LIFE E-VIA

"Electric Vehicle noIse control by Assessment and optimisation of tyre/road interaction"

LIFE18 ENV/IT/000201

Deliverable	Technical Report Actions A1, A2, A3
Content	Review on noise relevant differences between ICEV and EV tyres
Action/Sub-action	A3: Tyre role in the new context of EV and ICEV
Status - date	Draft Version - 20-07-2020

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Document history

Version	Date	Contributor	Input
1.0	11/08/2020	CRD	Document published

List of keywords and abbreviations

BEV	Battery Electric Vehicle
CPB	Controlled Pass-By
CPX	Close-Proximity
ETRTO	The European Tyre and Rim Technical Organisation
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
HWR	Height-Width-Ratio
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
LI	Load Index
OE	Original Equipment
PHEV	Plug-in Electric Vehicle
RPM	Rounds Per Minute
SL	Standard Load
SPL	Sound Pressure Level
SUV	Sports Utility Vehicle
XL	Extra Load

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Executive Summary

It is the LIFE E-VIA project's objective to reduce road traffic noise in future electric vehicle (EV) dominated urban scenarios. For this, holistic approaches for the optimization of road surfaces and EV tyres are used which aim to improve traffic noise while maintaining good performance in other relevant criteria such as rolling resistance or wet grip. This combined with a Life Cycle Cost approach to ensure a best practice approach.

As a part of the project three preparatory actions are carried out. These consist of state-of-the art studies on major topics surrounding road traffic noise in future EV dominated urban areas: the noise emission from EVs (preparatory action A1), quiet pavement technologies (preparatory action A2), and the tyre role in the context of the change from conventional internal combustion engine vehicles (ICEV) to EVs (preparatory action A3).

Action A3 aims at identifying the role of the tyre in the context of EVs vs. ICEVs with respect to rolling noise and related target conflicts, e.g. rolling resistance. EVs differ from their traditional ICEV counterparts in many technical or design features. Some of these changes can influence the rolling noise created by the interaction of the tyre with the road. The goal of this action is to identify the most relevant of these differences between EVs and ICEVs from a tyre/road noise point of view and derive the necessary design or performance requirements for a holistic low noise tyre for EV applications. This information is used as input for the development of such a tyre in actions B2 and B3 of the project, and the LCA/LCC support in B7.

The exterior noise performance of a tyre cannot be seen isolated from other requirements on the tyre. Legal and market requirements establish constraints which any tyre needs to fulfil. Safe driving requires reliable handling, and good dry and wet grip performance; user acceptance is for example also related to high mileage (i.e. low wear) and good fuel economy (i.e. low rolling resistance). The latter also directly relates to ecological aspects such as a reduction in the emission of CO_2 and other local pollutants. These different tyre performances can never be seen isolated from each other, they are related via the tyre design and construction, and there are many target conflicts between the performances which need to be balanced against each other. For this it is essential to understand the key differences between electric and internal combustion engine vehicles, and what this means for the design of a quiet, efficient and safe tyre for EV applications.

Traffic noise essentially includes power unit noise, tyre/road noise (rolling noise, generated by the interaction between the tyres and the road surface during rolling), and wind turbulence noise. With the progress of modern combustion engines, tyre/road noise dominates above 40 km/h for steady-speed traffic conditions. This threshold can be as low as 20 km/h for electric cars with strongly reduced engine noise, especially under acceleration. Consequently, there is a higher relative contribution of the tyre/road noise to the overall exterior noise for EVs. Similar effects can also be observed for the contribution of the tyre rolling resistance to the vehicle's fuel or energy consumption. Because of higher drivetrain efficiency for EVs the contribution of energy losses in the tyre are of higher relative importance for EVs than for ICEV. This does not only affect the emission of CO_2 and other air pollutants (either directly at the car or indirectly at the powerplant), but also the achievable mileage which is crucial for the public acceptance of EVs. Thus, because of the importance of the tyre rolling resistance for the ecological impact and the market acceptance of an EV, it is a key performance which needs to be addressed in addition to tyre/road noise. For EVs there are fundamental design differences which need to be considered in addition. These parameters are for example increased vehicle loads due to the battery weight which is necessary to provide acceptable mileage, special acceleration/deceleration behaviour due to the different torque characteristic of electrical motors and the recuperation, possible new tyre size trends ("tall-and-narrow") being introduced for mileage, handling or aesthetic reasons, etc.

Under most circumstances an increase in tyre load can be associated with an increase in tyre/road noise. While the extend of this load influence on rolling noise depends on tyre type, speed, road surface and inflation pressure, an increase in SPL of 0.5 dB(A) to 2.5 dB(A) per load doubling has been reported in literature. However, in some cases a reduction in rolling noise for an increase in load has also been observed. This complex behaviour is linked to the fact that a changing tyre load affects tyre/road noise generation and radiation in several ways: tyre sidewall and crown deflection changes, changes of local contact pressure and contact patch size, changes to the tyre/road contact geometry and the resulting radiation amplification, change of interaction between road surface asperities and tyre tread, etc. If an increase in tyre loads necessitates an increase in tyre inflation pressure or tyre construction, further negative effects on tyre/road noise can be expected.

Compared to free rolling conditions, tyre torque due to acceleration or braking can increase tyre/road noise by several dB(A). The extend of this increase is again highly dependent on test conditions; tyre construction, tread profile, and tread compound; driving speed, tyre load and inflation pressure. This increase in noise is caused by micro-scale adhesion and friction mechanisms which are responsible for phenomena like stick/slip and stick/snap which lead to additional tangential vibrations of the tread blocks which are of minor importance under free rolling. Torque effects can be minimized by a suitable choice of tyre construction, compound, and tread design.

The sound radiation from the area close to the contact patch between tyre and road is amplified by the horn-like geometry formed between tyre and road. This amplification is frequency dependent with the maximum usually reached somewhere between 1 kHz and 3 kHz. Even for complex pass-by situations in which distance and angle to the tyre vary continuously and the car body affects the sound propagation, average amplifications of 5 dB to 12 dB per third-octave band have been reported. The amplification is strongly affected by tyre width and road surface, with smaller tyres and higher surface porosity reducing the amplification effect. Tall-and-narrow tyre concepts as employed by some EVs (e.g. the BMW i3) have a significant influence on the amplification from the horn effect, affecting both the frequency and the amplitude of the peak amplification. Even small changes in the amplification can be crucial because tyres are usually designed in such a way that the main excitation orders from the tread block harmonics coincide as little as possible with the main amplification frequencies. Changes in tyre dimensions which significantly alter the horn effect of a tyre thus require a redesign of the tread pattern.

In an analysis of the current and future European EV market it is assessed whether there are systematic differences between EVs and ICEVs which would affect tyre/road noise by any of the previously described mechanisms. The results indicate that on average EVs are between 20% and 25% heavier than ICEVs in curb weight and roughly 10% to 15% in maximum weight. This will negatively influence tyre/road noise generation. Often this is accompanied by an increase in tyre inflation pressure – either for load carrying or rolling resistance reasons – which will further negatively impact rolling noise. Tyre design changes to carry these additional loads are not necessary on a general level because in most cases the tyre load carrying capacity (as indicated by the load index LI) is considerably higher than the maximum allowed vehicle weight.

Definite conclusions regarding EV tyre torque are difficult because of a lack of specific data and the large influence of electronic control systems and driving behaviour. It can be clearly stated that engine torque is in nearly all cases higher for EVs, both in terms of maximum torque as well as the RPM range where this is available. Assuming similar vehicle control systems and driving behaviour to ICEVs this means that tyre torque is potentially also higher for EVs. Combined with observations (see the accompanying A1 report) that over a third of EV fleet users gravitate towards a more aggressive driving behaviour a worst-case assumption of increased tyre torque for EVs seems necessary when optimizing an EV tyre for tyre/road noise.

New tyre size concepts, e.g. tall-and-narrow, are not widely employed for EVs. Contrary, for EVs based on an ICEV platform usually no changes in tyre size are observed. For new EV platforms often only slight adjustments in tyre sizes are noticeable, often in form of a small increase in tyre diameter and/or width. Accordingly, the relation between tyre height and width which is important for the acoustic radiation because of the horn effect mostly stays in the same range as established for classical ICEV applications. There are some prominent exceptions (e.g. BMW i3, Citroën C-Zero) to using well-established tyre sizes, but these vehicles are not representative for the EV market as whole. In summary, for the EV market of today and the foreseeable future there is no need for a special consideration of novel tyre dimensions for the design of a low-noise optimised EV tyre. Thus, the well-established 205/55 R16 91H size is chosen as the basis for the development of a noise optimized EV tyre. The 205/55 R16 size is the most common size in the current European ICEV and EV markets; it is expected to keep this position in the foreseeable future. This assures the highest ecological benefit and the highest return of investment for the development. Because it is used by many current and future ICEVs and EVs, it offers the greatest flexibility in vehicle choice for testing and the planned EV festival.

A load index of 91 is typical for a tyre of this size. The combined load carrying capacity of four tyres of 2460 kg is well above the highest maximum allowed vehicle weight of 2020 kg which is observed in the compact EV segment where this size is predominantly used. Although a standard LI is chosen, on EVs higher tyre loads are expected under operation. Independent of the maximum load carrying capacity, the higher operating loads need to be considered for tyre/road noise optimizations: exterior noise simulations which were carried out within this action highlight the importance of considering relevant and representative operating conditions for the development of the low noise optimized EV tyre. If these conditions are not properly chosen a goal-oriented optimization cannot be guaranteed.

Based on the limited top speeds of EVs, lower than usual speed symbols could be used. Though, this would severely limit the possibility to mount these tyres on ICEVs, e.g. for comparative noise measurements in the project, and is thus not recommended. This leads to a choice of a minimum speed symbol H (210 km/h max. speed).

As it can be assumed that there is a high likelihood that a tyre will be subject to higher torque on an EV than an ICEV, a requirement on the noise optimized EV tyre is that torque-related noise generation mechanisms like stick/slip and stick/snap are minimized, e.g. by special tread pattern designs or tyre constructions. Drum measurements which have been carried out within this action highlight, however, that an overambitious torque optimization can lead to increased tyre/road noise for free rolling. An optimal overall rolling noise performance is only achieved when the EV tyre is optimized for a well-balanced performance under both conditions.

For a safe, ecological, and economical EV tyre not only tyre/road noise is of relevance. Performances such as wet grip or rolling resistance, for example, affect safety, attainable mileage, and the environmental impact of the tyre. For the user acceptance of an EV especially the achievable mileage, i.e. the tyre rolling resistance, is important. With respect to the rolling resistance of the EV optimized tyre the requirement is to develop an optimized tyre which combines the EV requirements of low noise and rolling resistance.

Another important tyre property for safe driving is wet grip. The development of the noise optimized EV tyre needs to assure that any measures taken to improve tyre/road noise do not affect wet grip performance in such a way that label class B cannot be achieved. It shall also be assured that the noise optimized EV tyre will fulfil company and regulatory (e.g. R30 and R117) safety and environmental regulations.

Finally, operating conditions are assumed to reflect a typical EV of the compact segment (e.g. in terms of load, inflation pressure or camber angle) and in view of the project's aim to reduce road traffic noise in urban areas the main focus is for speeds of up to 50 km/h. In relation to the progress of the development of a low noise optimized road surface within this project the tyre development will successively emphasize optimal performance on this surface more and more as results from the road development become available.

1 Introduction

According to data presented by the European Environment Agency (EEA) more than 100 million EU citizens are affected by high noise levels negatively impacting human health. A significant part of this burden is caused by the road transportation sector in the form of traffic noise. A report by the World Health Organization (WHO) [1] estimates that within the EU about 50% of the population are regularly exposed to A-weighted road traffic noise levels exceeding the WHO guideline value for outdoor sound levels of 53 dB(A) [2], and about 10% to A-weighted road traffic noise levels exceeding 65 dB(A), i.e. levels with a 20% to 40% increased risk for cardiovascular diseases [3]. Other possible noise related health problems include cognitive impairment in children, sleep disturbance, tinnitus and annoyance. As a consequence, the WHO assumes that “at least one million healthy life years are lost every year from traffic-related noise in the western part of Europe” [1]. Although the contribution of noise originating from rail and air traffic cannot be neglected, road traffic noise comprises the main burden of this traffic-related noise [1] [4].

Road traffic noise can be separated into a vehicle’s power train noise, rolling noise and aerodynamic noise. For most classical internal combustion engine vehicles (ICEV), including trucks and other heavy vehicles, rolling noise is the dominating noise source at the most common driving speeds of roughly 40 km/h to 100 km/h [5] [6]. Power train noise dominates at lower, and aerodynamic noise at higher speeds. This threshold where the main noise contribution moves from powertrain to tyre/road noise as is even lower for electric cars which have a strongly reduced engine noise, especially under acceleration. Consequently, these vehicles have a higher relative contribution of the tyre/road noise to the overall exterior noise of the vehicle, and tyre/road noise becomes the major noise source already at speeds as low as 20 km/h [7] [8]. This lack of masking powertrain noise at low speeds emphasizes the increased importance of tyre/road noise for the overall traffic noise of an electric vehicle (EV) when compared to a classical ICEV.

Accordingly, the introduction of electric mobility has universally been recognized as one of the best solutions to reduce noise in urban areas. Importantly, this measure also helps with other environmental issues such as air quality and CO_2 emissions. In the WHO guidelines [2] interventions being able to reduce noise exposure by addressing the source, improvements by the choice of appropriate tyres and road surfaces, truck restrictions, and traffic flow lowering are additionally highlighted.

One of the main objectives of the project LIFE E-VIA is to reduce noise for roads inside very populated urban areas through the implementation mitigation measures aimed at providing optimized road surfaces and tyres for modern EVs.

For the optimization of a low noise EV tyre different boundary conditions than for an ICEV application need to be considered. For EVs the relative contribution of the tyre noise to the overall vehicle noise is considerably increased because of the nearly non-existent drivetrain noise. Because of the higher drivetrain efficiency of electrical engines also the tyre rolling resistance has a relatively higher contribution to the energy consumption of an EV than for an ICE vehicle. Depending on how the electric energy used for charging the EV is created, this also can have a significant contribution to the emission of CO_2 and other air pollutants. More importantly, the tyre rolling resistance has a large impact on the achievable mileage of an EV. A large mileage, in turn, is crucial for the public acceptance of EVs as means of transportation. Therefore, a low noise, low rolling resistance tyre is considerably more beneficial for EVs than for comparable ICE vehicles.

Within the action A3 the role of the tyre in the context of EVs versus ICEVs will be identified with respect to rolling noise and related target conflicts, for example rolling resistance. The goal is to gather the relevant input for the development of optimized tyres and the LCA/LCC support in later stages of the project.

For this in Section 2 first properties which might distinguish EVs from ICEVs are analysed in view of their influence on tyre/road noise. This is followed by a short analysis of the current ICEV market in Section 3. This forms the baseline for a subsequent study of the prevailing vehicle and tyre properties on the EV market in Section 4. This analysis considers both vehicles which are currently sold in the European market and vehicles which are scheduled for release in the near future. The data collected in this step is compared to the corresponding characteristics for classical ICE vehicles to identify the key tyre-related differences between these vehicle classes. This information is crucial to identify how the used tyres or the requirements on the tyres differ between the different vehicle types.

In Section 5.1 a requirement book for the holistic noise optimized EV tyre to be developed in action B7 is formulated. This will be based on the special requirements of EVs as identified the previous step and will especially consider the interaction between tyre/road noise and other tyre performances like rolling resistance or wet grip. Both simulations and lab measurements are used at this stage to identify points of special interest.

Finally, a development strategy is outlined in Section 5.2. This forms the basis for the activities in action B7 and ensures that the previously defined requirement book will be fulfilled.

