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Technical Support For EU Policy Making On Tyre Noise Reduction

Final Report

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Technical Support For EU Policy Making On Tyre Noise Reduction - Final Report

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Executive summary

TNO has been requested by the European Commission (EC) to perform a study regarding quiet tyres. For the purpose of this study, the EC defines a quiet tyre as a tyre with a noise level at least 4 dB(A) below the set current legal limit, as defined in UN regulation 117. The study has the following objectives:

- The primary objective is to assess whether a reduction in tyre noise is compatible with high level tyre performances for abrasion, rolling resistance and wet grip.
- The secondary objective is to perform a cost-benefit analysis of a reinforcement of a regulation on quiet tyres in the EU.

To assess whether a reduction in tyre noise is compatible with high level tyre performances for abrasion, rolling resistance and wet grip, the following approach has been followed:

- <u>Literature review:</u> a literature review has been performed regarding the physical aspects of tyre-road noise generation and tyre-road noise trade-offs with respect to other tyre performances.
- <u>Tyre test analyses:</u> tyre test results available from consumer tests and scientific studies are another source of information for investigating the relation of tyre noise with regard to other tyre performances. These tyre test results have been analysed to identify possible trends regarding tyre noise performance and other tyre performances.
- <u>Expert interviews:</u> findings from the literature review and tyre test result analyses have been input for interviews with experts from the scientific community and industry. The answers from the interviews have supplemented the interpretation of the literature review and analyses of tyre test results.
- <u>EPREL database analyses:</u> in the EPREL (European Product Registry for Energy Labelling) database the labels of tyres on the EU market are registered. From this database and from tyre sales figures it has been analysed what the current availability of quiet tyres is.

Regarding the secondary objective, a cost-benefit analysis of a reinforcement of a regulation on quiet tyres in the EU has been carried out regarding two aspects:

- Impact on safety from the effects of potential safety trade-offs on accidents with fatalities
- Impact on traffic noise and health effects

Below a summary of the results and main conclusions from the activities is given.

Tyre performance trade-off background

Tyre performance is related to the compound materials, construction and geometry, which are optimized to meet a wide variety of performance targets including performance for safety, energy, micro-plastic emission, tyre noise, etc. Trade-off of noise emission with performance aspects for safety and rolling resistance can to a large extent be explained by contact mechanics relations for wavelength content of road texture and related excitation frequencies (depending on the speed). Secondly, the viscoelastic properties of materials play a role, which are temperature dependent. Furthermore, the tyre tread pattern design and contact patch shape play a major role in noise generation, wet grip and aquaplaning resistance.
The main findings of this study based on literature review and expert interviews are summarized below:

- Tread patterns are relevant for aquaplaning performance and noise, a trade-off exists between both performances. Also, tread patterns are relevant for grip on snow and ice surfaces and trade-offs with noise performance exist.
- Wider tyres produce more noise.
- Rolling resistance and noise can be optimized with little trade-off.
- Tyre grip is related to material properties that also affect noise, which can result in a trade-off with noise.
- Main requirements such as maximum speed and load carry capacity dictate the design envelope of tyres, as these are related to warranting the structural integrity of tyres Depending on the load and speed specification an optimisation can be done within the design domain, which is getting more limited to high-load/speed tyres.
- The evolution in tyre technology results in tyres with improved performance. To assess the potential for further improvement the performance of state-of-the-art tyres, i.e. tyres that were recently developed, should be considered.
- Dedicated scientific studies of UTAC commissioned by ACEA and ETRTO [1] [2] [3], in which a limited number of tyres of the same size and load index have been tested, conclude on conflicts between tyre noise and safety performance. However, as those studies are based on this limited number of tyres of the same size, no conclusion can be drawn on trade-off between noise and safety for tyres in general.

Performance trade-off analyses

Consumer tests provide information on tyre performance for safety, energy, noise and (sometimes) micro-plastics emissions, using also (equivalent) protocols as used for regulatory tests. For safety performance the consumer tests are more extensive than regulatory tests (which addresses only wet grip performance for a specific operating condition). The results of consumer tests provide a good basis for a more comprehensive safety assessment since these include aquaplaning tests and grip related tests on wet road and dry road (i.e. braking and handling track driving).
The analysis is aimed to assess the relation of tyre noise to safety performance, energy (rolling resistance) and micro-plastic emissions (abrasion). Safety performance is analysed for individual safety performance components as well as considering the combination of performance for aquaplaning, wet grip, and dry grip.
It should be noted that for consumer tests, in contrast to regulatory tests, no reference tyre is tested. For the analysis, the results from tyres *within one test set* (typically having tyres from 10 or more manufacturers) is compared to have a ranking of their performance.
In addition to using consumer test data, data from the ACEA Tyre Performance Study [1], executed by UTAC, was processed specifically regarding safety aspects. Although in this study only one tyre designation is considered, it still contributes as the test procedures are very well documented. Furthermore the purpose of the ACEA Tyre Performance Study [1] was to understand the improvement potential of noise emissions by assessing the influences of tyre performances (rolling resistance, wet grip, noise level, …) on each other, which is well-aligned with the subject of the current study. The data has been processed to obtain a quantification of the relation between tyre noise and safety performance, whereas UTAC provided a qualitative assessment.
The main conclusions for tyre compatibility are listed below.

- **Noise versus rolling resistance**
    - Rolling resistance is a matter of contact mechanics as well as tyre structure. The relation of tyre rolling resistance and noise has been studied quite extensively and has resulted in tyres with little trade-off between these aspects. Analyses of test data reveals that this is also achieved for several tyres on the market. It can be concluded that rolling

resistance and noise can be compatible for current tyres. However, there is no information how further reduction of noise will affect rolling resistance and it is unclear what the trade-offs could be.

- **Noise versus micro-plastic emissions**
    - Micro-plastic emissions of tyres is caused by abrasion. Abrasion is a relatively new aspect for tyres, which has not been studied extensively in relation to noise. From theoretical considerations a trade-off is expected if a softer compound is used for noise reduction. The available data from tyre testing at the time of this study has been very limited. Therefore, it is concluded that the information gathered is insufficient to draw conclusions on compatibility between abrasion and noise.
- **Safety performance versus noise**
    - Tyre safety performance concerns different aspects such as grip under dry and wet conditions, aquaplaning, vehicle stability, etc. Compromises are made in tyre design between individual safety performance aspects, e.g. a better tyre for dry road can have reduced performance on a wet road.
    - From literature it is concluded that compromises need to be made to obtain desired noise performance and grip under all operating conditions, which can result in trade-offs. Main physical aspects that play a role are contact mechanics, material properties, tyre construction and tread pattern design.
    - Tyre safety in relation to noise has not been studied extensively in the past. Recent studies by UTAC (including results from the tyre industry) conclude that tyre safety performance and noise are conflicting or incompatible, without providing a quantification of a trade-off.
    - Analysis of consumer tyre test data does not indicate a clear relation between individual safety performance aspects and noise. No relation could be assessed for a combined safety performance (i.e. dry/wet grip and aquaplaning) with noise either. A final analysis was done on scientific data used in the ACEA Tyre Performance Study involving 14 tyres. This has not resulted in the identification of a trend with sufficient confidence for combined safety performance and noise. From that analysis it is concluded that insufficient data is available to draw any conclusions on the trade-off between tyre safety and noise.

Concluding, results from literature review, expert interviews, and qualitative assessments, show that compromises have to be made to achieve both safety and noise performance that can result in trade-offs. Industry uses holistic design methods to deal with this within current performance requirements. From experiments on state-of-the-art tyres no trend regarding safety and noise could be identified with sufficient confidence.
Based on the above, it cannot be assessed how much trade-off with respect to safety performance can be expected when noise performance criteria are changed.

Performance of tyres on the market

The most popular tyre designations on the EU market are assessed from tyre sales figures. This is done for Replacement tyres (i.e. tyres bought by the consumer to replace the original tyres that were on the vehicle when purchased) as well as for Original Equipment (OE) tyres (i.e. tyres installed on the vehicle during manufacturing, and/or sold by the OEM representatives as replacement tyres for this particular vehicle) in the C1 category. By studying these two categories of tyres, future trends can be identified. In terms of availability, it appears that 80% or more of popular C1 tyre designations are available with an A-label for noise in combination with A/B for wet grip and rolling

resistance. It is observed that the share of A-labelled tyre designations is reduced in the OE category for SUV tyres. Secondly, relatively more SUV tyres are sold in the OE category and thirdly SUV tyres are getting wider, allowing higher noise levels for obtaining an A-label. These three factors indicate a trend where tyre noise will become a more dominant factor in traffic noise. Finally, it should be noted that when lowering regulated noise levels by 3 dB the tyre designations that are currently not available with an A-label for noise require to be redesigned, with unknown trade-off for safety performance as stated above. Manufacturers that currently have no A-label tyre for other designations need to redesign their tyres as well.
The information on labelling is obtained from the EPREL database, which also contains the noise level of the tyre in dB(A). This noise level is combined with the tyre sales information of popular tyres and is used to calculate a tyre noise level for upscaling scenarios toward an EU level.

Upscaling

Impact on safety

In order to assess the effects of potential safety trade-offs on accidents with injuries in the EU, an analysis has been done to relate tyre grip and fatalities. As input for the safety analyses, both measurement results of consumer tests and the ACEA Tyre Performance Study have been used. As already mentioned above, no trend between noise reduction and safety performance on tyre level could be identified with sufficient confidence. This has also an implication on the safety upscaling analysis as the same data has been used as input. Also here, no clear trend between tyre noise reduction and fatalities could be identified, and a large spread regarding estimated fatalities was observed. Consequently, based on the available data no conclusion can be drawn regarding the impact of tyre noise on road fatalities at EU level.
However, the applied upscaling methodology indicates that a minor reduction in tyre grip can lead to a substantial increase in collision impact speed which affects the number of traffic fatalities, mostly concerning cyclists and pedestrians. With this sensitivity it is recommended to further study the relation between tyre noise performance and grip in order to understand the implication concerning traffic fatalities.
The safety upscaling analysis was performed for a specific set of accident scenarios, i.e., scenarios on straight roads where tyre grip performance is relevant and the grip limit is used. This set of scenarios is a subset of all accident scenarios where tyre grip is of importance. It is recommended to investigate on approaches to achieve an upscaling for all grip related accidents at EU level.

Impact on traffic noise and health effects

The impact of tyre noise reduction on the average traffic noise and associated health impacts was investigated.
A reduction of 3 dB in declared tyre noise is expected to reduce average traffic noise levels by up to 1.5 dB, taking a typical annual traffic growth of 1% into account, and by up to 2 dB in case of 0% traffic growth. The associated reduction in health impact in terms of DALYs (Disability Adjusted Life Years) is estimated to be about 8% for 1% traffic growth.
A reduction of 5 dB in declared tyre noise is expected to reduce average traffic noise levels by up to 2.3 dB in case of 1% traffic growth, and up to 2.8 dB in case of 0% traffic growth. The associated reduction in health impact in terms of DALYs is estimated to be about 13% for 1% traffic growth.
For comparison, a 3 dB reduction in traffic noise would also result from halving the traffic flow.
The potential traffic noise reduction and associated health benefit will depend on the actual evolution of traffic growth, as well as the average size and load capacity of tyres in the fleet.

Conclusion

Compatibility of noise with rolling resistance seems to be possible without noticeable trade-off. The compatibility of noise with abrasion cannot be concluded upon due to a lack of information. From literature study, a trade-off between tyre noise and safety performance is expected. The extent of this trade-off, could not be identified with sufficient confidence from tyre tests. Based on the above, it could not be concluded how much trade-off with respect to safety performance can result when noise performance criteria are changed. More than 80% tyre designations on the market are available with an A-label for noise from at least one manufacturer. Other tyre designations would require a redesign when lowering regulated noise limits by 3dB, which could have trade-off implications on safety performance with related impact on traffic fatalities. Lowering tyre noise limits with 3dB corresponds to a reduction in health impact in terms of DALYs (Disability Adjusted Life Years), which is estimated to be about 8% for 1% traffic growth.

Contents

1. Introduction

This report is written for the tender 998/PP/GRO/IMA/23/2124/14022 to provide technical support for EU policy making on tyre noise reduction. The European Commission (EC) asked TNO to perform a study regarding quiet tyres. The study has the following objectives:

- The primary objective is to assess whether a reduction in tyre noise is compatible with high level tyre performances for abrasion, rolling resistance and wet grip.
- The secondary objective is to perform a cost-benefit analysis of a reinforcement of a regulation on quiet tyres in the EU.

The aim of the study is to investigate how tyre performance can be affected in terms of safety, energy use and micro-plastic emissions on an EU scale when noise limits are reduced. In this report it is explained how tyre noise is generated, and which compromises with other tyre performance criteria can be expected based on theoretical grounds (Section 2.1, 2.2 and 2.3) and expert interviews (Section 2.4). Furthermore, an analysis is done on results from testing of recent tyres to assess the tyre performance criteria for different aspects in relation to external noise (Section 2.5). This provides indications to which extent trade-offs can be observed for current tyres.

To assess to which extent tyres with low noise levels are available an overview of most popular tyre designations on the market has been provided as a Top-30 for cars, SUVs and for Light Trucks (LTR) in Chapter 3.

In Chapter 4, the results for safety performance are upscaled to assess the impact on traffic casualties for related accident scenarios at EU level (Section 4.1). In section 4.2 an analysis is presented on the impact of tyre noise reduction on the average traffic noise and associated health impacts.

On the second objective, regarding a cost-benefit analysis, insufficient data/ results are available. Therefore, no clear conclusions could be drawn on this.

In Chapter 5 the overall conclusions of the study are presented.

2. Compatibility of tyre performance

This section describes activities and results for assessing the compatibility of tyre performance when lowering tyre noise. This involves different steps which are depicted in Figure 2-1.

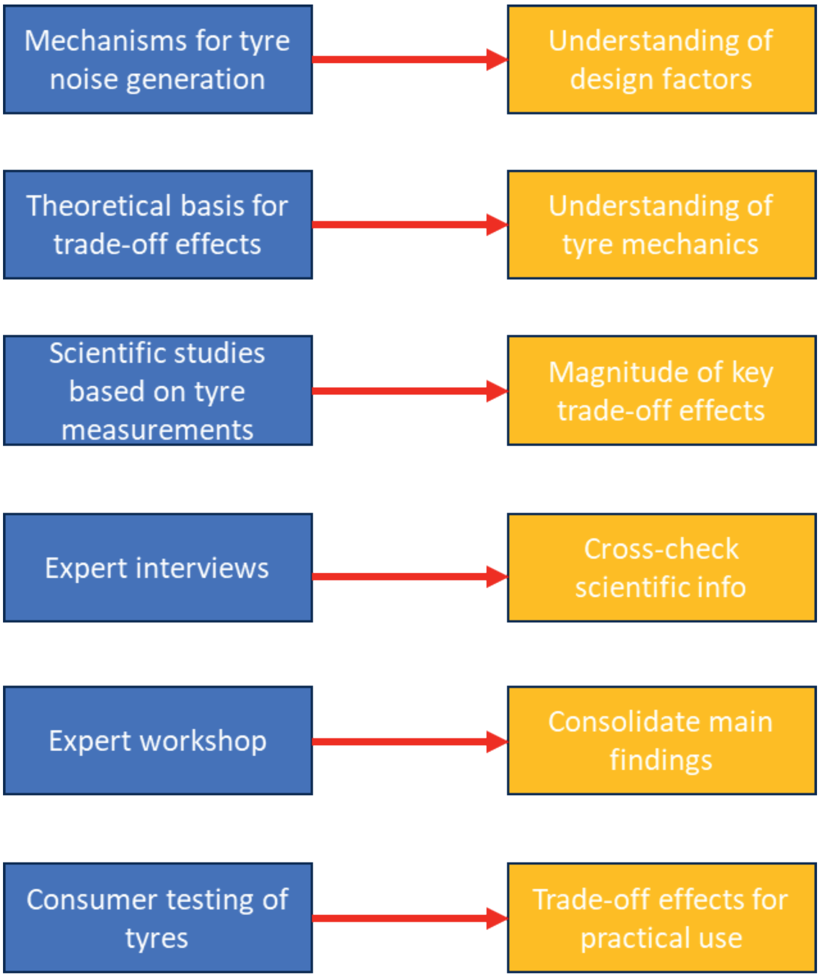


Figure 2-1 Overview of information used for assessing compatibility of tyre performance.

As indicated, the literature review will lead to an understanding of the design factors of tyres in relation to noise. Trade-off effects are the result of tyre mechanics for which the theoretical basis is provided. Scientific studies based on tyre experiments provide a magnitude of trade-off effects. Understanding tyre mechanics is supporting the interpretation of results from trade-off effects that have been found from these tyre experiments.

Consumer tyre tests offer another source of assessment of tyres. Consumer tyre tests are done frequently and provide a comparison of tyres that are currently on the market. Although these tests are not directly focused on analysing trade-off effects, the large availability of recent tyre test data is interesting for analysing in addition to the scientific studies, as these scientific studies are often not very recent - these may not represent the state-of-the-art of current tyres – and mostly only a limited number of tyre variants of a single tyre designation is assessed.

Interviews have been conducted with experts in the research field of noise and tyre design from the research community. Each expert focusses differently on the topics, and with that a wider view on the research domain is obtained. The interviews resulted in a cross-check on scientific information to consider for the study and some new sources were identified based on these interviews.

As a final step a workshop was organized with the experts and with attendance of representatives of the European Commission, and separately with the tyre industry. The main findings of the interviews were summarized and have been consolidated in section 2.4.

2.1 Tyre noise generation

This section addresses tyre noise principles to support a scientific background for interpretation of further descriptions in this report.

The physical mechanisms of tyre-road noise generation have been described by many sources and these are summarized in this section. The intention is to provide the non-expert reader an introduction into the topic with the aim of providing sufficient background information to understand tyre-road noise trade-offs.

A basic introduction into the topic of acoustics is given in the book of Michelin 'The Tyre: Mechanical and Acoustic Comfort' [4]. From this book, Figure 2-2 is taken, which explains the basics of tyre-road noise generation. In order to get noise, a source of excitation is required. For rolling tyres, the two main sources of excitation are the road surface and the tread pattern. It is important to understand that excitation leads to vibrations of the tyre and the air. Furthermore, it is important to understand that different excitation types can be distinguished that result into vibrations of the tyre structure or air.

When considering the road surface, the wavelength of road roughness plays a role. When the tyre rolls at a certain speed over the road surface it interacts with the road roughness, leading to excitation of the tyre in certain frequency ranges. Obstacles on the road surface typically have a lower wavelength compared to the wavelength of the macroroughness. Consequently, an obstacle on the road surface and macroroughness are excitation sources that excite the tyre structure at different frequencies.

Like any physical object, a tyre has several natural modes which are patterns of motion in which all parts of the system move sinusoidally with the same natural frequency and with a fixed phase relation. All objects are capable of vibrating at many different frequencies if these are imposed on them, but near the natural frequencies the vibration amplitudes are largest. The normal modes and corresponding normal frequencies depend on an object's structure, materials and boundary conditions (e.g. road contact). Next to vibrations also damping plays a role. Damping decreases the amplitudes of the vibrations by the dissipation of energy. For viscoelastic materials, such as elastomers (used in tyres), damping increases with frequency. The natural frequencies, their corresponding mode shapes and damping are together known as the object's natural modes. In Figure 2-2 the vibration behaviour of a tyre is depicted up to 10 kHz. The peaks in the graph correspond to the natural modes.

The rolling of the tyre on a macroroughness surface not only excites the tyre structure, but also the air inside the tyre. The column of air imprisoned in the tyre has its own natural modes. Its first natural mode, called cavity mode, lies between 200 and 250 Hz for a typical passenger car tyre, depending on the size of the envelope.

When considering excitation by the tyre tread pattern, three main types of excitation can be distinguished:

- Impact of tread blocks entering the contact patch and being freed on leaving.

- Stick-slip friction of the tyre tread on the road surface and relaxation of the tread blocks as they leave the contact patch.
- Air compression in the tread voids.

In Figure 2-3 it is described what vibrates due to these excitation sources and also the types of noise, which may affect comfort for vehicle occupants, are indicated. It must be noted that noise is also emitted outside the passenger cabin, but is not described by type of noise. Only its level is considered, in accordance with current regulations [5]. Finally, note that the reference to structure-borne and airborne are in relation to the propagation paths.

Figure 2-2: Basics of mechanisms leading to tyre-road noise (Source: Michelin, 2002 [4]; reprinted with permission of Michelin).

When an object vibrates, it can transmit its vibrations to structures in contact with it. The vibration is then said to be propagated through a structure. The vibrating object may also cause vibration of the surrounding air. This is known as airborne propagation, which is the main component for exterior noise. When the tyre structure or column of air in the cavity starts resonating, the vibrations are transmitted on the rim via the bead and via acoustic pressure on the wheel which can cause it to vibrate. The wheel then transmits its vibrations to the wheel centre, then to the passenger cabin through structure-borne propagation. Structure-borne propagation typically happens up to 300 to 800 Hz as is shown in Figure 2-3. Vibrations above 250 Hz are strongly damped and cannot propagate around the tyre. The tyre mainly vibrates in and near the contact patch in this frequency range and airborne propagation relevant for exterior noise takes place.

In Figure 2-4 and Figure 2-5 the mechanisms involved in tyre-road noise are shown graphically.

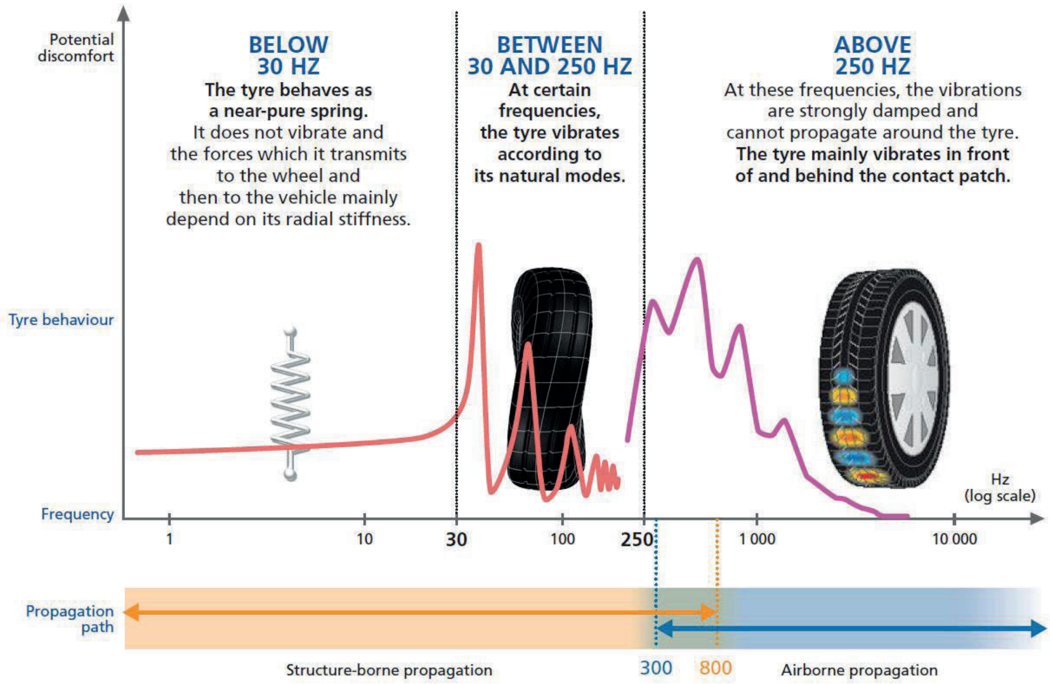


Figure 2-3: Vibration behaviour of a tyre up to 10 kHz (Source: Michelin, 2002 [4]; reprinted with permission of Michelin).

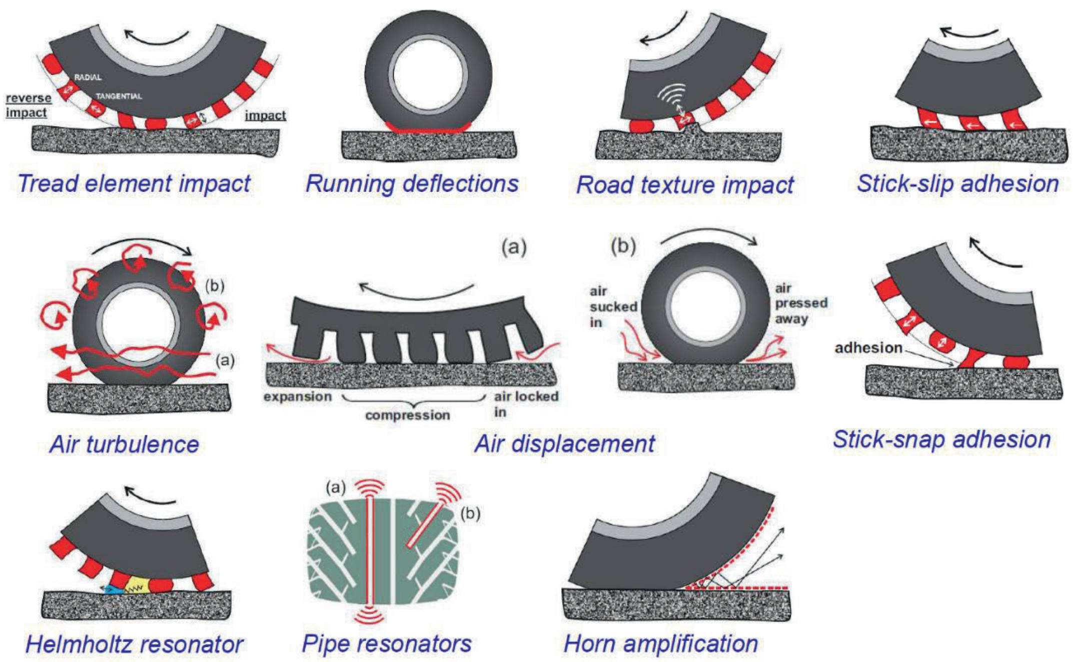


Figure 2-4: Mechanisms involved in tyre-road noise (Source: P.Kindt, 2018 [6]; reprinted with permission of P.Kindt).

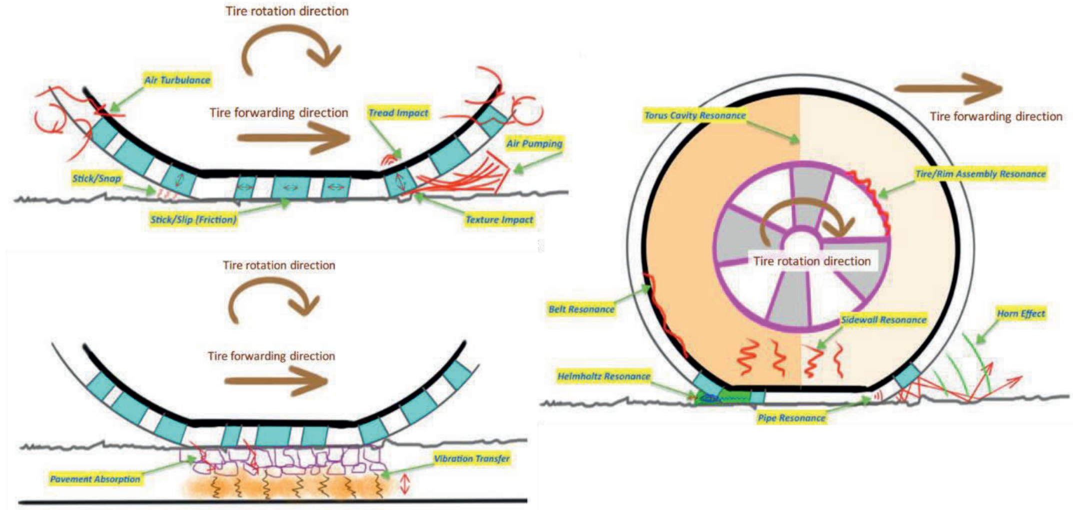


Figure 2-5: Mechanisms involved in tyre-road noise (Source: T.Li, 2017 [7]; reprinted with permission of T.Li).

The horn effect shown in Figure 2-4 and Figure 2-5 is an amplification effect. In front of and behind the contact patch, the tyre and the road surface form two horn-shaped areas, which amplify all the noises generated by the different sound sources in these areas. The horn geometry is such that the horns have an amplifying effect which increases up to 1 kHz and then stabilizes around 2 kHz. Figure 2-3 shows that above 250 Hz, the tyre mainly vibrates in front of and behind the contact patch, which is precisely where the horn effect is located. This partly explains why, in spite of the strong damping of the tyre's surface vibrations, the intensity of sound perceived alongside roads is very high. The amplification due to the horn effect depends on the shape of the deformed tyre around the contact area and the type of road surface, especially the road absorption coefficient.

The pavement absorption mechanism is depicted in Figure 2-5. Communicating voids in porous pavements act like a sound absorbing material. Due to this pavement absorption mechanism the type of pavement also plays a significant role. Draining mixes, which have a network of voids reaching the surface so as to allow rainwater to drain off, absorb most of the sound waves, unlike classic bituminous concretes whose "closed" surface reflects more than it absorbs. Next to absorption, also the stiffness of the pavement plays a role. A stiffer pavement gives more noise generation than a softer pavement. On a soft pavement, the vibrations of a tread element may be damped when impacted against the surface that is like a cushion. Several trials on road sections with a rubber mixture in asphalt have demonstrated that a significant noise reduction can be achieved [8].

Finally, in Figure 2-4 and Figure 2-5 the air turbulence mechanism is shown. Air turbulence is potentially caused by the tyre displacing air when it rotates and moves forward.

The various mechanisms discussed above, lead to noise production in different frequency ranges. Furthermore, due to the nature of the mechanisms, rolling speed also plays a major role in noise production.

This study is about exterior tyre-road noise, and in particular the noise perceived by humans outside of the vehicle. The human ear perceives sounds with a frequency between 20 and 20000 Hz, but the sensitivity to sound is different for different frequencies and the ear is less sensitive to low audio frequencies. Therefore, weighting functions are applied to assess sound/noise. When measuring tyre-road noise, e.g.

according to UNECE Regulation No 117 [5], A-weighting is applied to the measured sound, meaning that the sound is measured in dB(A). A-weighting gives the most weight to the frequency range of 1000-5000 Hz.
Typically, frequency spectra of tyre-road noise have a prominent peak in the range of 500-1500 Hz. The general understanding is that this peak is caused by dominant frequencies for many mechanisms that act in this range and the applied A-weighting, which attenuates frequencies of mechanisms below 1000 Hz.
In the table below from the thesis of Li [7] various factors resulting in the tyre-road noise spectrum peak around 1000 Hz are summarized. The column with dominant frequencies is provided for car tyres at a speed V of 100 km/h. The column with equations shows the dependency of the dominant frequencies with speed.

	Pertinent Parameters	Equation	Dominant Frequency f [Hz]
Tread Impact	Pattern pitch l: 20-40 mm	$f = V/l$	694-1389
Texture Impact	Prominent wavelength l: 16-25 mm	$f = V/l$	1111-1736
Stick/Slip (Friction)	Tread block properties	NA	1000-3000
Air Pumping	Groove pitch l: 10-30 mm	$f = V/l$	926-2778
Belt Resonance	Belt properties	NA	600-1300
Pipe Resonance	Groove length l: 50-150 mm	$f = c/2l$	1133-3400
Helmholtz Resonance	See 3.3.2.2	See 3.3.2.2	1000-2500
Horn Effect	Horn geometries	NA	700-3000

Figure 2-6: Various factors resulting in tyre-road noise spectrum peak around 1000 Hz (car tyres at highway speed V = 100 km/h, sound speed c = 340 m/s) (Source: T.Li [7]; reprinted with permission of T.Li).

2.2 Theoretical basis for trade-off effects

This section provides an overview of mechanisms that can produce trade-off effects of tyre performance, to support interpretation of results from tyre testing later on in this report (section 2.5).

Tyre design is a multi-variable optimization. A theoretical basis for the optimization challenge is described in this section. It can explain where compromises need to be made, however quantification of trade-offs is not provided.

A tyre is an important vehicle component for driving and safety performance. Tyres are the only components of a vehicle in direct contact to the road and have the following basic (safety-critical) functions:

- Support the vehicle's weight.
- Transmission of forces for accelerating, braking and steering under various operating conditions.
- To supplement the vehicles suspension (contribution to road holding and ride comfort).

Tyres cannot fulfil these basic functions without generating:

- Rolling resistance
- Wear
- Tyre-road noise

In general, the challenge is to develop tyres which can fulfil these basic functions, while keeping rolling resistance, wear and tyre-road noise as low as possible. In this section a brief overview is given regarding the main influence factors and trade-off effects with the focus on tyre-road noise.

Tread pattern design and wet grip.

As discussed in section 2.1, quite some mechanisms significantly contributing to tyre-road noise are affected by the tread pattern design. Generally, a plain tread tyre (“slick”) is considered as the tyre producing the lowest possible noise. A plain tread tyre is a tyre without tread pattern being carved in. Mechanisms like pipe and Helmholtz resonators are absent. However, such tyre has limited capabilities to resist aquaplaning. By grooving the tyre tread, the aquaplaning speed is significantly increased. Fundamentally, tyre void ratio and tread depth are important parameters for offering resistance to aquaplaning. Aquaplaning risk increases when the combined water-absorption capability of the tyre and the pavement are not sufficient to expel the water out of the contact area in a limited time. Consequently, the highest aquaplaning resistance is obtained for a new tyre and decreases with tread wear. Also, before full aquaplaning occurs, i.e. contact patch is fully lifted by the water, partial aquaplaning takes place in the contact patch, leading to lower wet grip at speeds below the aquaplaning speed. Apart from grooving the tyre tread, also the shape of the contact path affects the resistance to aquaplaning. A rounded contact patch increases aquaplaning speed.

Next to fundamental parameters as void ratio and tread depth, the design of the tread pattern is also important for achieving good wet grip and aquaplaning properties, while keeping tyre-road noise and tread wear to acceptable levels. In the thesis of Li [7] several tread wear parameters are listed that affect tyre-road noise, see Figure 2-7. Parameters such as increasing the offset between the left and right tread blocks and increasing the tread groove ventilation have a larger effect on reducing tyre-road noise than parameters such as randomization and addition of small sipes. Rotation Direction / Asymmetry is assessed to have a negative effect on tyre-road noise. The column ‘Potential Noise Variation’ in Figure 2-7 only indicates the noise reduction but not the trade-off with other tyre performance. Secondly, it can be assumed that the results in Figure 2-7 have been used for tyres on the market today already. Furthermore, the tread pattern is also designed for interacting with e.g. snow and is consequently different for winter and summer tyres. Last but not least, resistance to tread wear (i.e. abrasion) is also a parameter that has to be considered in tread pattern design.

