyre and one found a difference (max-min) of 7.8 and 3.8 dB. The large spread for the summer tyre was however caused by one outlier; if this one is removed a 4 dB difference max-min is also found for this tyre, which is actually in line with the previous. Measurements on 186 AC8 pavements in Switzerland by G+P yielded a standard deviation of 1,3 dB, which can be considered as an upper limit. Originally, the, calculation has been done with uncertainty contribution of test track equalling 0,92 and 1,3 dB.. The test track calibration procedure by means of coast-by measurements with vehicles equipped with SRTT tyres will reduce the uncertainty to 0.55 dB.
6	test track	influence of microtexture (affecting stick-slip)		syst.	0,00					
6	test track	influence of rubber-surface adhesion (affecting stick-snap)		syst.	0,00					
6	test track	influence of surface contaminations (dirt, rubber, etc)		syst.	0,00					
6	test track	influence of unevenness (causing variation of loads)		syst.	0,00					
6	test track	influence of possible melted bitumen in hot weather		syst.	0,00					
6	test track	influence of absorption of test track		syst.	0,00					
6	test track	influence of		syst.	0,00					

		absorption of propagation area								
7	test tyres	effect of assigning noise label of different tyre in same line		syst.	0,00	normal	0,13	0,13		Originally significant contribution to uncertainty: between 0.59 and 1.2 dB. By introducing a procedure of testing each member of the tyre line on a drum (4 tyres per member), this uncertainty contribution is reduced to 0.13 dB
7	test tyres	sample to sample differences		syst.	0,00	normal	0,26	0,26		value from tyre manufacturers data base is ,46 dB; uncertainty for measurements with tyres with nominally the same dimensions and ratings: uncertainty according to ETRTO analysis: 0,26 dB;
7	test tyres	tyre rubber hardness		syst.	0,00	half-normal	0,00	0,00		
7	test tyres	tyre run in differences	2.5.4	syst.	0,00	half-normal	0,00	0,00		tyres have to be run in for at least 100 km. What if one runs them in for a much longer distance?
7	equipment	tyre inflation	2.5.3	syst.	0,00	normal	0,00	0,00		literature ref of relation between tyre/road noise emission and tyre pressure?
7	equipment	tyre load (incl different load on the axles)	2.4.2 and 2.5.2	syst.	0,00	normal	0,00	0,00		literature ref of relation between tyre/road noise emission and tyre load?
8	calculation	rounding of result to lower integer	4.5	syst.	-0,45	rectangular	0,26	0,26		
8	calculation	arbitrary correction	4.4	syst.	-1,00	half-normal	0,00	0,00		
				E(Y)	**-0,70**		**u_c**	**0.93**	5.1.2 eq. (10) and Annex G.2	uncertainty on label expressed as standard deviation
							U_c	**1.8**		95 % confidence interval is ± U_c

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