2 Possible influences of EV related changes in tyre characteristics on tyre/road noise

Traffic noise essentially includes power unit noise, tyre/road noise (rolling noise, generated by the interaction between the tyres and the road surface during rolling), and wind turbulence noise. With the progress of modern combustion engines, tyre/road noise dominates over 40 km/h for steady-speed traffic conditions [6] [5]. The exterior noise at lower speeds is dominated by powertrain noise, and by aerodynamic noise sources for speeds above roughly 100 km/h. This threshold where the main noise contribution moves from powertrain to tyre/road noise as is even lower for electric cars which have a strongly reduced engine noise, especially under acceleration. Consequently, these vehicles have a higher relative contribution of the tyre/road noise to the overall exterior noise of the vehicle, and tyre/road noise becomes the major noise source already at speeds as low as 20 km/h [7] [8]. This lack of masking powertrain noise at low speeds emphasizes the increased importance of tyre/road noise for the overall traffic noise of an EV when compared to a classical ICEV.

However, even though the change in engine type is the most fundamental design difference between an ICEV and an EV, it is not the only difference which needs to be considered in relation to tyre/road noise. For example, in a comparison of CPB results for a set of ICEVs and an EV in [9] it was observed that while the EV was less noisy at low speeds where powertrain noise dominates, it was noisier at speeds of 30 km/h to 60 km/h which are dominated by tyre/road noise (see Section 4.1.2 in [10] for a more detailed discussion of the results). This might be related to other design differences between ICEVs and EVs like the increased vehicle loads due to the battery weight which is necessary to provide acceptable mileage; special acceleration/deceleration behaviours due to the different torque characteristic of electrical motors and the recuperation; and new tyre size trends (“tall-and-narrow”) being introduced for mileage, handling or aesthetic reasons. What is necessary is not only to understand how these aspects would affect tyre/road noise, but also whether the observed differences are generally valid assumptions for the complete EV fleet, or if they are just anecdotal observations based on a few examples. The first of these two questions will be answered in Sections 2.1 to 2.3 where it is analysed how increased vehicles weights, increased torque, or different tyre geometries can affect tyre/road noise. In how far the EV fleet differs from the ICEV fleet with respect to these parameters is then analysed in Sections 3 and 4.

2.1 Influence of tyre load

It is well known that in the majority cases there is an increase of tyre/road noise with increasing tyre load. A comprehensive overview of some earlier experimental studies on this topic is given in [6], where it was found that a doubling of tyre load results in a noise increase of roughly 0.7 dB(A) to 1.5 dB(A) if the inflation pressure is not adjusted to the load change, or 1.0 dB(A) to 2.5 dB(A) if the pressure is adjusted. The authors moreover concluded that “tyre/road noise is sensitive to tyre load for most but not all tyres”, that “[…] (this) sensitivity is different for different tyres […]”, that “the load influence is much higher at low speeds than at high speeds”, and finally that “the exact behaviour of noise with varying load is a complicated function of tyre type, speed and road surface”.

More recently, in a study on the tyre load influence on CPX measurements of eleven tyres, Berge and Haukland [11] reported an average increase of tyre/road noise levels of 0.55 dB(A) for an average load difference of 18.1%±7.5%. In [12] the influence of tyre load on tyre/road noise was investigated by simulations. For the overall SPL similar tendencies as already reported in [6] and [11] were reported. However, it was additionally observed that the relative increase in noise per increase of load is lower for lower loads than it is for higher loads. Furthermore, the SPL dropped by roughly 0.5 dB(A) when increasing the load from 4000 N to 4500 N. Similar exceptions to the expected behaviour were already reported in [6] for some special cases. Besides, several studies [6] [12] [13] also investigated the influence of tyre load on the spectrum of the radiated noise. While SPLs were reported to increase for increasing loads for frequencies in the range of 1.0 kHz to 2.5 kHz in [12], decreasing SPLs were observed in [13].

This complex behaviour is probably linked to the fact that a changing tyre load affects tyre/road noise generation and radiation in more than one way: tyre sidewall and crown deflection changes, changes of local contact pressure and contact patch size, changes to the horn-effect (cf. Section 2.3) due to changes in tyre/road contact geometry, changes of radial and tangential force spectra, changes of interaction between road surface asperities and tyre tread, a changed angle of attack for tread block impacts, and changes in the modal content of the tyre vibrations [6] [13] [14] [15]. From a noise point of view many of these mechanisms react negatively on an increase of tyre load. Especially the consequences of changes relating to the horn effect, force spectra or the modal content of the tyre are difficult to predict and might change considerably between different loads. This can explain the observations that for certain load conditions or frequencies rolling noise suddenly decreases even though the load was increased.

Two further aspects which need to be considered in relation to the tyre load are the recommended increase in tyre inflation pressure for increasing load (see e.g. [16]), and a possibly different tyre construction of the tyre when higher loads are already considered during the development of the tyre, for example when considering standard load (SL) vs. extra load (XL) versions of the same tyre and size. Extra load tyres are reinforced versions of a tyre which are designed to carry higher loads at higher inflation pressure than the corresponding standard version tyre. Both the increased inflation pressure and a change in construction towards higher load carrying-capacity are known to increase tyre/road noise levels [6] [14] [15] [17]. For the inflation pressure an increase of 1 dB(A) per 50 kPa increase in inflation pressure has been reported [17]. Because of the huge number of possible changes in tyre construction it is more difficult to quantify changes in tyre noise which are associated with a construction change in a general way. In [18] CPX measurements of 14, apart from different constructions identical, tyres were performed. The maximum difference in CPX levels which was observed was 2 dB(A).

The increase in tyre/road noise is a consequence of the stiffer tyre body which is obtained with both the increase in inflation pressure and a higher load-carrying capacity of the tyre construction. The increased stiffness potentially leads to an increase of wave speed on the tyre, and thus, since faster waves are better sound radiators [19], a better radiation of the tyre vibrations as airborne noise. Additionally, for a given tyre load a stiffer body can create pressure peaks in the contact area between tyre and road. This can lead to a stronger excitation of the tyre from the tyre/road interaction [15].

To sum up, an increase in tyre load can generally be associated with an increase in tyre/road noise. However, under certain conditions or for certain frequency regions exceptions to this rule can be observed. If an increase in tyre loads necessitates an increase in tyre inflation pressure or tyre construction, further negative effects on tyre/road noise can be expected.

2.2 Influence of tyre torque

It has been known for a long time that tyre torque due to acceleration or braking can increase tyre/road noise [6] [20]. The extend of the noise increase ranges from negligible for low torque to 10 dB(A) or more at a torque of 800 Nm [20]. In a more recent study involving drum tests of two regular replacement tyres an increase of up to 7.4 dB(A) was reported for a traction force of 3500 N at 80 km/h on an internal drum test bench [21]. The differences between the tyres varied from 0.4 dB(A) at 30 km/h to 1.8 dB(A) at 80 km/h including a role reversal, i.e. the noisier tyre at 30 km/h was the more silent tyre at 80 km/h. In the same study it was also reported that most of the noise increase occurs for frequencies at and above 1.5 kHz. Most studies show that the observed increase in tyre/road noise due to tyre torque is also highly dependent on test conditions; tyre construction, tread profile, and tread compound; driving speed, tyre load and inflation pressure [6] [20] [21].

The increase in rolling noise under torque can be explained as follows: under free rolling conditions on typical road/surfaces the main source mechanisms for tyre vibrations are time-varying radial excitations of the tyre structure due to the impact of the tread blocks on the road and the indentation of the tread rubber by the road roughness, see Figure 2-1a/b. The resulting waves propagate in the tyre and are finally radiated as airborne noise. With torque micro-scale adhesion and friction mechanisms which are responsible for phenomena like stick/slip and stick/snap become important, too. Stick/slip occurs due to tangential forces in the contact zone which are created by the change in tyre radius, see Figure 2-1c. These forces are resisted by frictional forces between the tread and the road surface. Friction is caused by hysteresis and adhesion, with the latter describing effects like molecular bonding, mechanical interlocking or pressure differences. When the frictional forces can no longer balance the tangential forces, the tread rubber is free to slip over the road surface, causing mostly tangential vibrations of the tread which can both radiate directly as airborne noise and act as source to further tangential excitation of the tyre body. Stick/snap, see Figure 2-1d, occurs when the tyre/road contact is sticky (e.g. for winter tyres on warm days and/or very clean roads). During the separation process at the trailing edge, strong adhesive bonds between the tread rubber and road surface must be overcome. When a certain number of micro-scale contact junctions have been broken, the remaining will break as well. This avalanche-like effect causes a very sudden acceleration (snap-out) of the tread block and maybe also a transient airflow through the opening slid. While stick/snap can also happen under free rolling, it is of special importance under torque conditions. These force the tread blocks to shear in the contact zone. When the blocks snap out of contact to the road at the trailing edge of the tyre/road contact they snap back to their un-sheared geometry. This leads to tangential vibrations of the tread blocks which again radiate as airborne noise and excite the tyre body. This effect explains why measured sound pressure levels under torque are usually higher at the trailing than the leading edge [22].

Concluding, tyre torque can have a significant impact on tyre/road noise. However, effects can be minimized by a suitable choice of tyre construction, compound, and tread design. For this, the complex interactions between different operating parameters such as speed, load, road surface etc. need to be considered.

Figure 2-1: Tyre/road noise excitation mechanisms. (a) Radial excitation due to tread impact and (b) road asperities, (c) stick/slip and (d) snap-out. (c) and (d) occur mostly under torque while (a) and (b) occur under free rolling and torque.

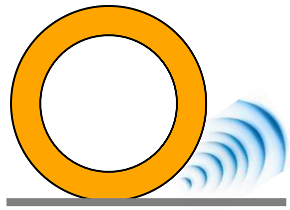


Figure 2-2: The horn-like geometry between tyre and road.

2.3 Influence of tyre dimensions

Close to the contact region, the geometry between tyre and road resembles that of a horn, see Figure 2-2. The exponentially widening geometry when moving away from the contact patch provides a gradual and smooth impedance match between the narrow throat at the contact edge and the ambient air. This has a significant amplification effect on the sound radiation because a majority of the rolling noise sources are situated at or near the contact patch. The amplification affects the whole frequency range from roughly 300 Hz upwards. The maximum lies between 1 kHz and 3 kHz, where amplifications of up to 25 dB(A) in the tyre plane have been reported, see Figure 2-3. At high frequencies interference becomes important and complex directivity patterns form [23] [24] [25]. Even for complex pass-by situations, in which distance and angle to the tyre vary continuously and the car body affects the sound propagation, average amplifications of 5 dB to 12 dB per third-octave band have been reported [23]. The horn effect is strongly affected by tyre width and road surface, with smaller tyres and higher surface porosity reducing the amplification effect [23] [24].

While the tyre dimensions used by ICEVs of a particular vehicle size class are usually similar enough that changes of the horn effect are of no major concern, the situation is different for some of the tall-and-narrow tyre geometries which have been observed for some EVs. The BMW i3 EV, for example, uses tyre sizes of 155/70 R19 (outer diameter 700 mm) and 175/60 R19 (outer diameter 693 mm) on the front and rear axles, respectively. A typical tyre size for an Audi A1, a comparable ICEV, is 185/65 R15 (outer diameter 622 mm) in an all-round fitment. These differences in tyre width and outer diameter will have a significant influence on the amplification from the horn effect. A reduced tyre width will slightly lower the amplitude of the peak amplification and move it to higher frequencies [24] [25]. In a simulation study in [25], a change of tyre width from 220 mm to 175 mm,

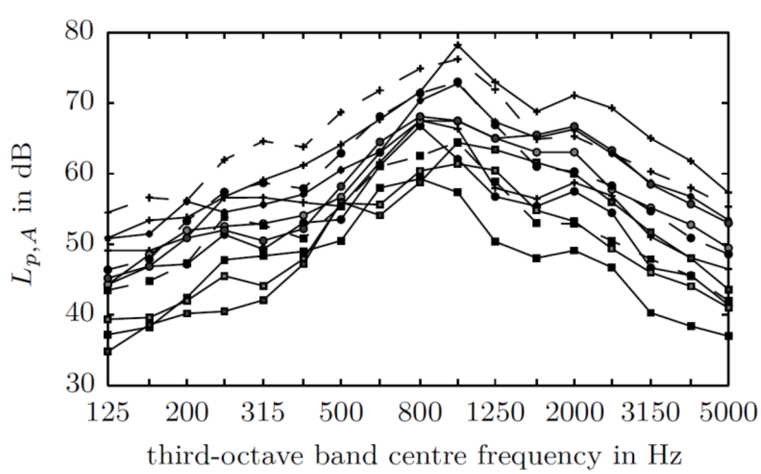


Figure 2-3: Examples for typical third-octave band rolling noise spectra: coast-by measurements for a 195/95 R15 tyre at speeds of 50 km/h (■), 80 km/h (●), and 100 km/h (+) on four different road surfaces (indicated by different lines/shades of grey). Microphone position 7.5 m from the road axis at 1.2 m. From [40].

for example, reduced the maximum amplification by 1 dB(A) and moved the peak position from roughly 1.2 kHz to roughly 1.6 kHz. To the author’s knowledge the influence of the tyre diameter on the horn effect has so far not been systematically studied in the available literature. It is known that for truck tyres the maxima in the horn effect amplification spectra is shifted to comparably low frequencies of around 500 Hz to 800 Hz, see e.g. [26]. Without a doubt this is at least partly related to the larger width of truck tyres. However, from general acoustic theory on wave propagation in horn like structures it is also known that the horn curvature effects the spectral behaviour of the radiation resistance and the radiation directivity [27]. Thus, it must be expected that the tyre diameter also influences the horn effect.

For the rolling noise performance of a tyre even small changes in the horn effect can be crucial because tyres are usually designed in such a way that the main excitation orders from the tread block harmonics coincide with the main amplification areas of the horn effect as little as possible. Changes in tyre dimensions which significantly alter the horn effect behaviour of a tyre would thus also require a redesign of the tread pattern.

3 Typical properties of common ICEVs and their tyres in the European market

Table 3-1: Examples for vehicle size classes.

Size class	Vehicle example
Microcar	Smart fortwo
Minicompact	Fiat 500
Subcompact	Renault Clio
Compact	Volkswagen Golf
Mid-size	Skoda Octavia
Full-size	Audi A8
Subcompact SUV	Renault Captur
Compact SUV	Nissan Qashqai
Mid-size SUV	Skoda Kodiaq
Full-size SUV	Volvo XC90

In order to adequately assess how EVs differ from their ICEV counterparts, the status quo in the ICEV market first needs to be established. In this section the focus lies on the prevalence of different vehicle classes in the market, and the typically used tyres. Further data is analysed in direct comparison to the corresponding data for EVs in Section 4. The market share analysis is derived from several internal, proprietary data sources. The analysis is limited to the 50 most sold vehicles in the European Market in the year 2019. Even though the data is technically not limited to ICEVs only, no EV is among these 50 most sold vehicles.

The vehicle size classes and examples of typical vehicles for each class are shown in Table 3-1. Compared to the segments presented in the accompanying A1 report [10], a slightly finer division is used to avoid the grouping of vehicles with too large differences in size or engine properties into the same group (as it would, for example, be the case with just one SUV class as shown in Figure 2-4 in [10]).

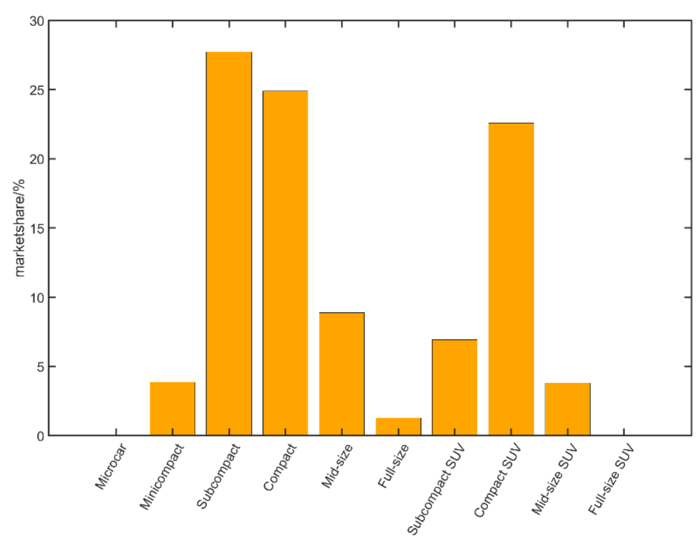


Figure 3-1: Size class market share among the 50 most sold vehicles in the European vehicle market in 2019. Microcar and Full-size SUV classes shown for completeness; there are no cars from these classes among the 50 most sold.