No.	Parameter	Pertinent Frequency [Hz]	Relation (↑↓)	Potential Noise Variation [dB]	Measurement Equipment	Relevant Mechanism
1	Randomization	600–1000	↓	0 or marginal	N/A	Tread impact
	Elimination of Groove Footprint Coinciding	800–1000	↓	N/A	N/A	Tread impact
	Offset between Left and Right Side	N/A	↓	5	Caliper	Tread impact
2	Rotation Direction / Side Asymmetry	N/A	↑	3	N/A	Various
3	Ventilation	800–1000 and 1600–4000	↓	2	N/A	Air pumping, air resonance
4	Addition of Mirror Image Grooves	Above 4000	↓	0	N/A	Air pumping, air resonance
	Addition of Lamellae	800–1000	↓	N/A	N/A	Air pumping, air resonance
	Groove Width	800–2000	↑ 9 mm ↓	N/A	Caliper	Air pumping
	Groove Angle (Relative to Lateral)	800–2000	↓	N/A	Protractor	Tread impact

Figure 2-7: Summary of tread pattern parameters affecting tyre-road noise (Source: T.Li [7]; reprinted with permission of T.Li).

In conclusion, a clear trade-off has to be made in tread pattern design regarding tyre-road noise and grip on wet road surfaces. Furthermore, additional trade-offs have to be made regarding e.g. interacting with loose soil surfaces like snow or mud, improving traction, braking and handling.

Tread rubber compound.

The tread rubber compound affects many tyre performance aspects. Rubber is a viscoelastic material. An important property of viscoelastic materials is hysteresis. These materials do not revert immediately to their initial shape after being subjected to deformation. This delay is accompanied by a dissipation of energy in the form of heat. Hysteresis plays a major role in the mechanics of grip (or skid resistance). Tread material wraps around the road roughness and can transfer additional horizontal (shear) forces which counteract skidding. Without this phenomenon, horizontal forces could only be transferred by adhesion, which is very much reduced for wet contact.

Hysteresis also contributes to damping of vibrations. Consequently, soft and high hysteresis compounds are both beneficial for grip and tyre-road noise reduction. On the contrary, hysteresis and energy loss inevitably go together. Therefore, rolling resistance is negatively affected by high hysteresis.

The hysteresis of rubber is non-constant and exhibits a maximum when the rubber is close to its so-called glass transition temperature, see Figure 2-8. Maximum grip of the tyre is achieved when it operates at maximum hysteresis conditions (peak of red curve).

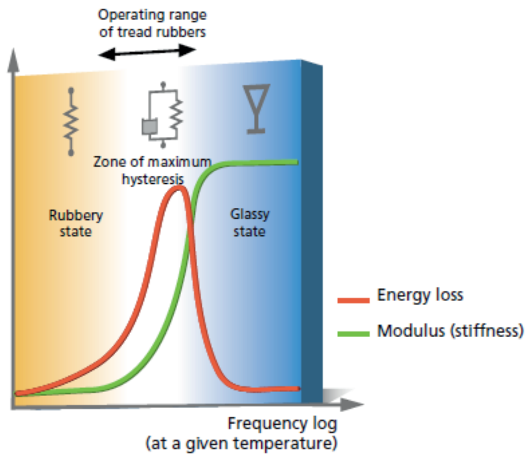


Figure 2-8: Energy loss and modulus (stiffness) of a viscoelastic material (Source: Michelin [9]; reprinted with permission of Michelin).

Consequently, tread rubber is designed such that it is in this transition state when the tyre is in service. The stress frequencies exciting the tread rubber are related to the wavelength of road texture. In Figure 2-9 road texture wavelength influence on various tyre-road interactions is shown.

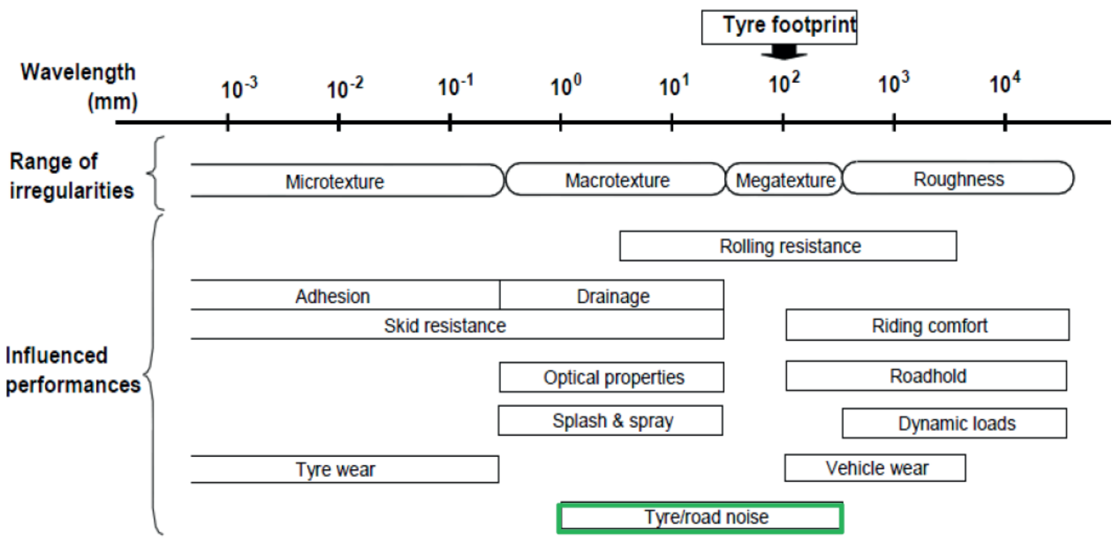


Figure 2-9: Texture wavelength influence on tyre/road interactions (Source: P. Kindt [6] and TYROSAFE [10]; reprinted with permission of P. Kindt and TYROSAFE). Note that grip is indicated as skid resistance.

The tread rubber compound also affects the cornering stiffness and longitudinal stiffness of the tyre, which consequently become lower with a softer compound and higher with a harder compound. A higher tyre cornering stiffness results in better vehicle handling performance and offers consequently more safety in e.g. collision avoidance manoeuvres.

Another property of viscoelastic materials is that their behaviour is temperature dependent. The frequency dependent stiffness and hysteresis curves shift with temperature. The rubber gets harder if temperature decreases and softer if it increases. Also, the zone of maximum hysteresis shifts with temperature to a different range. Rubber compounds are engineered to influence the tyre behaviour. For example, different compounds are used for summer and winter tyres to achieve the best performance of the tyre in the relevant temperature operating range. How compounds are engineered is generally a company secret.

The tread rubber compound also plays a role in tyre tread wear. Generally, a soft compound wears quicker than a hard compound.

In conclusion, a clear optimization has to be made in tread rubber compound design regarding trade-off of tyre-road noise, (dry/wet) grip, longitudinal/cornering stiffness, rolling resistance and tyre wear.

Tyre internal structure

One of the mechanisms causing tyre-road noise is tread impact. Belt vibrations are resulting from the impact of tread blocks on the road surface at the leading edge of the contact patch and their liberation at the trailing edge. The vibrations cause noise and decrease as the thickness of the under-tread, see Figure 2-10, increases. The under-tread is the material between the bottom of the tread rubber and the top layer of steel belts. Basically, a thicker under-tread will decrease contact stiffness; it acts like a cushion for tread impact. The drawback of making the under-tread thicker is that material is added to the tyre. Due to hysteresis, this additional material will dissipate more energy when deformed in a rolling tyre, leading to an increase in rolling resistance. Moreover, a thicker under-tread will increase the cost and weight of a tyre, as more material is needed.

Figure 2-10: Under-tread layer (image courtesy Michelin).

Stiffness of tyres is considered for noise optimization. Increasing the tyre belt stiffness (such as increasing the number of the plies, adding reinforcement rubber, and using steel ply materials) will increase tyre-road noise, but will decrease wear and increase cornering power (which improves safety performance).

Drawbacks of increasing the belt stiffness are increase of the tyre mass and inertia and the capability of the tyre to deform around obstacles (enveloping behaviour). Consequently, ride comfort decreases and vehicle energy consumption increases (due to potential increased weight) with increasing belt stiffness.

Tyre size

In the thesis of Li [7] it is concluded that wider tyres generally generate more tyre-road noise. With increasing tyre width, the tread impact becomes more extensive leading to larger vibrations. Stick/slip and stick/snap phenomena that occur in the tyre-road contact are also amplified. A tyre with a wider section involves also more displacement of air within the tyre-road interface, amplifying both air pumping and air turbulence. In addition, horn shape and Helmholtz resonator are easier to occur more prominently with larger tyre width.

Tyre width has a larger influence on tyre-road noise than tyre diameter. An increase in tyre diameter is assessed to have a small positive effect on tyre-road noise [7].

In Figure 2-11 and Figure 2-12 additional tables are shown from the thesis of Li [7]. Figure 2-11 shows modifications affecting tyre noise and drawbacks. In Figure 2-12 a summary of tyre-related parameters affecting tyre-road noise is given. These tables support the influence factors and trade-offs described in theory as elaborated above.

Parameter	Modification	Influence
Tread pattern	From 34 % void volume to slick	Increase in wet braking by 40 % Increase in aquaplaning in curve by 60 %
Tread material	From summer tread compound to ice tread compound (decrease rubber hardness/stiffness)	Increase in wear by 50 %
Tread material	From normal tread to thicker under tread (decrease contact stiffness)	Increase in rolling resistance by 15 %
Carcass	Increase belt stiffness (such as increasing the number of the plies, adding reinforcement rubber, and using steel ply materials)	Decrease in wear by 20 % Increase in cornering power by 10 %

Figure 2-11: Modifications affecting tyre noise and drawbacks (Source: T.Li [7]; reprinted with permission of T.Li). Note: the modifications regarding the tread decrease tyre noise, while increasing carcass stiffness will increase tyre noise.

No.	Parameter	Pertinent Frequency [Hz]	Relation (↑↓)	Potential Noise Variation [dB]	Measurement Equipment	Relevant Mechanism
1	Tire Type/Construction	N/A	Complex	3	N/A	Various
2	Tire Width	500–1000	↑	3	Measure tape	Various
3	Tire Diameter	N/A	↓	1	Measure tape	Impact, horn
4	Belt Stiffness	500–8000	↓	2	Loading test rig with bar	Tire resonance
5	Damping (Loss Factor)	250–500	↓	1	N/A	Tire resonance
6	Non-uniformity	20–200	↑	1	Wheel balancing machines	Tire resonance
7	Rubber Hardness	1000–3000	↑	3	Durometer	Stick/slip
8	Wear/Aging	1000–3000	↑ (then ↓)	5	N/A	Various
9	Retreaded	500 and 2000–3000	Complex	2	N/A	Impact
10	Studded	400–3000 and above 5000	↑	6	N/A	Impact, stick/slip
11	Tread Porosity	N/A	↓	7	N/A	Air pumping, horn effect
12	Tire Cavity Content	400–1100	Complex (↓)	2	N/A	Cavity resonance
13	Rolling Resistance	N/A	↑ (Weak correlation)	0	Dynamometer drum: ISO 18164 [141]	N/A

Figure 2-12: Summary of tyre-related parameters affecting tyre-road noise (Source: T.Li [7]; reprinted with permission of T.Li).

Also tyre manufacturers performed and presented material on trade-off effects with respect to tyre-road noise. The European Tyre and Rubber Manufacturers' Association (ETRMA), presented a position paper on tyre & road traffic noise [11], including results from scientific studies. In this position paper figures, see Figure 2-13, are shown that illustrate the design trade-offs that tyre manufactures face. The illustrations are mainly based on a study performed by Michelin of which the results are reported in the ACEA Tyre Performance Study Report [1]. The figures of the Michelin study are provided in Figure 2-14. In [1] it is mentioned that Michelin performed tests on a tyre launched in March 2006 (at that time state-of-the art) in order to predict the effects of tyre-road noise reduction on aquaplaning (longitudinal and in curve), wet grip, wear, handling and cost. The trade-offs shown can be explained from the scientific publications discussed above. With regard to the quantitative values the following remarks must be made:

- Values are only valid for the specific tyre from 2006. In the position paper from

ETRMA it is presented (without values) as the fundamental relationships between tyre performance.

- Extreme variations are considered, e.g. slick tyres are illegal for public road driving due to their unacceptable wet grip / aquaplaning safety. A slick tyre has no voids while void ratios between 27 and 37 % are typical for production tyres. Looking at the sensitivity around the standard “Sculptured Tyre” (slopes at 0 dBA in Figure 2-14) gives therefore a better indication about the real-life trade-offs.

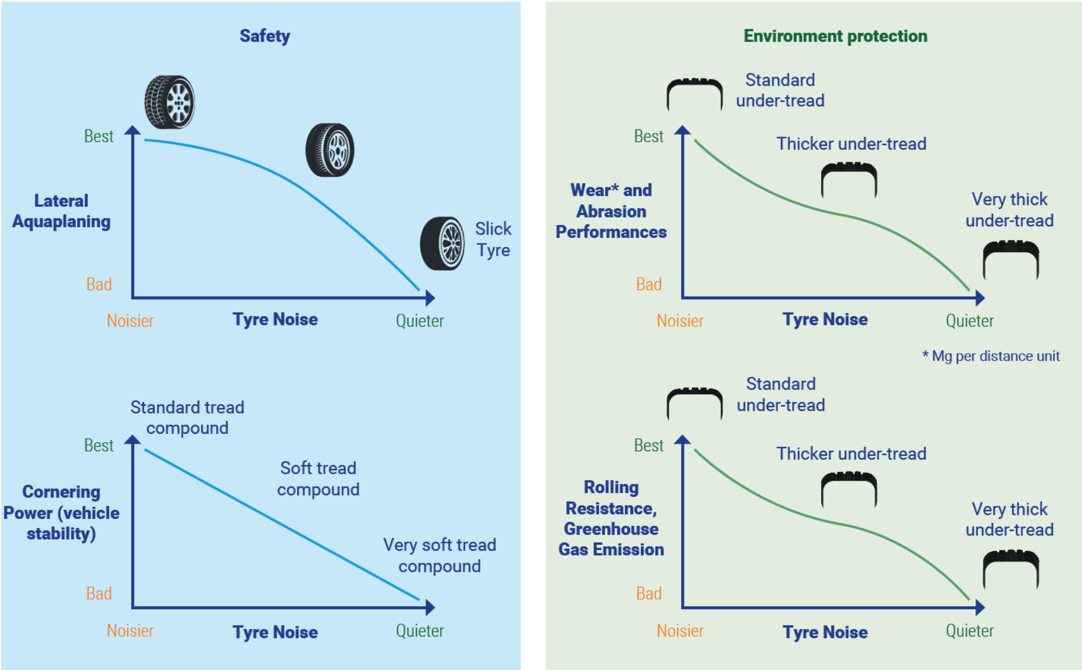
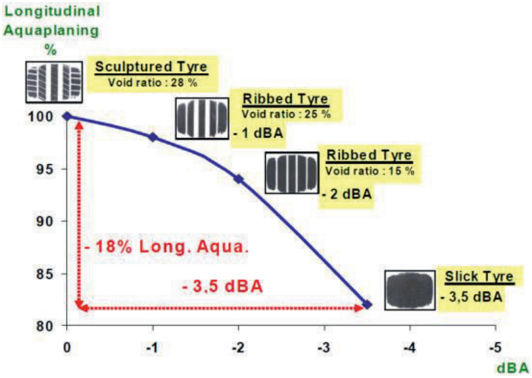


Figure 2-13: Illustrations to show the actual design trade-offs that tyre manufactures face (Source: ETRMA [11]; reprinted with permission of ETRMA).

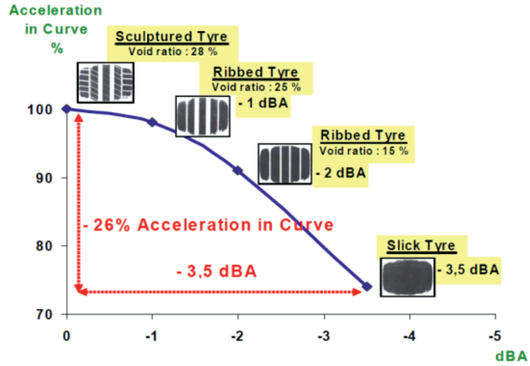
Longitudinal aquaplaning versus noise level

- Aquaplaning speed: 82 to 66 km/h
- Water depth: 8 mm



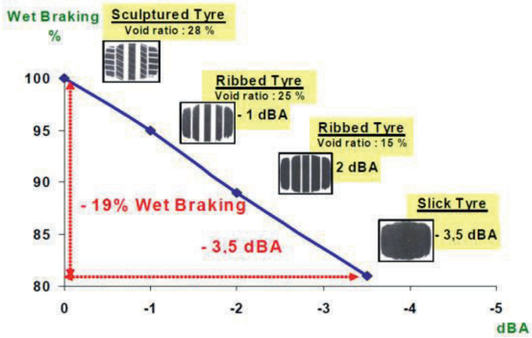
Aquaplaning in curve versus noise level

- Mean lateral acceleration: 85 to 55 km/h
- Water depth: 7 mm

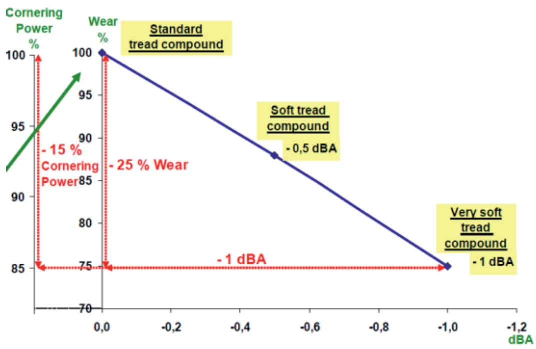


Wet braking performance versus noise level

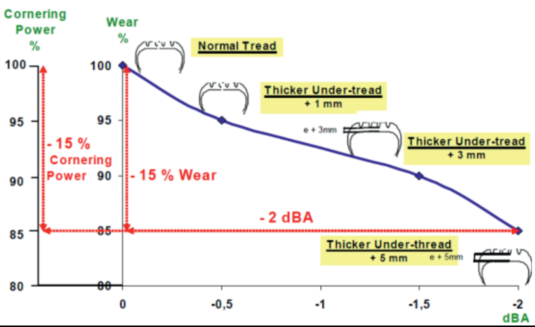
- Wet braking from 80 to 10 km/h
- Macro rough surface



Effect of tread rubber compound



Effect of under-tread thickness



Effect of under-tread thickness

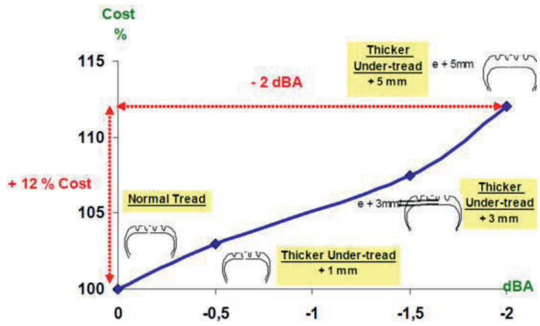


Figure 2-14: Tyre-road noise trade-offs from internal study of Michelin in 2007 reported in [1]. Tyre-road noise measured according to ISO 108844 acoustics. (reprinted with permission of Michelin)

Research efforts in making a quiet tyre.

As mentioned above, developing quiet tyres requires to make trade-offs between several tyre performance parameters. This is well-known and therefore a number of new design concepts to reduce tyre-road noise have been developed in the research community, see the dissertation of Li [7] for an overview. Modification has been applied to the tyre tread, tread pattern, tyre cavity, and rim. It is mentioned that few of these design concepts are commercially viable due to manufacturing complexities, cost, safety and durability. The sound-absorbing materials - mainly special polyurethane foams - attached inside the tyre cavity to reduce the cavity resonance, might be the most successful so far. However, although this technology significantly reduces structure born / interior noise, it only has a minor effect on exterior tyre-road noise. Nowadays, many of the top tyre manufacturers offer this technology for specific tyre types (e.g. tyres marketed for EVs and premium/prestige silent ICE cars). Figure 2-15 shows the effects on the noise spectrum by the inlay concept.

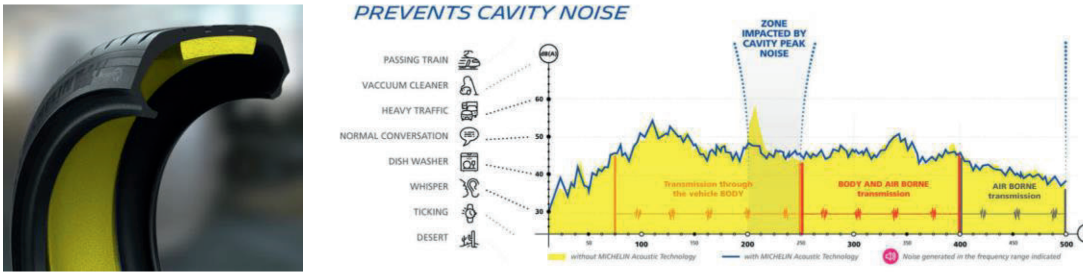


Figure 2-15: Sound-absorbing material attached inside the tyre cavity to reduce the cavity resonance noise. (image courtesy Michelin)

2.3 Scientific studies based on tyre testing.

This section summarizes results obtained from tyre testing for performance aspects that are subject of the study. A quantification of trade-off effects might be obtained from tyre testing.

Scientific studies based on tyre testing provide an explanation of the phenomena and relevance of the differences or trade-offs observed. It needs to be considered however, that non-recent studies might not be representative anymore for tyres on the market today. In other words, the results are only accurate (or valid) for the tyres that were tested.

One of the most recent studies regarding the improvement potential of noise emissions was conducted by the European Automobile Manufacturers Association (ACEA). ACEA selected UTAC CERAM to conduct a study to assess the relation between tyre performance for rolling resistance, noise level and wet grip. The study is reported in the ACEA Tyre Performance Study Report [1]. The study consists of a literature study, tyre testing and a statistical analysis of the performed tyre tests. Also, the European Tyre & Rubber Manufacturers Association (ETRMA) independently requested UTAC to perform a similar study [3]. Both studies were presented to the Working Party on Noise and Tyres (Groupe Rapporteur Bruit et Pneumatiques - GRBP), a subsidiary body of the World Forum for Harmonization of Vehicle Regulations. Some contracting parties as the United Kingdom, asked ACEA and ETRTO to rationalize the two studies in order to have a bigger sample and to confirm, or not, the conclusions. The aggregation of the two studies is described in the Tyre performance aggregation study report [2] for technical items that can be put in common.

In all three studies, tyres of size 205/55R16 (most sold on the EU market) have been tested and tests have been conducted according to standard test procedures, as is depicted in Figure 2-16.

		ACEA study	ETRTO study	Aggregation Study
Tyres tested	set/size	16 x 205/55 R16 91 H/ T/ V/W	10 x 205/55 R16 91/94 H/V/W	20 x 205/55 R16 91 H/V/W
Safety Related Tests	dry grip	ECE13H Type 0	Similar to ECE R117 wet grip	-
	dry handling	Flat trac bench	Flat trac bench	Flat trac bench
	wet grip	ECE R117	ECE R117	ECE R117
	aquaplaning	VDA methods (E08, E05)	VDA methods (E08, E05)	VDA methods (E08, E05)
Emission Related Tests	vehicle noise	ECE R51 cruises and acceleration	ECE R51 cruises and acceleration	ECE R51 cruises and acceleration
		-	Ditto (2nd vehicle)	-
	tyre noise	ECE R117 – rolling sound	ECE R117 – rolling sound	ECE R117 – rolling sound
	CO2	ECE R117 – RR	ECE R117 - RR	ECE R117 - RR
		weight, tread depth, void ratio	weight	weight

Figure 2-16: Test specifications. (Source: UTAC CERAM [2]; reprinted with permission of UTAC CERAM)

Radar charts from the statistical analysis are shown in Figure 2-17. In these charts the performance results of the different tests are represented on a scale of 0 to 10 (0 = worst performance in the group, 10 is best performance in the group). It is shown that the best 4 tyres for safety are quite noisy, the best tyres for noise have poor aquaplaning and wet grip and the best for rolling resistance have low cornering stiffness. It must be noted that tyres 1 and 4 are plain tread tyres, which were added for comparison, but are not representative for tyres on the market, as these are non-legal as they do not have a tread pattern. Due to the lack of tread pattern these tyres are best for noise, but also have extremely poor wet grip and aquaplaning properties, as can be seen in the middle radar chart. On the other hand, these two tyres have extraordinary handling performance on dry road (Flat trac). The difference between tyre 1 and 4 is that tyre 1 is based on a 3PMSF (winter) tyre. The softer winter tyre compound (and the non-existence of a tread pattern) probably explains its best noise performance, but also its lower handling performance compared to tyre 1. Finally, note that the scaling 1-10 of the radar charts for the noise tests (R117 50, R117 80, R51C 50, R51A 50) will change considerably if tyre 1 is removed.

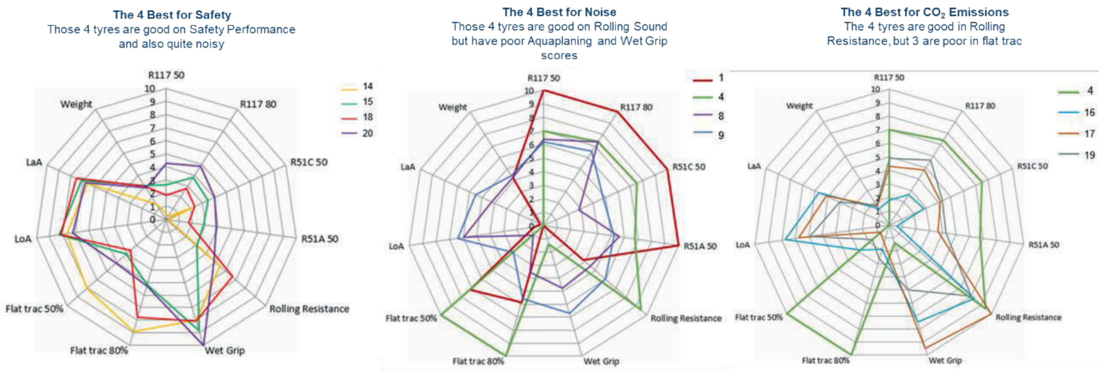


Figure 2-17: Aggregation study radar charts. LaA = lateral aquaplaning, LoA = longitudinal aquaplaning, Flat trac xx % = cornering stiffness at xx % of the load index of the tyre. Tyres 1 and 4 are plain tread tyres (not road legal, just for comparison). (Source: UTAC CERAM [2]; reprinted with permission of UTAC CERAM)

The conclusions of the statistical analysis of the aggregation study, as reported in [2], are:

- The radar charts and the principal components analysis show a conflict between rolling sound (R117) and safety performances (wet grip and lateral aquaplaning).
- Simple conclusions regarding rolling sound, rolling resistance, weight and safety performance (longitudinal aquaplaning) cannot be drawn.

The table in Figure 2-18 further summarises the results.

ACEA study	ETRTO study	Aggregation Study
summarize 8 characteristics to "safety", "handling" and "CO2-emissions": - conflict between rolling sound and safety performance - handling performance supports good rolling sound - undefined relation between sound and CO2-emission	summarize 7 characteristics to "wet safety", "dry grip/ CO2-emissions" and "flat trac 80% / dry grip": - conflict between rolling sound and wet safety - plain tread tyres represent an asymptote for rolling sound at a forbidden stage of wet safety	summarize 7 characteristics to "safety", "CO2-emissions" and "handling": **Confirmation of both conclusions**

Figure 2-18: Summary of conclusions of tyre performance studies conducted by UTAC. (Source: UTAC CERAM [2]; reprinted with permission of UTAC CERAM)

2.4 Consultation of experts

This section addresses interviews that were conducted with experts and a workshop to extend on information from literature on tyre trade-off effects which may not have been published.

Experts were consulted from the tyre research domain. From the scientific community experts were interviewed from Belgium, Germany, The Netherlands, Poland and Sweden. The interviews were conducted per organization. Several experts indicated to participate (in the past or currently) in joint research with EU tyre manufacturer(s).
In addition to the experts from the scientific community, also experts were interviewed from the tyre industry in a session organized together with the European Tyre & Rubber Manufacturers Association (ETRMA).
The complete reporting of the consultation is provided in Appendix A, which includes suggestions for literature and other scientific sources. In the current section, a summary is provided concerning tyre design and trade-offs.

The following factors that influence tyre noise performance and trade-offs are mentioned by the experts:

- Wider tyres produce more noise.
- Quite a lot of tyre research has been done on rolling resistance and noise combined. An integrated design can mitigate trade-off between these two aspects.
- The tread pattern is dominant for noise as well as aquaplaning performance. Optimization typically results in a certain level of trade-off between noise and safety performance.
- Tyre performance and trade-offs are influenced by road characteristics as well as temperature of operation. The variety of roads typically has more impact on noise than using different tyres. Tyre performance is optimal within a target temperature range.
- Baseline requirements such as load carry capacity and endurance for high speed, put main constraints on tyre design. Less challenging baseline requirements (e.g. reduced speed range) gives more design freedom and can reduce performance trade-offs for quieter tyres.
- Little information is known about the relation between tyre noise and abrasion. Generally softer materials reduce noise but increase abrasion. Abrasion is also affected by tread pattern design, which can be in conflict with noise.

Regarding tyre design and methods, the following was mentioned:

- Numerical models cannot quantitatively predict performance of rolling tyres for all aspects. The comprehensive performance can only be assessed from testing.
- Main new developments related to tyre noise generation are on (meta-) materials and construction. More additives are used, mainly by premium tyre brands.
- The EU tyre industry reports that their design methods have consolidated in 2021 towards a holistic approach. All key performance aspects seem connected and cannot be optimized independently. The state-of-the-art methods use a

holistic approach in which geometry, construction and material are optimized in an integral way. Changing (or optimizing) only one tyre parameter for improved noise will impact various other performance aspects (often adversely).

- Increasing the number of regulatory requirements (or making them more stringent) for various tyre performance is restricting the design freedom with less trade-off for other (non-regulatory) performance requirements.

Regarding the current noise levels considered by the EU, tyre industry states to be not far above what can be achieved by the most silent, (non-legal) slick/plain tread, tyre. The magnitude of noise reductions achieved in the past 10-15 years can no longer be made.

2.5 Analysis of consumer tyre testing

This section discusses analyses of comparative tyre testing for consumers, which provides state-of-the-art tyre performance information for tyres of different specification (tyre designation, brand and product range) and may form another basis to quantify performance trade-off effects.

Tyre technology is evolving and with that, the tyre performance and trade-offs between tyre performance aspects are changing. Conclusions from studies on older types of tyres may not be representative for tyres currently on the market. Consumer tyre testing is done regularly and results are easily accessible.

This section describes how consumer testing is used to obtain an overview of typical relations in performance of current tyres.

2.5.1 General overview

To find correlations between tyre noise and wet grip, rolling resistance, abrasion and other performance parameters, a study into passenger car tyres (C1) is performed. The test results are obtained from the website www.tyrereviews.com.

The test reports on the website have been obtained from well-established organizations or magazines (Auto-Motor und Sport, Auto Bild, Auto Zeitung, Allgemeiner Deutscher Automobil-Club (ADAC)), and also from Tyre Reviews LLC, which is the organization behind the website tyrereviews.com. The test procedures are well-defined and provide a wider overview of tyre performance than regulated tests. In each of the test sessions a collection of tyres with the same tyre designation from different manufacturers are tested to provide consumer information about the comparative performance.

Table 2.1 provides an overview of the consumer tests that have been used for the analyses. These tests concern summer tyres that have been tested in the last 2 years. Note that different test protocols have been used which are summarized in the Section 2.5.2. Next to the variety in test protocols also the test conditions may vary between sessions. It can be assumed that within one test session the results are suited for relative comparison of performance, since that is the main objective of consumer tests.

In Section 2.5.3 it is explained how the results are processed in order to combine results from different test sessions.

On https://www.tyrereviews.com/Article/Tyre-Reviews-Review-Ethics.htm, an ethics declaration regarding impartiality is stated. According to this declaration no financial interests are due in the covered products and a statement is made that website advertising is clearly marked as advertising. The webpage www.tyrereviews.com is cited in at least 10 other publications. Also, it has been cited in three patents of Michelin.

In the analysis several test series with summer tyres are used. In total, 300 tyres from 63 manufacturers are examined, ranging from premium to mid-range to budget brands. The distribution of manufacturers is given in Table 2.1.

.

Table 2.1: Overview of consumer tyre testing

Test set	Tyre size	Nr of tyres	Test data Supplier	Noise	Dry braking	Wet braking	Aqua straight	Aqua curve	Rolling res.	Abrasion	Tread life	Handling Dry	Handling Wet
1	245/45 R19 102 Y	10	Auto Motor und Sport	X	X	X	X	X	X	–	–	X	X
2	245/40 R19 98 Y	10	Auto Bild	X	X	X	X	X	X	–	–	X	X
3	225/45 R18	11	Auto Bild	X	X	X	X	X	X	–	–	X	X
4	215/55 R17	22	Auto Bild	X	X	X	X	X	X	–	X	X	X
5	215/55 R17 94 W	10	Auto Zeitung	X	X	X	X	–	X	–	–	X	X
6	225/45 R17 91 Y	9	Tyre Reviews	X	X	X	X	–	X	–	–	X	X
7	205/55 R16 91 V	50	ADAC	X	X	X	X	X	–	X	X	–	–
8	225/40 R18 92 Y	13	Auto Bild	X	X	X	X	X	X	–	–	X	X
9	225/45 R18 95 Y	21	Auto Bild	X	X	X	X	X	X	–	X	X	X
10	235/35 R19 91 Y	10	Auto Zeitung	X	X	X	X	–	X	–	–	X	X
11	225/65 R17 106 V	12	Auto Bild	X	X	X	X	X	X	–	–	X	X
12	255/45 R20 105 Y	10	Auto Motor und Sport	X	X	X	X	X	X	–	–	X	X
13	205/55 R16	8	The Polish Motor Magazine	X	X	X	X	–	X	–	–	X	X
14	225/40 R18 92 Y	11	Tyre Reviews	X	X	X	X	X	X	–	–	X	X
15	205/55 R16 91 V	13	Tyre Reviews	X	X	X	X	X	X	–	–	X	X
16	215/55 R17	16	ADAC	X	X	X	X	X	–	X	X	–	–
17	235/55 R18 100 V	8	Auto Motor und Sport	X	X	X	X	X	X	–	–	X	X
18	205/55 R16 91 V	21	Auto Bild	X	X	X	X	X	X	–	X	X	X
19	235/55 R19 105 Y	9	Auto Bild	X	X	X	X	X	X	–	X	X	X
20	235/55 R19	11	Auto Bild	X	X	X	X	X	X	–	–	X	X
21	205/55 R16	9	Tyre Reviews	X	X	X	X	X	X	–	–	X	X
22	245/45R19 102 Y	6	UTAC	X	–	–	–	–	–	X	X	–	–

Table 2.2: Distribution of test entries (#) per manufacturer

Manufacturer	#	Manufacturer	#	Manufacturer	#	Manufacturer	#
Aplus	1	Falken	18	Lassa	1	Sailun	1
Apollo	1	Firestone	4	Laufenn	2	Sava	3
Avon	1	Fulda	6	Linglong	3	Semperit	3
Barum	1	General	2	Maxtrek	1	Star-Performer	1
Berlin-Tires	1	Giti	8	Maxxis	11	Superia	1
BFGoodrich	4	Goodride	3	Michelin	24	Tomket	3
Bridgestone	20	Goodyear	18	Minerva	1	Toyo	9
Ceat	1	GT-Radial	9	Nankang	2	Triangle	1
Continental	21	Hankook	16	Nexen	11	Uniroyal	4
Cooper	2	Hifly	1	Nokian	4	Viking	1
Davanti	1	Kenda	1	Norauto	1	Vredestein	10
Debica	3	King-Meiler	2	Petlas	1	Westlake	1
Double-Coin	3	Kleber	4	Pirelli	11	Winrun	1
Dunlop	6	Kormoran	1	Premiorri	1	Yokohama	3
ESA-Tecar	1	Kumho	9	Rada	1	Zeetex	1
Evergreen	1	Landsail	1	Rotalla	2		

2.5.2 Test protocols

This section provides an overview of the test protocols used by the different testing organizations. It is reported by the website tyrereview.com that the tests mostly are conducted on proving grounds from tyre suppliers. This ensures that road conditions are suited for evaluation of tyre performance.