The market share data is presented in Figure 3-1. It is obvious that smaller cars dominate the European market. Each of the Subcompact, Compact and Compact SUV classes has a market share of over 20%. In fact, together the Subcompact and Compact classes account for roughly 50 % of the market, adding the Compact SUV class this number rises to more than 70%. The next two classes, Mid-size and Subcompact SUV, only account for 9% and 7%, respectively.

Tyre size market shares are derived by identifying the most representative tyre size for each vehicle based on technical information available from the vehicle manufacturer's website. As a simplification, only one tyre size is considered for each vehicle, this size is chosen based on best judgement approach utilizing internal, proprietary data.

The results are shown in Figure 3-2. In total there are 28 different tyre sizes ranging from 175 mm to 235 mm in width, from 14" to 18" in rim diameter, and from 45 to 70 in aspect ratio. This large variety is not surprising since the range of considered vehicles sizes ranges from Minicompact to Full-size vehicles. Accordingly, outer diameters range from 583 mm for a 175/65 R14 tyre to 737 mm for 235/60 18.

The most common size is 205/55 R16 with a market share of ca. 13%. There is no other tyre size with a market share of more than 9 %. The next most common size is 185/65 R15 with close to 9%, followed by 195/55 R16, 205/60 R16 and 215/65 R17, each with ca. 7.5% share, and 195/65 R15, 215/60 R17 and 215/65 R16 with slightly less than 7%. Approximately the same distribution, including the prominent position of the 205/55 R16 size as the, by a large margin, most common size has also been reported for the tyre replacement market [28]. Additionally, more than two-third of the tyres are between 185 mm and 215 mm wide. Most common rim sizes are 15" and 16", followed by 17".

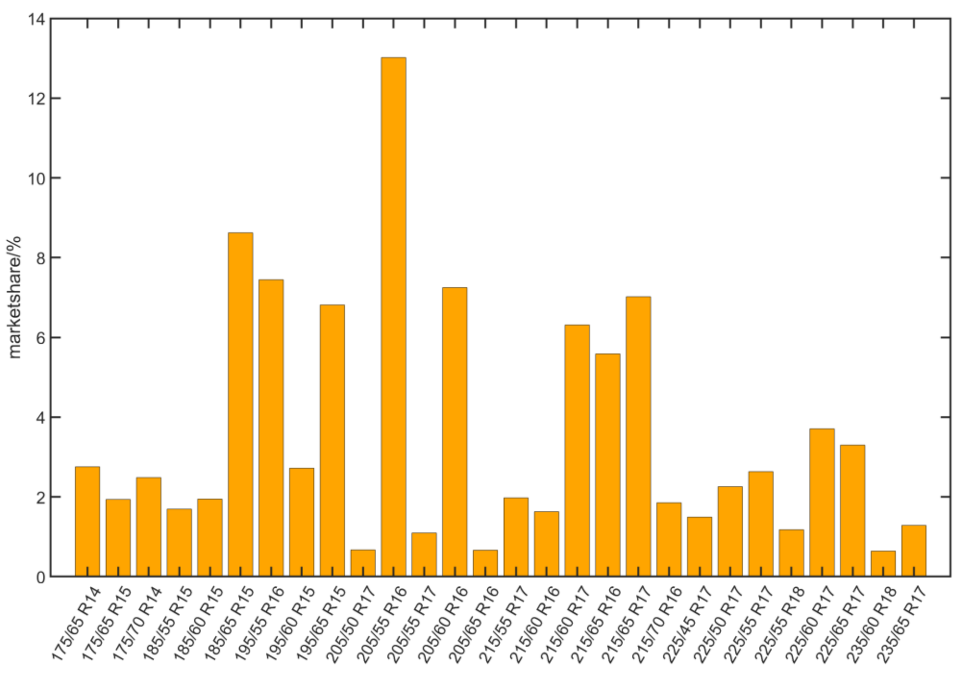


Figure 3-2: Sizes of OE tyres mounted on the vehicles dominating the European vehicle market.

With respect to the influence of the tyre geometry on the horn effect, cf. Section 2.3, it is useful to introduce the height-width-ratio *HWR* which is defined as

$$HWR = \text{tyre diameter/tyre width}\,. \tag{1}$$

Tyres with a similar *HWR* can be expected to have similar horn effect characteristics while tyres with a largely different *HWR* can be expected to also differ significantly in the horn effect behaviour. Note that simple amplification frequency and/or amplitude shifts will still occur between tyres of similar *HWR* but largely different diameter and width. More complex changes are expected if the *HWR* differs.

The *HWR* for the tyre sizes from Figure 3-2 is shown in Figure 3-3. A very homogeneous relation between tyre diameter and width can be observed: the average *HWR* is 3.20 and 30% of the tyres are within 5% of this value. Another two thirds are within 10%, and over 80% are not more than 20% away from the average. This means that even though the absolute dimensions of the tyres can differ significantly, the geometric proportions remain largely the same. A 195/65 R15 for example, has an *HWR* of 3.25, while the value is 3.22 for a 225/65 R17. In other words, for the most common tyre dimensions, size variations are achieved by a roughly proportional scaling of both width and outer diameter. This also ensures that only gradual variations in the horn amplification occur between neighbouring sizes.

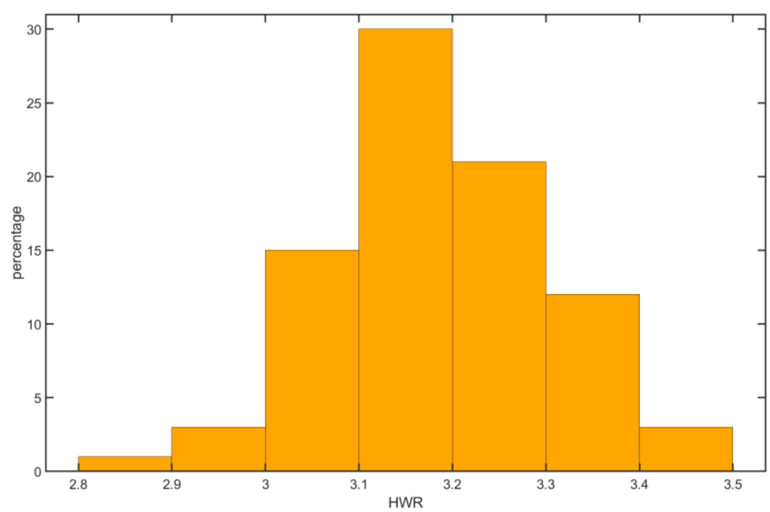


Figure 3-3: Height-width-ratio for OE tyres mounted on the vehicles dominating the European vehicle market

4 Statistics for current and upcoming EVs in the European market and comparison to ICEVs

4.1 Methodology

In the following the European EV market is analysed with respect to the parameters which have been identified as relevant for tyre/road noise in Section 2, i.e. vehicle weight, and torque and tyre properties. It was tried to cover all mass produced EVs which are either currently available or which have been discontinued only recently. Moreover, also vehicles which have been announced for future release are considered if sufficiently detailed technical information is available. In addition to the vehicle classes presented in Section 3, the Minivan and Van vehicle segments are included as well. Because of limited relevance dedicated sports cars are excluded from the analysis. Vehicles not officially being intended for distribution in the European market are omitted as well.

The study is limited to battery-powered electric vehicles (BEV). Hybrid and plug-in hybrid electric vehicles (HEV and PHEV, respectively) are not included. The reason for leaving out HEVs and PHEVs is that these vehicles usually are derived from ICEVs with minor modifications and different degrees of hybridization. Based on this no differences in tyre/road noise mechanisms are expected. Furthermore, this segment most likely is only a transitory one which will become less and less relevant as batteries and fuel cells become cheaper and more efficient. Fuel cell electric vehicles (FCEV) are excluded from the analysis because they are currently of no relevance as only two vehicles are available in Europe, the Hyundai Nexo and the Toyota Mirai (II).

For the comparison to ICEVs, within each size class representative internal combustion cars are chosen based on the following guidelines: all ICEVs considered in the analysis in Section 3 are included. In addition, for platforms which are shared by EVs and ICEVs (e.g. VW Golf and e-Golf, Renault Kangoo and Kangoo Z.E.) the ICEV version is also always included, even if it is not included in Section 3. For size classes which contain less than five ICEVs after these steps, additional representative ICEVs are added until the number of vehicles in the class is at least five. This was not possible for all segments, e.g. in the microcar class where there are less than five vehicles of significant market relevance. Even though nowadays each vehicle is available in many different configurations, or can even be configured individually, only one representative configuration of each vehicle is included in the analysis to reduce complexity. In total the analysis consists of 159 EVs and 69 ICEVs distributed over twelve size classes.

The information on vehicle and tyre properties is compiled from publicly available technical data from the vehicle manufacturers. For not yet available vehicles proprietary data sources have been used in addition. In some cases not at all information is available. For example, for an EV scheduled for future release information about the tyre size might already be available while the vehicle weight is not yet known. In these cases, the vehicle was included in the analysis with whatever information was available. All vehicles included in the analysis are considered with an equal weighting, i.e. market shares in terms of sales or registration numbers are not accounted for.

In the following a large part of the data is presented in form of boxplots, where the central ⊙ marker denotes the median of the data, the top and bottom edges of the box denote the 25th and 75th percentiles, respectively, and the dashed lines extend to most extreme points not considered outliers. The latter are marked by red + symbols.

Sometimes a plot might not show data for a specific vehicle size class and vehicle type (ICEV or EV). In this case no reliable input data was available (as outlined above).

4.2 Vehicle weight

There exists a widespread assumption that EVs are heavier than comparable ICEVs. This is mostly driven by the weight of the battery which is in the range of 220 kg to 550 kg [29], compared to which the weight of the electrical motor(s) of 30 kg to 70 kg is negligible. However, with the weight of the drivetrain components of an ICEV of around 150 kg to 350 kg for the engine, 50 kg to 150 kg for the transmission, and 50 kg to 80 kg for fuel and other operating consumables, it is not completely self-evident that EVs are always heavier than ICEVs of the same vehicle class. Because of this in the following the weight of ICEVs and EVs within the relevant vehicle size classes is analysed.

In Figure 4-1 the vehicle curb weight (i.e. the total vehicle mass including all standard equipment, consumables, fuel and a 75kg-driver) is shown for the different ICEV and EV vehicle size classes. Except for the Full-size class the curb weight is systematically higher for EVs than for ICEVs. In the Full-size class only a limited set of data is available for EVs. Even in this case the median vehicle curb weight is higher than for ICEVs. A large spread of the curb weight is observed for the EVs in the Van class. This is a consequence of the fact that this class contains such different vehicles like the Nissan e-NV200 small urban transporter (curb weight 1555 kg) and the large Streetscooter Work XL delivery van with extended cargo volume (curb weight 2900 kg). The ICEV vans cover a similar range of vehicle sizes (Nissan NV200 to Mercedes Sprinter) but the curb weight variation is smaller (1335 kg and 2125 kg, respectively, for the NV200 and the Sprinter). Not surprising is also the large spread in the Microcar class: most vehicles in this segment are four-wheeled two-seaters with around 1100 kg curb weight. However, this class also includes the one-seated Renault Twizy and the three-wheeled Uniti One with 562 kg and 600 kg curb weight, respectively.

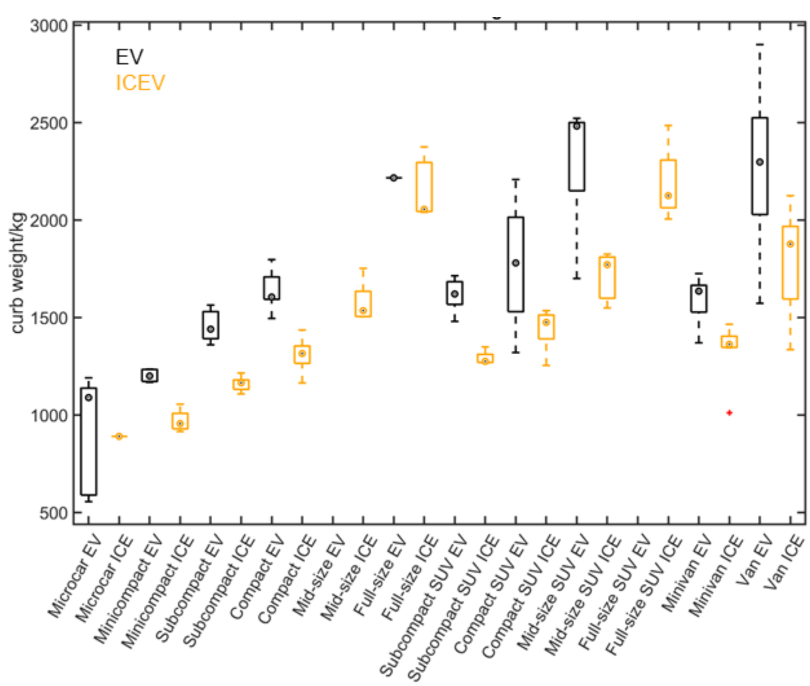


Figure 4-1: Vehicle curb weight for current ICEVs and current and upcoming EVs. No boxplots where not data available.

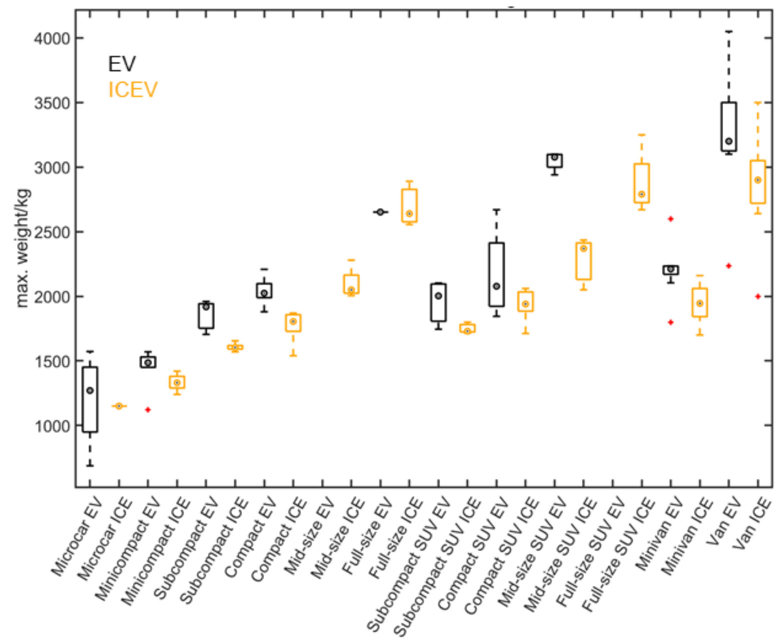


Figure 4-2: Maximum allowed vehicle weight for current ICEVs and current and upcoming EVs. No boxplots where not data available.

Similar observations, though slightly less pronounced, can be made for the maximum allowed vehicle weights (i.e. vehicle curb weight plus maximum allowed load) as shown in Figure 4-2. The slight differences in variation between ICEVs and EVs in Figure 4-1 and Figure 4-2 are more obvious in Figure 4-3 which shows the difference between the curb or maximum weights for EVs and ICEVs for each size class. For the smaller size classes (Microcar to Compact, (Sub-)Compact SUV) and the (Mini-)Van classes weight differences between EVs and ICEVs are more pronounced for the curb than the maximum weight. For the Mid-size SUV class, a bigger weight difference for the maximum weight than the curb weight is observed. However, this increase is still proportionally smaller than the increase in curb weight. This is exemplified by Figure 4-4 which shows the relative weight differences between the vehicle types for curb and maximum weight. On average the EV curb weight is between 20% and 25% higher than the ICEV curb weight but the maximum weight is only 10% to 15% higher on average.

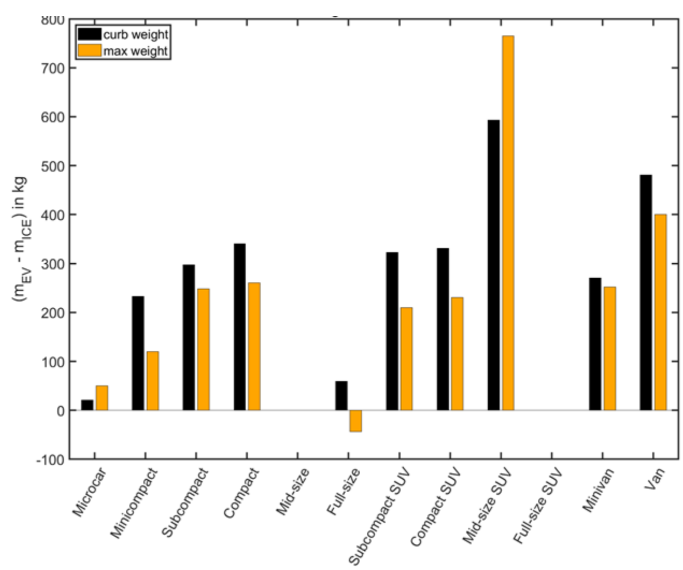


Figure 4-3: Absolute weight differences between current and upcoming EVs and current ICEVs. No bars where not data available.

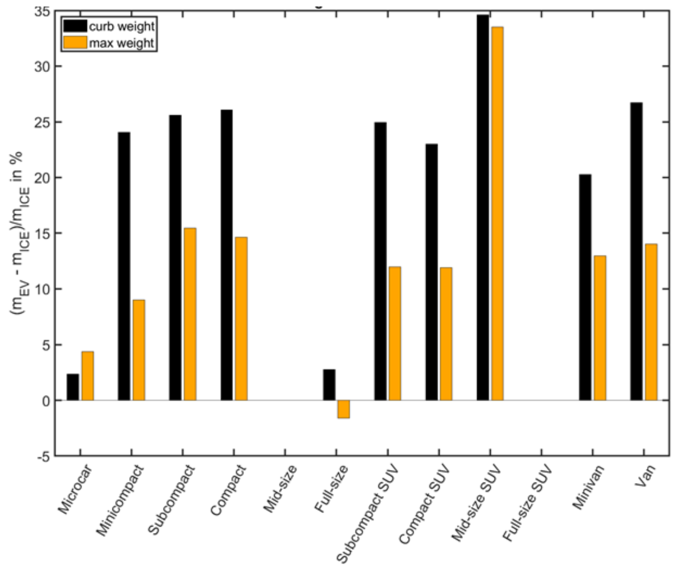


Figure 4-4: Relative weight differences between current and upcoming EVs and current ICEVs. No bars where not data available.

Based on this it can be stated that most EVs have a considerably higher curb weight than their ICEV counterparts, a slightly higher maximum weight and therefore a smaller payload than comparable ICEVs. This is demonstrated by Figure 4-5 and Figure 4-6 which show that for most EV size classes the curb weight is a larger fraction of the maximum weight than for ICEVs and that the absolute payload is also lower. To sum up, it seems that for many EVs the extra weight from the battery is compensated by a reduced payload allowance.

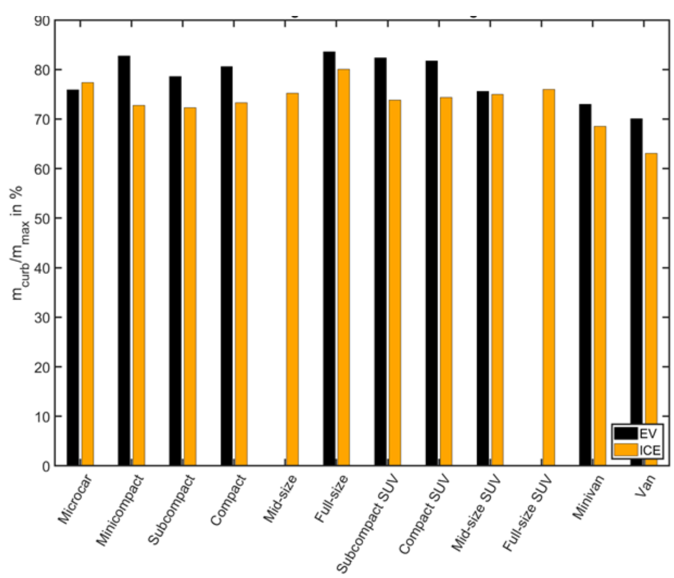


Figure 4-5: Curb weight as percentage of maximum allowed vehicle weight for current and upcoming EVs and current ICEVs. No bars where not data available.

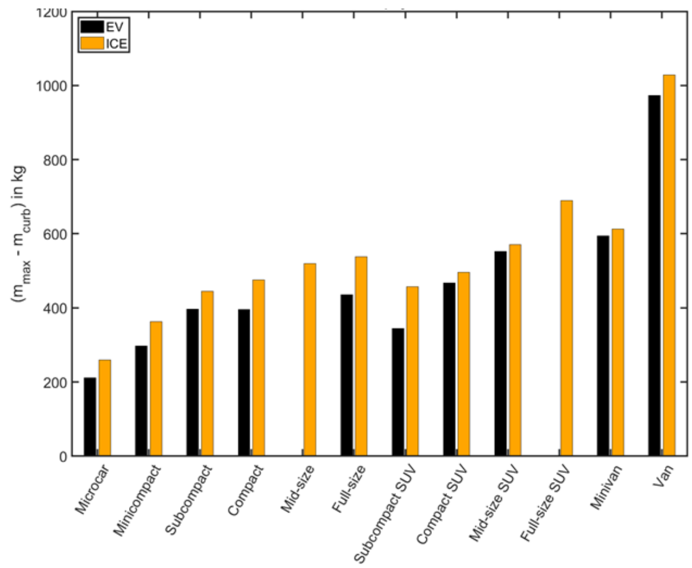


Figure 4-6: Absolute payload (i.e. difference between curb weight and maximum allowed vehicle weight) for current and upcoming EVs and current ICEVs. No bars where no data available.

4.3 Vehicle torque

As pointed out in Section 2.2 tyre torque can have a substantial influence on tyre/road noise. Unfortunately, it is very difficult to obtain realistic and reliable information about tyre torque for different vehicles. Tyre/torque does not only depend on the engine type and power, but also the gearing, driving behaviour (cf. Section 3.1 in [10]) and electronic control systems such as ESP or torque vectoring. Consequently, the maximum available engine torque is analysed as a proxy in the following. This data is easily available from vehicle data sheets and can give an impression about a potential worst case scenario for tyre torque: if a vehicle *A* has a higher available engine torque than an otherwise comparable vehicle *B*, then it is highly likely that a part of that higher engine torque will also be available as higher tyre torque which would also be utilized by more aggressive drivers.

It must be pointed out that the following analysis also does not consider the influence of RPM on available torque because it is difficult to obtained detailed information on this. However, the main fundamental difference between electrical and internal combustion powertrains with respect to torque is that maximum torque is only achieved for mid-range RPMs for ICEs whereas the typical electric motors used in EVs are characterized by near constant maximum torque output over nearly the whole RPM range beginning from standstill. Consequently, based on this even for identical maximum engine torque values the torque effect is probably higher for EVs than for ICEVs because of the wider range of RPMs at which near maximum torque is available.

Maximum engine torque data for different vehicle classes is shown in Figure 4-7. For nearly all vehicle classes EVs have a considerably higher engine torque than comparable ICEVs. Exceptions are the Microcar and Full-size classes where no significant torque differences can be observed. This might be related to the fact that these two classes are the edge cases of engine power requirements: in the Microcar class a constraining factor for EVs might be the limited battery size and weight, thus requiring very efficient electrical motors which are made possible by the lower than usual maximum speeds and the low overall vehicle mass. Contrary to this, Full-size cars basically always also are luxury cars which are characterised by high top speeds and fast acceleration despite the high vehicle mass. Accordingly, engine power is a much more important target performance than in all other

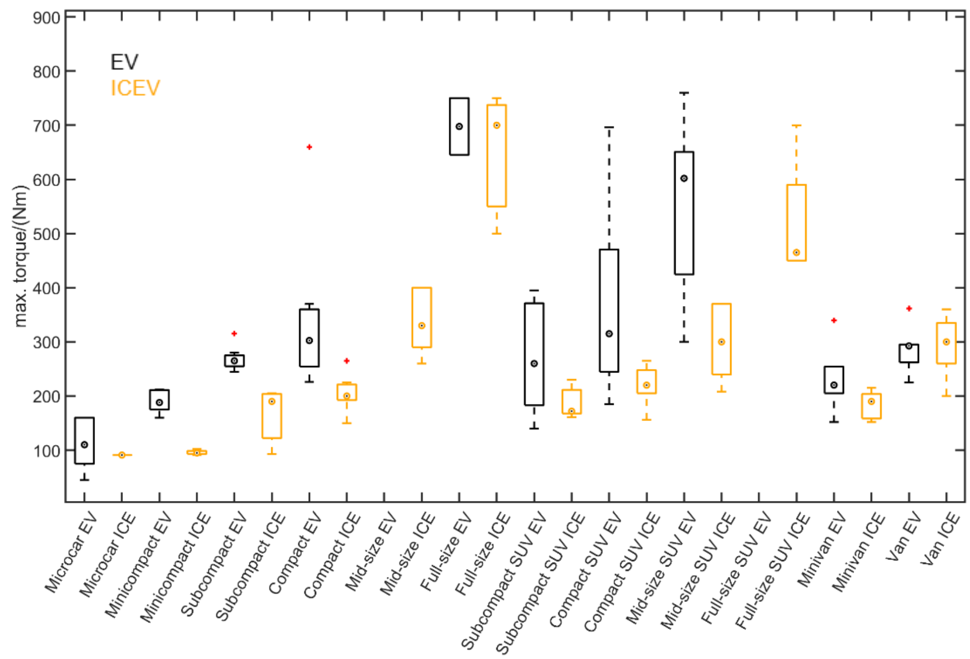


Figure 4-7: Engine torque for current ICEVs and current and upcoming EVs. ICEV data includes gasoline and diesel vehicles. No boxplots where not data available.

vehicle classes apart from Full-size Luxury SUVs and true sports cars. Finally, torque differences are also not observed for Vans. This is possibly due to a combination of the requirement for a high cargo capacity in terms of mass and volume (e.g. necessitating low gross weight but high maximum weight), thus limiting battery capacity and consequently requiring more energy efficient electrical engines which are again made possible by limited driving speeds of these vehicles. All this might put an upper limit on a reasonable torque output. On the ICEV side the high maximum weight argument, at the same time, necessitates the need for - for ICEs at least - comparably high torque engines.

4.4 Tyre properties

4.4.1 Tyre geometry

In Figure 4-8 to Figure 4-12 aspects of tyre geometry are analysed. Figure 4-8 shows that for half of the size classes there is a minor tendency towards slightly wider tyres for EVs than for the ICEVs. In the other six classes the tyre widths are comparable or even slightly narrower for EVs. The trend towards wider EV tyres seems to be most pronounced for SUVs and Vans, whereas little to no increase in width is observed for the Mircocar to Compact size classes and the Minivans.

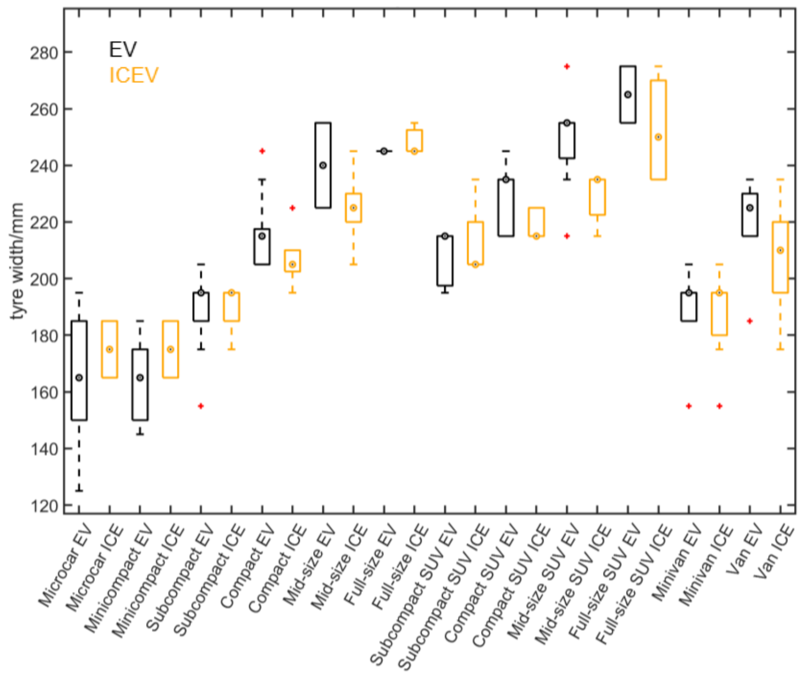


Figure 4-8: Tyre width for current ICEVs and current and upcoming EVs.

No relevant differences between ICEVs and EVs are observed for the tyre aspect ratio (i.e. the height of the tyre cross-section to its width) which is shown in Figure 4-9. Median values are identical for ten of the twelve size classes. Only for Full-size vehicles the median differs by a value of more than five between the different propulsion techniques and this is likely more related to the fact that for only one of the EVs in this class tyre data was available than to any systematic differences.

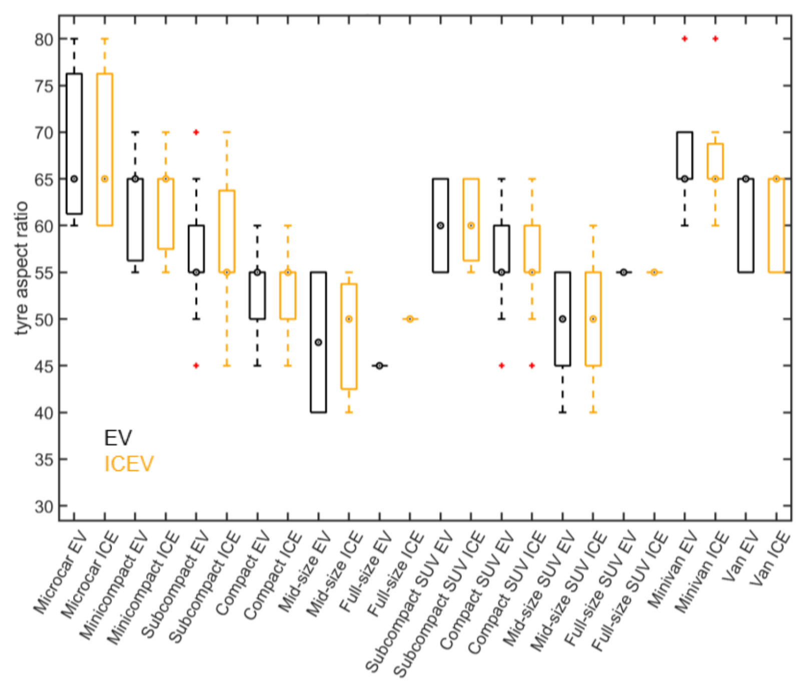


Figure 4-9: Tyre aspect ratio for current ICEVs and current and upcoming EVs.