It should be remarked that (nearly) new, i.e. unworn, tyres are tested, except for specific tests assessing e.g. abrasion or tyre life. This is corresponding to tests for regulatory purposes.
The noise performance is assessed from test procedures similar to Annex 3 from UN regulation 117 [5].

The safety performance is assessed from the following:

- Braking tests (Dry and Wet Road, Dry braking and Wet braking in Table 2.1)
    - The tyre grip level is derived from the braking distance. The test procedures are similar to Annex 5 of UN regulation 117 [5]. The initial speed for braking as used in the tests has been 80 km/h or 100 km/h.
- Aquaplaning tests (Straight driving and Curve driving, Aqua straight and aqua curve in Table 2.1)
    - The maximum speed is assessed for driving though a high-water layer until skidding occurs. The test procedures can vary between testing organizations, but generally they are equivalent to what is described in detail on https://www.tirestesting.com.
- Handling tests (Dry and Wet Road, Handling Dry and Handling Wet in Table 2.1).
    - The minimal lap time is assessed for driving on a circuit. This is governed by the tyre grip level (including braking and lateral acceleration) as well as vehicle stability, which is affected by tyre cornering power.

The energy performance is assessed from measurement of the tyre rolling resistance (Rolling res. in Table 2.1). The test procedures are similar to Annex 6 from UN regulation 117.

The performance for Micro-plastic emissions is assessed from measurement of abrasion (Abrasion in Table 2.1). The test procedures are in line with a new proposal for incorporation in UN regulation 117 by September 2025, see https://www.etrma.org/news/unece-agreed-on-first-ever-methodology-to-measure-tyre-abrasion/ and https://unece.org/sites/default/files/2024-01/GRPE-90-29r2e.pdf.

2.5.3 Evaluation method

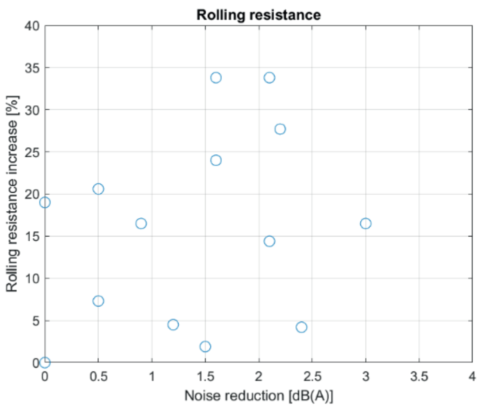
The consumer test sessions have been executed at different proving grounds, different weather conditions and using a variety of test protocols and test vehicles. This affects the test outcome in an absolute sense, but it can be assumed that the results within one test session provide a proper relative assessment of tyres within that group (i.e. performance ranking). It should be noted that the test sets are mostly for a specific target consumer (e.g. high performance) or topic (e.g. low rolling resistance) and may therefore not be a sample of tyres that is representative for the whole tyre population. Consequently, the best tyre in the group may not be the best tyre on the market.

An initial (single component) evaluation was executed which provides a comparison between performance of the quietest tyre in a test set and best performing tyre for individual aspects that are obtained from the consumer testing. Results for energy (i.e. rolling resistance) and micro-plastic emissions (i.e. abrasion) from the single component methodology were found useful and are presented in Section 2.5.4.

2.5.4 Results

2.5.4.1 Energy and micro-plastic emissions

This section contains a summary of results from single component evaluation of consumer tyre testing for rolling resistance and abrasion / tyre lifetime. The data corresponding to the performance figures is provided in Appendix D.
In Figure 2-19 for each of the 19 test sessions, the tyres with the lowest rolling resistance and lowest noise of each test session are taken. The rolling resistance increase, which is plotted on the y-axis is the percentage of rolling resistance increase of the quietest tyre compared to the tyre with the lowest rolling resistance in the test session. On the x-axis the noise reduction is plotted, which is the difference in noise emission of the quietest tyre versus the tyre with the lowest rolling resistance in the test session. Example: the data point (0.5 dB(A),7.5%) means that the quietest tyre in that test session is 0.5 dB(A) quieter than the tyre with the lowest rolling resistance, but also has 7.5% rolling resistance increase. Quite a spread of results can be observed in Figure 2-19. In most cases the quietest tyre has a rolling resistance increase. It is however most remarkable that, as indicated below the figure, that in case of 5 of the 19 test sets the quietest tyre has the lowest rolling resistance (5 data points are on (0, 0)). This suggests that a trade-off between rolling resistance and tyre noise can be avoided, which is in-line with results from other sources.

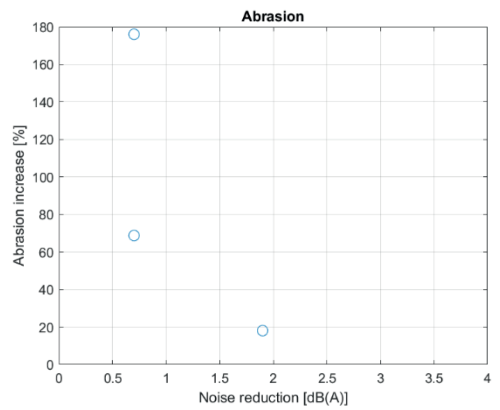


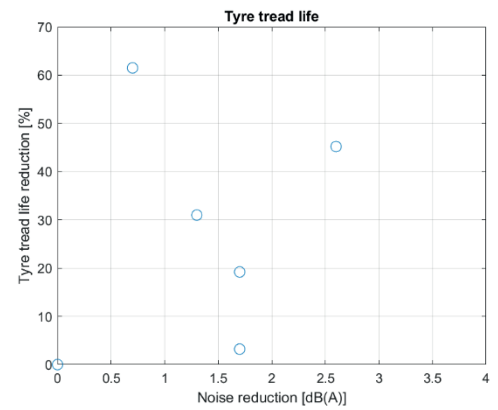
Quietest tyre = Performance winner: 2, 3, 4, 12, 20

Figure 2-19: Summary for rolling resistance performance and noise.

For Abrasion and predicted tyre tread life only a few test sessions provide information of which the processed results are displayed in Figure 2-20. Results for abrasion (3 test sessions) are shown on the left and for predicted tyre tread life (6 test sessions) on the right. A very big spread of results can be observed and from the limited number of test sessions no conclusions can be drawn on trade-off between micro-plastic emissions and tyre noise.

Abrasion	**Predicted tyre tread life**





Quietest tyre = Performance winner: none	Quietest tyre = Performance winner: Test set 18

Figure 2-20: Summary for tyre wear performance and noise.

The results for rolling resistance are in line with results from literature and reports of related studies, while for abrasion the extent of available data does not allow to conclude on the relation with tyre noise.

Based on the results as reported in this section no upscaling can be made for effects on energy and micro-plastic emissions.

2.5.4.2 Tyre safety performance

This single component methodology as described in section 2.5.3, proved however to be inadequate for assessment of tyre safety performance. Tyre safety performance is a combination of performance with multiple components.

The full description of the single component analyses and results is provided in Appendix B.

The multi-component tyre safety evaluation methodology and results are described in section 4.1.

2.6 Conclusion tyre compatibility

Tyre compatibility is investigated through a literature study, interviews with experts from the scientific community and the tyre industry, and by analyses of publicly available test data of tyres recently on the market.

From both literature and expert interviews, it is concluded that compromises between various performance criteria have to be made when designing tyres. This means that the tyre industry uses multi-factor optimization approaches to meet performance targets in the design of tyres. Changing one performance aspect (e.g. noise) requires a re-assessment of the optimal design to avoid trade-offs. Tyre design is reported by the tyre industry as being close to the physical limits for noise performance while still satisfying other performance requirements on e.g. rolling resistance and wet grip. In this study public available tyre test data (from consumer tests and the ACEA Tyre Performance

Study executed by UTAC [1]) was analysed with the aim to identify and quantify the effect of potential trade-offs when lowering tyre noise.

Below, the conclusions are provided for the different compatibility aspects derived from consumer tests and UTAC tests:

- **Noise versus rolling resistance**
  - Rolling resistance is a matter of contact mechanics as well as tyre structure. The relation of tyre rolling resistance and noise has been studied quite extensively and has resulted in tyres with little trade-off between these aspects. Analyses of test data reveals that this is also achieved for several tyres on the market. It can be concluded that rolling resistance and noise can be compatible for current tyres. However, there is no information how further reduction of noise will affect rolling resistance and it is unclear what the trade-offs could be.
- **Noise versus micro-plastic emissions**
  - Micro-plastic emissions of tyres is caused by abrasion. Abrasion is a relatively new aspect for tyres, which has not been studied extensively in relation to noise. From theoretical considerations a trade-off is expected if a softer compound is used for noise reduction. The available data from tyre testing is limited. Therefore, it is concluded that the information gathered is insufficient to draw conclusions on compatibility between abrasion and noise.
- **Safety performance versus noise**
  - Tyre safety performance concerns different aspects such as grip under dry and wet conditions, aquaplaning, vehicle stability, etc. Compromises are made in tyre design between individual safety performance aspects, e.g. a better tyre for dry road can have reduced performance on a wet road.
  - From literature it is concluded that compromises need to be made to obtain desired noise performance and grip under all operating conditions, which can result in trade-offs. Main physical aspects that play a role are contact mechanics, material properties, tyre construction and tread pattern design.
  - Tyre safety in relation to noise has not been studied extensively in the past. Recent studies by UTAC (including results from the tyre industry) conclude that tyre safety performance and noise are conflicting or incompatible, without providing a quantification of a trade-off.
  - Analysis of consumer tyre test data does not indicate a clear relation between individual safety performance aspects and noise. No relation could be assessed for a combined safety performance (i.e. dry/wet grip and aquaplaning) with noise either. A final analysis was done on scientific data used in the ACEA Tyre Performance Study involving 14 tyres. This has not resulted in the identification of a trend with sufficient confidence for combined safety performance and noise. From that analysis it is concluded that insufficient data is available to draw any conclusions on the trade-off between tyre safety and noise.

Concluding, results from literature review, expert interviews, and qualitative assessments show that compromises have to be made to achieve both safety and noise performance that can result in trade-offs. Industry uses holistic design methods to deal with this within current performance requirements. From experiments on state-of-the-art tyres no trend regarding safety and noise could be identified with sufficient confidence. Based on the above, it cannot be assessed how much trade-off with respect to safety performance can be expected when noise performance criteria are changed.

3. Analyses on noise levels of available tyres

This section provides indications which tyre designations[1] are already available with good noise performance (label A) and for which tyre designations noise levels potentially can be reduced (from labels B and C to label A), accompanied by trade-off effects for other performance. Secondly, baseline information of tyre noise is obtained for upscaling to an EU level.

In this research, the EPREL database [12] is used for analysis of tyre noise in relation to various tyre properties and to assess availability of tyres with specific labelling. EPREL is the abbreviation for “European Product Registry for Energy Labelling”. In this database, manufacturers of a selection of products (e.g. washing machines, air conditioners, refrigerators, and more) are obliged to register their products and provide the relevant labels for them (e.g. energy consumption, noise level, and more). Tyres also fall under this obligation.

The EPREL database is used to provide an overview (or distribution) of the tyre labels for energy, noise and wet grip classes. In Appendix B a general introduction into the contents of the EPREL database is presented as well as an overview of the tyre registrations in the database. The results of analysis on noise levels in relation to tyre designation is provided in section 3.1. In section 3.2 - 3.4 a detailed analysis on tyres, labelling and noise levels is performed.

All figures, tables and other results that are presented in this chapter are the results of queries to the state of the EPREL database of March 2024.

3.1 Noise level characteristics

In this section we will analyse the noise level characteristics in relation to the tyre’s geometry and load index.

In Figure 3-1, all of the C1 tyres (see Appendix C for an overview of all tyre-classes) in the EPREL database are ordered in a grid. The x-axis, represents the tyre radius and along the y-axis, the tyre width is ordered. Each cell in the grid represents a number of tyres in the EPREL database for that combination of radius and width. For some combinations of radius and width, there are no tyres to be found in the EPREL database. These are shown as blank cells in the figure. Otherwise, the cell will be color-coded with the averaged load index of the tyres within that cell, where blue colours represent a low load index and the yellow colours represent a high load index.

In Figure 3-1, the focus is on showing the relation of the load index with respect to the tyre dimensions for the C1 tyre entries in the ERPEL database. For this reason, additional filtering on other tyre properties (e.g. seasonality, speed category, etc…) is not executed.

From the figure, it can be seen that there is more load index variation amongst tyres with the same tyre width, than for tyres with the same tyre radius. Therefore it can be concluded that the load index is more sensitive to the tyre radius than to the tyre width, i.e. tyres with a high load capacity (yellow colours) tend to be bigger in radius, not necessarily wider.

1 The term “tyre designation” is used to describe the geometric, load and velocity properties of a tyre, (e.g. “205/55R16 88V”)

Figure 3-2 shows the tyre noise level (represented by the coloured cells) versus tyre width (on the x-axis) and the load index (on the y-axis). From this figure, more than proportional noise increase can be identified at specific tyre widths of 185, 245 and 275 mm. These widths correspond to the noise level limits for type approval in relation to tyre width categories as listed in UN Regulation 117 [5]. The data gives the impression that, once a tyre is (just) falling within a higher noise-level category, a disproportional higher noise level is accepted.

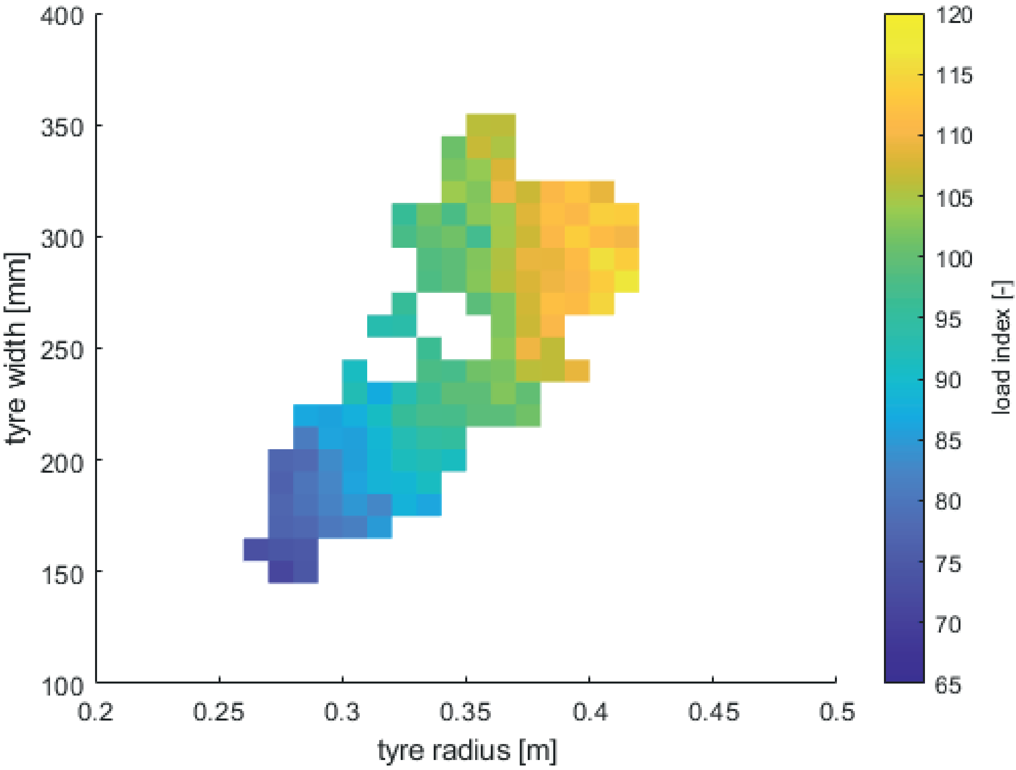


Figure 3-1: Tyre load index value in relation to tyre radius and tyre width for C1 tyres in the EPREL database.

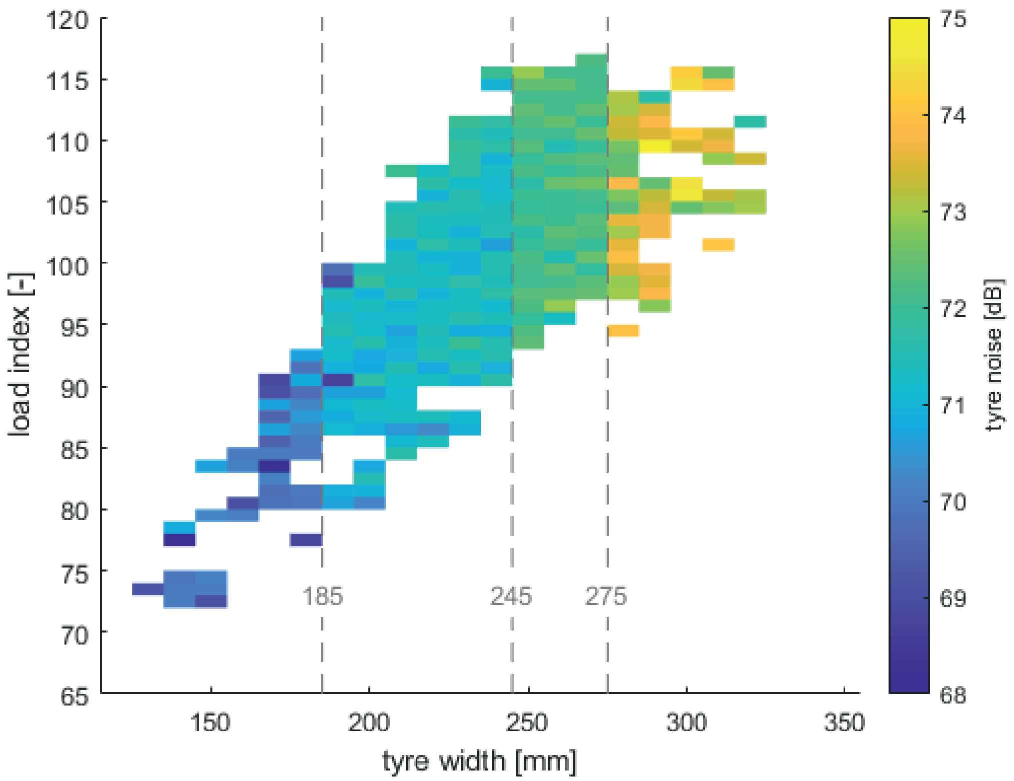


Figure 3-2: Tyre noise in relation to load index and tyre width for all C1 tyres in the EPREL database.

3.2 Top-30 tyre sales.

To analyse the available tyre labels and noise levels, as well as the impact of each specific tyre in practice, it is important to know how many tyres of a specific designation are actually on the road. For this, the market size of the top-30 tyre sales has been obtained from an overview provided by ETRMA. The sales amount will be used as a scaling factor in the remainder of this chapter.

The information of tyre sales has been provided by ETRMA for three categories, within the C1 and C2 tyre-classes (see Appendix C for an overview of all tyre-classes):

- Tyres for normal passenger vehicles,
- Tyres for SUV (Sports Utility Vehicle), and
- Tyres for Light Trucks (LTR (Vans up to 3.5t))

For each of the above, the Top-30 sales has been provided for Replacement tyres (that are typically available at tyre stores) and for Original Equipment (OE) tyres (mostly provided to car manufacturers for mounting on new vehicles).

Comparing the Top-30 Replacement tyres to top Top-30 OE tyres provides insights in the trend in tyre use on new vehicles. Additionally, vehicle manufacturers may equip new vehicles with tyres with A-labels for noise or wet-grip. However, vehicle owners may replace them later with differently labelled tyres. Analysis of differences in tyre labels between OE and Replacement tyres may reveal a trend.

The market shares represented by the Top-30 sales for the different categories varies as indicated in Table 3.1.

Table 3.1: Market share of Top-30 tyre sales for OE and replacement tyres for different vehicle categories.

Vehicle category	Abbreviation	Market share of Top-30		Total market share	
		Replacement tyres	OE tyres	Replacement tyres	OE tyres
Passenger vehicles	CAR	46%	47%	80%	72%
Sports Utility Vehicle	SUV	40%	61%	12%	17%
Light trucks	LTR	87%	96%	8%	11%

The tyre designations in the Top-30 have been anonymized, however the width of the tyres is indicated using subclasses of C1 (see Table 3.4) as defined in EC Regulation No 661/2009 [13] since it defines the noise limits for tyre labels.

Table 3.2 shows the market share per tyre within the Top-30. Also, the total number of tyres for which the Top-30 has been determined is given. For the light truck OE category, it shows that only 64 different types of tyres are sold, which explains the high value for the total market share of the Top-30.

With the introduction of (full) electric vehicles, the vehicles became significantly heavier due to the added mass of a battery-pack. This weight increase translated into a need for bigger tyres with higher load indices. This will shift the market share from the passenger vehicle to the SUV. The results given in the previous section (see Figure 3-1 and Figure 3-2) indicate that this will result in more sales of tyres with a higher noise level.

Table 3.2: Market share of Top-30 tyres and total number of tyres in each category.

	Passenger vehicles		SUV (sport utility vehicle)		Light Trucks	
Position in TOP-30	Replacement	OE-tyre	Replacement	OE-tyre	Replacement	OE-tyre
1	5,43%	4,42%	3,18%	8,58%	8,96%	9,11%
2	4,38%	3,29%	2,79%	4,72%	7,81%	7,53%
3	3,16%	3,05%	2,32%	3,84%	7,34%	7,05%
4	3,05%	2,63%	2,31%	3,83%	7,24%	6,81%
5	2,50%	2,44%	1,91%	3,53%	6,17%	6,45%
6	2,28%	1,96%	1,78%	2,29%	4,96%	5,78%
7	1,98%	1,94%	1,78%	2,15%	4,02%	4,75%
8	1,86%	1,88%	1,62%	2,13%	3,66%	4,60%
9	1,81%	1,72%	1,49%	2,12%	2,89%	4,06%
10	1,77%	1,71%	1,45%	2,01%	2,84%	3,73%
11	1,77%	1,59%	1,41%	1,98%	2,75%	3,71%
12	1,53%	1,50%	1,37%	1,98%	2,63%	3,60%
13	1,24%	1,38%	1,35%	1,69%	2,51%	3,17%
14	1,17%	1,29%	1,21%	1,59%	2,44%	3,05%
15	1,13%	1,23%	1,17%	1,57%	2,02%	2,74%
16	0,98%	1,19%	1,12%	1,50%	1,84%	2,55%
17	0,97%	1,18%	1,10%	1,39%	1,73%	2,52%
18	0,86%	1,09%	1,05%	1,28%	1,72%	1,90%
19	0,80%	1,05%	0,99%	1,26%	1,70%	1,89%
20	0,80%	1,04%	0,99%	1,20%	1,48%	1,60%
21	0,74%	1,00%	0,99%	1,18%	1,47%	1,47%
22	0,70%	0,96%	0,88%	1,18%	1,34%	1,45%
23	0,70%	0,93%	0,83%	1,17%	1,09%	1,41%
24	0,70%	0,91%	0,81%	1,15%	1,07%	1,20%
25	0,69%	0,90%	0,80%	1,05%	1,00%	0,99%
26	0,69%	0,89%	0,79%	1,01%	0,97%	0,92%
27	0,69%	0,88%	0,79%	1,00%	0,83%	0,63%
28	0,64%	0,87%	0,76%	0,95%	0,80%	0,53%
29	0,64%	0,85%	0,74%	0,91%	0,72%	0,47%
30	0,64%	0,85%	0,73%	0,89%	0,68%	0,44%
Total market share	46,32%	46,61%	40,51%	61,13%	86,69%	96,11%
Total tyre number	1906	697	1467	371	254	64

3.3 Availability of low noise tyres

The availability of A-label noise tyres in the Top-30 combined with good performance (i.e. either A- or B-labels) on safety and energy is assessed from the EPREL database using the following label combinations:

- AAA (i.e. A-label for Noise, A-label for Energy Class and A-label for Wet Grip Class)
- ABA
- AAB
- ABB

The order of the letters in these combinations is as follows:

- Noise Class
- Energy Class
- Wet grip Class

The database search resulted in Table 3.4 in which the availability of low noise variants is indicated for each tyre in the Top-30, both for replacement tyres and OE tyres. The tyre width is indicated by class C1A-C1E according to EC-Regulation No 661/2009 [13], which indicates different noise limits per class.

The availability of a label combination is indicated for each tyre designation (green checkmark means that it is available, red cross means that it is not available), and in the bottom line the total number of available tyre designations with a specific label combination is listed .
Table 3.4 shows the occurrence of the tyre class (C1A, C1B or C1C) from Table 3.4.

Table 3.3: Overview of the availability of a specific label combination of the Top-30 tyre designations in the EPREL database.

Passenger vehicles (CAR)

Position in TOP-30	Replacement Class	AAA	AAB	ABA	ABB	OE-tyre Class	AAA	AAB	ABA	ABB
1	C1B	✓	✓	✓	✓	C1B	✗	✓	✗	✓
2	C1B	✗	✓	✓	✗	C1B	✓	✓	✓	✓
3	C1A	✗	✗	✗	✓	C1B	✓	✓	✗	✓
4	C1B	✗	✓	✓	✓	C1B	✗	✓	✗	✓
5	C1A	✗	✗	✗	✗	C1C	✓	✗	✓	✓
6	C1B	✗	✗	✗	✗	C1B	✗	✓	✗	✓
7	C1B	✓	✓	✓	✓	C1B	✓	✓	✓	✓
8	C1C	✓	✗	✓	✓	C1C	✓	✓	✗	✓
9	C1B	✓	✓	✗	✓	C1C	✓	✗	✗	✓
10	C1B	✓	✓	✓	✓	C1A	✗	✗	✗	✗
11	C1A	✗	✗	✗	✗	C1B	✓	✓	✓	✓
12	C1B	✓	✓	✓	✗	C1C	✓	✗	✓	✓
13	C1C	✓	✗	✓	✗	C1B	✗	✓	✓	✓
14	C1C	✗	✗	✓	✗	C1C	✗	✗	✗	✗
15	C1B	✓	✓	✓	✓	C1B	✓	✓	✓	✗
16	C1A	✗	✓	✗	✓	C1C	✓	✓	✓	✓
17	C1A	✗	✗	✗	✓	C1B	✓	✓	✗	✓
18	C1A	✗	✗	✗	✗	C1B	✓	✗	✓	✓
19	C1B	✗	✗	✗	✗	C1B	✓	✓	✓	✓
20	C1B	✗	✗	✓	✗	C1B	✗	✓	✓	✓
21	C1B	✗	✗	✓	✓	C1C	✗	✗	✓	✓
22	C1B	✗	✗	✗	✗	C1B	✓	✓	✓	✓
23	C1B	✗	✓	✓	✓	C1C	✓	✓	✓	✗
24	C1B	✓	✓	✓	✓	C1B	✓	✗	✓	✓
25	C1A	✗	✗	✗	✓	C1B	✓	✓	✓	✓
26	C1C	✓	✓	✓	✗	C1C	✗	✓	✗	✗
27	C1B	✗	✓	✗	✓	C1B	✓	✓	✓	✓
28	C1C	✓	✓	✓	✗	C1B	✗	✓	✓	✗
29	C1C	✗	✓	✓	✓	C1C	✗	✗	✓	✓
30	C1B	✗	✓	✓	✓	C1B	✓	✓	✗	✓
Total		11	16	18	17		19	21	19	24

Sport Utility Vehicles (SUV)

Position in TOP-30	Replacement Class	AAA	AAB	ABA	ABB	OE-tyre Class	AAA	AAB	ABA	ABB
1	C1B	✗	✓	✓	✓	C1B	✗	✓	✗	✓
2	C1B	✗	✓	✗	✓	C1D	✗	✓	✗	✗
3	C1C	✗	✗	✓	✓	C1B	✗	✓	✓	✓
4	C1B	✓	✓	✓	✓	C1C	✓	✗	✓	✓
5	C1B	✓	✗	✓	✓	C1C	✓	✓	✓	✓
6	C1C	✓	✓	✓	✓	C1B	✗	✗	✗	✓
7	C1C	✓	✗	✗	✓	C1D	✗	✗	✗	✗
8	C1C	✓	✗	✓	✓	C1E	✗	✓	✗	✓
9	C1C	✗	✗	✓	✓	C1C	✗	✗	✗	✗
10	C1B	✗	✗	✗	✓	C1B	✓	✗	✓	✓
11	C1C	✗	✗	✗	✗	C1C	✗	✗	✓	✓
12	C1C	✓	✓	✓	✓	C1E	✗	✗	✗	✗
13	C1C	✗	✗	✓	✓	C1D	✓	✓	✗	✗
14	C1C	✓	✓	✗	✓	C1D	✓	✗	✓	✗
15	C1C	✗	✗	✗	✗	C1C	✗	✗	✓	✓
16	C1C	✗	✗	✓	✓	C1D	✗	✓	✓	✗
17	C1B	✓	✓	✓	✓	C1B	✗	✗	✗	✓
18	C1B	✗	✗	✗	✗	C1C	✗	✗	✗	✗
19	C1C	✗	✗	✓	✓	C1D	✗	✗	✗	✗
20	C1C	✗	✗	✓	✓	C1D	✗	✓	✗	✗
21	C1C	✗	✗	✗	✓	C1C	✗	✗	✗	✓
22	C1B	✗	✗	✓	✓	C1D	✗	✗	✗	✗
23	C1C	✗	✗	✓	✓	C1D	✓	✓	✓	✓
24	C1C	✗	✗	✗	✗	C1B	✗	✗	✗	✗
25	C1B	✗	✗	✗	✓	C1D	✓	✓	✓	✗
26	C1C	✓	✓	✓	✓	C1C	✓	✓	✗	✓
27	C1C	✗	✗	✓	✓	C1D	✓	✓	✓	✓
28	C1C	✗	✗	✗	✗	C1C	✗	✗	✗	✗
29	C1C	✗	✗	✗	✓	C1D	✗	✓	✗	✗
30	C1B	✗	✗	✗	✗	C1E	✓	✓	✓	✓
Total		9	8	17	24		10	14	12	15

Light Trucks (LTR)

Position in TOP-30	Replacement Class	AAA	AAB	ABA	ABB	OE-tyre Class	AAA	AAB	ABA	ABB
1	C1B	✗	✗	✓	✗	C1C	✗	✗	✓	✓
2	C1C	✓	✗	✓	✗	C1B	✗	✗	✓	✗
3	C1C	✓	✗	✓	✗	C1B	✓	✗	✓	✓
4	C1B	✓	✗	✓	✓	C1B	✗	✗	✓	✗
5	C1B	✗	✗	✗	✗	C1C	✓	✗	✓	✗
6	C1B	✗	✓	✓	✓	C1B	✗	✓	✓	✓
7	C1B	✗	✗	✗	✗	C1C	✗	✗	✓	✓
8	C1B	✗	✗	✗	✗	C1C	✗	✗	✗	✗
9	C1B	✗	✗	✓	✗	C1B	✗	✗	✗	✗
10	C1B	✗	✗	✗	✗	C1B	✗	✗	✓	✗
11	C1C	✗	✗	✓	✗	C1C	✗	✗	✓	✓
12	C1C	✗	✗	✓	✓	C1C	✗	✗	✓	✗
13	C1B	✗	✗	✓	✗	C1B	✗	✗	✗	✗
14	C1B	✓	✗	✓	✗	C1B	✗	✗	✗	✗
15	C1B	✗	✗	✓	✗	C1B	✓	✗	✓	✓
16	C1B	✗	✗	✓	✓	C1C	✓	✗	✓	✗
17	C1C	✗	✗	✗	✗	C1B	✓	✗	✓	✗
18	C1B	✓	✗	✓	✓	C1C	✗	✗	✗	✗
19	C1B	✗	✗	✓	✗	C1B	✗	✗	✓	✓
20	C1B	✗	✗	✓	✗	C1B	✗	✗	✓	✗
21	C1B	✗	✗	✓	✓	C1C	✗	✗	✗	✗
22	C1C	✗	✗	✓	✓	C1C	✗	✗	✗	✗
23	C1C	✗	✗	✓	✗	C1C	✗	✗	✗	✗
24	C1B	✗	✗	✓	✗	C1B	✗	✗	✓	✗
25	C1B	✗	✗	✓	✗	C1C	✗	✗	✗	✗
26	C1C	✗	✗	✓	✓	C1B	✗	✗	✗	✗
27	C1C	✗	✗	✗	✗	C1C	✗	✗	✓	✓
28	C1C	✗	✗	✗	✗	C1C	✗	✗	✗	✗
29	C1B	✗	✗	✗	✗	C1B	✗	✗	✗	✗
30	C1A	✗	✗	✓	✗	C1B	✗	✗	✗	✗
Total		5	1	22	8		5	1	17	8

Table 3.4: Occurrence of tyre width class in Top-30 tyre overview.

Tyre width [mm]	Noise limit [dB(A)]	Car tyres		SUV tyres		Light Truck tyres	
		Replacement	OE	Replacement	OE	Replacement	OE
C1A:<185	70	7	1			1	
C1B:195-215	71	17	19	10	6	19	16
C1C:225-245	71	6	10	20	9	10	14
C1D:255-275	72				12		
C1E:285>	74				3		
Total		30	30	30	30	30	30

The availability of low noise variants of the Top-30 tyres (with A-or B-label for Wet Grip and Rolling Resistance) is summarized in Table 3.1 The table provides an overview of the number of tyre designations in the Top-30 which have an A-rating for noise and A-and/or B-ratings for Energy Class and Wet-Grip Class respectively. Tyre designations that do not have an A-label for noise and/or have a C-label (or lower) for Energy Class and/or Wet-Grip Class, are listed under ‘other label’ in the table (four red crosses in Table 3.1). Furthermore, it is indicated in the table how many tyre designations in the Top-30 have a triple-A label.

As can be seen, the number of low noise tyres in the OE category for SUV and LTR is lower, compared to the replacement tyres. The number of low noise tyres in the passenger car category of OE tyres is higher.
It appears that for CAR tyres relatively more triple-A tyres are available than for tyres in the SUV and Light Truck category.

Table 3.5: Availability of low noise tyre designations, in the top-30 sales, with A-or B-label for Wet Grip or Rolling Resistance

Category	Replacement tyres			OE tyres		
Label	AAA,AAB,ABA,ABB	Other labels	Total	AAA,AAB,ABA,ABB	Other labels	Total
Car	24 (of which 11 AAA)	6	30	28 (of which 19 AAA)	2	30
SUV	24 (of which 9 AAA)	6	30	22 (of which 10 AAA)	8	30
LTR	22 (of which 5 AAA)	8	30	17 (of which 5 AAA)	13	30

3.4 Tyre noise level analysis

This section will provide an insight in the noise levels of tyres that are sold using the sales numbers of the top-30 tyres. This is done for the CAR, SUV and LTR categories, and for replacement and OE tyres respectively.

For each tyre designation in the top-30, a query is performed in the EPREL database. This will result in a number of entries with the exact same tyre designation (e.g. rim size, tyre section, tyre width, load index, velocity index, etc…), but with different labels, manufacturer, production dates, etc. There is no data available that further specifies the number of sales for each tyre designation in the top-30 (e.g. it is not known how many tyres with the same tyre designation are being sold by manufacturers A, B, C, etc…). Therefore, in the analysis the assumption is made that each query result has an equal share in the total sales number for the top-30 entry.

Given this assumption, in Figure 3-3 the combination of all of the top-30 tyres and their occurrences in the EPREL database, scaled with their sales numbers is represented in histograms. Note that the vertical scale is different in the histograms, due to the fact that absolute sales numbers for CAR tyres are significantly higher than for SUVs and Light Trucks.

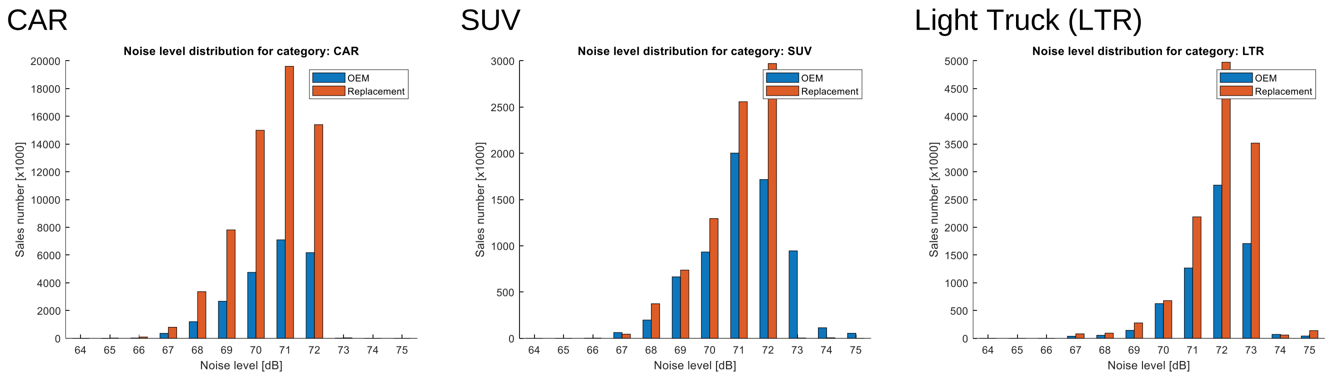


Figure 3-3: Tyre noise level distribution for CAR, SUV and LTR tyres (Orange = Replacement, Blue = OE).

It can be seen that relatively more Top-30 OE tyres with higher noise level are sold compared to the sold Top-30 Replacement tyres. This is most visible for SUV tyres as only in the OE category tyres are found with noise levels exceeding 72 dB(A). Note that the market share of SUV tyres in the OE category is larger than for Replacement tyres (see Table 3.1), indicating that the share of SUV tyres will increase. A larger share of SUV tyres, and a shift of SUV tyres to higher noise levels will result in higher noise levels from tyres in traffic. Table 3.1 indicates that the share of SUV tyres will increase. A larger share of SUV tyres, and a shift of SUV tyres to higher noise levels will result in higher noise levels from tyres in traffic.

In conclusion, the noise levels from the histograms in Table 3.3 are combined in Table 3.4 which can be used for upscaling towards EU level.

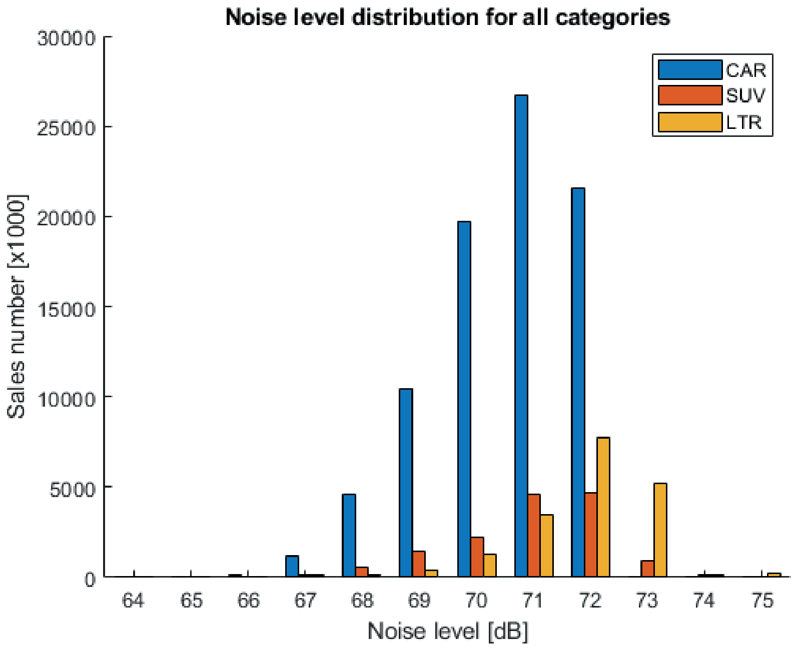


Figure 3-4: Noise level distribution for all categories.

3.5 Conclusions current tyre noise levels

The Top-30 tyres for Replacement and Original Equipment (OE) have been analysed for label availability using the EPREL database. This has been done for categories Car, SUV and Light Truck which all concern C1 tyres. OE tyres are for new(er) vehicles.

Most of the Top-30 tyre designations are available in AAA, ABA, AAB and ABB labels, however for SUVs and Light Trucks that share is less in the OE categories. SUVs and Light Trucks are heavier vehicles (and may get heavier due to electrification), which seems to indicate that it is more challenging to achieve good labelling performance for tyres with a higher load capacity.

When looking at the sales numbers it can be seen that the distribution of noise levels for CAR tyres is almost equal between OE and replacement tyres, in contrast to the SUV tyres.

For SUV tyres, a relatively larger amount of the OE tyres distribution has higher noise levels, compared to the distribution of the replacement tyres. On the other hand the market share of the higher noise tyres (71-72 dB) for SUV replacements is significantly larger than that of the OE tyres. The share of replacement tyres is less compared to the OE tyres, which is probably due to the fact that a lot of young SUV vehicles did not require a tyre change yet.

With the trend of vehicle’s getting heavier (due to the weight of their batteries) and the foreseen sales increase in SUV replacement tyres, the market share of higher noise tyres is likely to increase, most likely at the cost of the CAR tyres share. From Figure 3-4 it may then be concluded that the amount of higher noise tyres will increase.

Although there is a noise label A tyre for the majority of tyre designations in the Top-30, there is no information about their market share.

4. Modelling the EU scenario

4.1 Impact on tyre safety

4.1.1 Methodology

This section describes an approach to assess traffic fatalities at EU level for specific accident scenarios related to tyre performance for grip and aquaplaning.

The safety assessment approach makes use of information from two accident databases, GIDAS and CARE. This paragraph provides brief descriptions of these databases and their limitations, as well as a listing of the resulting assumptions that were made for the analysis.

GIDAS database

The GIDAS database contains information of accidents occurring in Germany with at least personal injury. The accident information is gathered with great detail by a team of experts attending the scene as soon as possible after occurrence of an accident, with the aim of reconstruction of the accident and to assess the prime causes. This provides information about e.g. the road and tyre condition, the way the driver has acted, and collision impact speed. Access to information from the database is via VUFO, and further information can be found on https://www.gidas.org/start-en.html.

In the current study, information from the GIDAS database is used to determine the distribution of collision impact speeds in accidents . Furthermore, based on GIDAS it was established that maximum braking was applied in about 17% of the collision accidents.

In the current analysis it is assumed that:

The GIDAS database contains information of the collision impact speed occurring in collisions with personal injury or fatality for accidents in Germany. It is assumed that the distribution of collision impact speed and level of brake application is similar on EU level.

CARE database

The CARE database contains information of accidents occurring in EU member states, see https://road-safety.transport.ec.europa.eu/european-road-safety-observatory/statistics-and-analysis-archive/about-care_en. The accident information is based on police reports, and it is categorized for specific scenarios. Information of the type of road users and road (weather) condition is available, but no details (such as tyre use) to allow reconstruction of the accident. The database can be accessed via national contact points, or requests can be made to the European Commission to extract information.

In the current study, the CARE database is used to obtain fatality numbers for a selection of accident scenarios for which tyre performance on grip is relevant. This is a subset of all scenarios where grip affects accident occurrence and severity. For instance, accident scenarios on curved roads are excluded, since insufficient information is available to calculate the effect of grip in these conditions. Also information on the level of braking applied prior to collision is not available.

For the analysis, it is assumed that:

The grip limit is utilized in 17% of the collision accidents (from GIDAS results (see above)).

Furthermore, the CARE database specifies road speed categories, but the exact vehicle speed prior to collision is not known. For the analysis, it is assumed that vehicles are driving at the maximum speed of the category.

The safety assessment analysis addresses a specific set of accident scenarios, i.e. scenarios that are relevant for the considered tyre performance metrics grip and aquaplaning.

1. Grip is considered most relevant in scenarios with collisions in which the car was braking and the grip level will affect the collision impact speed, either on dry or wet road.
2. Aquaplaning can lead to vehicle instability at high speed.

To extract the relevant scenarios in the CARE database, the selection in Figure 4-1 was made.

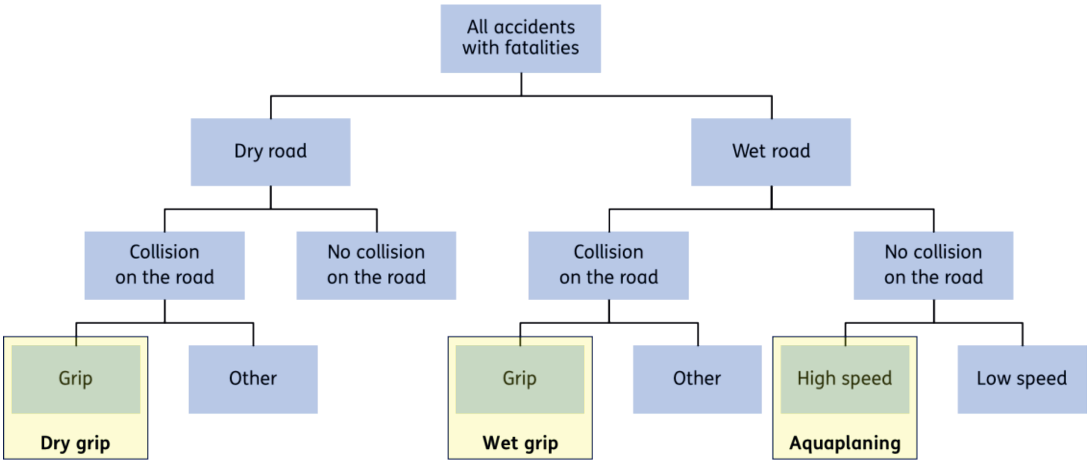


Figure 4-1 Selection of accident scenarios (yellow boxes) considered relevant for tyre performance metrics grip and aquaplaning.

The approach, depicted in Figure 4-2, is based on the notion that these tyre safety performance metrics may impact the occurrence and/or severity of specific accident scenarios, which in turn may impact the number of fatalities. For example, dry grip performance is relevant for braking accidents on dry road, and a change in dry grip performance may impact the severity of these accidents and result in a change of fatalities. The same holds for wet grip performance and aquaplaning performance on wet roads respectively.

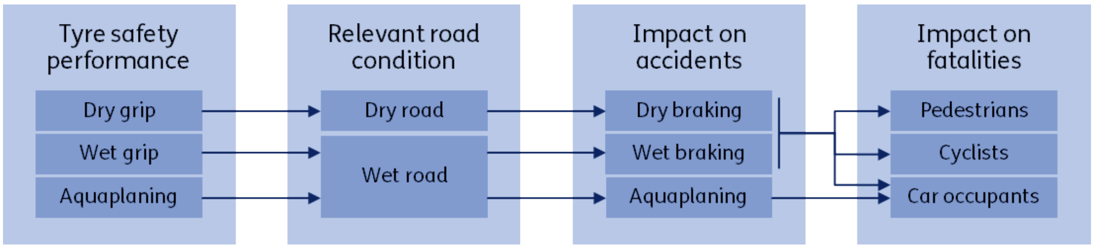
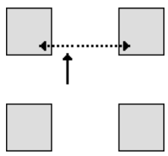
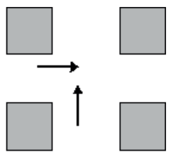
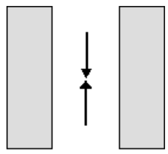
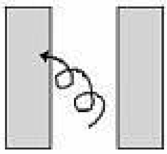


Figure 4-2 Tyre safety impact assessment.

Table 4.1 gives an overview of the selection criteria used to extract the relevant fatality statistics on EU level for the figures above.

Table 4.1 Accident scenarios extracted from the CARE database for performed safety assessment. VRU: Vulnerable Road User including pedestrians and cyclists. (source: CARE database)

Grip (wet and dry) selection			Aquaplaning selection
VRU	Side collision	Head-on collision	
			
- Car straight driving - VRU crossing the road - VRU walking or standing on the road	- Car straight driving - Collision with cars crossing at an intersection - Collision with cars that are turning	- Car straight driving - Collision with other cars - Collisions with obstacles	- Car straight driving - Wet road only - Speed limit > 80 km/h
Relevant collision speed > 30 km/h	Relevant collision speed >50 km/h	Relevant collision speed >70 km/h	No collision on the road

Approach to assess traffic fatalities

Figure 4-3 shows a high-level illustration of the approach to assess traffic fatalities in collision accidents that are impacted by tyre grip performance.
In brief, the approach is based on the reasoning that a change in tyre grip will result in a change in speed reduction during emergency braking, which will result in a change in collision impact speed. The latter will impact the severity of accidents and hereby the probability of fatality, which will impact the total number of expected fatalities. The various steps of the approach are explained in more detail in the next paragraphs.

Figure 4-3: High-level illustration of the approach to assess traffic fatalities in collision. accidents that are impacted by tyre grip performance.

The risk of a fatality in a collision is displayed for Figure 4-4. According to Jurewicz et al. [14] the probability of fatality increases significantly with collision speed for all different accident scenarios.

For the analyses, a value of 10% probability of fatality is used.

This results in a corresponding collision speed of 30 km/h for pedestrian/cyclist collisions, 50 km/h for side impact collisions and 70 km/h for head-on collisions.

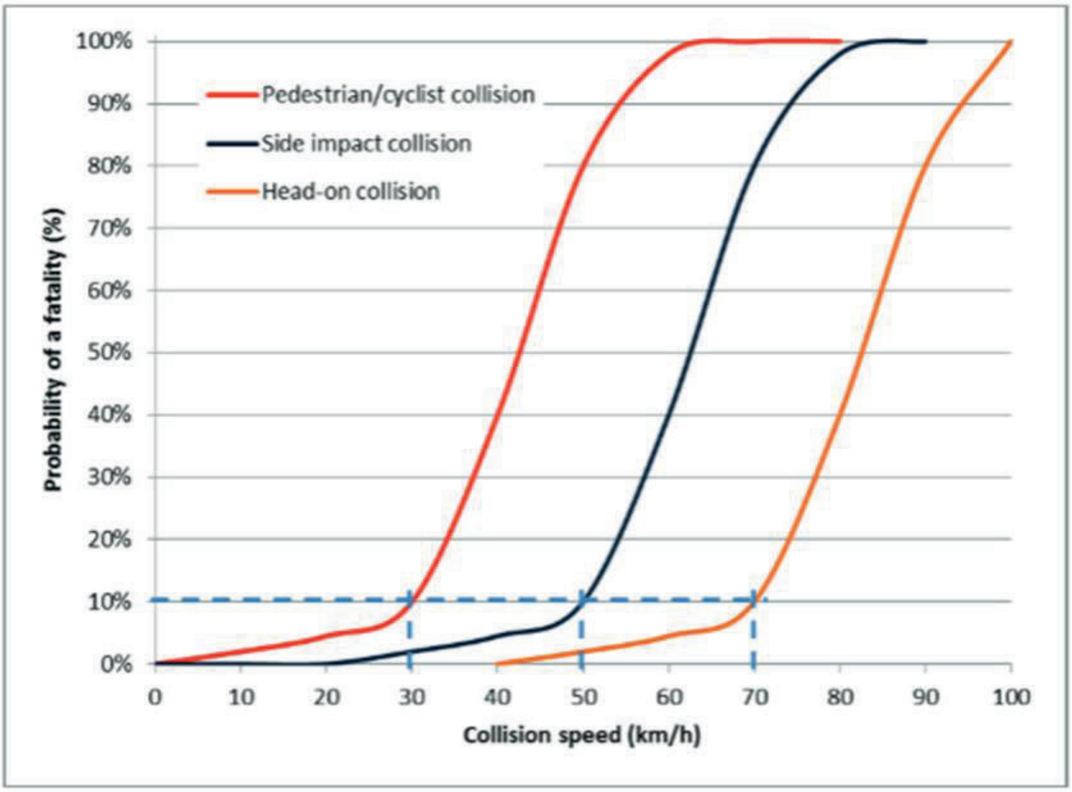


Figure 4-4: Collision speed and probability of fatality for VRUs and car occupants. (Source: Jurewicz et al. [14]; Published by Elsevier as an open access article free to use under license CC BY-NC-ND 4.0).

Figure 4-5 shows a distribution of impact speed in collision accidents. This distribution is obtained from accidents in the GIDAS database, which concerns scenarios where the amount of braking has been decisive for accident severity. It should be noted this concerns accidents with personal injury including all categories of light, severe or fatal.

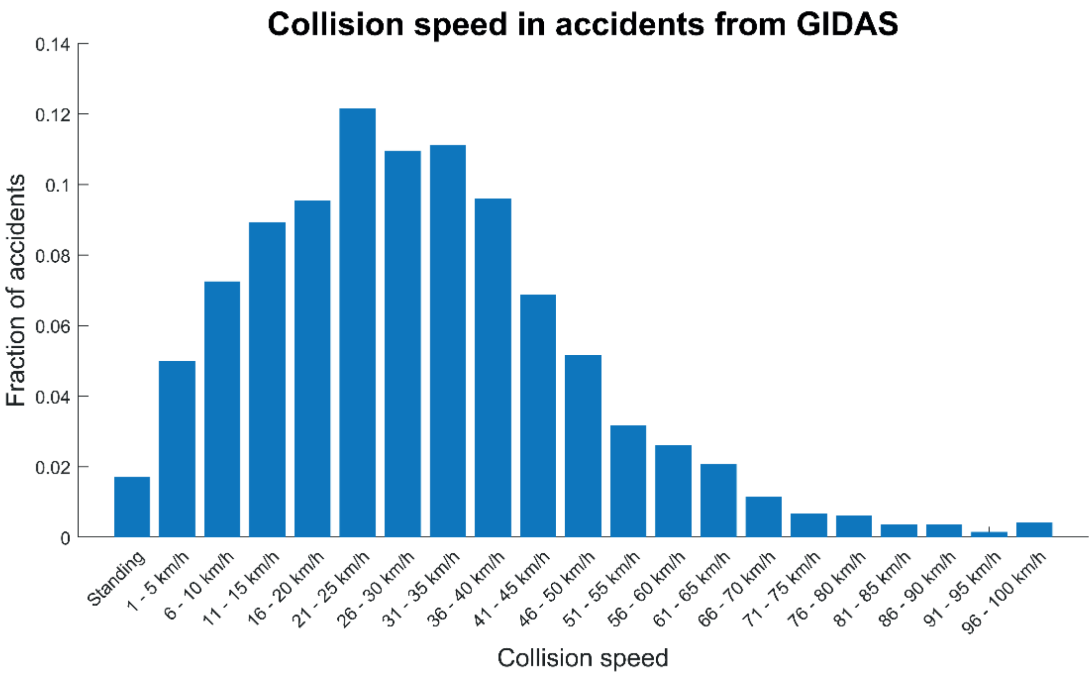


Figure 4-5: Collision speed distribution from GIDAS database.

The maximum braking of a vehicle to reduce speed prior to a collision is defined by the tyre grip. Consequently, this means that a change of tyre grip affects the collision speed. A better grip performance allows a vehicle to slow down more prior to a collision, which will reduce the collision speed. For this reason it can be assumed that better grip will reduce the population of accidents above a certain collision speed threshold (e.g. 30 km/h for Vulnerable road users). As a result, the number of fatalities will reduce. This mechanism is depicted in Figure 4-6.

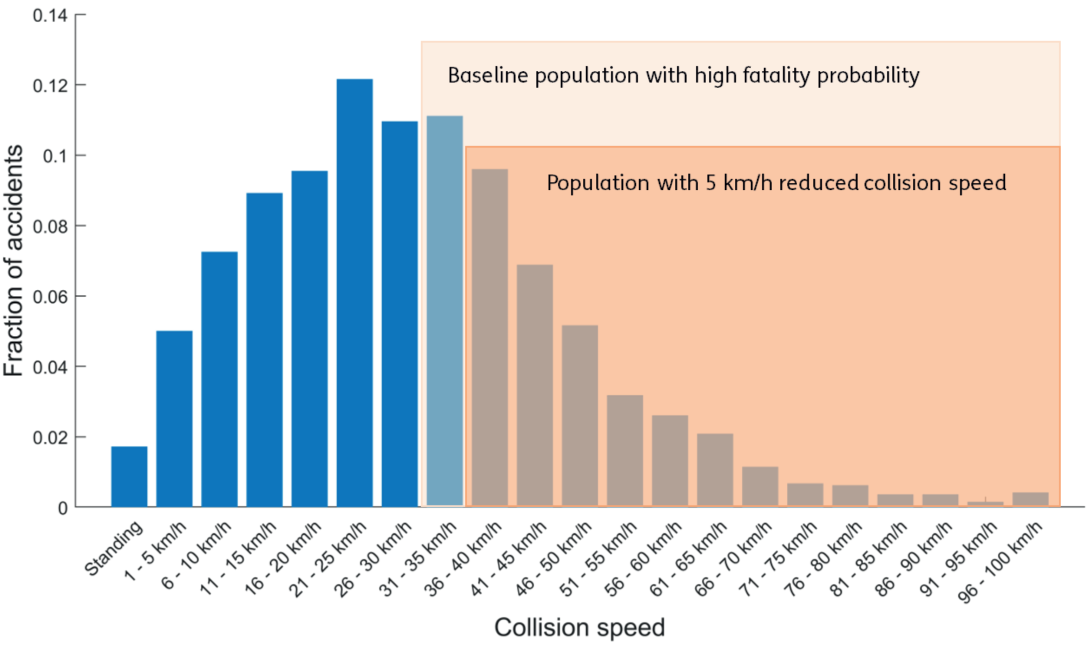


Figure 4-6: Population reduction for improved grip taking the critical impact speed of 30 km/h for vulnerable road users as example.

The sensitivity of speed reduction with a change of tyre grip is depending on the difference between the initial speed of the striking vehicle and the collision speed. As an example Figure 4-7 shows the sensitivity around 30 km/h impact speed (relevant speed for VRU collisions), calculated using basic equations of motion.

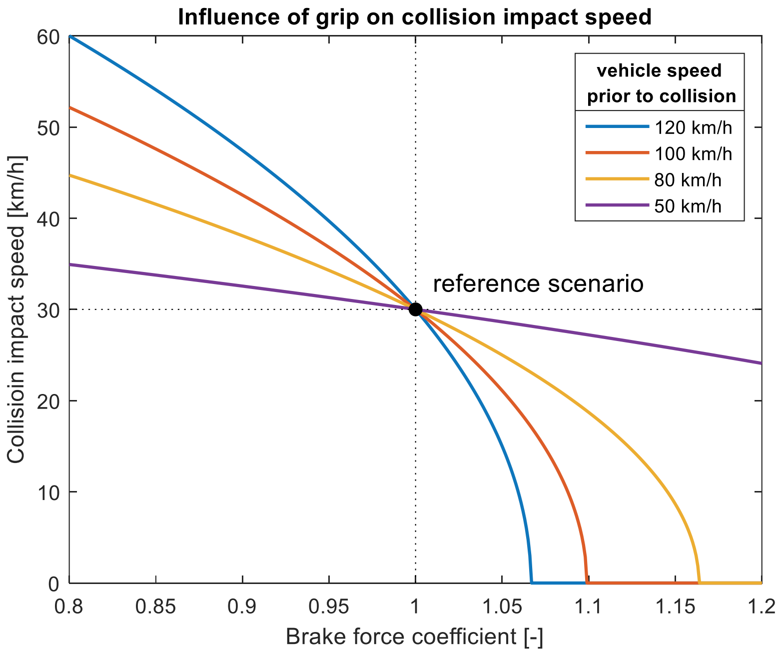


Figure 4-7: Influence of tyre grip on the collision impact speed for different initial vehicle speeds prior to the

collision. The reference scenario concerns a brake force coefficient of 1.0 and an impact speed of 30 km/h, which is relevant for VRU collisions.

A reduction of impact speed can be seen as an increase of tyre grip, which is indicated for an initial speed of the striking vehicle of 50, 80, 100 and 120 km/h respectively. In this example a 10% increase of tyre grip (brake force coefficient from 1.0 to 1.1) is sufficient to avoid a collision when the initial speed of the striking vehicle is 100 km/h or higher (i.e. impact speed zero). The change in sensitivities for different initial speed can be understood by considering that the brake distance before impact is affected by the initial speed. Consequently, the braking distances of the reference situations (impact speed 30 km/h and brake force coefficient of 1.0) are different for different speeds. At high speed the braking distance is longer and therefore also more sensitive to a grip change.

To account for the relevance of the initial speed of the striking vehicle, the accident data is analysed for roads with different speed limits as listed in Table 4.2. The CARE database specifies road speed categories. However, the exact vehicle speed prior to the accident is not known.
In the current study it is assumed that:

Vehicles are driving at the maximum speed of the corresponding speed category.

Table 4.2: Speed selection for accident analyses CARE database

Road legal speed category [km/h]	Assumed vehicle speed [km/h]	VRU accidents	Side collision accidents	Head-on collision accidents	Aquaplaning accidents
101 – 120	120	X	X	X	X
81 – 100	100	X	X	X	X
51 – 80	80	X	X	X	X
31 – 50	50	X			

Traffic fatalities estimation method

Figure 4-8 shows an overview of the approach to assess the impact on traffic fatalities for a specific tyre compared to a reference tyre. Obtaining an overall estimate for the number of fatalities involves the summation of fatality numbers for all accident categories (see the table at the top in Figure 4-8). For each accident category the following steps are performed to calculate the associated number of fatalities (see the bottom part of Figure 4-8):

- Each accident category is defined by four parameters (orange boxes): road condition (wet/dry), vehicle speed prior to braking (50, 80, 100, or 120 km/h), collision type (VRU collision, side collision, head-on collision) and associated critical impact speed (30, 50, or 70 km/h).
- First, information on tyre grip for the selected road condition is acquired for the set of tyres of interest (green boxes). For example, data on tyre deceleration levels for dry and wet road conditions can be obtained from consumer tyre tests (section 4.1.2), or a study performed by UTAC (section 4.1.3). A reference tyre is selected and the corresponding grip level is used in the next step.
- Based on the grip level of the reference tyre, and the vehicle speed and collision impact speed of the examined accident category (orange boxes), the braking distance till collision is calculated (first blue box).

- Based on the previously calculated braking distance and the grip level of the tyre under test, the impact speed at collision for the tyre under test is calculated (second blue box).
- Based on the calculated impact speed for the tyre under test, the fraction of accidents with an impact speed above the critical impact speed (speed at which the probability of fatality increases substantially) is calculated (third blue box). The distribution of impact speeds based on the GIDAS database is used for this purpose (see also Figure 4-8).
- Based on the calculated fraction of accidents with an impact speed above the critical impact speed, and the fatality occurrence number of the examined accident category (which is associated to the reference tyre), the expected number of fatalities for the tyre under test is calculated (fourth blue box). The fatality occurrence number is obtained from the CARE database and multiplied by 17% to obtain an estimate for the subset of cases where maximal braking is applied.

Above steps provide an estimate for the number of fatalities in collision-based accidents impacted by grip.

In a final step, the number of fatalities due to aquaplaning accidents is estimated assuming an inverse proportional relationship between aquaplaning speed and probability of fatality, i.e. an increase in speed at which aquaplaning occurs (compared to a reference tyre) results in a proportional decrease in fatalities (compared to a reference tyre).

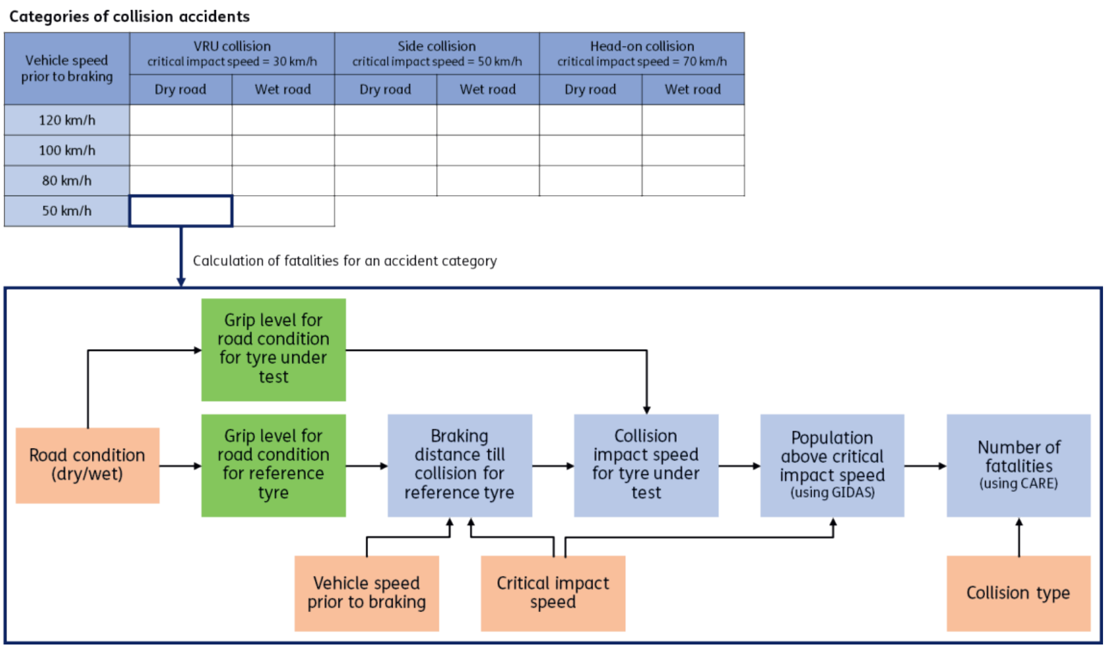


Figure 4-8: Overview of the approach to assess traffic fatalities based on tyre grip performance.

4.1.2 Upscaling results from consumer tyre testing

The method described in section 4.1.1 was applied on the consumer tyre testing data listed in Table 2.1 to assess the impact of tyre performance for grip and aquaplaning on traffic fatalities at EU level. The number of fatalities is estimated for each tyre, taking the quietest tyre of corresponding test set as reference. A summary of the results based on aggregation of all consumer test data is presented in Figure 4-9. This graph displays the estimated total number of fatalities in relation to corresponding tyre noise levels, where each blue dot represents the result of a single tyre. A linear regression analysis was performed to assess whether a relationship exists. The black line shows the linear regression fit, surrounded by dark- and light-blue regions that respectively represent corresponding 95% confidence interval and prediction interval. A considerable variation in fatality estimations can be observed. From this analysis it can be concluded that no statistically significant relation between tyre noise and estimated fatalities can be identified from the consumer testing data (p-value of 0.720 for the slope parameter).

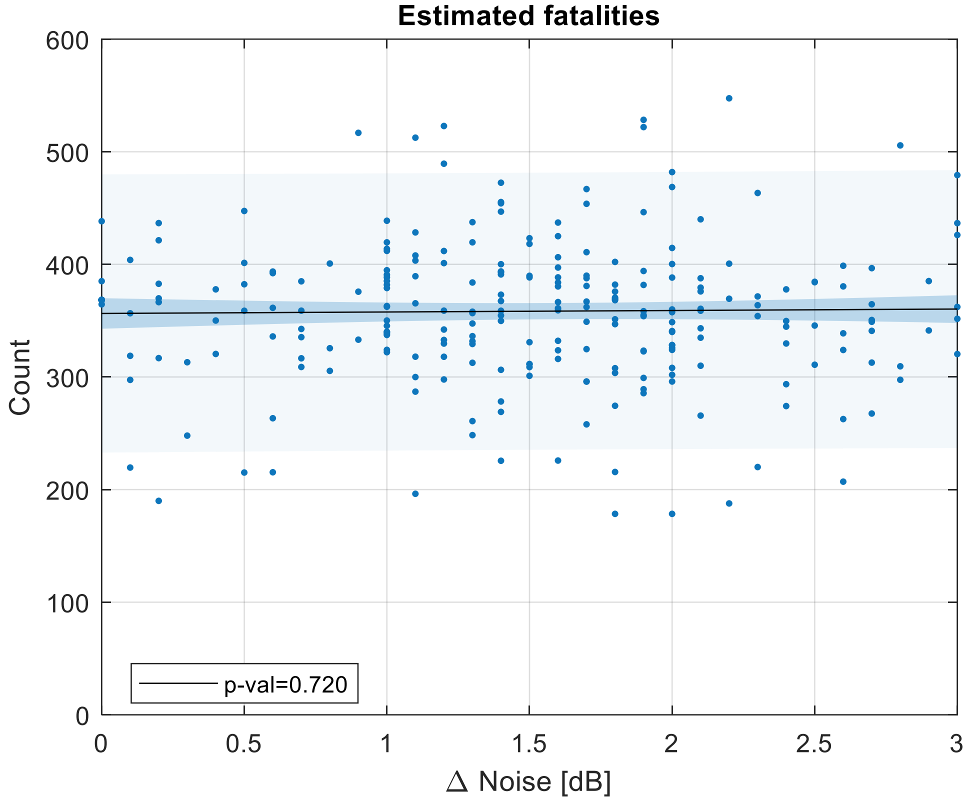


Figure 4-9: Estimated fatalities in relation to tyre noise based on aggregated consumer tyre test data. Each blue dot represents a tyre. The black line represents the linear regression fit, and the dark- and light-blue regions respectively represent corresponding 95% confidence and prediction intervals. The slope parameter is not significant (p-value of 0.720).

4.1.3 Upscaling results from scientific tyre testing

The results from analyses of consumer test data show a very large range of potential impact on traffic safety of tyre performance without a statistically significant trend in relation to tyre noise. The same methodology, as described in Section 4.1.1, was applied on a dataset from the ACEA Tyre Performance Study executed by UTAC [1]. This study was specifically designed to investigate relations between rolling noise and tyre performance characteristics using standardized measurement protocols. This section presents the results.