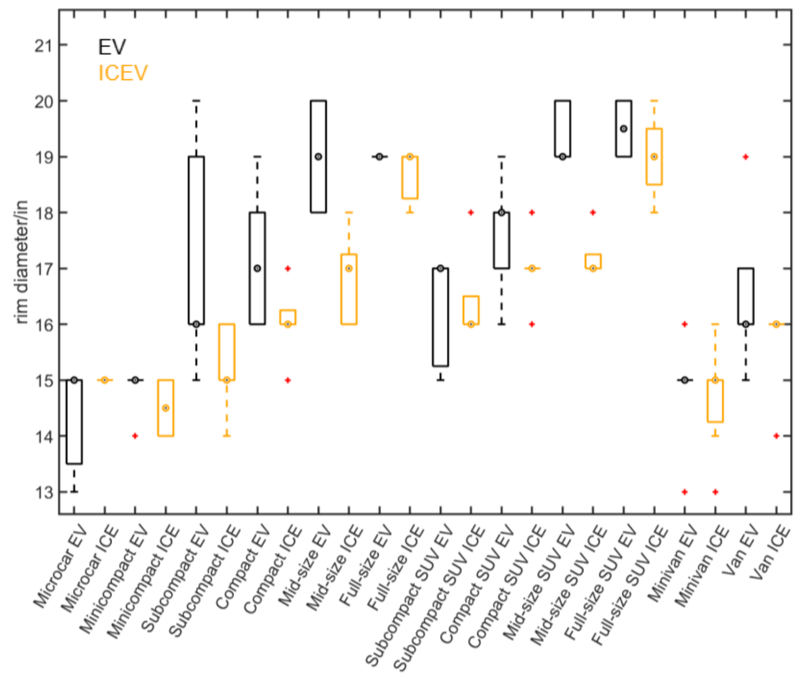


Figure 4-10: Rim diameter for current ICEVs and current and upcoming EVs.

In the majority of size classes rim diameters are larger for EV vehicles, see Figure 4-10: larger rim diameters are observed for all classes apart from Microcar, Full-size, and (Mini-)Van. This does not hold true anymore for the full tyre diameter as shown in Figure 4-11 where only in the Compact (SUV), Mid-size, and Full-size SUV classes larger tyre diameters are observed.

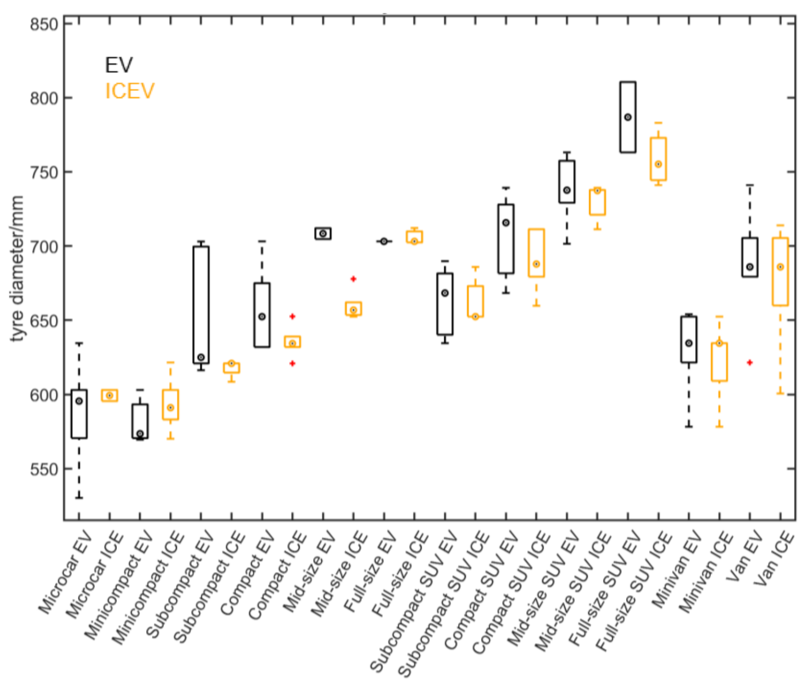


Figure 4-11: Tyre diameter for current ICEVs and current and upcoming EVs.

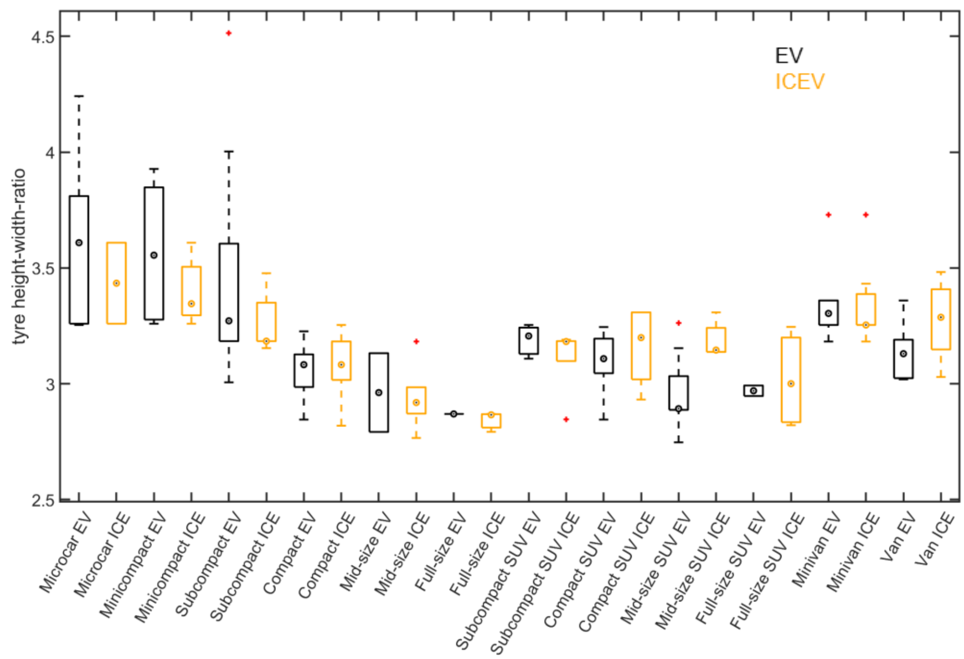


Figure 4-12: Tyre height-width-ratio for current ICEVs and current and upcoming EVs.

In Figure 4-12 the acoustically important relation between tyre width and outer diameter (cf. Section 2.3) is again analysed in term of the Height-width-ratio *HWR*. In general, the *HWR* is very similar for ICEVs and EVs for most of the vehicle classes. For the Non-SUV/-Van classes there is slight tendency towards higher *HWR* for EVs, whereas the opposite is true for SUVs and Vans. Most of the observed data is within the normal range of values (*HWR* of 2.9 to 3.4) which was observed for typical ICEVs in Figure 3-3. A wider distribution of *HWR* values with a tendency towards values of >3.4 is observed for the smallest EV size classes. This is mostly driven by individual EVs with *tall-and-narrow* tyre concepts:

› Microcar: Renault Twizy (145/80 R13, *HWR* 4.24)

› Minicompact: Citroën C-Zero (145/65 R15, *HWR* 3.93)

› Subcompact: BMW i3 (155/70 R19, *HWR* 4.51)

Apart from these single outliers the data does not show any general tendencies towards taller and narrower tyres for EVs.

4.4.2 Other tyre properties

For safety reasons all tyres are designated with a speed symbol and load index (LI) which declare the maximum allowed driving speed and load carrying capacity, respectively. With two exceptions, Subcompact and Mid-size SUVs, speed symbols are identical or even slightly lower for EV tyres when compared to ICEV tyres, see Figure 4-13.

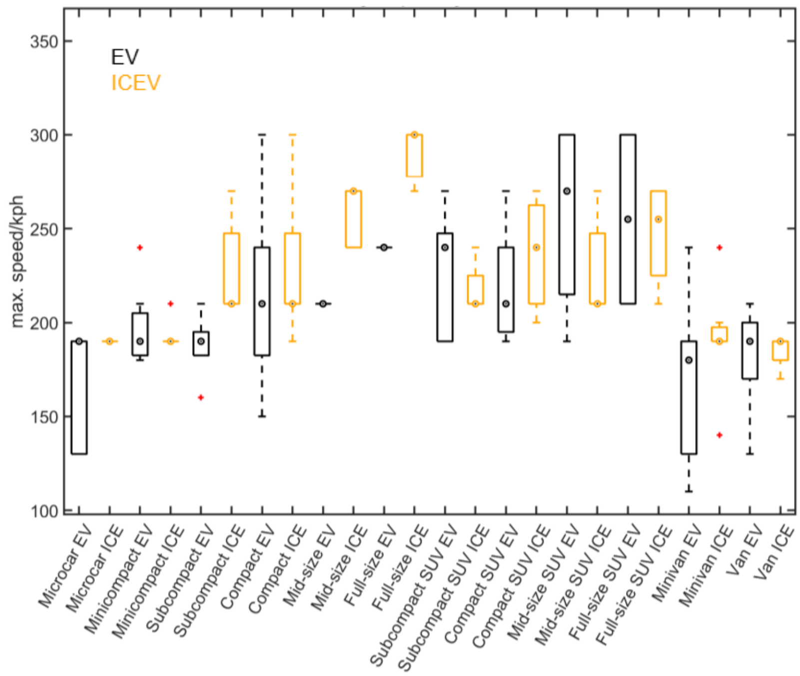


Figure 4-13: Maximum allowed driving speed as derived from tyre speed symbol for current ICEVs and current and upcoming EVs.

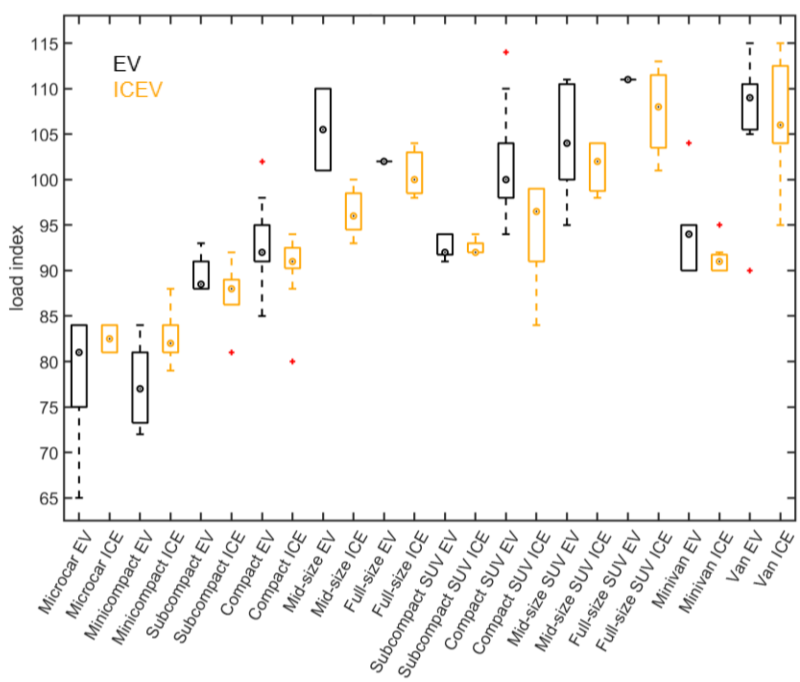


Figure 4-14: Tyre load indices for current ICEVs and current and upcoming EVs.

A more diverse picture is obtained for the LI in Figure 4-14: for some of the size classes (Mid-size, Compact/Mid-size/Full-size SUV and Minivan) the LI is higher for EVs; for Minicompact EVs it is lower; and no major differences between ICEVs and EVs are found for the remaining half of the size classes. This result is insofar interesting as it was shown in Section 2.1 that on average EVs have a 10 % to 15 % higher maximum allowed load than comparable ICEVs. In view of this it seems at first sight obvious that the load carrying capacity of EV tyres should be higher by roughly the same amount. Based on Figure 4-14 this is, however, not the case. The explanation for this is that for typical ICEVs the load carrying capacity of the tyre, as expressed by the LI, is way higher than what is needed based on the maximum vehicle weight. This is shown in Figure 4-15 where the difference between the load carrying capacity of all four tyres in kg, LI_{kg}, and the maximum allowed vehicle weight m_{max} is shown. For ICEVs the LI is grossly over dimensioned: in all cases the tyres can carry more than 500 kg higher loads than the specified maximum vehicle weight. This is a by-product of the fact that the LI cannot be chosen independently of other tyre characteristics, especially the tyre size. For different reasons (handling, appearance, etc.) this size is larger than what would be needed to carry the vehicle weight, resulting in the observed surplus in load carrying capacity. It also acts as safety measure in case vehicles are overloaded by the user. As is visible in Figure 4-15, for most EV size classes a part of this surplus is used to account for the increase in maximum vehicle weight. Basically, EVs utilize a higher percentage of the available tyre load capacity, meaning that despite the higher vehicle weight, EVs still can be equipped with tyres with the same (or only slightly higher) LIs than ICEVs.

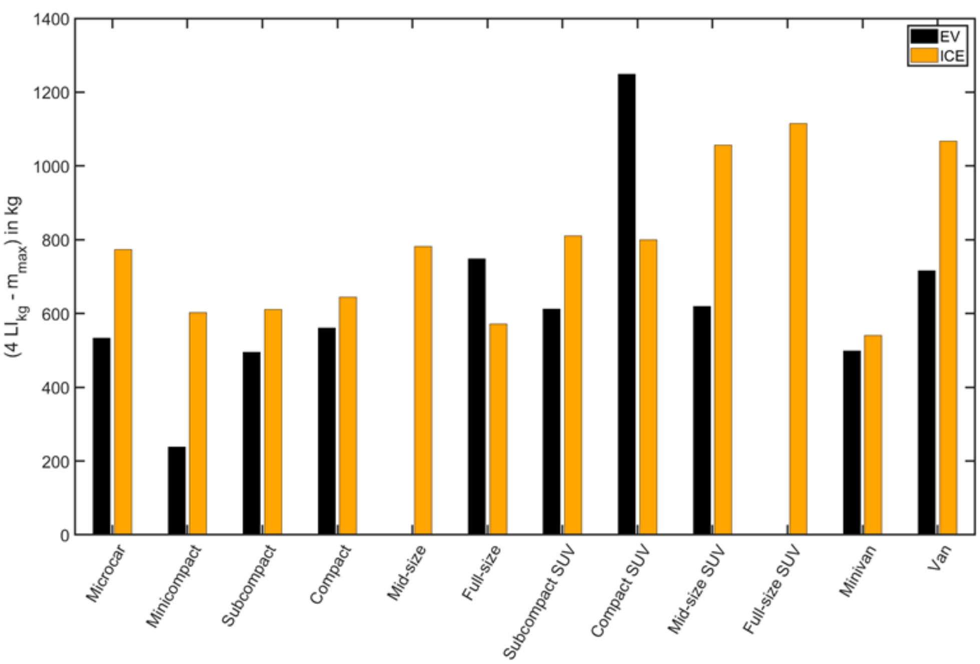


Figure 4-15: Difference between maximum tyre load capacity as given by the tyre load index and the maximum vehicle weight for current and upcoming EVs and current ICEVs. LI_{kg} is the load index expressed in kg load capacity and m_{max} is the maximum vehicle weight. No bars where not data available.

4.5 Conclusions

In Sections 4.2 to 4.4 the aim was to find answers to the following questions which are of relevance for the tyre/road noise generation of EVs:

1. Are EVs heavier than comparable ICEVs?
2. Do EVs have a higher tyre torque than comparable ICEVs?
3. Do EVs use different tyre sizes than comparable ICEVs?