4.1.3.1 Dataset description

The dataset of the ACEA Tyre Performance Study [1] is obtained from a presentation by UTAC that was held in the UNECE Working Party on Noise and Tyres. Figure 4-10 provides a screen view of the dataset including relevant measurements for the analysis on dry grip, wet grip, aquaplaning, and rolling sound. The study has tested 16 tyres (letters A to P) of dimension 205/55 R16 with a load index of 91 and speed index of H, T, V, or W. Among the tyres are 2 snow tyres (J and M) which were excluded from the analysis.

	Rolling sound				Wet grip	Dry grip	Aquaplaning
Tyre	R117 50 km/h	R117 80 km/h	R51C 80 km/h T° corr	R51C 50 km/h T° corr	m/s^2	m/s^2	km/h
A	64.8	70.7	72.4	65.5	10.0	10.0	83.5
B	64.9	70.3	72.2	65.7	9.4	9.7	88.0
C	65.0	70.8	72.8	66.1	9.8	10.1	86.7
D	65.1	71.1	73.0	66.4	10.0	10.0	86.3
E	65.8	72.4	73.8	66.8	10.0	10.2	84.0
F	64.7	70.3	72.5	65.4	9.1	10.4	87.2
G	63.6	69.6	71.7	64.9	9.1	9.7	80.6
H	63.2	68.5	71.1	64.6	8.0	9.5	75.0
I	62.9	68.4	70.4	64.3	10.7	10.1	79.2
~~J~~	~~63.0~~	~~70.1~~	~~71.8~~	~~63.8~~	~~7.0~~	~~8.0~~	~~75.7~~
K	65.1	71.0	73.0	66.6	9.9	10.3	84.5
L	63.9	69.7	71.5	65.0	9.6	10.0	79.2
~~M~~	~~66.0~~	~~70.6~~	~~72.6~~	~~66.8~~	~~10.7~~	~~8.9~~	~~89.8~~
N	65.1	70.9	72.5	66.0	10.0	9.8	86.4
O	63.6	69.2	71.2	64.7	8.5	9.4	74.9
P	63.9	69.7	71.4	64.9	11.0	10.5	81.7

Figure 4-10: Screen view of data from UTAC study.(Source: UTAC CERAM; reprinted with permission of UTAC CERAM)

The overview of the relevant test procedures for the analysis is given below (as presented by UTAC).

Rolling Sound

- 8 passes at 50 and 80 km/h according to UN Regulation No.117 procedure
- Cruising at 50 and 80 km/h according to UN Regulation No. R51

Wet Grip

- UN Regulation No.117 procedure
- Test Speed: 65 km/h
- Water depth: 0.9 mm
- Track texture depth: 1.0 mm
- Load: 461 kg

Dry Grip

- UN Regulation No. R13H procedure Type 0
- Test speed: 100 km/h

Aquaplaning

- VDA E08 Longitudinal Aquaplaning

4.1.3.2 Results

Similar as for the consumer testing data, the analysis method as described in Section 4.1.1, was applied on the UTAC dataset to assess the impact of tyre performance for grip and aquaplaning on traffic fatalities at EU level. For this purpose, tyre ‘P’ was used as reference, which is in accordance with the analysis performed by UTAC.

The estimated number of fatalities were analysed in relation to the different tyre noise measurements, which were obtained via above described procedures based on UN Regulations R117 [5] and R51C [15].

Figure 4-11 shows an overview of the results, where each letter indicates the result of the corresponding tyre. These graphs show that the results obtained for the four different noise measurement procedures are very similar. The ranking of tyres according noise level only slightly depends on the selected procedure (e.g., tyre I is always the quietest tyre, tyre E is always the loudest tyre). Hence, the current analysis does not critically depend on the selection of the noise measurement procedure.

A linear regression analysis was performed to investigate whether a relationship between tyre noise and estimated fatalities exists. The black lines in Figure 4-11 show the 'linear regression fits', and the blue areas represent associated '95% confidence intervals'. The regression slope parameters are negative in all cases indicating a downward trend might exist. However, statistical significance is not reached. The p-values range from 0.219 to 0.359 as indicated in the graphs, which is considerable lower compared to the consumer test data (p-value of 0.720), but nevertheless substantially distant from being statistically significant (typically a p-value < 0.05).

Therefore it is concluded that no statistically significant relation between tyre noise and estimated fatalities can be identified based on this data.

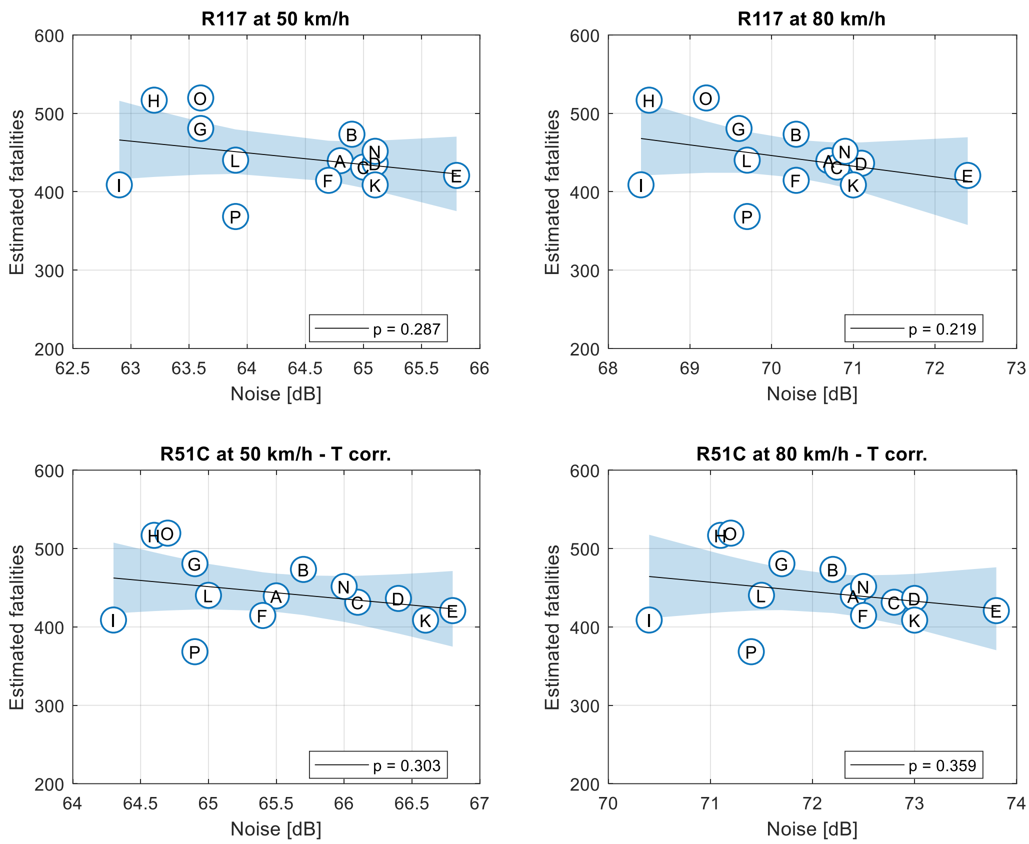


Figure 4-11: Estimated fatalities in relation to tyre noise (for 4 different noise measurement procedures as indicated by the titles). Each letter indicates the result of corresponding tyre. The black lines show the linear regression fits with associated 95% confidence intervals in blue. The slope parameters are not significant as indicated by the p-values.

4.1.4 Conclusion on impact on tyre safety

In order to assess the effects of potential safety trade-offs on accidents with injuries in the EU, an analyses has been done to relate tyre grip and fatalities. As input for the safety analyses, both measurement results of consumer tests and the ACEA Tyre Performance Study have been used. As mentioned in section 2.5.4, no trend between noise reduction and safety performance on tyre level could be identified with sufficient confidence. This has also an implication on the safety upscaling analysis as the same data has been used as input. Also here, no clear trend between noise reduction and fatalities could be identified, and a large spread regarding estimated fatalities was observed. Consequently, based on the available data no conclusion can be drawn regarding the impact of tyre noise on road fatalities at EU level.

4.2 Potential effects of quieter tyres on traffic noise

In this chapter, an analysis is given on the potential effects of quieter tyres on traffic noise.
The noise emission of tyre/road rolling noise depends on several factors:

- tyre properties such as width, diameter, compound, tread profile, tread and wall structure, all implicitly included in the tyre noise level in dB(A.)
- road surface properties, mainly surface roughness and porosity
- vehicle speed (and acceleration)
- vehicle properties such as tyre well and vehicle geometry

The environmental noise exposure from traffic noise also depends on the traffic composition, flow rate, speed and sound propagation at a specific location.

As the main quantity for environmental noise analysis is based on traffic data averaged over a year, the influence of individual vehicles and tyres is less relevant. However, on roads where tyre/road noise is the dominant source, especially above 50 km/h but even down to 30 km/h, the composition of the tyre fleet determines the average noise level. In particular, passenger cars are by far the most numerous and therefore determine this level, together with the road properties. Trends towards heavier vehicles lead to wider and larger tyre size thereby increasing the average traffic noise levels. Assumptions on the vehicle fleet and its evolution are based on fractions of the fleet that comply with vehicle noise limits as they change over time in accordance with EU Regulation 540/2014 [16], and the expected increasing fractions of electric and hybrid. This is set out in Appendix D, following the methodology applied in the MN-vehicle sound limits study [17]. In general, propulsion noise in the fleet gradually reduces over time leaving tyre-road noise as a predominant source.

Environmental noise calculation models for noise mapping such as CNOSSOS [18] or national models only distinguish a limited number of vehicle classes, such as light, medium and heavy duty vehicles and two-wheeler (L-category) vehicles, all having a fleet- averaged noise emission level based on traffic noise measurements. No distinction between cars, SUVs or the tyre label is made.

In order to assess the effects of changes in the average tyre noise levels, the tyre contribution is therefore added to the CNOSSOS model together with the effect of road surface, as set out in Appendix D. Quieter tyres with a smoother tread pattern will have most effect on smoother and quieter road surfaces, as this is similar to the regulated test conditions for tyre noise, but this benefit can be less on a rougher surface. No distinction is made between OE (Original Equipment) and Replacement tyres.

The impact of such changes at EU level is calculated from the noise source levels of traffic flows at several characteristic locations such as urban main roads, arterial roads, motorways and rural roads. The changes in average tyre noise levels are applied to the rolling noise.
The subsequent changes in noise levels at exposure positions are used together with numbers of dwellings along all of these road types in the EU to estimate the impact on

Lden noise levels[2] and numbers of annoyed and sleep disturbed people. Here, the methodology used in the MN sound limits study [17] is applied with some modifications, which is similar to that applied in the Phenomena study [19]. This is set out in Appendix D.

4.2.1 Scenarios for quieter tyres

According to the Phenomena study [19], the effects of the introduction of quieter tyres have been considered to be beneficial at a large scale and in the short term due to the expected average life of tyres, of about 4-5 years). Such effects depend on the baseline of the current tyre fleet and the change in average tyre noise levels, assuming road surfaces remain of the same quality. The increase in passenger car weight and the continuous growth of road traffic[3] counteract the benefits of quieter tyres for reducing traffic noise. Traffic growth is therefore an additional scenario of interest, in order to quantify the effect of tyre noise level reduction. An average growth rate used in previous studies such as Phenomena [19] was 1%, based on growth in vehicle numbers and mileage. An increase was observed in recent years in monitored noise along roads in the Netherlands [20], considered to be due to traffic growth and heavier cars.

The baseline scenario is based on the tyre fleet reflected in the EPREL database referred to in this study, with first year in 2024. The road types, average speeds, traffic flows and population distribution are the same as those used in the MN-vehicles sound limits study [17]. The range of tyre noise levels is based on the EPREL database, and assuming scenarios for 1 to 5 dB noise reductions in the tyre noise level values, meaning a shift in the whole level distribution by these values.

4.2.2 Current noise label distribution based on EPREL data

The assumed tyre noise level distribution of C1 tyres is shown in Figure 4-12 below for the top 30 tyre designations, for cars, SUVs and LTR vehicles. The average effective level of the shown tyres noise level distribution is 71 dBA, with the minimum at 67 dBA and maximum at 73 dBA. For this analysis, an effective level of 71 dBA is chosen for C1 tyres. A reduction in the tyre noise label is applied to the shown distribution, shifting the histogram to the left in 1 dB steps.

2 The Lden level is the average sound level weighted for day, evening and night, resulting from traffic noise, not for individual vehicles. It is used for noise mapping of traffic noise as required by the Environmental Noise Directive (END).
3 Heavier vehicles tend to have wider tyres and higher noise emission, as reflected in the tyre noise limits; traffic growth is caused by the combination of numbers of registered vehicles and their annual mileage; registered cars in the EU27 grew by 6.7% between 2018 and 2023 according to Eurostat. Total car passenger distance increased continuously until Covid19, after which it picked up again.

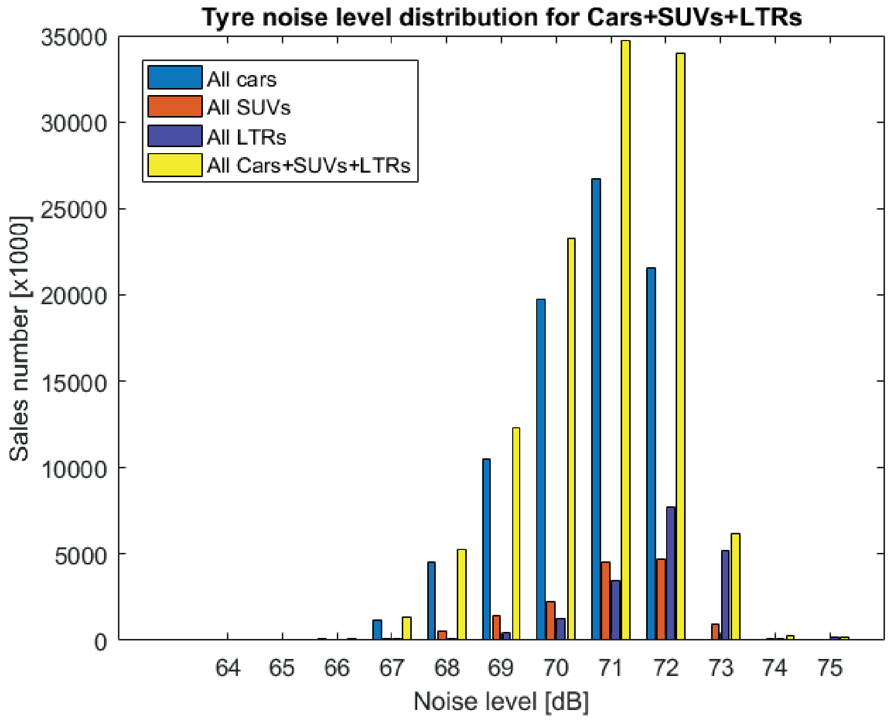


Figure 4-12: Distribution of tyre noise levels from the EPREL database, for cars, SUVs and LTRs and all combined, for OE and replacement tyres combined.

4.2.3 Noise impact results

In Table 4.3, calculated future Lden and Lnight levels near urban and non-urban roads are shown for several scenarios of quieter C1 tyres, and the differences with the baseline levels for each scenario. The baseline scenario assumes autonomous evolution of noise legislation.
As mentioned in section 4.2.1, in previous studies 1% annual traffic growth is assumed for the period 2024-2045. For comparison, also the case for 0% traffic growth is shown. In that case, the effects of quieter tyres are stronger.

As seen in Table 4.3, in order to achieve a reduction in the Lden level of around 1 dB or more, in the situation of 1% traffic growth, 2 dB or more in tyre noise levels are required. This is assuming that on average, road surface quality at a large scale does not change very much. For comparison, halving the traffic flow would result in a 3 dB reduction in traffic noise.

Reduction in the health-related impacts in percentage of highly annoyed people (HA), highly sleep disturbed people (HSD) and in health impact in terms of DALYs are shown in Table 4.4. DALY stands for Disability Adjusted Life Years, referring to a quantity reflecting the number of life years with reduced health, for example due to cardiovascular disease.

From the table it can be concluded that a 2 dB or larger reduction in tyre noise is required to achieve more than 5% health benefits.

Table 4.3: Calculated average Lden and Lnight sound levels at typical distance from the road, and the differences resulting from a change in tyre noise levels with -1, -2, -3, -4 and -5 dB, relative to a starting value of 71 dB of average tyre noise levels. Also, the data from the MN limits study is shown, for – 3dB reduction. The calculated levels are at the end of the period in 2045. Note that the fleet baseline in 2024 is 6% larger than in the MN study (2017 fleet size).

	Lden dB(A)	Lden dB(A)	Lnight dB(A)	Lnight dB(A)	dLden dB	dLden dB	dLnight dB	dLnight dB
Scenario	Urban	Non-urban	Urban	Non-urban	Urban	Non-urban	Urban	Non-urban
Baseline (MN, 1% growth)	59.9	67.3	51.3	58.7				
Quieter tyres -3dB (MN)	58.5	65.5	50.0	56.9	-1.4	-1.8	-1.3	-1.8
Baseline (2024-2045) 1% traffic growth	59.6	67.0	51.0	58.4				
Quieter tyres -1dB	59.2	66.5	50.6	57.9	-0.4	-0.5	-0.4	-0.5
Quieter tyres -2dB	58.8	66.0	50.3	57.5	-0.8	-1	-0.7	-0.9
Quieter tyres -3dB	58.4	65.6	50.0	57.1	-1.2	-1.5	-1.1	-1.3
Quieter tyres -4dB	58.1	65.2	49.7	56.7	-1.5	-1.9	-1.4	-1.7
Quieter tyres -5dB	57.7	64.8	49.4	56.4	-1.8	-2.3	-1.7	-2
Baseline (2024-2045) 0% traffic growth	58.7	66.1	50.1	57.5				
Quieter tyres -1dB	58.3	65.6	49.7	57.0	-0.9	-1.0	-0.9	-1.0
Quieter tyres -2dB	57.9	65.1	49.4	56.6	-1.3	-1.5	-1.2	-1.4
Quieter tyres -3dB	57.5	64.7	49.0	56.2	-1.7	-2.0	-1.6	-1.8
Quieter tyres -4dB	57.1	64.2	48.7	55.8	-2.0	-2.4	-1.9	-2.2
Quieter tyres -5dB	56.8	63.9	48.5	55.5	-2.3	-2.8	-2.2	-2.5

Table 4.4: Reduction in percentage of highly annoyed people (HA), highly sleep disturbed people (HSD) and in health impact in terms of DALYs, including 1% traffic growth.

Scenario	Δ% HA	Δ% HSD	Δ% DALY
Quieter tyres -3dB (MN)	10.5	8.5	9.4
Quieter tyres -1dB (2024)	3.4	2.7	3
Quieter tyres -2dB (2024)	6.5	5.2	5.8
Quieter tyres -3dB (2024)	9.2	7.4	8.2
Quieter tyres -4dB (2024)	11.8	9.5	10.5
Quieter tyres -5dB (2024)	14.1	11.3	12.5

4.2.4 Uncertainties

Any analysis based on tyre label data has a number of uncertainties which require further research to quantify. These include:

- Correspondence of tyre labels with real noise levels. Little information is available on this. Representativeness of the declared tyre noise level can depend on limited datasets, actual spread in production, and wear and ageing effects.
- Road surface quality and level above which the tyre label value is ineffective. A smooth road surface, similar to the test track, is a precondition to benefit most from quieter tyres.
  This is illustrated by the example of cobbled roads or those with rougher surfaces, for which the effect of tyre profile is far exceeded by the effect of the road surface profile. In this sense it would be expected that a slick tyre would produce a similar noise level to a profiled tyre with similar dimensions and materials.

4.2.5 Conclusions

The impact of reduced tyre noise levels has been evaluated following the methodology applied in the Phenomena study and the MN-vehicle sound limit study. The average traffic noise reduction and health impacts were estimated for the period 2024-2045 and the average current declared tyre noise levels listed in the EPREL database for passenger cars (i.e. equipped with C1 tyres). Passenger cars dominate average traffic noise in many situations due to their large numbers. The effects of reduced tyre noise levels depend on road types and surface quality. Also, the effect of typical annual traffic growth of 1% was taken into account. A 3 dB reduction in declared tyre noise is expected to reduce average traffic noise levels by up to 1.5 dB, and in the case of 0% traffic growth, by up to 2 dB. The corresponding health impacts are estimated at up to 9% reduction for 3 dB and up to 14% for 5 dB reduction of tyre noise levels. If a reduction of 5 dB in declared tyre noise is considered, this could result in up to 2.3 dB reduction in traffic noise for 1% growth and 2.8 dB reduction in the case of 0% traffic growth. Besides traffic growth, also the evolution of average tyre size and load capacity in the fleet is a factor that will affect the potential traffic noise reduction. The pace at which these reductions can occur depend on the introduction date and magnitude of tyre noise limits, after which a period equal to tyre life of 4-5 years should be added for the full effect to take place at EU scale.

5. Conclusions

Based on the study the following conclusions are drawn:

Tyre performance trade-off

The main findings from literature review and expert interviews are:

- Tread patterns are relevant for aquaplaning performance and noise, a trade-off exists between both performances. Also, tread patterns are relevant for grip on snow and ice surfaces and trade-offs with noise performance exist.
- Wider tyres produce more noise.
- Rolling resistance and noise can be optimized with little trade-off.
- Tyre grip is related to material properties that also affect noise, which can result in a trade-off with noise.
- Main requirements such as maximum speed and load carry capacity dictate the design envelope of tyres, as these are related to warranting the structural integrity of tyres Depending on the load and speed specification an optimisation can be done within the design domain, which is getting more limited to high-load/speed tyres.
- The evolution in tyre technology results in tyres with improved performance. To assess the potential for further improvement the performance of state-of-the-art tyres, i.e. tyres that were recently developed, should be considered.
- Dedicated scientific studies of UTAC commissioned by ACEA and ETRTO [1] [2] [3], in which a limited number of tyres of the same size and load index have been tested, conclude on conflicts between tyre noise and safety performance. However, as those studies are based on this limited number of tyres of the same size, no conclusion can be drawn on trade-off between noise and safety for tyres in general.

From test data analysis of consumer tests and the ACEA Tyre Performance Study, executed by UTAC [1]), the following conclusions are provided regarding the different compatibility aspects:

- **Noise versus rolling resistance**
  - Rolling resistance is a matter of contact mechanics as well as tyre structure. The relation of tyre rolling resistance and noise has been studied quite extensively and has resulted in tyres with little trade-off between these aspects. Analyses of test data reveals that this is also achieved for several tyres on the market. It can be concluded that rolling resistance and noise can be compatible for current tyres. However, there is no information how further reduction of noise will affect rolling resistance and it is unclear what the trade-offs could be.
- **Noise versus micro-plastic emissions**
  - Micro-plastic emissions of tyres is caused by abrasion. Abrasion is a relatively new aspect for tyres, which has not been studied extensively in relation to noise. From theoretical considerations a trade-off is expected if a softer compound is used for noise reduction. The available data at the time of the study from tyre testing is limited. Therefore, it is concluded that the information gathered is insufficient to draw conclusions on compatibility between abrasion and noise.
- **Safety performance versus noise**

- Tyre safety performance concerns different aspects such as grip under dry and wet conditions, aquaplaning, vehicle stability, etc. Compromises are made in tyre design between individual safety performance aspects, e.g. a better tyre for dry road can have reduced performance on a wet road.
- From literature it is concluded that compromises need to be made to obtain desired noise performance and grip under all operating conditions, which can result in trade-offs. Main physical aspects that play a role are contact mechanics, material properties, tyre construction and tread pattern design.
- Tyre safety in relation to noise has not been studied extensively in the past. Recent studies by UTAC (including results from the tyre industry) conclude that tyre safety performance and noise are conflicting or incompatible, without providing a quantification of a trade-off.
- Analysis of consumer tyre test data does not indicate a clear relation between individual safety performance aspects and noise. No relation could be assessed for a combined safety performance (i.e. dry/wet grip and aquaplaning) with noise either. A final analysis was done on scientific data used in the ACEA Tyre Performance Study involving 14 tyres. This has not resulted in the identification of a trend with sufficient confidence for combined safety performance and noise. From that analysis it is concluded that insufficient data is available to draw any conclusions on the trade-off between tyre safety and noise.

Concluding, results from literature review, expert interviews, and qualitative assessments, show that compromises have to be made to achieve both safety and noise performance that can result in trade-offs. Industry uses holistic design methods to deal with this within current performance requirements. From experiments on state-of-the-art tyres no trend regarding safety and noise could be identified with sufficient confidence. Based on the above, it cannot be assessed how much trade-off with respect to safety performance can be expected when noise performance criteria are changed.

Tyre availability

From an analysis of the EPREL database for the most popular tyre designation on the market, the following conclusions are drawn:

- Firstly, in terms of availability, it appears that 80% or more of popular C1 tyre designations are available with an A-label for noise in combination with A/B for wet grip and rolling resistance. It is observed that the share of A-labelled tyre designations is reduced in the OE category for SUV tyres.
- Secondly, relatively more SUV tyres are sold in the OE category.
- Thirdly, SUV tyres are getting wider, allowing higher noise levels for obtaining an A-label.
- These three factors indicate a trend where tyre noise will become a more dominant factor in traffic noise.
- Finally, it should be noted that when lowering regulated noise levels by 3 dB the tyre designations that are currently not available with an A-label require to be redesigned. Manufacturers that currently have no A-label tyre for other designations also need to redesign those tyres.

Upscaling

Impact on safety

From the conducted safety analyses, the following is concluded:

- No clear trend between tyre noise reduction and fatalities could be identified, and a large spread regarding estimated fatalities was observed. Consequently, based on the available data no conclusion can be drawn regarding the impact of tyre noise on road fatalities at EU level.
- However, the applied upscaling methodology indicates that a minor reduction in tyre grip can lead to a substantial increase in collision impact speed which affects the number of traffic fatalities, mostly concerning cyclists and pedestrians. With this sensitivity it is recommended to further study the relation between tyre noise performance and grip in order to understand the implication concerning traffic fatalities.
- The safety upscaling analysis was performed for a specific set of accident scenarios, i.e., scenarios on straight roads where tyre grip performance is relevant and the grip limit is used. This set of scenarios is a subset of all accident scenarios where tyre grip is of importance. It is recommended to investigate on approaches to achieve an upscaling for all grip related accidents at EU level.

Impact on traffic noise and health effects
From investigations on the impact of tyre noise reduction on the average traffic noise and associated health impacts the following conclusions are drawn:

- A reduction of 3 dB in declared tyre noise is expected to reduce average traffic noise levels by up to 1.5 dB, taking a typical annual traffic growth of 1% into account, and by up to 2 dB in case of 0% traffic growth. The associated reduction in health impact in terms of DALYs (Disability Adjusted Life Years) is estimated to be about 8% for 1% traffic growth.
- A reduction of 5 dB in declared tyre noise is expected to reduce average traffic noise levels by up to 2.3 dB, in case of 1% traffic growth, and up to 2.8 dB in case of 0% traffic growth. The associated reduction in health impact in terms of DALYs is estimated to be about 13% for 1% traffic growth.
- For comparison, a 3 dB reduction in traffic noise would also result from halving the traffic flow.
- The potential traffic noise reduction and associated health benefit will depend on the actual evolution of traffic growth, as well as the average size and load capacity of tyres in the fleet.

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Appendix A: Expert consultation reporting

This appendix contains the following.

- Results from interviews conducted with experts from the scientific community.
- Results from interviews conducted with experts from the tyre industry.
- Results from a workshop with experts from the scientific community and the EC.
- Questions used in the interviews.

Scientific community
Interview sessions were organized with seven research organizations, two of them had participation of two experts. Below the summary is provided for the group of experts in relation to the questions that are at the end of this appendix.

Literature

- The “TYRE/ROAD NOISE REFERENCE BOOK” by Sandberg and Ejsmont [21] is considered a good basis for understanding the tyre noise mechanisms and it is also used for education. Since publication of the book in 2002 the main research has been on the impact of pavement, which has led to alternative ways to describe the noise interaction between tyre and road. This however is not considered crucial for the study.
- Various publications exist on the interaction of tyre noise and rolling resistance. No publications describing the relation between tyre grip and noise, or abrasion and noise were suggested.
  - Several developments on the evolution of tyre design were mentioned.
  - The compound composition contains more silica than a decade ago. Changes in compound for other additives seem marginal, but apparently have resulted in significant performance improvement.
  - Meta-materials are more widely used to engineer the vibration behaviour of tyres, which can lead to noise reduction.
  - New production methods of tyres for innovative designs are available, allowing new tyre structures and inclusion of material elements specific for noise reduction.
  - New materials are used in addition to rubber.
  - New methods to optimize tread pattern design.
  - Performance criteria have changed.

Statements from experts based on their research experience.

- The tread pattern can give indications of the noise level of a tyre, other design factors (e.g. compound, construction) are also important but are not visible.
- Trade-offs between tyre noise and rolling resistance can be avoided by using an integrated design.
- Tyre grip is a key factor in accidents, and it is very much influenced by road surface conditions. Studies on this topic are regularly requested by a variety of actors in traffic safety.
- Real-life tyre performance is very much depending on the road surface condition.
  - A road surface change can have much bigger impact on noise than a tyre change.
  - Speed dependency for noise is affected by the road surface.
- Accurate noise predictive models from tyre design are not known. They always need to be validated and parameterized using tyre measurements. Models to predict vibrations of 1 kHz and higher are not easily validated. Modelling rolling tyres (required for integral assessment of noise, grip performance and rolling resistance) is not trivial due to interaction with road and gyroscopic effects.

- Challenging load and speed requirements result in less design freedom to optimize tyres. High drive torques (e.g. from EV) are relevant in this respect.
- All tyre performance seems connected and cannot be optimized independently.
- Testing on the quietest road (e.g. ISO) is not representative for real-world performance. Rolling resistance and noise should be tested on the same road surface to excluded effects of road condition.
- Operational temperature is relevant for tyre performance. It concerns ambient temperature, road temperature, and also the tyre temperature. Many tests are conducted under a temperature that is not representative for real-world applications. Tyre suppliers design tyres for different markets considering the real-world temperatures.
- The tyre composition has evolved in the last 10-15 year towards more silica and other additives. Composition changes are not very large, suggesting very precise design and manufacturing techniques. Current budget tyres tend to have less silica and additives.
- Abrasion for a given tyre is very much depending on the road surface roughness and driving profile. It is the result of micro-vibrations, stick-slip and transfer of forces in longitudinal and lateral direction. Abrasion is considered optimal when the tyre is used in the target operating temperature.
- Absorption materials can be added, but typically address lower frequencies that are not a large contributor to tyre exterior noise.

Potential for improving noise.

- Improving tyre noise will influence other performance of tyres and optimization is needed to achieve or maintain adequate tyre performance in all aspects.
    - A compromise with rolling resistance is often possible.
    - A reduced performance of wet grip is expected by most experts. Some experts have found no conclusive evidence in past studies that a trade-off exist and expect that a trade-off can be mitigated.
    - Low noise tyres may have softer materials, which generally have less resistance to abrasion. There may be a trade-off between tyre noise and abrasion resistance that is related to tread pattern design.
    - Aquaplaning performance is adversely affected when changing the tread pattern for noise optimization.
- New materials may allow width reduction of tyres for current loads. Narrower tyres produce less noise.
- Strong contradictions in tyre performance aspects were not found in earlier studies.
- The biggest achievements are in the material. New materials can allow different construction of the tyre. Softer materials typically are less resistant to abrasion.
- Noise is a (vehicle) system property, optimizations can also be achieved by design of the wheel bay in which the tyre is mounted. The road is a dominant factor for noise generation, but also affects noise transmission.

- **General questions**
- No information could be provided on the compromise for Reinforced tyres.
- One of the experts commented on differences between C1 and C3 tyres. The design freedom for C3 tyres is very limited due to the challenging baseline requirements of being capable to carry the high load. Secondly, they are designed for minimal operational cost, i.e. low rolling resistance and maximum lifetime.
- As mentioned by several experts, Summer tyres and Winter tyres should be evaluated in their target operating conditions, and any indication of trade-off should be assessed for that target operating condition. For winter tyres the

information is generally not available at below zero temperatures. The material of winter tyres is too soft at higher temperatures, which results in high abrasion. Rolling resistance and noise can be less for softer tyres.

Tyre industry
Below a summary of the interview session with experts from the industry which was co-organized with ETRTO/ETRMA. The questions were shared beforehand, and a slide set was prepared with answers which was presented by ETRMA members and discussed.

The summary from the discussion is provided below.

Literature
- The following literature is recommended for the study.
    - ACEA - Tyre Performance Study. This is the most extended study involving recent tyre testing. Studies based on testing of older tyres are not representative for current tyres due to the evolution in tyre design methods over the years.
    - ETRMA-Tyre-Road-Traffic-Noise_2022. This provides a summary overview of the main design challenges for tyre suppliers in relation to tyre noise.
    - ACEA/ETRTO Tyre Performance Aggregation Study
    - Several sources on road design, pavement and speed effects
    - Advanced Tyre Mechanics by Y Nakajima is a more recent book on tyre noise.
    - Not many results are available for C2 and C3 tyres. C3 tyres are designed for fitment (steering, drive, trailer) and use profile (long-haul), resulting in many subcategories.

Findings from research by the tyre industry
- Findings of own research is shared only in public documents such as listed under “literature”.

Potential for improving noise.
- The interaction between tyre and road is key for noise generation. The most relevant factor is considered the road surface, secondly the driving speed, and thirdly the tyre. It is noted that the most silent tyre on one road may not be the most silent tyre on another road. Secondly, roads can account for a much larger difference in noise than a tyre, and it is mentioned that there is a significant potential to optimize roads for specific use of the road (e.g. type of traffic, driving speed).
- The tyre research and design has reached maturity around 2021 at the main tyre manufacturers. No drastic changes have been made since then. The current developers can improve tyre performance only by a holistic approach in which geometry, construction and material are optimized in an integral way. Changing (or optimizing) only one parameter for improved noise will impact various other performance adversely.
- Increasing the number of regulatory requirements (or making them more stringent) for various tyre performance is restricting the design freedom and potential to improve on noise levels.
- Tyre noise is only one aspect of vehicle sound emissions. To reduce vehicle sound emissions a holistic method should be used. It is emphasized that vehicle and tyre noise is very much depending on the operating conditions such as road surface, driving speed, weather conditions, etc.
- Current noise levels are considered not far above what can be achieved by the most silent tyre (i.e. slick tyre on smooth surface). This means that the

optimization for noise is getting close to the physical limits. The magnitude of noise reductions achieved in the past 10-15 years can no longer be made. Studies based on tests of tyres that are outdated may not give representative indications of the noise reduction potential of state-of-the-art tyres that are currently on the market and related trade-offs.
- The tread pattern for truck tyres cannot be changed due to the strength and durability requirements. This is limiting the possibility for improvement compared to passenger car tyres. Tyres for ultra-high performance (300 km/h+) have similar restrictions. Tyres with limited speed application on the other hand provide more design freedom.

General questions
- Assessment of lower noise values increases the required level of precision in measurement to ensure an adequate assessment. In that respect the level of uncertainty in noise measurement procedures should be reduced to ensure sufficient validity of the assessment of tyre labels and other regulatory results.
- Regulated performance is assessed for new tyres, while tyres generally are not new. Tyres generally become more silent when they wear.
- Aquaplaning performance is assessed at high water layers, road characteristics are more relevant for low water layers. Road surface characteristics influence the water level that can occur. The challenge of testing on wet roads is that the test needs to be representative and reproducible. A test proposed by VDA is used for aquaplaning assessment.
- Reinforced tyres may more easily achieve triple-A as they are tested at higher load, and e.g. rolling resistance results are normalized by load.
- Requirements for C1, C2 and C3 are very different, as well as the inflation pressure under which they operate.
- Winter tyres, All-season (not regulated) and Summer (“normal”) tyres can differ in all aspects (geometry, construction, compound) to ensure optimal performance in their target (temperature) operating window.
- The study on abrasion is recommended to be based on results from the test
- procedure that is under development in the related UNECE working group.

Expert workshop
A workshop has been organized with experts from the scientific community that were interviewed, and participation from the EC.

The purpose of the workshop was to reflect on conclusions from the expert interviews, and to identify further topics that could be helpful to conclude on the literature study. The analysis of tyre label information in the EPREL database was not available prior to the workshop.

The following statements are summarized from interviews, and they were not contradicted by the scientific experts in the workshop:
- Rolling resistance and tyre noise concern different frequency/wavelength ranges and may be optimized without trade-off. The frequency/wavelength range concerned with tyre grip overlaps with the relevant range for rolling resistance as well as for tyre noise.
- Increasing tyre width increases noise.
- The tread pattern is dominant for tyre noise and for wet road grip (e.g. aquaplaning), there may be a compromise.
- Tyre noise performance depends on the road surface. The quietest tyre on one road surface (e.g. ISO), may not be the quietest tyre on other road surfaces.
- Tyre noise is speed dependent, this dependency is affected by the road surface.

- Designing or optimizing tyres with models to predict noise (and other performance) in rolling conditions is beyond state-of-the-art.
- Tyres for Electric Vehicles have different performance requirements.
- Properties of compound materials (and thus tyre performance) depend on temperature.
- Main new developments are on (meta-)materials and construction.

From the discussions in the workshop the following summary has been made:

- Lower exterior tyre noise is not always quieter for interior noise.
- Models can be used to indicate trends, but some effects are difficult to capture. Parametrization of models always requires testing of tyres to make them accurate.
- The real-life and real use situations have been discussed. Road surfaces and climatic conditions of real use have a significant impact on noise and other performance, as well as the trade-off between this various performance.
- The participants were challenged to make relations between the tyre performance quantifiable, but no conclusions could be made other than that it is very tyre specific and not possible to assess without measurement of the specific tyre.
- Noise in conjunction with rolling resistance has been studied by participants, tyre grip was not studied in conjunction with other tyre performance.
- Abrasion is a complex topic, which is influenced by tread block design. For truck tyres (having tread designs for minimal wear) mitigation measures have been made to avoid excessive noise. Abrasion still is a relatively unknown area.
- Winter tyres were introduced for having grip under low temperatures and snow/ice conditions. This is mainly safety related.
- Winter tyres have different compound, geometry and tread patterns, which all have an effect on noise. Their performance is optimized for low temperature conditions.
- Some results from a study by ACEA were presented that indicate that tyres with optimal grip performance produce more noise, and that the quietest tyres have less grip. The link with tyre labels is not visible in the presented results, making it difficult to conclude upon in terms of outcome from regulatory tests.
- The theory of contact mechanics indicates that optimization of noise and rolling resistance can largely be done without a compromise between both. Trade-off effects for grip are expected. Results from tyre testing are shown and it includes one tyre with both good noise and rolling resistance performance. That specific tyre has a significant degraded grip performance, which is in line with expectations following the theory of contact mechanics.

Conclusions from the workshop:

- The principles of contact mechanics result in trade-offs between tyre grip and tyre noise. The trade-off magnitude that can be assessed from tests will be depending on tyre operating conditions such as road type and temperature.
- The trade-off between tyre noise and other performance could only be derived from models that are validated for that specific performance. Validation (and model parameter assessment) typically requires extensive tyre testing. There are no models known by the participants of the workshop for describing both noise and grip performance.
- Results from available sources on tyre performance and trade-offs may not directly be related to outcome for tyre labels and type approval testing.

Questions for experts

The list of questions that was used in the interviews with experts is summarized below.

Literature

- Which literature would you recommend that describes principles and/or relation between tyre noise and:
  - Tyre grip
  - Rolling resistance
  - Tyre abrasion
- Tyre testing for scientific studies
  - Outdated tyres
  - How much is state-of-the-art different? What can we concern the main developments?
- Tyre consumer testing
  - https://www.tyrereviews.com/
  - Other known sources?

What are your findings from own research?

- What kind of research have you done on tyres?
- To which extent can you predict noise levels and other performance of test subjects?
- Which are most influencing tyre design factors for tyre noise?
- What kind of trade-offs in tyre performance have you observed?
- Other observations?

Potential for improving noise and compromise

- What would you expect as degradation in tyre performance when reducing noise level?
  - Rolling resistance
  - Wet Grip
  - Tyre Abrasion
- Which other tyre performance do you expect to be adversely affected when reducing noise level?
- Which innovations could improve a compromise?
  - Construction
  - Geometry
  - Material
  - Other?

General questions

- How are Standard Load tyres and Reinforced tyres different concerning the compromise?
- What kind of difference can be expected between C1 (car), C2 (small truck) and C3 (big truck) tyres?
- What kind of difference can be expected between Summer, Winter and All-Season tyres?
- 1-mm water layer, how to predict?

Appendix B: Single component evaluation

This appendix contains results of a single component evaluation of consumer test results.

The consumer test sessions have been executed at different proving grounds, different weather conditions and using a variety of test protocols and test vehicles. This affects the test outcome in an absolute sense, but we can assume that the results within one test session provide a proper relative assessment of tyres within that group (i.e. performance ranking).

The evaluation method is taking this relative assessment to provide a general overview of performance in relation to noise. The method is depicted in Figure B-1.

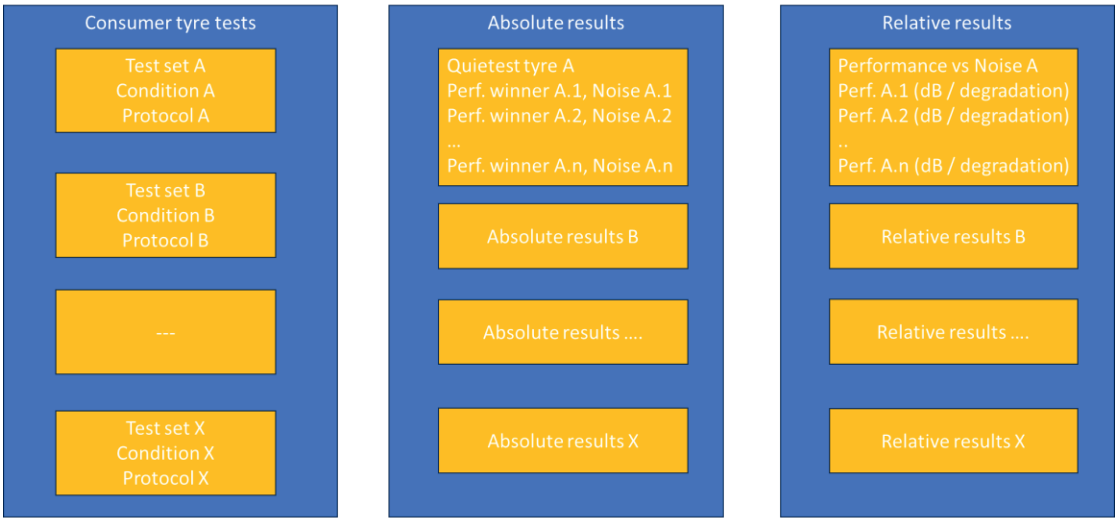


Figure B-1: Method of evaluation

A test set provides results of different brands for a specific tyre size, and one brand is the quietest tyre. The test set contains a range of performance aspects (e.g. noise, braking, aquaplaning, handling, rolling resistance, abrasion and predicted tyre life), of which different brands can be the performance winner. These are absolute results.

The results of the winner of each performance aspect are compared to the quietest tyre. This indicates how much performance is degraded for the quietest tyre, and also how much more noise is generated by the performance winner. These are relative results.

The relative results of different test sets are combined to provide an overview of noise levels and performance for braking, aquaplaning, handling, rolling resistance, abrasion, and predicted tyre life.

The evaluation is done on the following aspects which are the performances considered.

- Tyre grip (on dry and wet surfaces)
- Aquaplaning (straight and curve)
- Rolling resistance
- Abrasion and predicted tyre tread life
- Handling (on dry and wet surfaces)

Tests for braking result in a stopping distance which is depending on the test speed. To combine results for braking from different test speeds the tyre grip is calculated in accordance with UN Regulation 117.

To obtain relative test results within a test session the performance of the quietest tyre is compared to the best tyre for a specific performance, i.e. performance winner.

For each of the performance aspects, the degraded performance (in %) of the quietest tyre (QT) is compared to the performance winner (PW) using the formula:

$$Degraded\ performance\ QT = \frac{abs(Performance\ PW - Performance\ QT)}{Performance\ PW} * 100$$

$$Noise\ reduction = Noise\ (PW) - Noise(QT)$$

This approach is explained using the example in Figure B-2 showing results for wet braking and rolling resistance respectively for a test session that involved a group of 19 tyres. The performance is shown in relation to measured noise levels. For this example, the tyres are marked as premium, mid-range or budget tyres according to the categorization on www.tyrereviews.com/Tyre.

The performance winner for grip in the group is a premium tyre and it achieves a deceleration of $8.97\frac{m}{s^2}$ on wet road and a noise level of 68.9 dB(A). In the first subplot, the brake degradation is shown with respect to the performance winner. The performance winner is at y-value 0 while the (coincidentally two) worst performing tyres have a 20% degraded brake grip performance, one is the quietest (premium) tyre with noise level 67.1 dB(A), and the other is a budget tyre with a noise level of 68.8 dB(A).

Rolling resistance degradation is shown in the second subplot of Figure B-2. The lowest rolling resistance is found for a premium tyre at $5.69\frac{Kg}{t}$, which is the performance winner. As can be seen from the figure, the performance winner rolling resistance is actually the quietest tyre. In this test session, five out of six premium tyres have lower rolling resistance than the mid-range and budget alternatives.

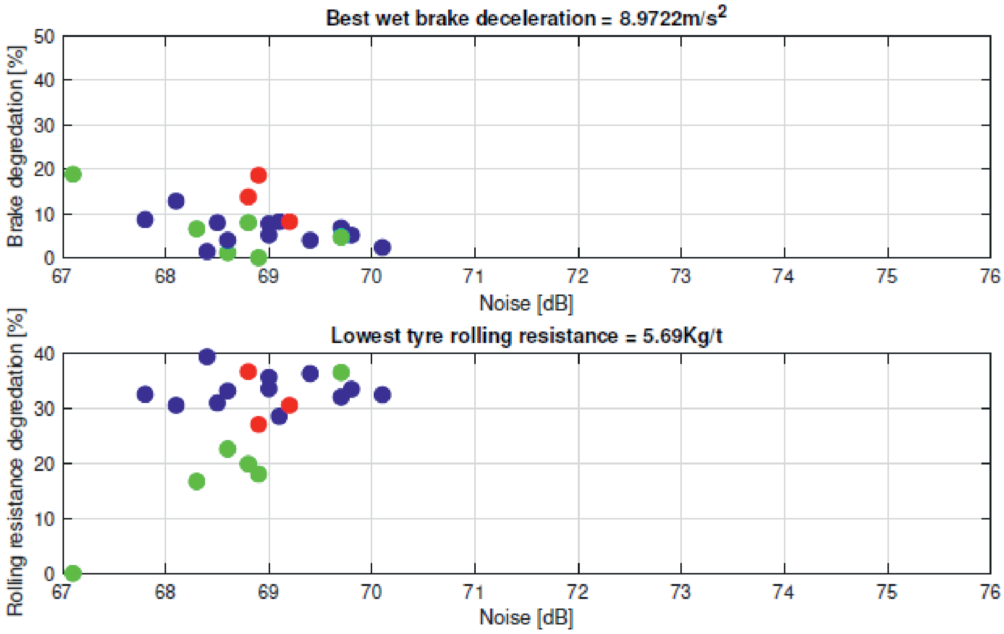


Figure B-2: Example performance indicators for Premium (green), Mid-range (blue) and Budget (red) summer tyres in one test session.

In Figure B-2 it can be seen that the performance winner for wet grip is not the quietest tyre. Compared to performance winner for wet grip, the quietest tyre has almost 2 dB(A) reduced noise. The quietest tyre however has a 20% reduced grip performance. For each of the test sessions the noise reduction of the 44 quietest tyre is assessed compared to the performance winner, as well as the grip degradation for the quietest tyre in the specific group. In this example, the values of 2 dB(A) of the quietest tyre and 20% reduction of performance would be added in the summary Table for the specific set.

Table B.1 provides the overview for grip and noise as assessed for all sessions.

Table B.1: Noise reduction and performance for wet grip in selected test sessions

Test set	Performance winner (PW)	Quietest tyre (QT)	PW Noise [dB(A)]	QT Noise [dB(A)]	PW wet braking deceleration [m/s^2]	QT wet braking deceleration [m/s^2]	Noise reduction [dB(A)]	Wet braking performance degradation [%]
1	Tyre 3	Tyre 5	70.6	67.3	8.4	8	3.3	4.2
2	Tyre 2	Tyre 1	70.7	70.6	7.8	7.4	0.1	5
3	Tyre 6	Tyre 11	74.1	70.8	8.4	5.9	3.3	30.3
4	Tyre 20	Tyre 5	68.9	67.1	9	7.5	1.8	15.9
5	Tyre 5	Tyre 3	72	70	8.3	8.2	2	0.9
6	Tyre 3	Tyre 1	69.2	67.8	8.4	7.6	1.4	9.5
7	Tyre 26	Tyre 14	71.4	69.1	7.2	6.5	2.3	9.7
8	Tyre 1	Tyre 4	67.5	66.5	9.9	9.5	1	4.9
9	Tyre 2	Tyre 5	72.2	71.9	10	8.8	0.3	11.4
10	Tyre 1	Tyre 4	71	67	10.1	9.5	4	6.2
11	Tyre 1	Tyre 4	68.9	67.3	7.7	7.4	1.6	4.2
12	Tyre 2	Tyre 2	71.9	71.9	10.3	10.3	0	0
13	Tyre 1	Tyre 5	64.6	64	7.5	6.5	0.6	14.3
14	Tyre 2	Tyre 8	70.9	69.7	10.4	9.8	1.2	5.6
15	Tyre 1	Tyre 13	72.2	70.2	6.9	4.7	2	31.4
16	Tyre 1	Tyre 13	71.3	70	8.7	7.6	1.3	12.8
17	Tyre 1	Tyre 5	73.2	69.3	7.8	7.2	3.9	7.9
18	Tyre 12	Tyre 19	74.1	72.3	9.6	8.5	1.8	11.6
19	Tyre 2	Tyre 3	70.3	68.6	10.2	9.8	1.7	4.3
20	Tyre 2	Tyre 5	70.4	68.6	7.8	7.5	1.8	4.6
21	Tyre 1	Tyre 9	72	70.2	6.9	4.7	1.8	31.4

The noise reduction and performance degradation (last two columns of Table B.1 are used for evaluation and are displayed in Figure B-3. From the Noise reduction column, it can be seen how much noise reduction is possible by selecting the quietest tyre in each of the tested tyre groups in favour of the performance winner. From the last column the degradation of wet grip is shown for the quietest tyre compared to the performance winner for wet grip in the group. Figure B-3 displays the results of 19 comparative tests for a visual overview which are discussed in the next section.

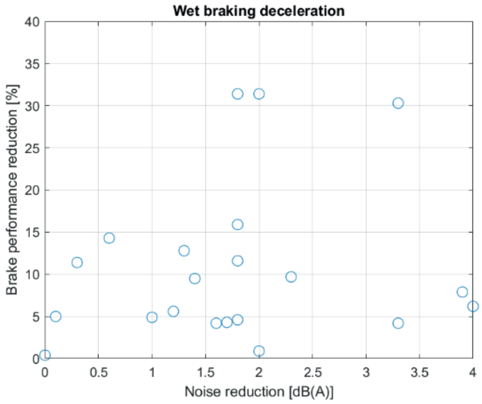


Figure B-3: Summary for wet braking performance and noise.

This type of analysis is done for each of the performance indicators of which the results are displayed and discussed in the next section.

Results
This section contains figures with results from evaluation of consumer tyre testing. Some of the test sets indicate trade-offs of tyre noise with a specific safety performance aspect.
As explained in Section 2.5, an overview is created of comparing within a test group the quietest tyre to a tyre that has the best performance for a specific aspect (Performance winner). In this section the results for several performance aspects are discussed. Table 2.1 provides an overview of the available data in test sets and the number of tyres concerned in the test group.

Tyre grip (on dry and wet surfaces)
The grip performance reduction for the quietest tyre compared to the grip performance winner as assessed in 21 test sessions is displayed in Figure B-4 for dry road and wet road respectively. In some cases, the quietest tyre is the performance winner, resulting in zero noise reduction and zero performance reduction which is difficult to see. The test set(s) in which this occurs are indicated below the graph.

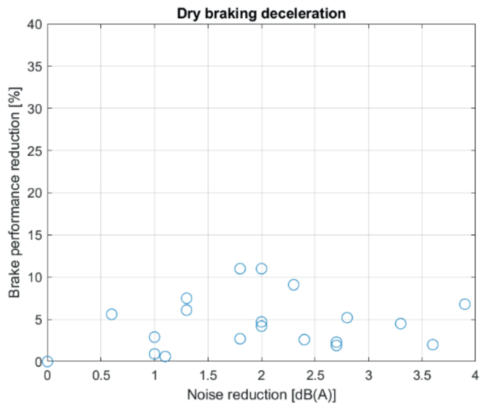
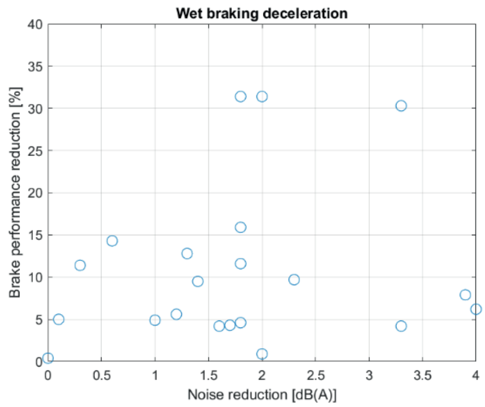
Dry road	Wet road
	
Quietest tyre = Performance winner: Test set 6, 19	Quietest tyre = Performance winner: Test set 12

Figure B-4: Summary for braking performance and noise.

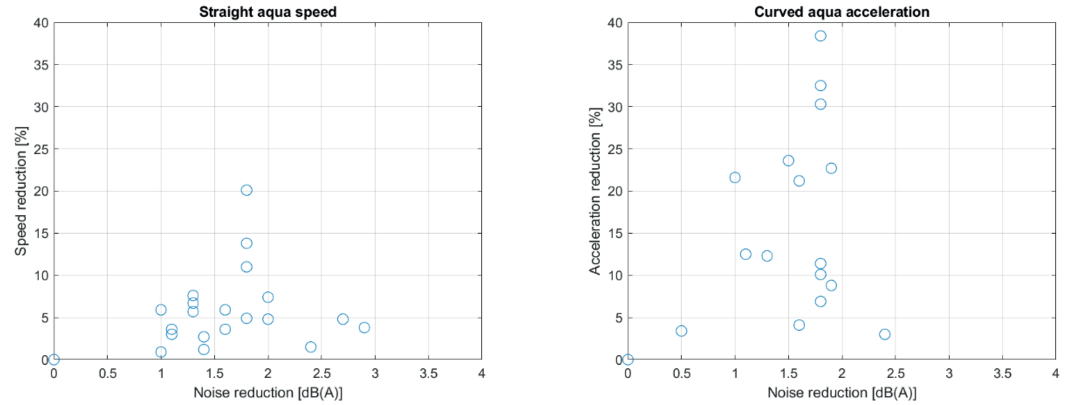
As can be seen in Figure B-4 the reduction in wet braking performance for the quietest tyre can be much larger than for dry braking performance. A reduction of brake performance on wet roads is found to be in the range of 4% - 16% for the quietest tyre in most test sessions, while for dry roads this is generally in the range of 2% - 11%.
In two test sets the quietest tyre has the best grip on dry road, and in one test set the quietest tyre has the best grip on wet road. Those three tyres have however the highest

degradation in aquaplaning performance, so the safety performance overall seems also for those tyres incompatible with low tyre noise.

The performance winner for grip in some test sets can produce up to 4 dB(A) more noise.

Aquaplaning (straight and curve)
The aquaplaning performance reduction for the quietest tyre as assessed in different test sessions is displayed in Figure B-5 for straight driving (21 test sessions) and curve driving (18 test sessions) respectively.

Straight driving	Curve driving



Quietest tyre = Performance winner: Test set 1	Quietest tyre = Performance winner: Test set 17

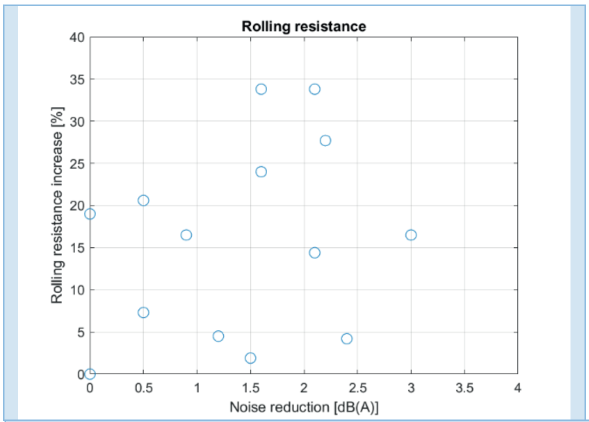
Figure B-5: Summary for aquaplaning performance and noise.

As can be seen in Figure B-5 the maximum speed for aquaplaning for the quietest tyre when driving straight is mostly below 8% reduced compared to the best tyre with outliers up to 20%. In curve driving the speed of aquaplaning of the quietest tyre is mostly below 25% reduced with outliers up to almost 40%.
In one test set the quietest tyre has the best aquaplaning performance for straight driving, and in one other test set the quietest tyre has the best aquaplaning performance. For both tyres a reduced vehicle stability is reported, which is a degradation of safety.

The performance winner for aquaplaning in some test sets can produce up to about 2.5 dB(A) more noise.

Rolling resistance
The rolling resistance increase for the quietest tyre as assessed in 19 test sessions is displayed in Figure B-6.

Straight driving



Quietest tyre = Performance winner: 2, 3, 4, 12, 20

Figure B-6: Summary for rolling resistance performance and noise.

As can be seen, the quietest tyre in most test sessions has 5% -35% more rolling resistance.
In five test sets the quietest tyre also has the lowest rolling resistance. In other test sets the tyre with lowest rolling resistance can produce up to 3 dB(A) more noise.

Abrasion and predicted tyre tread life
Only a few test sessions provide information related to tyre wear, which concerns abrasion and/or tyre tread life prediction.

The tyre wear performance reduction for the quietest tyre as assessed in different test sessions is displayed in Figure B-7 for abrasion (3 test sessions) and predicted tyre tread life (6 test sessions) respectively. The quietest tyre is not found to be the tyre with lowest abrasion in any of the 3 test sessions. In one of the 6 test sessions the tyre with the highest predicted tread wear is also the quietest tyre.

The number of test sessions is considered too limited to draw any conclusions.

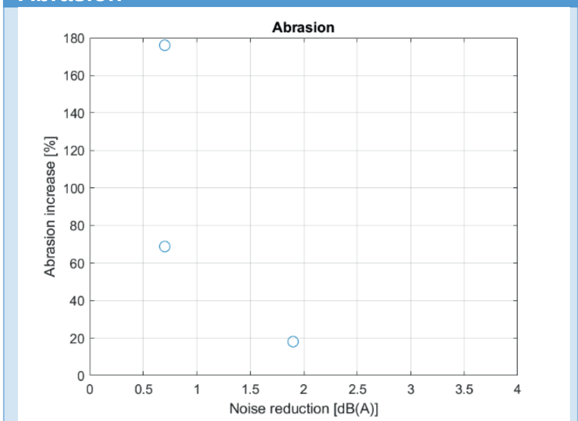
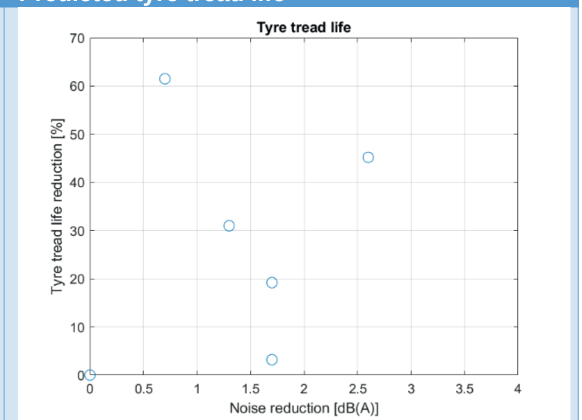
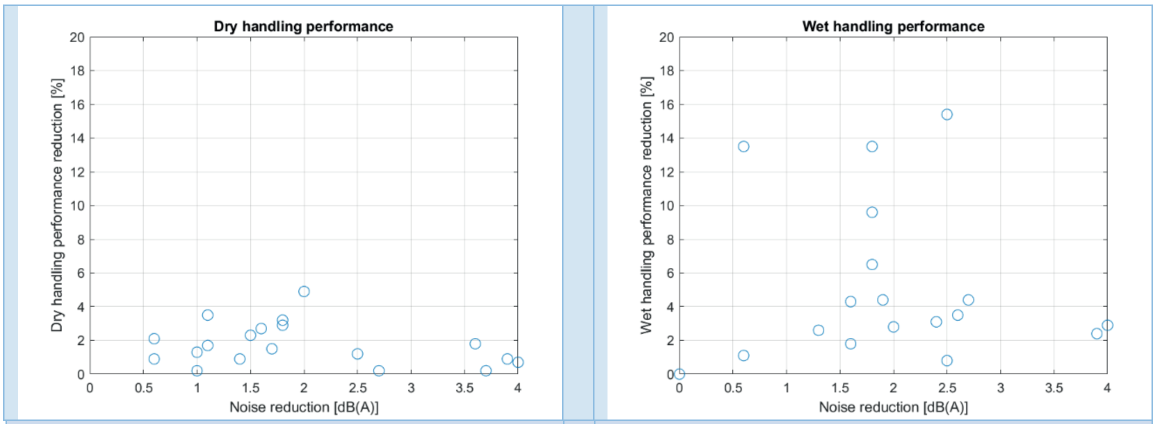
Abrasion	Predicted tyre tread life
	
Quietest tyre = Performance winner: none	Quietest tyre = Performance winner: Test set 18

Figure B-7: Summary for tyre wear performance and noise.

Handling (on dry and wet surfaces)
The vehicle handling performance is an indication of both vehicle stability and tyre grip. The handling performance reduction for the quietest tyre as assessed in 19 test sessions is displayed in Figure B-8 for dry road and wet road respectively.

Dry road	Wet road



Quietest tyre = Performance winner: none	Quietest tyre = Performance winner: Test set 2, 6

Figure B-8: Summary for dry handling performance and noise.

The results for handling are somewhat similar as for tyre grip, which is according to expectation since tyre grip is a main factor for lap times (or speed) around handling tracks due to the many curves and braking zones. The spread in performance reduction of the quietest tyre is much larger for handling on a wet road than for handling on a dry road. A similar result is found for braking on wet road compared to braking on dry road.

In two test sets the quietest tyre is also the performance winner for handling on wet road. These concern different sizes of the same tyre designation, and in both test sets these tyres have a degraded aquaplaning performance.

The performance winner for handling in other test sets can produce up to 4 dB(A) more noise.

Appendix C: EPREL Database overview

Each tyre in the EPREL database for tyres contains a number of properties which can be used for database query. An overview of all available properties in the database is given below:

- additionalInfos
  - id
  - language
  - orderNumber
  - text
- allowEPRELLabelGeneration
- aspectRatio (*)
- blocked
- calculatedEnergyClass (*)
- commercialName (*)
- contactDetails
  - addressBloc
  - city
  - contactByReferenceId
  - contactReference
  - countOfModelsUsed
  - countOfPublishedVersionsUsing
  - country
  - defaultContact
  - email
  - id
  - municipality
  - orderNumber
  - phone
  - postalCode
  - province
  - serviceName
  - status
  - street
  - streetNumber
  - webSiteURL
- contactId
- dateEndProductionWeek
- dateEndProductionYear
- dateStartProductionWeek
- dateStartProductionYear
- energyClass (*)
- energyClassComparisonIndex
- energyClassImage
- energyClassRange
- energyLabelId
- EPRELRegistrationNumber
- exportDateTS
- externalRollingNoiseClass (*)
- externalRollingNoiseValue (*)
- firstPublicationDate
- firstPublicationDateTS
- formType
- generatedLabels
- iceTyre (*)
- implementingAct
- importedOn
- lastVersion
- loadCapacityIndex (*)
- loadCapacityIndex2
- loadCapacityIndex3
- loadCapacityIndex4
- loadCapacityIndicator (*)
- modelIdentifier
- onMarketEndDate
- onMarketEndDateTS
- onMarketFirstStartDate
- onMarketFirstStartDateTS
- onMarketStartDate
- onMarketStartDateTS (*)
- orgVerificationStatus
- organization
  - blocked
  - businessRegisterId
  - closeDate
  - closeStatus
  - constructedEUID
  - EPRELSuggestedOrgIdentifier
  - firstName
  - identityTypeReference
  - isClosed
  - lastName
  - modelTransferActive
  - organisationIdentifier
  - organisationName
  - organisationTitle
  - supplierTypes
  - website
- otherIdentifiers
  - modelIdentifier
  - orderNumber
  - type
- placementCountries
  - country
  - orderNumber
- productBlockAndUnblockLogs
- productGroup
- productModelCoreId
- publishedOnDate
- publishedOnDateTS
- registrantNature
- rimDiameter (*)
- severeSnowTyre (*)
- sizeDesignation (*)
- sizeDesignationFiltered (*)
- skipScaleValidation
- speedCategorySymbol (*)
- speedCategorySymbol2
- status
- supplierOrTrademark (*)
- trademarkId
- tyreClass (*)
- tyreDesignation (*)
- tyreSection (*)
- uploadedLabels
- versionId
- versionNumber
- visibleToUkMsa
- wetGripClass (*)

Table C.1 provides an overview of the fields that are used for the analysis.

Table C.1: Relevant tyre properties from the EPREL database used in analysis.

Relevant tyre properties	
tyreClass	onMarketStartDate
tyreSection	onMarketEndDate
aspectRatio	externalRollingNoiseValue
rimDiameter	externalRollingNoiseClass
loadCapacityIndex	wetGripClass
loadCapacityIndicator	energyClass
speedCategorySymbol	severeSnowTyre
	iceTyre

The **tyreClass** property relates to the field of application of the tyre. These can be divided into three groups:

- passenger car tyres (C1),
- light truck tyres (C2) and
- heavy truck tyres (C3)

The following properties relate to size, load and velocity index of a tyre, where between brackets an example is given for a tyre with designation 195/55R16 87 V:

- **tyreSection:** width of the tyre (195)
- **aspectRatio:** ratio of tyre height versus rim radius (55)
- **rimDiameter:** rim diameter (R16)
- **loadCapacityIndex:** load index (87), see Table C.2
- **loadCapacityIndicator:** additional load classifier, see Table C.4
- **speedCategorySymbol:** speed rating (V), see Table C.3

Regarding noise categorization, two properties are available: **externalRollingNoiseValu**e and **externalRollingNoiseClass**. The first is a noise value in the unit's dB (decibel), the second is the regulated tyre noise label, represented by a letter A, B or C. Noise label A represents the lowest level of noise.

The properties **wetGripClass** and energyClass are other tyre label categories, represented with letters A to F and A to G respectively. The **wetGripClass** provides an indication of the grip behaviour (related to safety) in wet road conditions. The **energyClass** indicates the amount of energy consumption of the tyre, derived from rolling resistance.

And lastly, the properties **severeSnowTyre** and **iceTyre** are used to exclude these special tyres from the study as requested in the Terms of Reference (ToR).

Table C.2: Tyre Load Index (referred to as loadCapacityIndex in the EPREL database) and load at reference pressure.

Load Index	Load [kg]	Load Index	Load [kg]	Load Index	Load [kg]	Load Index	Load [kg]	Load Index	Load [kg]
		80	450	100	800	100	800	120	1400
		81	462	101	825	101	825	121	1450
62	265	82	475	102	850	102	850	122	1500
63	272	83	487	103	875	103	875	123	1550
64	280	84	500	104	900	104	900	124	1600
65	290	85	515	105	925	105	925	125	1650
66	300	86	530	106	950	106	950	126	1700
67	307	87	545	107	975	107	975		
68	315	88	560	108	1000	108	1000		
69	325	89	580	109	1030	109	1030		
70	335	90	600	110	1060	110	1060		
71	345	91	615	111	1090	111	1090		
72	355	92	630	112	1120	112	1120		
73	365	93	650	113	1150	113	1150		
74	375	94	670	114	1180	114	1180		
75	387	95	690	115	1215	115	1215		
76	400	96	710	116	1250	116	1250		
77	412	97	730	117	1285	117	1285		
78	425	98	750	118	1320	118	1320		
79	437	99	775	119	1360	119	1360		

Table C.3: Speed rating (referred to as speedCategorySymbol in the EPREL database).

Rating	Speed [km/h]	Rating	Speed [km/h]	Rating	Speed [km/h]
B	50	K	110	S	180
C	60	L	120	T	190
D	65	M	130	U	200
E	70	N	140	H	210
F	80	P	150	V	240
G	90	Q	160	W	270
J	100	R	170	Y	300
				ZR	>240

Table C.4: Possible values for the loadCapacityIndicator.

Load range	Abbreviation
Light Load	LL
Standard Load	SL
Extra Load	XL
Reinforced	RF

General statistics

The EPREL database contains close to 130.000 tyres in total. As can be seen in Figure C-1: Number of database entries per tyre class., the majority of them are C1 tyres.