The findings can be summarized as follows:

Regarding point one, the weight of the vehicles, it can be stated that on average EVs are between 20% and 25% heavier than ICEVs in curb weight, and roughly 10% to 15% in maximum weight. As was shown in Section 2.1 this will negatively influence tyre/road noise generation. Because of the available reserve in tyre load capacity (cf. Figure 4-15), these increased vehicle weights do not necessitate changes in the specification of the tyre which would arise from the need for a higher load index. However, what has been neglected in the analysis because of lack of detailed information for a wide variety of cars is the influence of the increased vehicle weights on the tyre inflation pressure which is also known to affect tyre/road noise. According to the ETRTO Standards Manual [16], for a reinforced tyre with an LI of 95 (roughly the average over all vehicle classes in Figure 4-14) being operated at an inflation pressure below the XL reference pressure of 290 kPa, a 10% (20%) increase in tyre load capacity necessitates an increase in inflation pressure of 20 kPa (40 kPa). An additional important driver for a tendency towards higher inflation pressures for EVs is the resulting reduction in rolling resistance, and accordingly increase in mileage [30]. Taking a concrete example, Volkswagen recommends 220 kPa inflation pressure for a 2019 Golf VIII (curb/max. weight 1315 kg/1800 kg) whereas the recommendation is 280 kPa for a 2019 e-Golf (curb/max. weight 1615 kg/2020 kg) with the same 205/55 R16 91H tyres [31]. According to [17] a 50 kPa increase in inflation pressure correlates with a 1 dB(A) increase in tyre/road noise. Concluding, an increase in tyre/road noise generation is to be expected based on increased vehicle weights and the because of this needed higher inflation pressures.

For point two, higher tyre torque can significantly increase tyre/road noise creation. However, specific conclusions regarding EV tyre torque are difficult because of a lack of specific data and the large influence of electronic control systems and driving behaviour. What can be clearly stated is that engine torque is in nearly all cases higher for EVs, both in terms of maximum torque as well as the RPM range where this is available, see Section 4.3. Even assuming similar vehicle control systems and driving behaviour this means that tyre torque is potentially also higher for EVs. Combined with the observation in [32] (see also 3.1.2.1 in the accompanying A1 [10]) that over a third of EV fleet users gravitate towards a more aggressive driving behaviour a worst-case assumption of increased tyre torque for EVs seems necessary when optimizing an EV tyre for tyre/road noise.

With respect to the final point three, it was stated in Section 2.3 that the tyre dimensions can influence tyre/road noise generation and radiation. In the analysis in Section 4.4 it was shown that new tyre size concepts, e.g. tall-and-narrow, are not widely employed for EVs. Contrary, for EVs based on an ICEV platform usually no changes in tyre size are observed. For new EV platforms often only slight adjustments of tyre sizes are noticeable, often in form of a small increase in tyre diameter and/or width. In many cases this results simply in an increase in size towards a typical ICEV tyre size of the next larger vehicle size class (i.e. a Subcompact EV might use a tyre size traditionally associated with a Compact sized ICEV). Accordingly, the relation between tyre height and width which is important for the acoustic radiation because of the horn effect mostly stays in the same range as established for classical ICEV applications. Even though it was also shown in Section 4.4 that there are some prominent exceptions (e.g. BMW i3, Citroën C-Zero) to using well-established tyre sizes, these vehicles are not representative for the EV market as whole. In summary, for the EV market of today and the foreseeable future there is no need for a special consideration of novel tyre dimensions for the design of a low-noise optimised EV tyre.

5 Consequences for a holistic low-noise optimized EV tyre

In Sections 3 and 4 ICEVs and EVs in the European market have been analysed with respect to certain vehicle and tyre properties which are relevant for tyre/road noise. Based on the conclusions drawn there, a requirement book and an initial development strategy for the holistic, noise optimized EV tyre demonstrator which is to be developed in Action B7 are defined in the following.

5.1 Requirement book definition

5.1.1 Tyre size

In Section 4.4.1 it was shown that the large majority of vehicles in the European EV market still use tyre dimensions which are identical, or very close to, those used in classical ICEV applications. Sizes which dominate the ICEV market (cf. Figure 3-2) are also used by a variety of common EVs, e.g. 205/55 R16 is used by the Hyundai IONIQ, Nissan Leaf and VW e-Golf EVs, or 185/65 R15 which is used by the Nissan e-NV200 and Renault Zoë EVs. This means that the dimensions for the noise optimized EV tyre demonstrator in Action B7 can be chosen among a set of tyre sizes which are already well established in the market. The question which remains unanswered is exactly which size would be representative for the largest number of EVs. For the current ICEV market this was answered in Section 3: the dominating size is 205/55 R16. In the following three different scenarios are presented which aim at establishing the most representative tyre dimensions for EVs. Contrary to the ICEV analysis in Section 3 not only the current situation shall be covered but also the one in the near future. Thus, the choice of tyre size will not be only based on the current status quo of the EV market, but also future trends.

5.1.1.1 Scenario 1

This scenario is vehicle sales volume independent. It is based on the vehicle size class market shares for ICEV vehicles as shown in Figure 3-1. The assumption is that these market shares are applicable to EVs as well, and that they will not change significantly in the near future. Within each size class, the assumption is that the share for each individual vehicle is the same (i.e. each manufacturer sells the same number of cars). Using the market share VS_i of vehicle size class *i* and the number of different vehicle models $MS_{i,j}$ using tyre size *j* in class *i*, the tyre size market share $TS_{\text{tot},j}$ can be predicted as

$$TS_{\text{tot},j} = \sum_i TS_{i,j} \qquad (2a)$$

with

$$TS_{i,j} = VS_i \cdot \frac{MS_{i,j}}{MS_{i,\text{tot}}}\,, \qquad (2b)$$

where $MS_{i,\text{tot}}$ is the total number of different vehicle models in vehicle class *i*.

The tyre size per vehicle is chosen in a similar way as was done in Section 3: based on public or proprietary technical data all possible tyre dimensions for a given vehicle are identified. Among these the most common size is identified based on best knowledge and available data. Only this size is considered in Equations (2a/b).

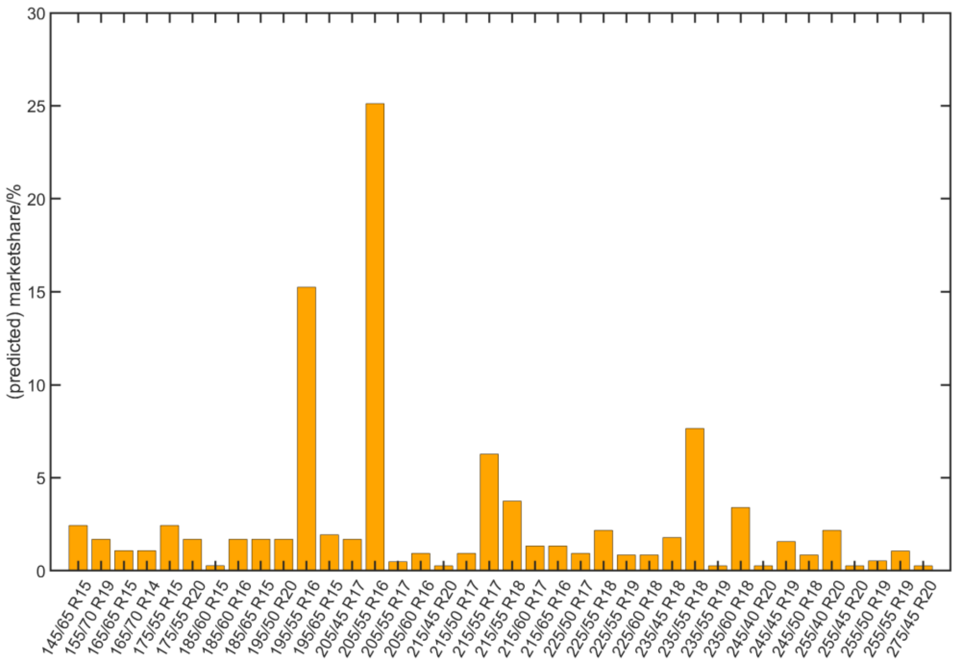


Figure 5-1: Common tyre sizes for current and upcoming EVs – Prediction scenario 1 (sales volume independent).

The predicted tyre size market shares are shown Figure 5-1. Compared to the analysis for the ICEVs in Figure 3-2 the number of tyre sizes increases from 28 to 38. This could indicate a possibly larger variation of tyre sizes among EVs, but the more likely explanation is that Figure 3-2 considers only the 50 most sold ICEVs in the European market whereas Figure 5-1 includes data from 135 EVs[1]. The 205/55 R16 size, which already had the highest market share among ICEV tyres, also is the most common tyre size for EVs in this scenario. Compared to Figure 3-2 its market share nearly doubles from 13 % to 25 %. Only one other size, 195/55 R16, has a market share of more than 10 %. This tyre was also the third-most common size for ICEVs in Figure 3-2. Only two other sizes have market shares higher than 5 %.

5.1.1.2 Scenario 2

The shortcoming of scenario one is that it neglects the fact that some vehicles are sold more often than others. This can be overcome by considering the actual number of vehicles using a tyre size *j* instead of the number of vehicle models as was done in the previous section. Thus, in (2a) the term for $TS_{i,j}$ is replaced by

$$TS_{i,j} = VS_i \cdot \frac{CS_{i,j}}{CS_{i,\text{tot}}} , \tag{2c}$$

where $CS_{i,j}$ is the number of cars sold using tyre size *j* in vehicle class *i*, and $CS_{i,\text{tot}}$ is the total number of sold cars in vehicle segment *i*.

While in principal more precise than scenario one, this approach is highly dependent on the availability of reliable sales figures for, if not all, at least a sufficiently large number of EVs. Ideally, this data also needs to include forecasts for future sales. Based on a set of proprietary data on projected sales figures and forecasts, estimates of $CS_{i,j}$ have been calculated. It must be stressed that care is not only needed with the general reliability of these

[1] All EVs considered in Section 4 apart from those belonging to the Minivan and Van segments.

estimates. It can also be expected that the data quality differs for different vehicle manufacturers or that no data is available for certain vehicles.

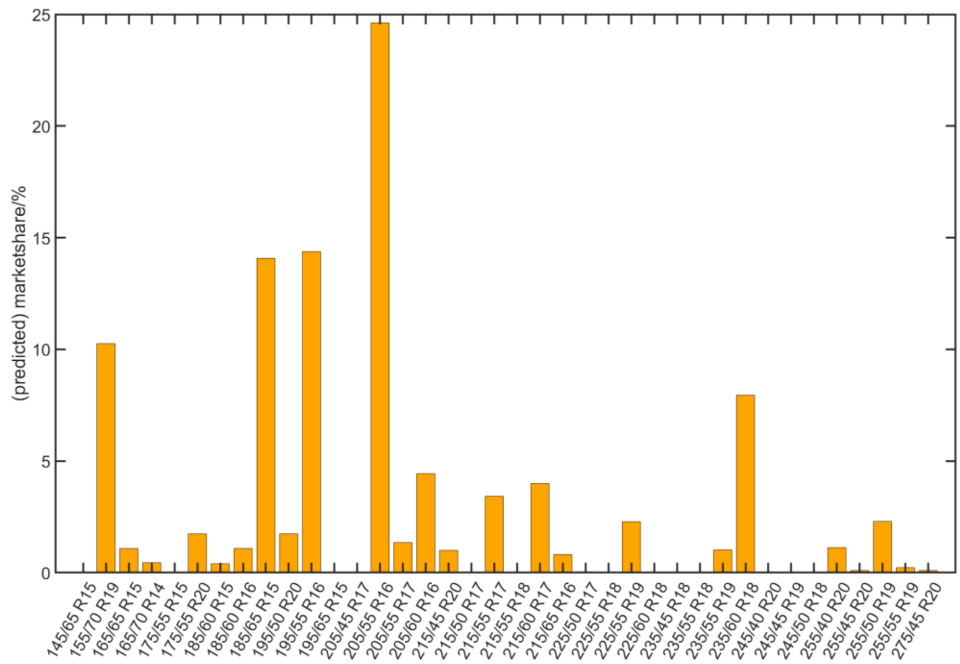


Figure 5-2: Common tyre sizes for current and upcoming EVs - Prediction scenario 2 (sales volume dependent). No bars where not data available.

Based on these assumptions the predictions are shown Figure 5-2. Only for 23 of the 38 tyre sizes sufficient data for the estimation of the market share is available. Despite this and the questions regarding the reliability of vehicle sales figures and forecasts, the results shown in Figure 5-2 do not seem to be implausible when compared to both the results for ICEVs in Section 3 and the findings for scenario one in the previous section. Like the results shown in Section 5.1.1.1, the 205/55 R16 size still is dominating, again followed by the 195/55 R16. Additionally, the market shares of ca. 25% and 15% are nearly identical to the results of scenario one. The third most common size is 185/65 R15 with also close to 15% share. This was the second most common tyre size for ICEVs in Section 5.1.1.1. The 155/70 R19 size, which did not appear among the ICEV tyre sizes in Figure 3-2 is used by the BMW i3, a vehicle which has a considerable market share among BEVs [10].

5.1.1.3 Scenario 3

This scenario neglects all assumptions about vehicle size class market shares and vehicle sales figures. It only considers the number of different EV models which are using a tyre size. Results are shown in Figure 5-3. The number of relevant tyre sizes increases to 46 compared to the 38 in scenario one, cf. Figure 5-1. This is a consequence of removing the vehicle class market shares from the analysis. This adds Microcars, Full-size SUVs and (Mini-)Van EVs to the analysis which previously, based on Section 3, were considered with a market share of 0%. Roughly half of the sizes are used by one vehicle model only. Twelve sizes are used by three or more vehicles. The most common sizes are 215/55 R17, 205/55 R16 and 195/65 R15 with five, six and seven models each. Based on the statistics for ICEVs in Section 3, and the EV scenarios one and two, Sections 5.1.1.1 and 5.1.1.2, the prevalence of the 205/55 R16 is not surprising. The 215/55 R17 size is less common but still of some relevance in the results of Sections 3, 5.1.1.1 and 5.1.1.2. While this size can be associated with several different Subcompact and Compact SUVs from Asian manufacturers (e.g. Hyundai Kona Elektro, Kia e-Niro, Kia e-Soul, Mazda CX-30 FE), the (expected) market share of these vehicles is rather low. The emergence of the 195/65 R15 tyre size can be attributed to its wide use among EVs in the Minivan (e.g. Renault Rapid Z.E.) and Microcar (e.g. e.GO Life) classes which previously were not considered. While being used by variety of vehicle models, its overall market relevance is probably still very low as the market share of the vehicles using this size is quite low.

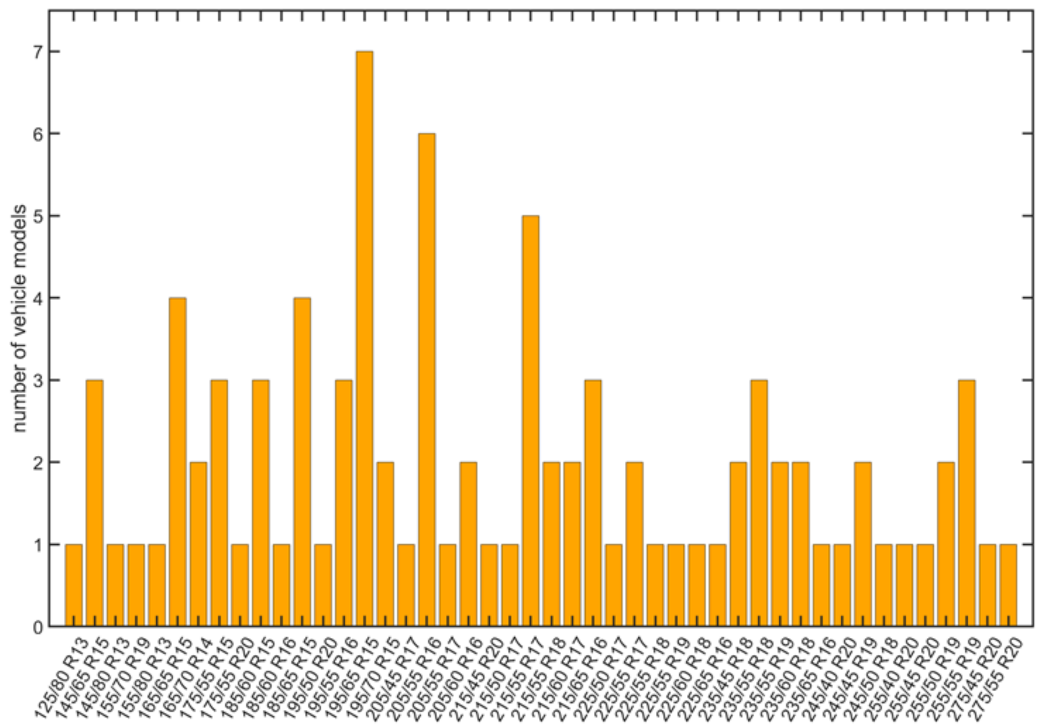


Figure 5-3: Number of different current and upcoming EV models utilizing a tyre size.