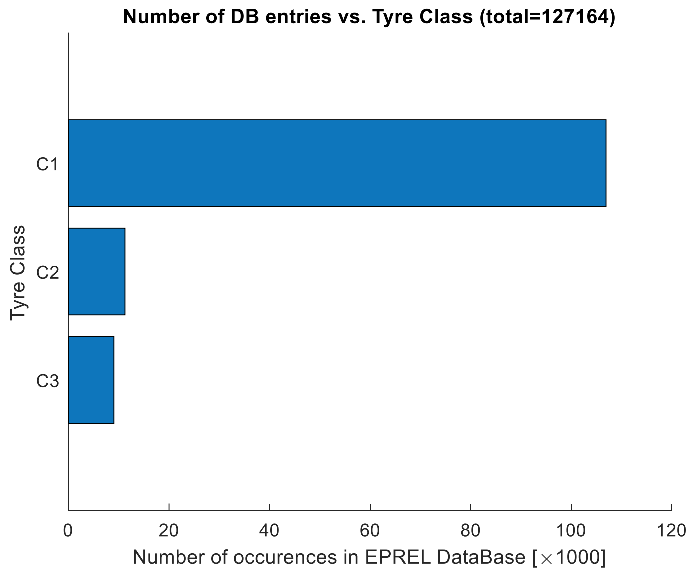


Figure C-1: Number of database entries per tyre class.

Figure C-2 shows the distribution of the tyre sections for all of the C1 tyres in the database. From the figure it can be seen that tyre sizes between 195 and 255 are most represented.

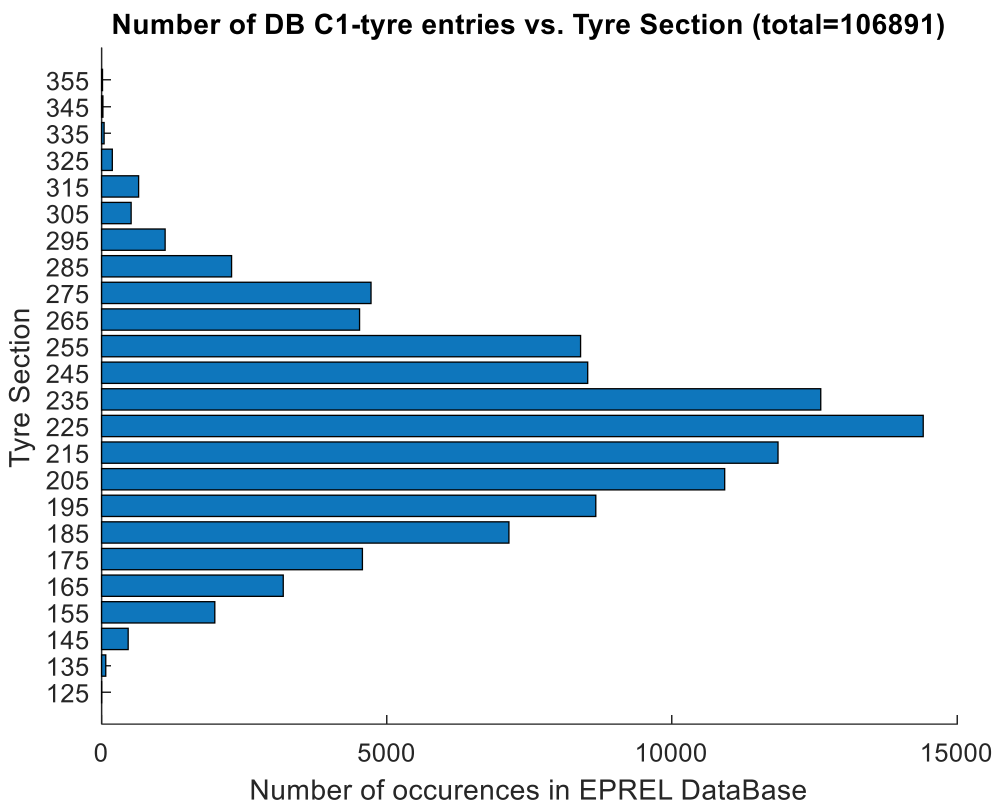


Figure C-2: Distribution of tyreSection property for all C1 tyres in the database.

Noise classification for C1 tyres

Figure C-3 shows the distribution of the tyre noise classes for all of the C1 tyres in the database. As can be seen, most of the registered tyres have a B-label for noise. It should be noted that different tyres brands or types are available for each designation, possibly including a variant with an A-label. This is investigated further below for the most popular tyres.

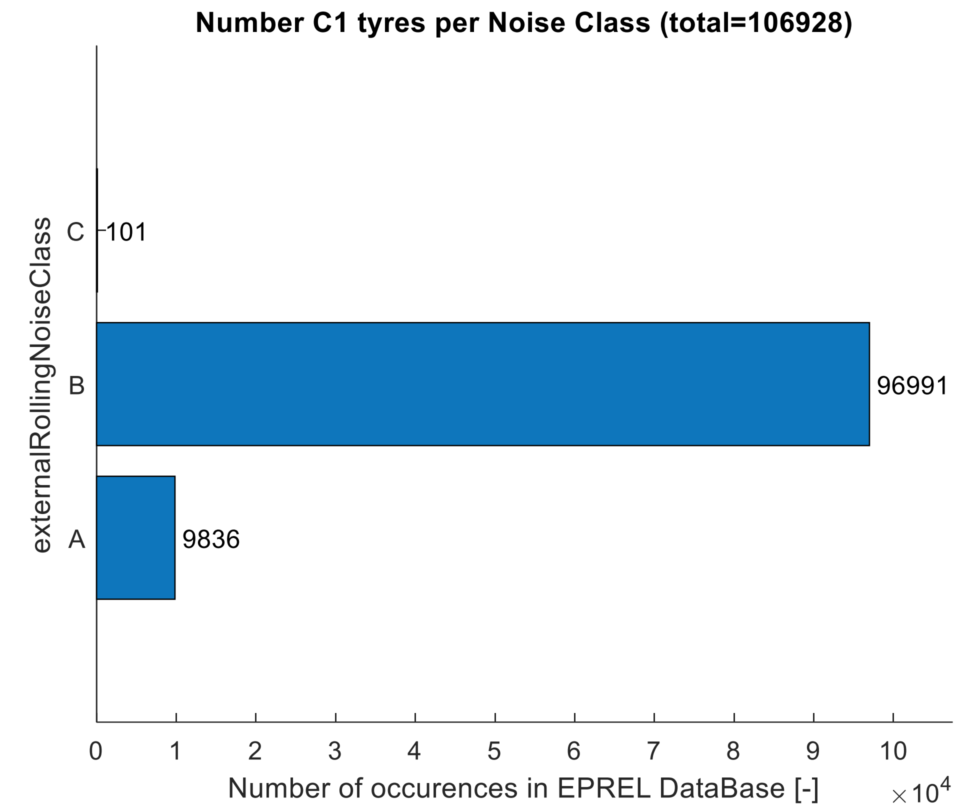


Figure C-3: Noise category for all C1 tyres in the database.

Figure C-4 shows the distribution of the tyre sections for all of the C1 tyres with noise label A.

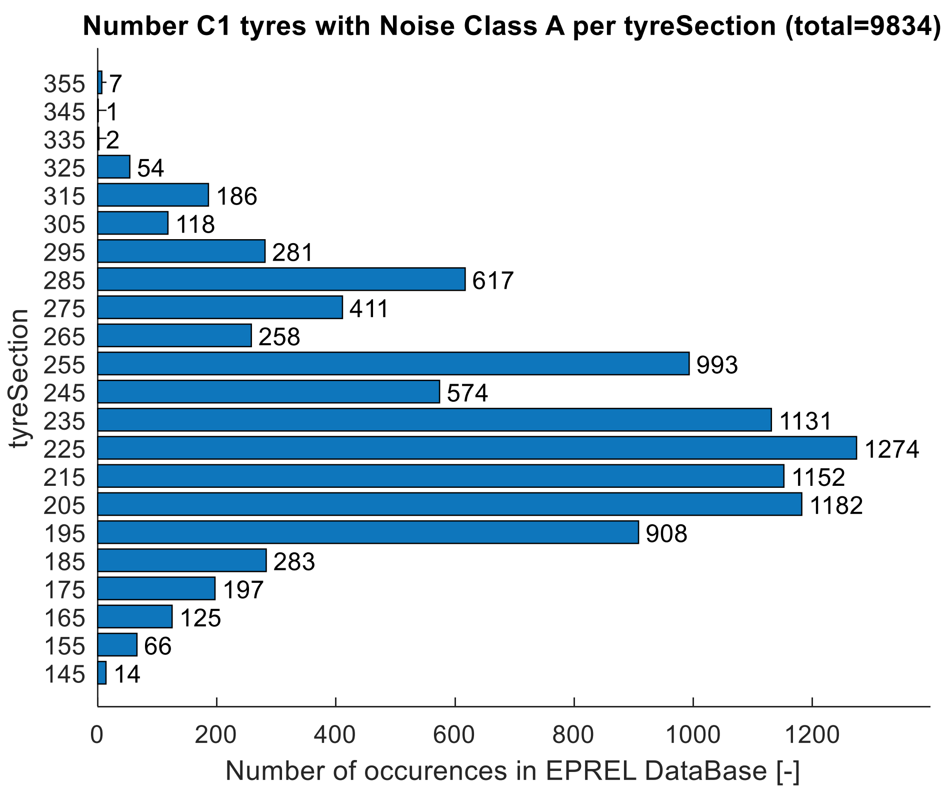


Figure C-4: Distribution of C1 tyres with an A-label for noise.

Appendix D: Impact modelling of tyre noise reduction

The methodology to estimate reductions in sound immission levels and health impacts is based on that applied in the MN sound limits study and the Phenomena study, with some modifications:

- the reference year is 2024 instead of 2017. This results in a lower contribution from vehicle propulsion noise than in 2017 as the vehicle fleet complies with stricter noise limits over time.
- a range of tyre noise level reductions are included in steps from 1 to 5 dB, whereas previously only 4 dB was considered.
- for the tyre labels the averages based on the EPREL database were used. For C1 tyres the average noise level was set at 71 dB, versus 70 dB in previous studies.
- monetized health impacts are not analysed, and no quantitative CBA is performed due to lack of data on non-noise related tyre parameters.

For the fleet evolution, the same percentage increases for EVs and HEVs over time are used as previously.

Average roadside noise levels are expected to be higher in 2024 than in 2017 due to traffic growth and the increase in heavier cars such as SUVs, EVs and HEVs. The actual reduction in roadside noise levels due to lower average tyre noise levels only, between 2017 and 2024 (i.e. disregarding propulsion noise), is estimated to be less than 1 dB.

The methodology is summarized below, adopted from the MN sound limits study, which in turn was adapted from the Phenomena study. It was developed to cope with a variety of noise mitigation solutions over time and is therefore broader than only for tyre noise mitigation.

The available END noise exposure distributions of 2017 are used as a starting point. Noise level changes are calculated for the period 2024-2045 and are applied to the 2017 exposure distributions. This is illustrated by the following examples for road traffic:

- For the baseline scenario, the noise levels gradually change due to various effects:
    - Autonomous traffic growth (typically 1% per year for road traffic),
    - Gradual change of vehicle fleet with increasing numbers of hybrid and electric vehicles.
- For an alternative scenario such as quieter tyres, additional noise level reductions may be achieved.

If, for example, all vehicles were to become 5 dB quieter, then all noise levels on the noise map would decrease by 5 dB. The level change of 5 dB is applied to the 2017 exposure distribution, which results in a changed exposure distribution for the years after which the solution has been implemented. This is illustrated in Figure D-1 and Table D.1.

The health effects (expressed in three ways) are calculated for the two scenarios from the exposure distributions. Finally, the difference between the effects for the two scenarios is equal to the health benefit for the noise solution.

A positive value for the health benefit represents an improvement. i.e. a situation where health effects (annoyance, sleep disturbance, myocardial infarction, DALYs, Euros) are lower for the alternative scenario than for the baseline scenario.

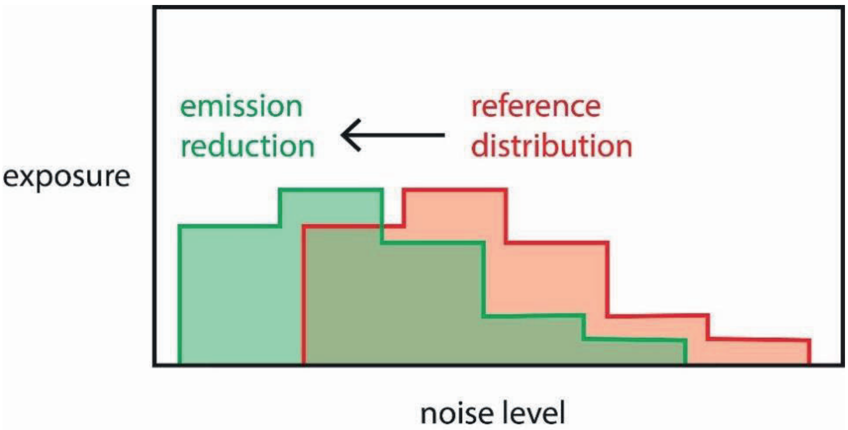
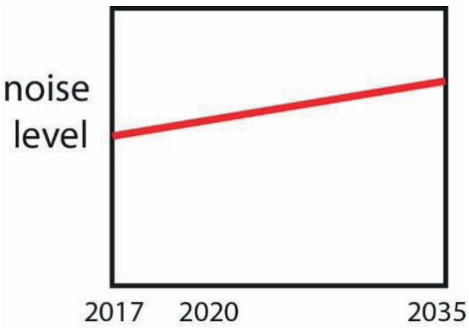
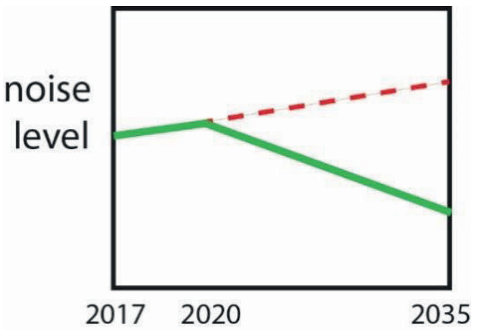
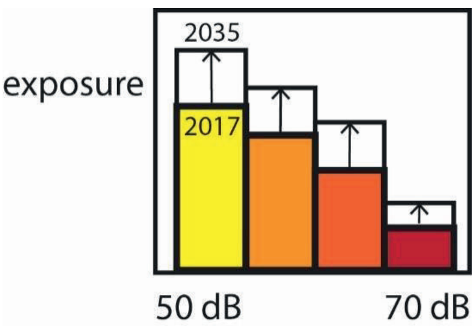
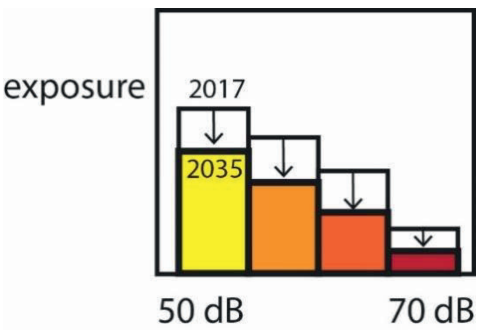
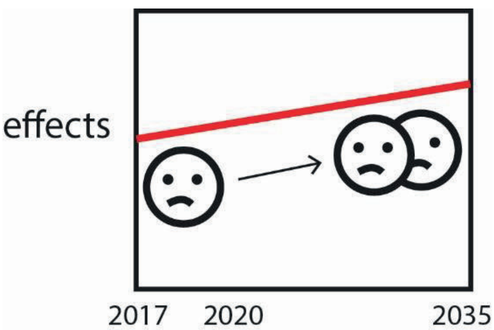
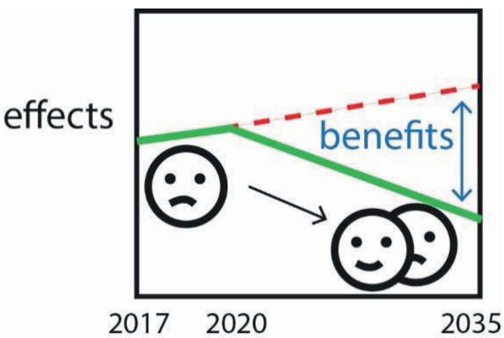


Figure D-1: Illustration of the effect of an emission reduction on the reference exposure distribution (Source: Phenomena Study).

Table D.1: Illustration of methodology for calculating health effects for a baseline scenario and an alternative scenario. The difference between the two is equal to the health benefits. (Source: Phenomena Study).

<table>
<tr><th></th><th>baseline scenario</th><th>alternative scenario</th></tr>
<tr><td>traffic emission levels</td><td>
</td><td>
</td></tr>
<tr><td>exposure</td><td>
</td><td>
</td></tr>
<tr><td>effects</td><td>
</td><td>
</td></tr>
</table>

Exposure distributions
The END prescribes that exposure distributions must be calculated both for Lden and for Lnight. The distributions are illustrated schematically in Figure D-2. The values of Lden and Lnight are given in 5 dB intervals. The heights of the five bars in a distribution represent either absolute numbers of people or percentages of people exposed to the five level intervals (this is explained further below). The distributions depend on many parameters, such as traffic parameters, road network, population density, infrastructure and topography. The calculated exposure distributions are subject to uncertainties due to uncertainties in the input parameters. In addition, there are uncertainties due to model limitations and approximations. It should be noted that different (national) noise models have been used for calculating the distributions for the various EU Member States, resulting in an averaged overall EU distribution.

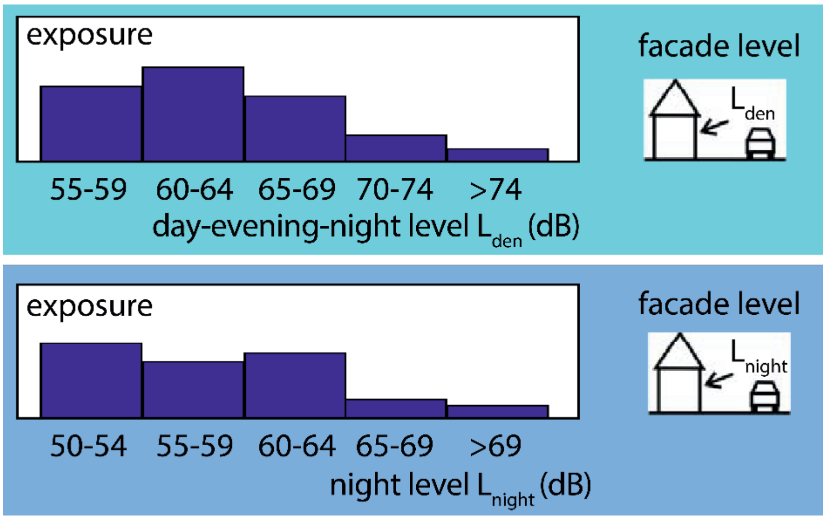


Figure D-2: Schematic illustrations of END exposure distributions with Lden (top) and Lnight (bottom).

Figure D-3 shows EU average exposure distributions for road traffic noise in urban agglomerations, derived from the END data for 2017. The END data is not complete, as data from many agglomerations was not reported. Data from 229 agglomerations was used here, with a total population of 84 million. The exposure in Figure D-3 is expressed as a percentage of the total population. The total EU urban population is around 334 million (excluding UK) – i.e. four times higher than the agglomerations total. By expressing the exposure as a percentage, the distributions in Figure D-3 can be used also for the EU.

Summing over the 5dB intervals in Figure D-3 yields a total exposure with Lden ≥ 55 dB of 44.8%. For the population of 84 million this corresponds to 37.7 million. For the population of 334 million in EU urban areas this corresponds to about 150 million. This linear extrapolation to the total urban EU population is an approximation. It is assumed that the END data, which is based on cities with inhabitants of 100,000 and higher, also applies approximately to cities with a population of less than 100,000.

Figure D-4 shows EU summed exposure distributions for major roads outside agglomerations, derived from the END data for 2017. In this case the exposure is expressed not as percentages, but as the absolute number of persons exposed in millions. The data for major roads is assumed to be more complete than the data for agglomerations, based on the data submitted to the EEA. The total road length represented by the data is about 350,000 km, as follows from the data on the EEA website.

The differences with previous mapping rounds in 2012 and 2017 are relatively small, although some fixed uncertainty over 2007-2017 cannot be excluded.

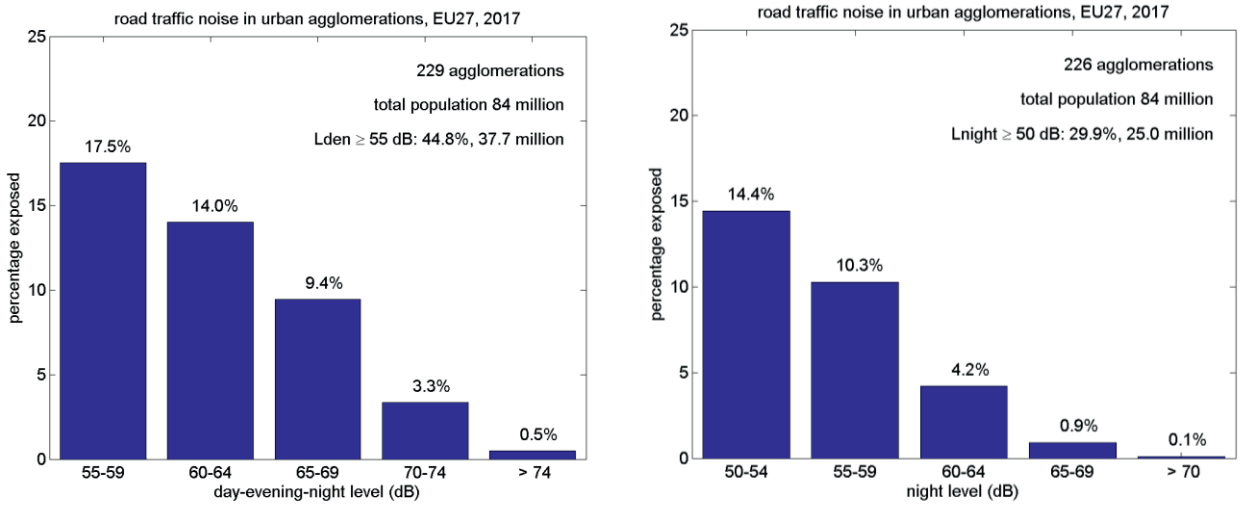


Figure D-3: EU average exposure distributions for road traffic noise in agglomerations, based on the END data for 2017. Note: 3 agglomerations did not provide night data.

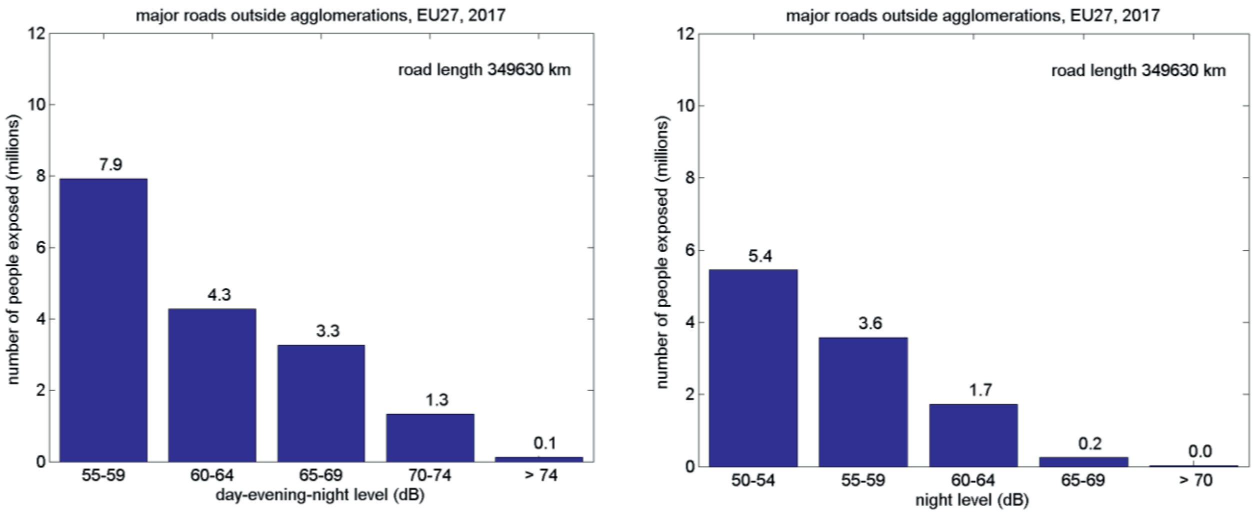


Figure D-4: EU summed exposure distributions for noise from major roads outside agglomerations, based on the END data for 2017.

Extrapolation below the END exposure limits

For the application of the health impact assessment methods described in previously, the exposure distributions were extrapolated to include two 5dB intervals below the END exposure limits of 55 dB Lden and 50 dB Lnight[4,5]. Results are shown in Table D.2 and Table D.3 for Lden and Lnight respectively. For road traffic noise in urban areas, the extrapolation approach developed in the project Heimtsa[6] is used here:

$$P_1 = 1/3 \text{ Prem}, \; P_2 = 2/3\, P_{rem}, \text{ with } P_{rem} = 100 - (P_3+P_4+P_5+P_6+P_7). \quad (1)$$

Here P_j is the percentage exposure of interval j (j=1-7), where j=3-7 correspond to the original distribution with five intervals. This is an approximation. The form of the

4 "Methodological guidance for estimating the burden of disease from environmental noise", World Health Organization 2012.
5 "Implications of environmental noise on health and wellbeing in Europe", Eionet report – ETC/ACM 2018/10.
6 E. Salomons, D. van den Hout, S. Janssen, U. Kugler, V. Máca, "Method for predicting future developments of traffic noise in urban areas in Europe", proceedings Internoise 2010, Lisbon, Portugal.

exposure distribution depends on the precise layout of buildings and roads in a city[7]. For major roads outside urban areas, the following approximation is used:

$$N_1 = N_3 + 2\,\Delta N,\ N_2 = N_3 + \Delta N, \text{ with } \Delta N = \max(0, N_3\text{-}N_4). \qquad (2)$$

Here Nj is the absolute exposure (in millions) of interval j (j=1-7), where j=3-7 correspond to the original distribution with five intervals. The approach is used both inside and outside urban agglomerations. Again, this is an approximation.

Table D.2: EU27 exposure (in millions) as a function of Lden, for the year 2017, including extrapolated values below the END limits (first 2 columns are extrapolated).

Lden range (dB)	45-49	50-54	55-59	60-64	65-69	70-74	>75	total
urban	61.37	122.75	58.50	46.79	31.53	11.17	1.64	333.75
non-urban	15.23	11.58	7.93	4.28	3.27	1.33	0.13	43.74

Table D.3: EU27 exposure (in millions) as a function of Lnight, for the year 2017, including extrapolated values below the END limits (first 2 columns are extrapolated).

Lnight range (dB)	40-45	45-49	50-54	55-59	60-64	65-69	70-74	total
urban	77.96	155.92	48.17	34.31	14.01	3.05	0.32	333.75
non-urban	9.18	7.31	5.45	3.58	1.73	0.25	0.03	27.53

Effect of noise abatement solutions on the exposure distributions
In principle, the effect of a noise solution (at source) is straightforward. If the emission of a source is reduced by 5 dB, for example, then received sound levels due to this source are all reduced by 5 dB. In practice, however, there are many different sources, such as motorways and urban streets, with different emission reductions. Therefore, the approach is to first calculate a weighted average emission reduction over all sources, and next apply this reduction to the reference exposure distribution (from 2017 END data).

Some road traffic noise solutions require a detailed consideration of various types of roads in an urban agglomeration. For example, quiet road surfaces are more effective on motorways than on low speed urban streets. Therefore, use is made of a model for calculating the noise level change that takes into account different road types, based on a model previously developed for the Netherlands[8,9]. The model distinguishes various road types: residential streets, arterial roads, main roads, motorways, with a further distinction between urban and nonurban roads, and also between intermittent or free flowing traffic. The model allows for a noise solution to be implemented only on some of the different road types.

Method for calculating the health burden and the costs of noise
Two different calculation methods are used for the calculation of health effects:
- Method 1, described in a handbook on the external costs of transport[10,]
- Method 2, developed in the framework of EU project Heimtsa.

For both methods, the EU exposure distributions with 5 dB intervals are used as input. The distributions are extrapolated below the lower limits of 55 dB Lden and 50 dB Lnight as described previously.

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7 E.M. Salomons and M. Berghauser Pont, “Urban traffic noise and the relation to urban density, form, and traffic elasticity.” Landscape and Urban Planning 108 (2012) 2-16.
8 M. Dittrich, F. de Roo, “Beleidsindicator geluid wegverkeer” (Policy Indicator for road traffic noise), TNO-report June 2015, TNO 2015 R10673.
9 M. Dittrich, J. Sliggers, “A policy indicator for road traffic noise emission”,Proceedings Internoise, Hamburg 2016
10 “Handbook on the external costs of transport”, January 2019, report prepared by H. van Essen (CE Delft) et al for the European Commission.

Method 1 yields the total external costs of health effects caused by noise[11]. Method 2 also yields the total costs, but in addition, numbers of affected people are calculated, as well as numbers of healthy life years lost (DALYs). By using both methods, a broader picture of the health burden is provided than with a single method. The costs estimated with method 1 are considerably higher than the costs estimated with method 2, up to a factor of 4. This difference reflects the fact that noise impact assessments are subject to a large uncertainty.

Figure D-5 gives a simple graphical illustration of method 2. The elements in the figure, such as exposure-response relations, are described in the subsections below.

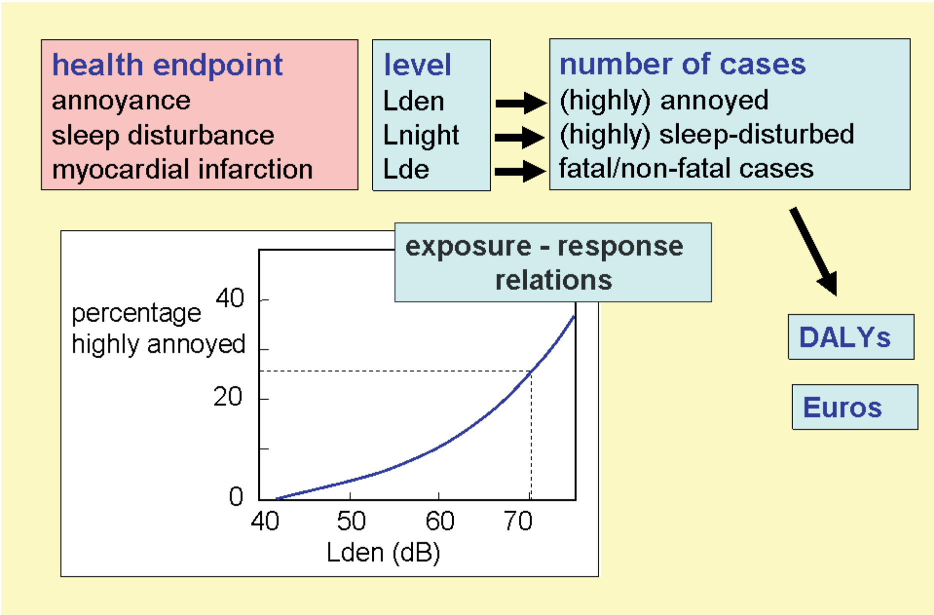

Figure D-5: Illustration of method 2 for calculating health effects of noise. The exposure response relation for high annoyance by road traffic noise is shown as an example. Source: Heimtsa report.

Effects of noise, exposure-response functions

Long-term exposure to environmental noise causes various negative health effects[12]:

- annoyance,
- sleep disturbance,
- myocardial infarction / cardiovascular disease,
- tinnitus,
- cognitive impairment in children.

The focus here is on the first three effects: annoyance, sleep disturbance, and myocardial infarction[13], following the approach in EU project Heimtsa. The prevalence of these effects is calculated with exposure-response functions (ERFs). For example, there is an ERF for the percentage of annoyed persons in a population as a function of the façade level Lden. There is also an ERF for the percentage of highly annoyed persons[14], which is shown in Figure D-6. Similar ERFs are available for sleep disturbance, with the noise level Lnight as exposure level. For myocardial infarction an ERF has been derived

11 The costs of the health effects of noise (or the "costs of noise") are also referred to as monetized health effects of noise. These should be distinguished from the costs of noise solutions.
12 "Burden of disease from environmental noise. Quantification of healthy life years lost in Europe", WHO publication, 2011.
13 The EU health burden contributions of the three health effects annoyance, sleep disturbance, and myocardial infarction are much larger than the contributions of tinnitus and cognitive impairment in children (EEA 2018).
14 The category 'highly annoyed' represents all people with annoyance ratings higher than 72 on a rating scale from 0 (not annoyed at all) to 100 (extremely annoyed). The category 'annoyed' represents people with annoyance ratings higher than 50. The categories 'highly sleep-disturbed' and 'sleep-disturbed' are defined analogously.

that yields the odds ratio[15] for myocardial infarction as a function of exposure level Lden or Lday,16h, which is the equivalent level over the period 7h-23h. The ERFs have been derived from the results of a large number of surveys of the effects of noise.

Exposure-response functions (ERFs) are used for annoyance and sleep-disturbance, developed by Miedema and co-workers and reported for WHO in 2011[12] and 2009[16]. In 2018, WHO published new ERFs for high annoyance (HA) and high sleep-disturbance (HSD)[17]. The new ERFs are given in the form of tables with percentages HA and HSD at levels Lden and Ln in 5 dB steps. The ERFs of Miedema and WHO are compared in the graphs below. Also shown are the graphs of ERFs of Miedema for Annoyed (A) and Sleep Disturbed (SD).

Since there are no ERFs of WHO for Annoyed and Sleep disturbed (only for high annoyance and high sleep disturbance), the previously used Miedema ERFs for road are used.