5.1.1.4 Summary

All of the scenarios presented in Sections 5.1.1.1 to 5.1.1.3 are subject to certain assumptions and uncertainties. The same is valid for the ICEV analysis in Section 3. This must be considered when deciding on a representative tyre size for the development of a noise optimized EV tyre in Action B7. However, regardless of these uncertainties a relative unambiguous choice for the development size emerges from the different scenarios: the 205/55 R16 size has, by a wide margin, the highest market share among current and future EVs, regardless of whether vehicle sales volumes are considered or not. It is also the second most common tyre size in scenario three, and the relevance of most common tyre size in that scenario is not backed up by an equal importance in the other scenarios. In addition, it also has the highest market share among current ICEVS, both on the OE and the replacement market (see Section 3 and [28]), which enhances the possibility for technology and knowhow transfer and enhances possibilities for direct comparisons between the tyre's performance on EVs and ICEVs.

Concluding, an EV optimized tyre prototype in size 205/55 R16 would give the highest ecological benefit and the highest return of investment. Because it is used by many current and future ICEVs and EVs, it offers the greatest flexibility in vehicle choice for testing and the planned EV festival. Furthermore, this size is somewhere in the middle of the main size range in the market, which facilitates technology and knowhow transfer to a broad range of other sizes. Considering the uncertainties regarding the assumptions made in scenarios one to three it is also the most robust choice as it had the highest or second highest relevance in all three studies.

5.1.2 Noise related tyre properties

5.1.2.1 Tyre load, inflation pressure, vehicle camber and road inclination

Besides the tyre size, other tyre/road noise related tyre parameters which might be affected by a change from ICEV to EV mobility were identified in Section 2 and then further analysed for their actual relevancy in Section 4.

The first two important properties are both related to the vehicle weight and the resulting tyre load. The results of Section 4.2 show, that both the curb weight and the maximum vehicle weight increase for EVs. However, in Section 4.4.2 it could be shown that this is of no consequence for the required load index of an EV tyre as on average for all nowadays typically used vehicle-tyre-pairings the weight bearing capacity of the tyre as indicated by the LI is actually much higher than the maximum weight of the vehicle. It was in particular shown that this still holds true for EVs as well. Thus, no constructive changes to the tyre are required from a weight bearing point of view. Standard LIs for 205/55 R16 are 91 (SL) or 94 (XL), giving a combined load carrying capacity of 2460 kg and 2680 kg, respectively. Among the EVs analysed in Section 4 which use this tyre size, the highest maximum allowed vehicle weight is 2020 kg. Accordingly, despite the higher weight of an EV, it is sufficient to design the noise optimized EV with standard LI values in mind.

The second vehicle weight related property which needs to be considered is the load a tyre will be used with. That both curb and maximum vehicle weights are higher for EVs also implies that the same holds true for any vehicle weight between these two extrema. Thus, for any given vehicle load condition, the tyre on an EV will typically have to carry a higher load than on an ICEV operating under the same conditions. Section 2.1 showed that this alone will have a direct negative influence on tyre/road noise. Additionally, there is a further indirect negative influence on tyre/road noise because due to the higher tyre loads also inflation pressures will be higher for the EV. With respect to the development of the noise optimized EV tyre this needs to be considered, for example by considering the influence of higher load and inflation pressure on the interaction between tyre and road, or the pressure distribution inside the contact area.

The 205/55 R16 size is predominantly by vehicles in the Compact segment. Figure 4-1 shows in this size class the curb weight increases from a median value of 1315 kg for ICEVs to 1605 kg for EVs. It seems reasonable to focus on a similar EV weight during the development of the EV tyre. Thus, a tyre load of 400 kg will be assumed. Additionally, the inflation pressure should properly account for this load, e.g. according to [16].

To gain an initial understanding of the extent to which load and pressure changes influence tyre/road noise for a state-of-the-art summer tyre an initial study was carried out. It is based on a Continental EcoContact 6 of size 205/55 R16 91V as shown in Figure 5-4.

Figure 5-4: Continental EcoContact 6.

Besides tyre load and inflation pressure also the influence of the vehicle suspension camber angle and road inclination was investigated. The camber angle is the angle between the horizontal axis of the wheels and the horizontal axis of the vehicle when viewed from front or rear. Because of handling requirements this angle is basically never equal to 0°, i.e. the horizontal wheel axis and the horizontal vehicle axis are not parallel. Additionally, many roads are sloped laterally to aid with water drainage. The angle between the road surface and true horizontal is the road inclination. Vehicle camber and road inclination add up, so in the following the term vehicle/road inclination is used for both. Because of this vehicle/road inclination the tread is laterally no longer aligned parallel to the road surface. For example, for the typical negative camber of passenger cars, the tread will get earlier into contact with the road surface on the inside than on the outside. It will also leave contact later. Consequently, the edge of the contact between tyre and road is no longer perpendicular to the driving direction of the car. As this affects the excitation of the tread blocks when entering or leaving the contact zone also tyre/road noise is influenced. Vehicle camber angles can differ significantly, not only between different vehicles but also between the front and the rear axle of the same vehicle, typical values are between (but not limited to) -0.5° and -1.5°. Road inclinations typically vary between -0.5° and -1.0°. Thus, a representative combined range for the vehicle/road inclination would be -1.5° to -2.5°.

Table 5-1: Tyre load, inflation pressure and vehicle/road inclination combinations used in the study.

Configuration	A	B	C	D	E
Tyre load	4218 N	4600 N	4600 N	4070 N	4070 N
Inflation pressure	210 kPa	220 kPa	220 kPa	260 kPa	260 kPa
Vehicle/road inclination	0.0°	-1.5°	-2.0	-1.3°	-1.8°

In the study, the five different combinations of tyre load, inflation conditions and vehicle/road inclination shown in Table 5-1 are investigated regarding their influence on the rolling noise performance of the EcoContact 6. As a first step the shape of the contact area between tyre and road is determined experimentally using a pressure sensitive pad. The resulting footprint contours are shown in Figure 5-5. Clear differences can be observed not only between configuration A without vehicle/road inclination and configurations B to E with inclination, but also among configurations B to E. The footprint length, for example, is ca. 125 mm for configurations B and C, while D and E with higher pressure and lower load are considerably shorter at around 113 mm. Another obvious difference is that the contour for E is resembling a half-circle on the tyre outside, while for B and C the contour in this area is dominated by a long straight edge segment which is parallel to the driving direction.

As a second step, tyre/road noise is predicted for the five different configurations using a simulation approach. First, the interaction between tyre and road is simulated using a simplified model of the tyre including tread geometry and a nominal road surface. This step considers the influence of tyre load, inflation pressure and vehicle/road inclination on the tyre/road contact. With the tyre/road interaction acting as excitation, tyre/road noise is predicted for controlled coast-by conditions using physical wave propagation and sound radiation methods.

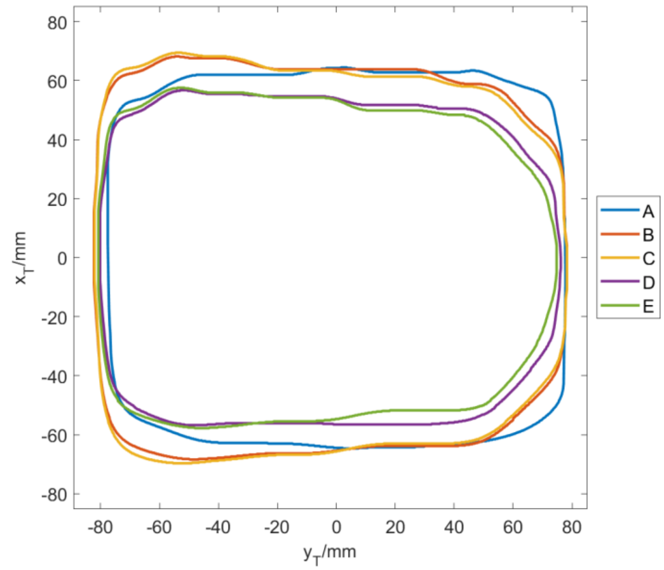


Figure 5-5: Contour of contact area between tyre and road for configurations A to E. x_T denotes driving direction, y_T lateral direction. Tyre inside on left, leading edge on top.

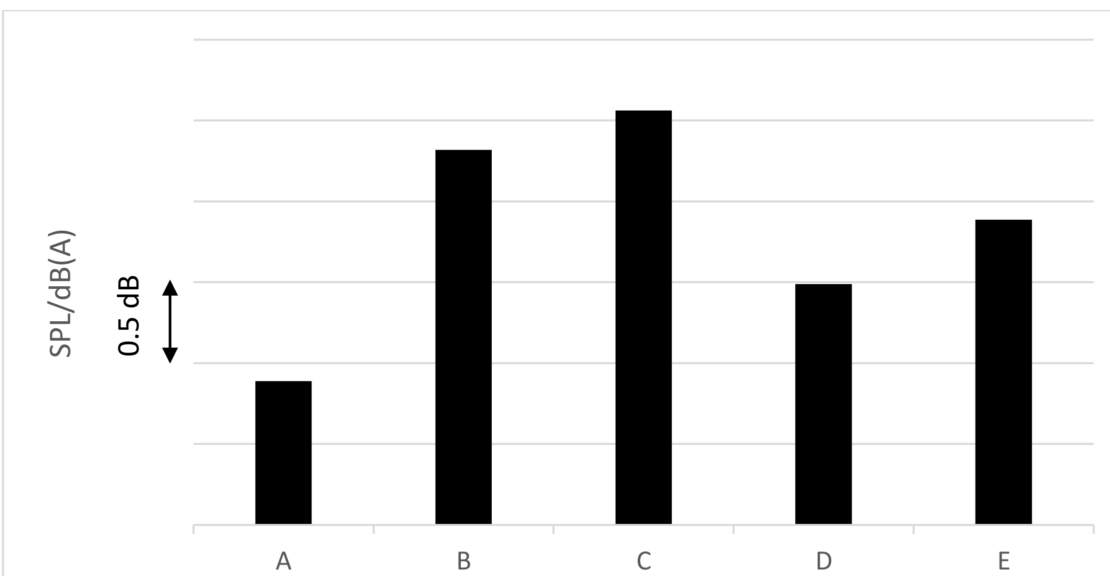
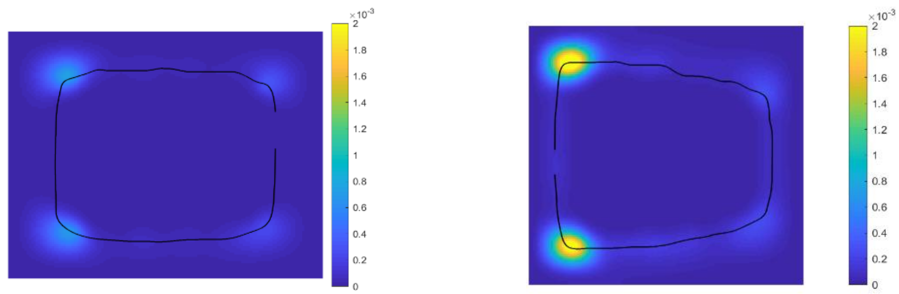


Figure 5-6: Tyre/road noise coast-by simulation results for configurations A to E.

The results of these simulations are shown in *Figure 5-6*. The difference between configurations A and C, the most silent one the loudest one, respectively, is ca. 1.7 dB(A). Configuration B performs only slightly better than C and is still 1.4 dB(A) louder than A. Configurations D and E perform somewhat better and are only 0.5 dB(A) and 1.0 dB(A) louder than configuration A. The complex interaction between the different operating conditions are obvious as well. Based on Section 2 it should be expected that a higher load or a higher inflation pressure increases tyre/road noise. For the load is true between configuration A on the one hand, and B and C on the other hand. As expected, B and C are louder. However, configurations D and E have a lower tyre load than A, yet they are louder than A. Another example is the inflation pressure which goes up from B and C to D and E, but the noise goes down. One consistent behaviour is that each of the two load and inflation pressure pairs (i.e. B and C, and D and E) the tyre with the higher vehicle/road inclination is the slightly louder one. All this emphasizes that while the negative influence of higher load and higher inflation pressure on tyre/road noise which have been reported in Section 2 are correct as general tendencies, the situation is more complex for single individual tyre model operating under a certain set of conditions. This is especially true if vehicle camber and road inclination need to be considered as well. In this case the complex interaction between tyre load, inflation pressure, vehicle/road camber, footprint shape and tread pattern design need to be evaluated individually.



Configuration A Configuration C

Figure 5-7: Tyre excitation plots for the tyre/road noise simulations of configurations A and C. Tyre inside on left, leading edge on top.

As an example this is done for configurations A and C in Figure 5-7 where the tyre excitation in the tyre/road contact area is shown for coast-by noise simulations of configurations A and C. These two cases are chosen because they are the most silent and the noisiest one and to highlight the differences between them. For configuration A the excitation is distributed relatively equally among the shoulders on both the leading and trailing edge of the contact area. Lower excitation amplitudes are also visible in the tyre centre. In total the excitation for this configuration is quite homogenous and symmetric. This is a consequence of the neutral road/vehicle inclination.

The excitation distribution for configuration C, in contrast, is visibly influenced by the vehicle/road inclination of -2.0° which leads to a sheared footprint which is also slightly longer than for configuration A due to the higher load. Because of these differences, the tyre is mainly excited on the inside shoulder, considerably less on the outside shoulder, and nearly not at all in the tyre centre. The excitation amplitude on the inside shoulder is two to three times higher than the maximal amplitude which can be observed for configuration A. This is possibly caused by the higher load (4600 N vs. 4200 N), the slightly higher inflation pressure (220 kPa vs. 210 kPa) and the influence of the vehicle/road inclination on the shape of the tyre/road contact area.

This example highlights the importance of considering relevant and representative operating conditions for the development of the low noise optimized tyre in action B7. If these conditions are not properly chosen a goal-oriented optimization cannot be guaranteed. Additionally, in all simulations only one nominal road surface was considered. Results and interactions might vary considerably for different road surfaces.

Figure 5-8: Drum measurement laboratory.

5.1.2.2 Tyre torque

Though no direct conclusions on tyre torque could be made in Section 4.3, it can be assumed that there is high likelihood that a tyre will be subject to higher torque on an EV than an ICEV. In Section 2.2 the increase of tyre/road noise was associated with stick/slip and stick/snap effects related to tangential deformation of the tread blocks under torque. A requirement on the noise optimized EV tyre is that these effects are minimized, for example by choice of a special tread pattern design, a special tread compound or a special tyre construction.

To investigate these approaches laboratory drum measurements (cf. Figure 5-8) were carried out for three different 205/55 R16 tyres: a reference with soft pattern and stiff construction, variant A with stiff pattern and stiff construction, and variant B with soft pattern and soft construction. All tyres were inflated to 180 kPa and the load was 4530 N. The microphone was positioned with 3 m axial distance from the tyre centre at a height of 0.48 m. Sound pressure levels were measured under free rolling conditions from 30 km/h to 100 km/h on two different road surfaces: a copy of an ISO 10844 [33] surface and a generic rough road surface. Measurements for 500 Nm torque were carried out on the ISO surface at a speed of 50 km/h.