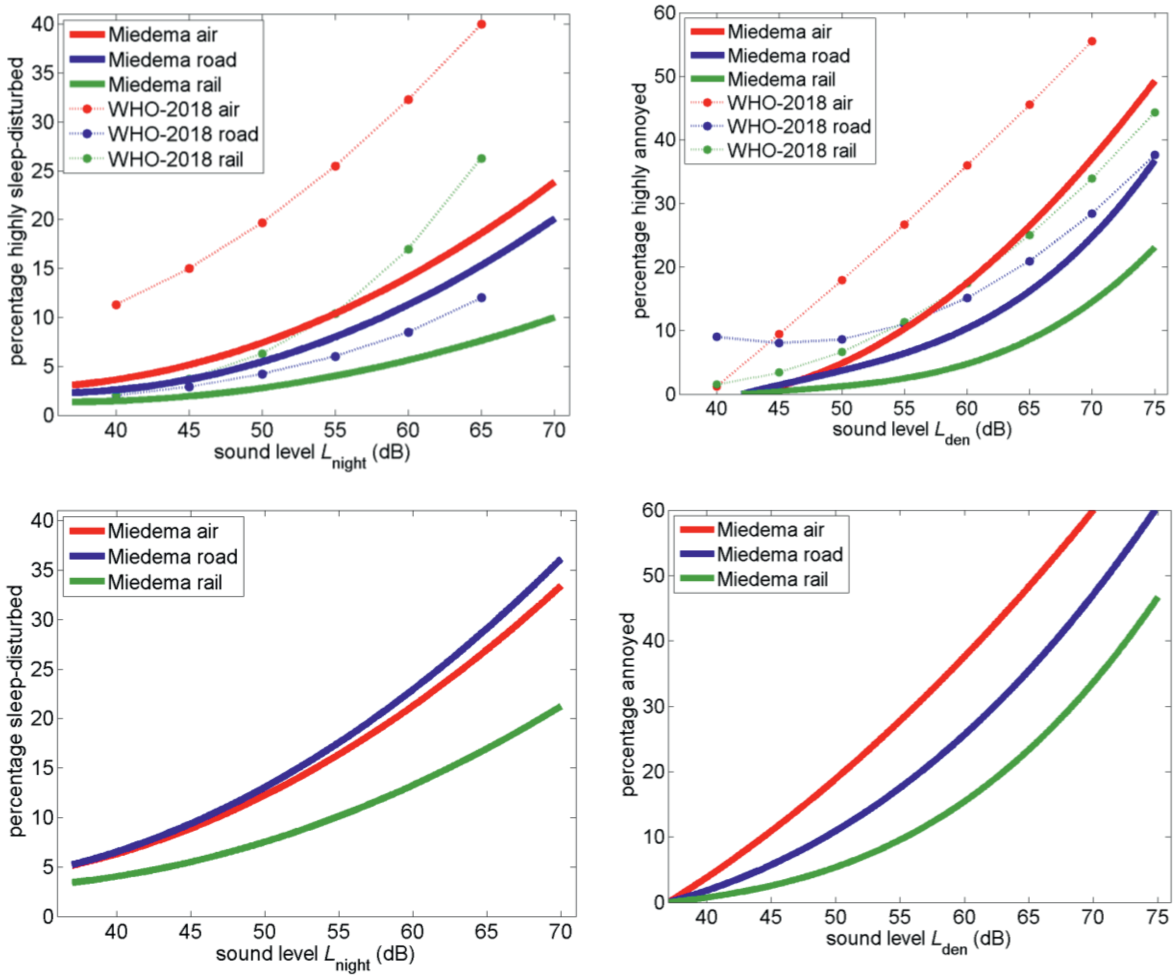

Figure D-6: Exposure-response functions for high annoyance, high sleep disturbance, annoyance, and sleep disturbance.

DALYs

For method 2, the health effects are expressed in DALYs (Disability Adjusted Life years), or ‘healthy life years lost’. The DALYs are calculated from the numbers of people that are highly annoyed, highly sleep disturbed, and people affected by myocardial infarction.

15 The odds ratio is a good approximation of the relative risk, from which the percentage of myocardial infarction cases attributable to environmental noise is calculated.
16 “Night noise guidelines for Europe”, World Health Organization 2009, http://www.euro.who.int/document/e92845.pdf
17 Environmental Noise Guidelines for the European Region, WHO, 2018.

A DALY weight of 0.02 is used for 'high annoyance' and 0.07 for 'high sleep disturbance'. For myocardial infarction, the definition DALY = YLL + YLD is used. Here the number of life years lost, YLL, is equal to the number of fatal cases (25% of the total number) multiplied by the mean number of life years lost per case (8 years). The years lost due to disability, YLD, is equal to the number of non-fatal cases multiplied by the DALY weight of 0.405[18].

Monetary valuation
The methodology includes a monetary valuation of the health burden. Ideally the valuation includes all changes in welfare caused by the noise, including for example medical expenses for treatment, lost wages, and a change in life expectancy or premature death. As indicated before, two different methods are used for monetary valuation, method 1 and method 2.

Monetary valuation with method 1
Method 1 is based on a table of values for the costs of environmental noise, reflecting the welfare loss per decibel increase. The values are based on studies reported in the literature and are reproduced here in Table D.4. For a given Lden level the costs over the lower dB bands are integrated. Below 50 dB Lden the costs are zero.

Table D.4: Values of the costs of traffic noise for the EU28, in units of Euro/dB/person/year.

Lden (dB)	Road annoyance	health	total
50-54	14	3	17
55-59	28	3	31
60-64	28	6	34
65-69	54	9	63
70-74	54	13	67
>74	54	18	72

A distinction is made between two contributions to the costs of noise, one from annoyance and one from health; sleep disturbance is assumed to be part of annoyance[19]. The cost increase with increasing sound level is also in line with the general shape of the exposure-response relations. A threshold of 50 dB is assumed, which means that effects are neglected below 50 dB. The total integrated costs for a person exposed to 62 dB road traffic noise, for example, is calculated as follows:

$$5 \times 17 + 5 \times 31 + 2 \times 34 = 308 \text{ Euros/person/year.}$$

The total integrated costs for the EU are calculated by combining the table with the EU exposure distributions.

Monetary valuation with method 2
Method 2 for monetary valuation of the effects of noise is based on an extensive literature survey. As described before, a distinction is made between three health endpoints: annoyance, sleep disturbance, and myocardial infarction.

- For annoyance, a fixed cost of 85 Euro per annoyed person per year, based on

18 The total values are used, referred to here as health costs, since annoyance and sleep disturbance are considered also as health effects.
19 In the present study the total values in are used, referred to here as health costs, since annoyance and sleep disturbance are considered also as health effects.

HEATCO[20], is used[21].
- For sleep disturbance, the costs are calculated in terms of productivity loss caused by high sleep disturbance, with a value of 2% of EU average GDP per employee[22].
- The total costs for myocardial infarction are calculated from the morbidity costs (7300 Euro per case) and the costs of life years lost with 40 000 Euro per life year[23].

In the Heimtsa project it has been found that monetary values calculated with method 2 are about a factor of 2 lower than monetary values calculated from the DALYs for the three endpoints, using the monetary value of a life year indicated above. A difference of a factor of 2 may be considered as a good agreement for this type of calculation. Monetary valuation via the DALYs has also been used or considered in other studies[24]. The approach of the EEA calculator of health effects and costs[25] is similar to the approach of Heimtsa.

Road traffic noise emission model

For road traffic noise, the methodology described in the foregoing is based on the following EU exposure distributions for the year 2017:
- exposure distributions for urban agglomerations (Lden and Lnight),
- exposure distributions for major roads outside agglomerations (Lden and Lnight).

Effects of noise abatement solutions (and autonomous developments) in the period 2017-2035 are taken into account by estimating a change of the 2017 exposure distributions. This is illustrated schematically in Figure D-7.

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20 S. Navrud, Y. Trædal, A. Hunt, A. Longo, A. Gressmann, C. Leon, R. Espino, Markovits-Somogyi, F. Meszaros (2006) Economic values for key impacts valued in the Stated Preference surveys, Deliverable four, HEATCO – Developing Harmonized European Approaches for Transport Costing and Project Assessment, available at https://www.yumpu.com/en/document/view/2210784/.
21 The value of 85 Euro per annoyed person (including highly annoyed persons) is based on the HEATCO project and is valid for road and rail traffic noise. For aircraft noise, the same value is used as for road and rail traffic noise (HEATCO gives no value for aircraft noise). This is based on the fact that in Method 1 the values for aircraft noise are about a factor of 2 higher than for road traffic noise, which approximately corresponds with the difference between the exposure-response functions for road traffic noise and aircraft noise.
22 This is based on Godet-Cayré et al., "Insomnia and absenteeism at work. Who pays the cost?", Sleep Vol. 29, 2006, pp. 179-184. The same value of 500 Euro is used as in the HEIMTSA project, since the variation of the GDP since 2011 is negligible (https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=EU).

23 The contribution from myocardial infarction is typically one order of magnitude smaller than the contributions from annoyance and sleep disturbance. In the literature, various values have been used for the value of a life year. A value of 78 500 Euro is used, for example, in "Environmental noise in Europe – 2020", EEA report No. 22/2019. A value of 110 987 Euro is used in "Evaluation of Directive 2002/49/EC relating to the assessment and management of environmental noise", EC report, 2016. In the present study the value of 40 000 Euro is used, which was used in the Heimtsa project.
24 "Environmental noise: valuing impacts on sleep disturbance, annoyance, hypertension, productivity and quiet", Defra report, November 2014, www.gov.uk/defra
25 "Noise Health and Costs Calculatorv3 EEA", excel file downloaded from the CIRCA website.

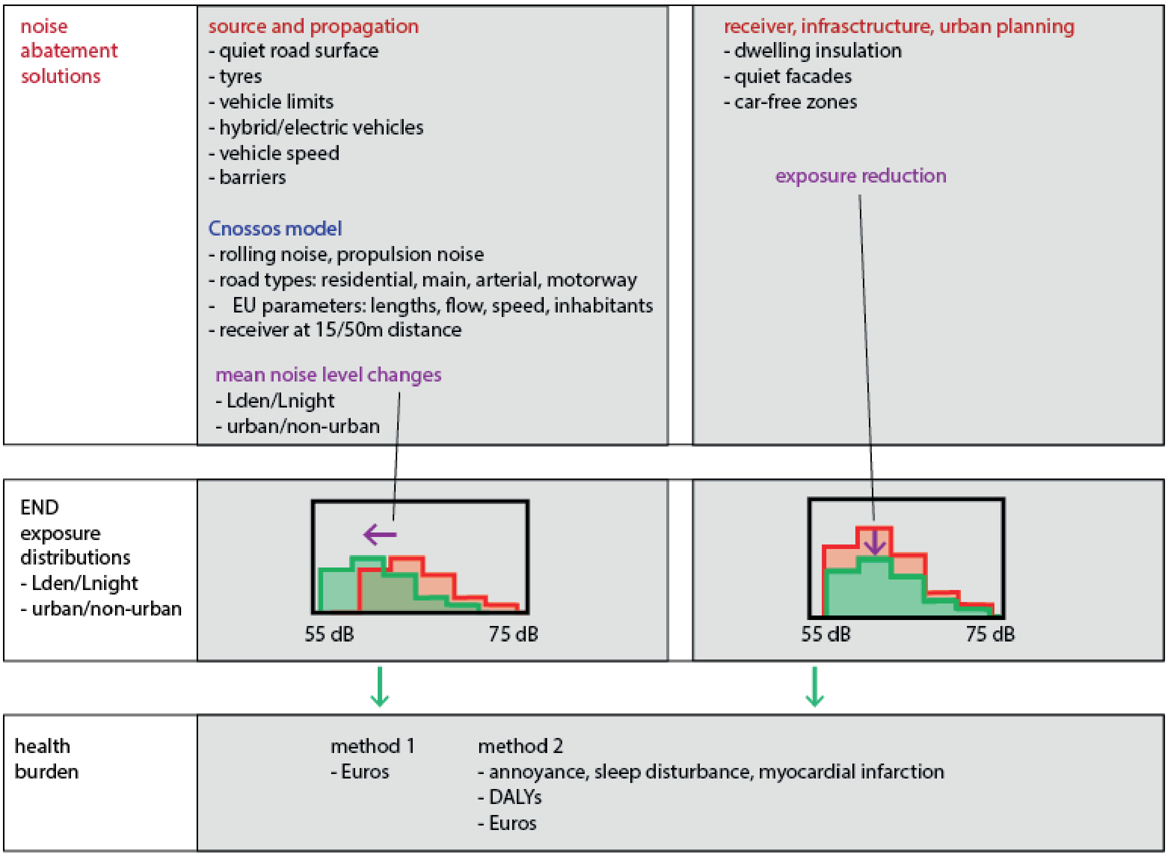

Figure D-7: Illustration of the effects of different types of noise abatement solutions on the END exposure distributions, which are used to calculate the (reduced) health burden.

The average noise level change due to noise abatement at source is calculated with an environmental model for road traffic noise emission. The model yields average noise levels Lden and Lnight along eight different types of roads[26]. Noise levels $\mathrm{Lden}_{,j}$ and $\mathrm{Lnight}_{,j}$ are calculated for each year in the period 2017-2045 (j = 2017, 2018, …, 2045). From these levels noise level changes are calculated:

$$\Delta \mathrm{Lden,j} = \mathrm{Lden,j} - \mathrm{Lden,j{=}2017} \qquad (11)$$

$$\Delta \mathrm{Lnight,j} = \mathrm{Lnight,j} - \mathrm{Lnight,j{=}2017}. \qquad (12)$$

The level changes are zero for year *j* = 2017, and gradually change over time. The level changes are different for the baseline scenario and the alternative scenario with the noise solution.
The road traffic noise emission model takes into account:

- the emission of individual road vehicles (calculated with the Cnossos model),
- intensities and speeds of the vehicles on the different types of roads.

The model has been developed for situations in the Netherlands[27,28,] and was adapted for this study by using parameters appropriate for the EU. The most important elements of the model are described below; for details, the reader is referred to the references[27,28].

Eight road types are distinguished in the model, also previously defined in the Venoliva study and subsequent studies:

1) urban residential streets with intermittent flowing traffic,

26 These noise levels are not true emission levels, but rather noise levels at short distance from the roads.
27 M. Dittrich, F. de Roo, “Beleidsindicator geluid wegverkeer”, TNO-report June 2015, TNO 2015 R10673.
28 M. Dittrich, J. Sliggers, “A policy indicator for road traffic noise emission”, Internoise, Hamburg 2016

2) urban residential streets, free flowing traffic,
3) urban main roads, intermittent flowing traffic,
4) urban main roads, free flowing traffic,
5) urban arterial roads,
6) urban motorways,
7) non-urban motorways,
8) nonurban main roads.

For residential streets and main roads, 1/3 of the overall road length is assumed to have intermittent traffic flow with acceleration and deceleration, whereas 2/3 of overall road length has free traffic flow: Intermittent traffic is mainly around crossings, junctions and accelerating & decelerating traffic applies to residential and main roads. Dense traffic, saturated traffic and congestions are more temporary and not relevant for Lden, due to shorter time and lower noise levels. They might be more relevant for exhaust emissions, depending on the behaviour. Inhabited road lengths of the 8 types were estimated for the EU, and also numbers of inhabitants per km (see Table D.5). Vehicle intensities and speeds were also estimated for the different road types (Table D.6). The fleet composition varies with road type. For example, the percentage heavy vehicles (trucks) is generally higher on non-urban motorways than on residential streets.

For each road type four subtypes are considered[29]:
i) roads with a standard road surface,
ii) roads with a standard road surface and noise barriers,
iii) roads with a quiet road surface,
iv) roads with a quiet road surface and noise barriers.

This results in 4x8 =32 different road types. For road types 5-8 in the EU 5% is assumed with a quiet road surface. These are applied far less on road types 1-4 with lower speeds.

From the vehicle intensities and speeds for the different road types and the vehicle emission model (described below), noise levels Lden and Lnight are calculated at a distance of 15 m (non-motorway) or 50 m (motorway) from the road. For sound propagation, only geometrical spreading of sound waves is taken into account. Ground attenuation and air absorption are neglected. For barrier attenuation a mean reduction of 10 dB is applied[30].

Table D.5: Lengths of eight road types (inhabited) and numbers of people along the roads.

	Type		Inhabited length (km)	Number of people per km
1	Residential street, intermittent	Urban	1/3 * 965652	250
2	Residential street, free	Urban	2/3 * 965652	250
3	Main road, intermittent	Urban	1/3 * 199796	500
4	Main road, free	Urban	2/3 * 199796	500
5	Arterial road	Urban	94118	500
6	Motorway	Urban	3824	1000
7	Motorway	Non-urban	34141	50
8	Main road	Non-urban	1517922	20

Table D.6: Parameters of the vehicle flow on the eight road types

29 The distinction between roads with a standard road surface and a quiet road surface is made because it is assumed noise barriers are first put along road sections with a quiet road surface.
30 In practice, barrier attenuation varies due to variations of barrier height and other geometrical parameters. For a 5 m barrier along a road, the typical attenuation is 10 dB. For practical reasons, only this typical value is considered.

	Type		Vehicle flow (vehicles per 24h)	Speed C1/C2/C3[31] (km/h)
1	Residential street, intermittent	Urban	500	30 / 30 / 30
2	Residential street, free	Urban	500	50 / 40 / 40
3	Main road, intermittent	Urban	20000	50 / 40 / 40
4	Main road, free	Urban	20000	50 / 50 / 50
5	Arterial road	Urban	33700	80 / 70 / 70
6	Motorway	Urban	48500	100 / 85 / 85
7	Motorway	Non-urban	48500	115 / 85 / 85
8	Main road	Non-urban	16000	80 / 80 / 80

Cnossos vehicle emission model with corrections

In order to calculate the emission of individual vehicles, the Cnossos model for vehicle noise emission is used[32]. The implementation of Cnossos for this study is described in this section and is illustrated in Figure D-8. The Cnossos model has separate contributions from propulsion noise and rolling noise. Three vehicle categories[33] are considered:

- light vehicles (C1),
- medium-heavy vehicles (C2),
- heavy vehicles (C3).

Other vehicle types such as motorcycles are not included here. The reason for this is that the other vehicle types have a very limited contribution to the year-averaged Lden and Lnight levels at EU level, and they are normally not included in END noise-mapping calculations. When the vehicles of categories C1-C3 become quieter in the future, contributions from the other vehicle types may become more important.

A correction term is applied[27,28] to make the Cnossos noise emission model match the Dutch and German models. The correction term is 4 dB for light vehicles and 5 dB for medium heavy and heavy vehicles. The underestimation of road vehicle emission levels by Cnossos has been found also in other studies performed in the Netherlands and is partly due to a mismatch between the emission model and the propagation model in Cnossos[34].

The Cnossos model contains the following emission corrections:

- correction for quiet road surfaces,
- correction for vehicle acceleration at crossings or other obstacles,
- correction for studded tyres.

The correction for quiet road surfaces depends on frequency and driving speed. The same correction is used in the Dutch calculation method[35]. To keep the methodology practical for the purpose of this study, the non-spectral version of the Dutch method was

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31 See Cnossos subsection below.

32 “Commission Directive (EU) 2015/996, of 19 May 2015, establishing common noise assessment methods according to Directive 2002/49/EC of the European Parliament and of the Council”. Official Journal of the European Union. 19 May 2015. The annex describes the calculation method “Cnossos-EU” of simply “Cnossos”.

33 The annotation C1-C3 is also used for tyres but there it covers slightly different vehicle ranges.

34 RIVM report 2019-0023, “Amendments for CNOSSOS-EU”, Table 16.29.2.

35 Dutch calculation methods for environmental noise: Reken- en meetvoorschrift geluid 2012 (RMG2012), Staatscourant Nr. 11810, 27 juni 2012. For road and rail traffic noise, a non-spectral method SRM1 is described and a spectral method SRM2.

implemented. In line with this, the Dutch model was also used for the correction for vehicle acceleration, which is applied for roads with intermittent traffic flow. The correction for studded tyres in the CNOSSOS model is replaced by a more general correction for quiet tyres.

This formulation of the vehicle emission model makes it possible to calculate the effects of the following noise reduction measures, for the three vehicle types:

A. vehicle emission reductions (propulsion noise correction)
B. reduction by quiet tyres (rolling noise correction)
C. reduction by a quiet road surface (rolling noise and propulsion noise correction).

For the vehicle emission reductions (A), six types are considered:

1) 2015: no reduction, fleet as in 2015,
2) 2016: reduction according to 2016 emission limits (540/2014 phase 1),
3) 2020/22: reduction according to 2020/22 emission limits (540/2014 phase 2),
4) 2024/26: reduction according to 2024/26 emission limits (540/2014 phase 3),
5) hybrid vehicles: reduction of propulsion noise by 5 dB (mainly for plug-in hybrids),
6) electric vehicles: reduction of propulsion noise by 10 dB.

The first two vehicle groups are included as they are also in the current and future fleet until replaced.

The values of the vehicle emission corrections $\Delta L_{W,veh}$ are given in Table D.7, for five vehicle categories. The conversion to categories C1-C3 is as follows:

$$\Delta L_{W,veh}(C1) = 10 \log_{10} (0.9\ 10^{(\Delta LW,veh(car)/10)} + 0.1\ 10^{(\Delta LW,veh(van)/10)}) \quad (13)$$

$$\Delta L_{W,veh}(C2) = 10 \log_{10} (0.1\ 10^{(\Delta LW,veh(bus)/10)} + 0.9\ 10^{(\Delta LW,veh(truck)/10)}) \quad (14)$$

$$\Delta L_{W,veh}(C3) = \Delta L_{W,veh(heavy\ truck)} \quad (15)$$

The reduction of tyre noise (B) is also a type of vehicle emission reduction but is included here as a separate reduction. It is quantified by the tyre label. The correction for tyre noise reduction is calculated with the following formula[27]:

$$\Delta L_{W,\ tyre} = (L_{label} - L_{label,mean}) \cdot f_{road} \quad (16)$$

where Llabel is the tyre label, Llabel,mean is the mean tyre label (see Table D.8), and froad is a factor given by

$$froad = a + b \cdot v \quad (17)$$

where v is the vehicle speed in km/h and a and b are coefficients given in Table D.7 for the five road surface types considered in this study (see below).

For the reductions by a quiet road surface (C), the following five road surface types are considered (abbreviation in the Dutch model in brackets. These surfaces are also applied in other countries):

1) standard surface, dense asphalt concrete (DAB)
2) thin top layers (DGD)
3) porous asphalt (ZOAB)
4) double-layer porous asphalt (ZOAB2L)
5) double-layer porous asphalt fine (ZOABF2L).

The emission correction is zero for road surface type 1. The correction for quiet road surfaces is calculated with the following formula based on the Dutch calculation method[36].

$$\Delta LW, \text{surface} = s + t \;.\; \log_{10}(v/vref) \qquad (18)$$

where reference speed Vref is equal to 80, 70, and 70 km/h for vehicle categories C1-C3, respectively. This correction is applied both for rolling noise and propulsion noise, but for propulsion noise t=0 is used. The values of the coefficients s and t are given in Table D.10.

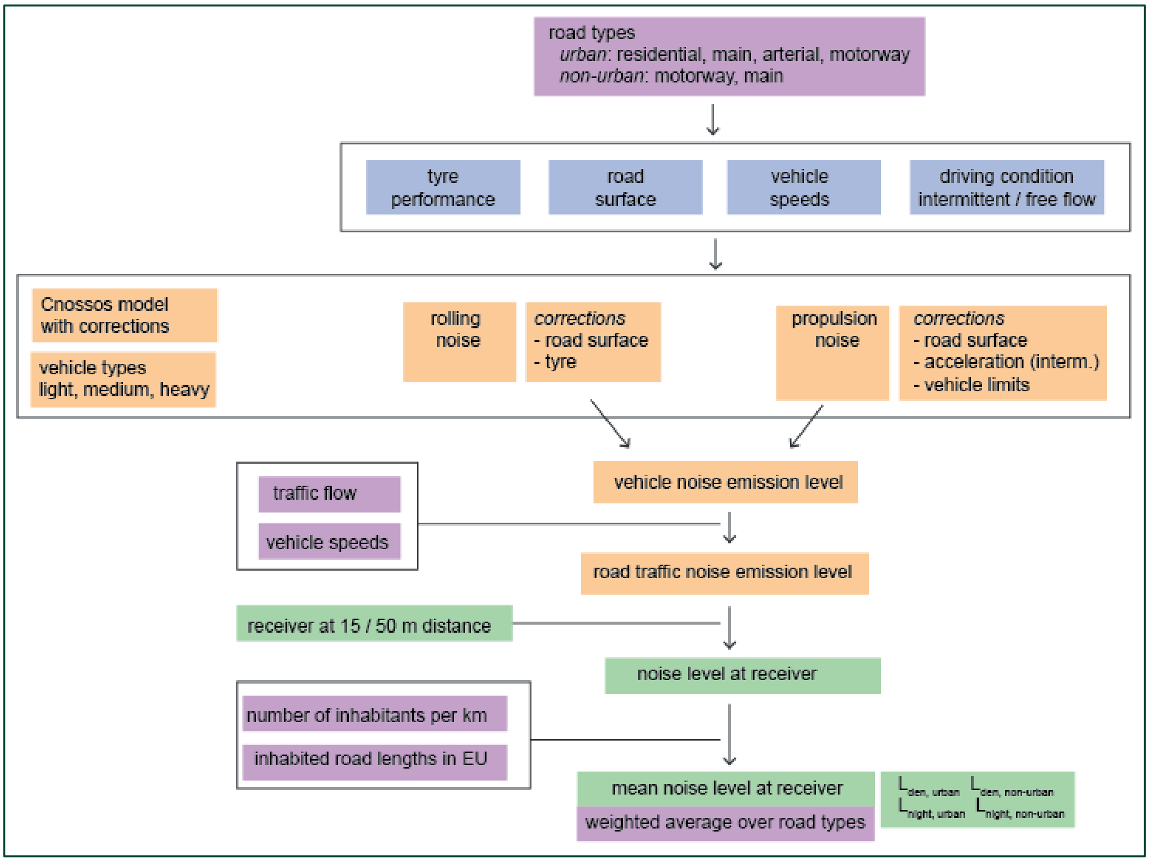

Figure D-8: Implementation of the Cnossos model for this study. The final mean noise levels ($L_{den,urban}$, $L_{den,non-urban}$, $L_{night,urban}$, $L_{night,non-urban}$) are used for modification of the END exposure distributions, as illustrated in Figure D-7.

36 Dutch calculation methods for environmental noise: Reken- en meetvoorschrift geluid 2012 (RMG2012), Staatscourant Nr. 11810, 27 juni 2012. For road and rail traffic noise, a non-spectral method SRM1 is described and a spectral method SRM2.

Table D.7: Vehicle emission corrections (propulsion noise) for six emission limits / vehicle types and five vehicle categories.

Vehicle category	2015 dB	2016 dB	2020/22 dB	2024/26 dB	Hybrid dB	Electric dB
car, C1	0	-0.186	-2.1	-4.1	-5	-10
van, C1	0	-0.186	-2.1	-4.1	-5	-10
bus, C2	0	0	-1.8	-2.8	-5	-10
truck, C3	0	0	-1.8	-2.8	-5	-10
heavy truck C3	0	0	-1.5	-3.5	-5	-10

Table D.8: Minimum, maximum, and mean tyre labels, for tyre categories C1-C3, based on EPREL database for C1 tyres.

Tyre category	minimum dB(A)	maximum dB(A)	Mean dB(A)
C1	64	72	71
C2	69	76	72
C3	70	78	75

Table D.9: Coefficients a and b for the tyre noise correction, for vehicle categories C1-C3 and road surface types 1-5 (1=Dense asphalt concrete, 2= thin top layers 3= porous asphalt 4=double-layer porous asphalt, 5=double-layer porous asphalt fine).

Vehicle category	coefficient	1	2	3	4	5
C1	a	0.7167	1	0.4203	0.5288	1
	b	0.000621	0	-0.000690	-0.000493	0
C2	a	0.6661	0.95	0.3607	0.6	0.95
	b	0.0008036	0	-0.001786	0	0
C3	a	0.6038	0.9	0.2188	0.7	0.9
	b	0.001164	0	0.005822	0	0

Table D.10: Coefficients s and t for the road surface correction[37], for vehicle categories C1-C3 and road surface types 1-5 (1=Dense asphalt concrete, 2= thin top layers 3= porous asphalt 4=double-layer porous asphalt5=double-layer porous asphalt fine).

Vehicle category	coefficient	1	2	3	4	5
C1	s	0	-3.4	-1.4	-4.5	-6.5
	t	0	-2.5	-6.5	-3.0	-0.1
C2	s	0	-1.3	-3.1	-5.2	-5.3
	t	0	0.5	0.2	4.7	-0.8
C3	s	0	-1.3	-3.1	-5.2	-5.3
	t	0	0.5	0.2	4.7	-0.8

Baseline scenario

The baseline scenario (Business as Usual, BAU) is defined by the situation for road traffic noise in the reference year, and its autonomous development in the period until 2045. Traffic growth, if sufficiently large and continuous, can increase the health burden and in some cases cancel out the effects of noise abatement efforts. A 1% annual growth in traffic from 2020 leads to a total growth of 28% by 2045. In general, parameters of a baseline scenario for road traffic noise are:

- Infrastructure length/size and characteristics,
- Traffic volume and fleet characteristics,
- Foreseen evolution of vehicle source levels,
- Foreseen evolution of scale and effectiveness of noise abatement solutions,
- Population density and exposure near infrastructure,

37 Road surface correction terms for the Dutch road noise calculation method 2012

- Urban and rural spatial planning and land use.

Each of these parameters change with growth of traffic, infrastructure and land use. They also can strongly interact with developments in other domains such air quality, safety, and energy consumption.

The average numbers of exposed people and exposure levels for each road type are set out in Figure D-9 for the baseline in the MN limits study. These are based on the input parameters and model described in the previous section. The 2024 baseline has slightly higher Lden values due to traffic growth over time and the applied tyre label values from the EPREL database. The evolution of the vehicle fleet and its percentages of vehicles that fulfil each sound limit phase is shown in Table D.11. Also the assumed average tyre labels and road lengths are set out in this table, which for the baseline remain unchanged over time.

In this analysis, the baseline scenario includes forecasts from the EC reference scenario[38]. The developments in the baseline scenario reflect existing noise reduction solutions based on existing legislation (whereas additional noise reduction solutions are considered as elements of alternative scenarios). The annual traffic growth of 1% is based on EU growth figures[38] for passenger and freight road traffic.

The 2016 EU reference scenario[38] forecasts the following percentages for hybrid and electric vehicles in 2030: 25% hybrid and 2% electric. From a more recent EC document[39] and communication with the EC[40], the following values were derived, showing interpolation in brackets:

- cars
  - Hybrid 6% in 2030 (3% in 2025, 9% in 2035)
  - Electric 14% in 2030 (7% in 2025, 21% in 2035)
- vans
  - Hybrid 6% in 2030 (3% in 2025, 9% in 2035)
  - Electric 8% in 2030 (4% in 2025, 9% in 2035)
- buses
  - Hybrid 7% in 2030 (3.5% in 2025, 10.5% in 2035)
  - Electric 18% in 2030 (9% in 2025, 27% in 2035)
- trucks (heavy goods)
  - Hybrid 16% in 2030 (8% in 2025, 24% in 2035)
  - Electric 1% in 2030 (0.5% in 2025, 1.5% in 2035).

These new values were used here and were linearly extrapolated to 2045, assuming zero values in 2020 as an approximation (in 2018 there were 0.8% hybrid and 0.2% electric in the EU[41]). In addition, the expected development of the EU population is taken into account in the baseline scenario. A total EU population of 445 million in 2017 is assumed (excluding UK). It is assumed that 75% live in urban areas[42]. A value of 0.1% is assumed for annual population growth[38].

For this analysis it is assumed that the average lifetime of a vehicle is 12 years for passenger cars, vans & busses and 13 years for trucks[43], whereas the average lifetime

38 “EU reference scenario 2016 energy, transport and GHG emissions trends to 2050”, See: https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf
39 EC document 2020, “Investing in a climate-neutral future for the benefit of our people”, https://eur-lex.europa.eu/legal-ontent/EN/TXT/HTML/?uri=CELEX:52020SC0176&from=EN
40 Email from Marco Paviotti DG Environment, 8 October 2020
41 European Automobile Manufacturers Association, “Vehicles in use, percentage share 2018”.
42 “The state of European Cities 2016”. Eurostat https://ec.europa.eu/eurostat/statistics-explained/
43 Average vehicle lifetime can vary widely depending on type and country, see also ACEA report ‘Vehicles in use Europe’, January 2021

of a tyre is between 3 years for trucks and 4 years for light vehicles. For the baseline scenario no reductions for tyre noise are foreseen in this period upto 2045.

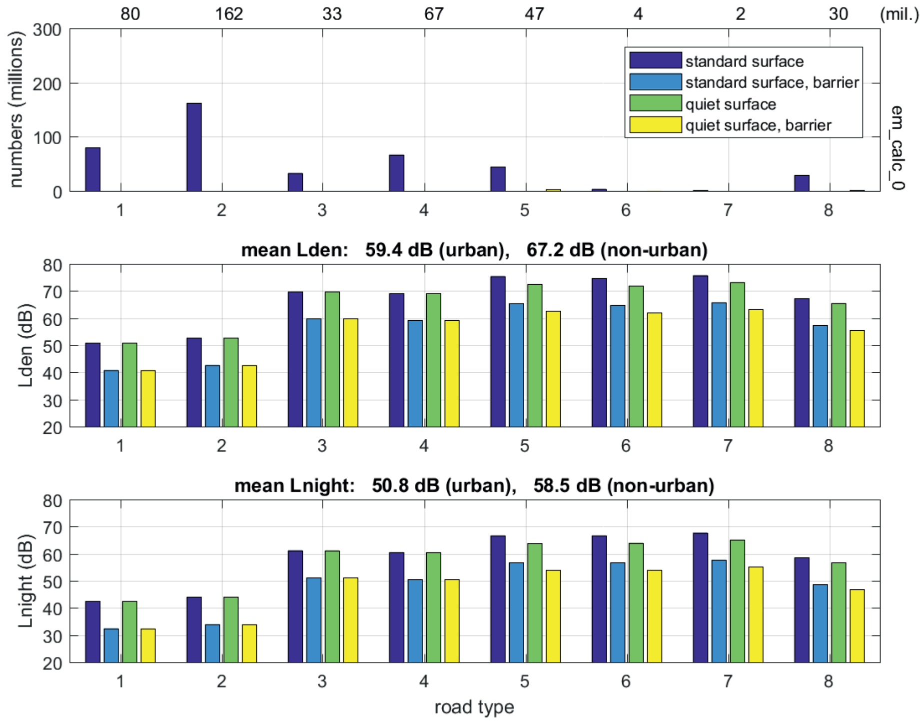

Figure D-9: Exposure data for the 2017/2020 baseline scenario from the MN limits study. Top: millions exposed along road types 1 to 8 (most are near standard surface roads without barriers); middle and bottom: average Lden and Lnight exposure levels per road type and averages for urban/non-urban.

Table D.11: Emission model parameters for the baseline scenario in the MN study illustrating the evolution of the fleet in terms of sound limits and road characteristics.

Percentage compliance with vehicle emission limits

vehicle limits 2017-2020

vehicle	2015	2016	2020/22	2024/26	hybrid	electric
car/C1	100	0	0	0	0	0
van/C2	100	0	0	0	0	0
bus/C3	100	0	0	0	0	0
truck/C3	100	0	0	0	0	0
heavy truck/C3	100	0	0	0	0	0

vehicle limits 2035

vehicle	2015	2016	2020/22	2024/26	hybrid	electric
car/C1	0	0	0	50	15	35
van/C2	0	0	0	65	15	20
bus/C3	0	0	0	37	18	45
truck/C3	0	0	0	57	40	3
heavy truck/C3	0	0	0	57	40	3

Tyre label

tyre label 2017-2020		tyre label 2045	
C1	70	C1	70
C2	72	C2	72
C3	75	C3	75

Traffic growth

annual traffic growth percentage 2017-2045 : 1.0

Road lengths

roads 2017-2020

1-2	3-4	5	6	7	8[1]	
965652	199796	94118	3824	34141	1517922	km inhabited road length
250	500	500	1000	50	20	inhabitants per km
0	0	4706	191	1707	75896	km barrier
0	0	4706	191	1707	75896	km quiet road length
1	1	2	2	3	3[2]	type quiet road surface

roads 2045

1-2	3-4	5	6	7	8	
965652	199796	94118	3824	34141	1517922	km inhabited road length
250	500	500	1000	50	20	inhabitants per km
0	0	4706	191	1707	75896	km barrier
0	0	4706	191	1707	75896	km quiet road length
1	1	2	2	3	3	type quiet road surface

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