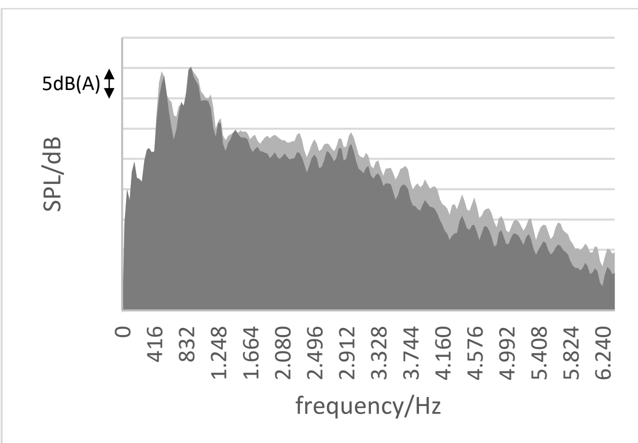
The results for 50 km/h are summarized in Table 5-2. Under free rolling conditions variant A is 0.5 dB(A) louder than the reference on the ISO surface, and 0.3 dB(A) louder on the rough surface. Variant B is 0.3 dB(A) better than the reference on the ISO surface, and 1.2 dB(A) on the rough surface. These results are generally in line with the expected influence of tyre stiffness on rolling noise as discussed in Section 2.1. It is known that the tyre tread properties are more important for rolling noise on smooth surfaces whereas noise generation on rough surfaces is dominated by the road surface texture [6] [14].

Table 5-2: Measured sound pressure levels (in dB(A)) for different rolling conditions and road surfaces, and speeds of 50 km/h.

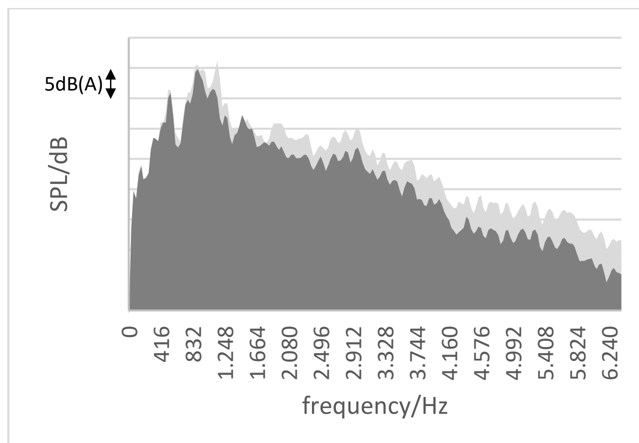
	Variant A	Reference	Variant B
Design highlights	stiff pattern, stiff construction	soft pattern, stiff construction	soft pattern, soft construction
Free rolling, ISO surface	69.6	69.1	68.8
Free rolling, rough surface	76.4	76.1	74.9
500 Nm torque, ISO surface	70.3	71.1	71.7

This explain why on the ISO surface sound pressure levels change by a larger extend when going from the reference towards variant A, and to a lesser extend when going to variant B: variant A is characterized by a change in pattern properties when compared to the reference whereas variant B keeps the pattern and changes the construction. The opposite is observed on the rough surface where the pattern properties are of lesser importance. Here, the smaller change is observed going from the reference to variant A, and a quite drastic change is obtained for going to variant B instead.

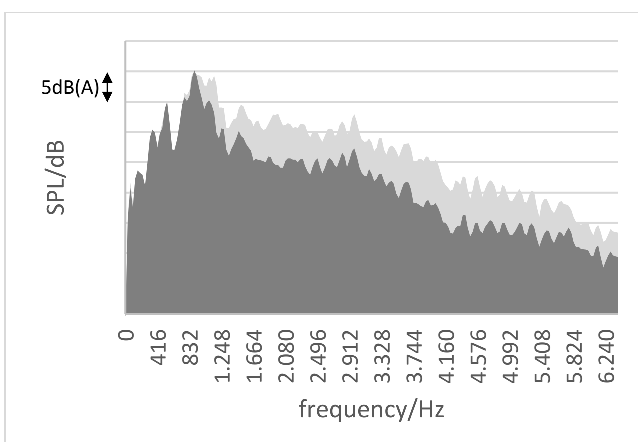
With respect to the torque effects, Table 5-2 shows some interesting results. While variant A is only slightly louder under torque than when free rolling (+0.7 dB(A)), for the reference and variant B sound pressure levels increase by 2.0 dB(A) and 2.9 dB(A), respectively. Consequently, variant A, which was the loudest for free rolling on both road surfaces, is now the least noisy one. It can be assumed that this a consequence of the beneficial impact a stiffer pattern has on stick/snap and stick/slip noise generation mechanisms which occur under torque (cf. Section 2.2). This is supported by the frequency spectra shown in Figure 5-9: both stick/snap and stick/slip mechanisms are known to mainly affect frequencies higher than 1 kHz. This fits very well with the shown spectra where for all three tyre variants no significant change between free rolling and torque is observed below this frequency. Above 1 kHz, only a small increase in SPL is observed for variant A, a moderate one for the reference, and large increases of up to 5 dB or more per frequency band for variant B.



Variant A



Reference



Variant B

Figure 5-9: Comparison of frequency spectra for drum measurements on ISO surface for free rolling (dark grey) and for 500 Nm torque (light grey).

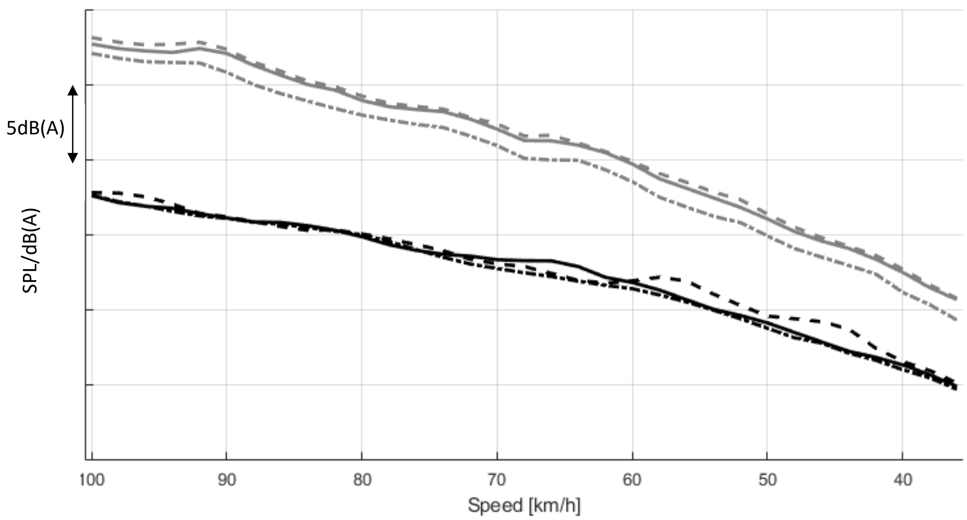


Figure 5-10: SPL over speed for free rolling on ISO (black) and rough (grey) drum surfaces. (—) reference, (– –) variant A, (-·-) variant B.

The differences between noise performance for free rolling and under torque emphasize that the noise optimized EV tyre will need to be well balanced for a good performance under both conditions.

The influence of driving speed on tyre/road is shown in Figure 5-10 for both drum surfaces. These results confirm the previous observations about the importance of the tread pattern for the noise generation: for the ISO surface not only the relative differences but even the ranking of the different tyres varies with speed. Variant A, which was the loudest at 50 km/h, is more silent than the reference between 65 km/h and 70 km/h. This is a consequence of the differences in tread pattern excitation between the variants. The stiffness variations lead to differences in tread excitation and footprint shape. The influence of changes on rolling noise varies with speed as dominant radiation frequencies are obtained from the horn effect, see Section 2.3, and the tread block impact frequency which is depending on the tyre speed. As expected, this dependency of tyre/road noise on tread excitation is not visible for the rough surface where the differences between three tyres are constant over a wide range of frequencies. Together with the results from Table 5-2 this highlights the importance of an adequate consideration of the effects of the road surface on possible tyre measures.

5.1.2.3 Other noise relevant parameters

Based on the findings of Section 4.4.2 no special considerations are required for the speed symbol. Normally, this would be chosen based on the maximum speed of the vehicle the tyres are mounted on. Based on the limited top speeds of EVs, this can lead to some differences in speed symbol for ICEVs and EVs based on the same vehicle platform and using the same tyre size. One example would be for the 205/55 R16 size used by both the VW Golf VII and the e-Golf. The Golf VII uses tyres with speed symbol H, i.e. 210 km/h maximum speed, whereas the e-Golf uses speed symbol Q which has a top speed of 160 km/h. However, the noise optimized EV tyre which will be developed in Action B7 is not aimed at a specific vehicle but a demonstrator which should be applicable to a large variety of vehicles. As such the results shown in Figure 4-13 indicate that a speed symbol which is in the range of typical speeds symbols used for ICEVs or slightly slower should be used. For the proposed 205/55 R16 size for ICEVs this would be speeds symbols H (210 km/h max. speed) or V (240 km/h max. speed). Without a loss of general applicability for EV use these speeds could maybe be reduced to 180 km/h (symbol S) if needed if a positive influence of this on tyre/road noise is identified. However, this would severely limit the possibility to mount these tyres on ICEVs, e.g. for comparative noise measurements in the project, and is thus not recommended.

Finally, as was discussed in Section 2, there is a dependency of the noise performance of the tyre on external factors such as driving speed or road surface. As it is the project's objective to reduce noise for roads inside very populated urban areas, the EV tyre optimization will be aimed at improving noise performance under typical urban driving conditions up to 50 km/h on city roads. Performance for speeds up to 80 km/h should be beneficial as well, if possible. In any case the tyre should fulfil the tyre type approval limits specified in UNECE regulation 117 [34]. Regarding the road surface special consideration shall be given to an excellent behaviour on the noise optimized road surfaces which are developed and build in actions B1 and B2.

5.1.3 Other tyre performances

Besides exterior noise there are many other important requirements for a safe, ecological, and economical tyre. Performances such as wet grip or rolling resistance for example, affect safety, fuel efficiency (i.e. attainable mileage for EVs) and the environmental impact of the tyre. None of these performances can be seen isolated as they are linked by the physical properties of the tyre (e.g. construction, pattern, material properties). It is not uncommon that an improvement in one area will lead to a decreased performance in another area. A classic example for such a target conflict is low noise (benefiting from high mass and high damping) versus low rolling resistance (realized via low mass and low damping). For a holistically optimized EV tyre especially this target conflict is of high relevance because of the importance of the tyre rolling resistance on achievable mileage. Because of the higher drivetrain efficiency of electrical engines also the tyre rolling resistance has a relatively higher contribution to the energy consumption of an EV than for an ICE vehicle. It is expected that about 40% of the electric energy used by an EV during free rolling is lost due to rolling losses between the tyre and the road [32]. Thus, a competitive rolling resistance is a vital requirement for a state-of-the-art EV tyre. That this does not necessarily conflict with a low noise requirement is for example shown by the results presented in [35], where it is shown for different EV tyres and road surfaces that low noise and low rolling resistance do not mutually exclude each other. The same results have also been obtained for ICEV tyres [36]. This does not necessarily contradict the above-mentioned example of a rolling noise versus rolling resistance target conflict which was based on the example of a modification of tyre mass and material damping. Though tyre mass and damping are among the most important predictors for rolling resistance and rolling noise performance, other measures exist which potentially can improve one performance without too much of a negative impact on the other one. Tread block design modifications, for example, do not affect rolling resistance too much and thus could be used to improve tyre road noise, ideally under free rolling and torque conditions. With respect to the rolling resistance of the EV optimized tyre the requirement is to develop an optimized tyre which combines the EV requirements of low noise and rolling resistance.

An important tyre property for safe driving is wet grip. This has been recognized by legislative decision makers by including the wet grip performance in the EU tyre label [37]. State-of-the-art premium summer tyres sold in the European market of size 205/55 R16 91H are typically in wet grip label class B or in a few cases class A. The development of the noise optimized EV tyre needs to assure that any measures taken to improve tyre/road noise do not affect wet grip performance in such a way that label class B (or better) cannot be achieved.

Finally, it shall be assured that the noise optimized EV tyre shall fulfil company and regulatory (R30 and R117) safety and environmental regulations such as UNECE R30 and R117 [34] [38].

5.1.4 Summary

The requirements for the development of a holistic, noise optimized EV tyre in action B7 which have been derived in Sections 5.1.1 to 5.1.3 are summarized in Table 5-3.

Table 5-3: Summary of the requirement book for the holistic development of a noise optimized EV tyre action B7.

Property	Value	Comment
Tyre dimensions	205/55 R16	
Load index	91 SL / 94 XL	Corresponding to 615 kg / 670 kg
Speed symbol	H (max. speed 210 km/h)	Minimum requirement
Tyre load	400 kg	Based on median EV weight in Compact segment
Inflation pressure	Based on LI and tyre load.	In accordance with [16].
Vehicle/road inclination	Representative angle (-1.5° to -2.5°)	
Rolling conditions	Free and under torque	
Noise performance	Excellent exterior noise performance on an EV operating under urban driving conditions up to 50 km/h.	Special focus on performance on noise optimized road surface property to be developed in B1/B2. Good performance up to 80 km/h.
Rolling resistance	R117 compliant, Label class A	
Wet grip	R117 compliant Label class B	Class A if achievable
Other performances	R30 and R177 compliant	

5.2 Development strategy

Based on the requirement book defined in Section 5.1 the development strategy for the holistic, noise optimized EV tyre to be developed in action B7 is laid out in the following.

1. Because the proposed tyre size, load index, and speed symbol, and the requirements on rolling resistance and wet grip are typical for a premium European summer tyre it is proposed to start the development with an existing product which already fulfils the label requirements on rolling resistance and wet grip (label classes A/A or A/B), and is competitive regarding other performances. This also establishes a baseline reference for the assessment of the following optimization.

2. In the next step it needs to be identified which modifications to the reference will be needed to optimize exterior noise performance for EV applications. Special focus will be laid on an optimization which adequately considers the changed operating conditions (i.e. tyre load, inflation pressure, torque) for usage on EVs when compared to ICEVs. At the same time, it must be guaranteed that the solution assures a certain robustness of noise performance when used under conditions which differ from typical EV usage. This step will mainly focus on an optimization of the tread design because the tread geometry plays a major part in both the adjustment of the tyre/road contact to the increase in tyre load and inflation pressure for EVs (cf. the simulations in Section 5.1.2.1), and the adjustment of stick/slip and stick/snap mechanisms caused by the potentially higher tyre torque. Additionally, tread geometry changes only have a limited impact on rolling resistance. This minimizes the risk of introducing a target conflict rolling noise versus rolling resistance. In this step, laboratory measurements will be needed to establish the boundary conditions of the tyre/road contact for the EV conditions summarized in Table 5-3. To minimize development costs virtual tools will be used whenever possible during the tread optimization. A small number of carved prototype tyres and indoor lab measurements will be used for a rapid validation of simulation results. While the focus is on the tread geometry, modifications to other tyre properties are also considered in parallel, especially when a positive influence on tyre/road interaction under EV conditions is expected. However, the benefit from these other measures might be limited because of the greater risk of having negative side effects on other tyre performances than rolling noise.

3. The most promising proposals will then be evaluated regarding the expected performance in rolling resistance, wet grip, etc. This is done virtually or by lab measurements.

4. Steps (2) and (3) are repeated to allow for further optimisations of the tyre based on the outcome of the measurements. Each of these loops might also focus on an optimization of different parts of the tyre. In relation to the progress of the development of a low noise optimized road surface in actions B1 and B2 the tyre development will successively emphasize optimal performance on this surface more and more as results of B1 and B2 become available.

5. To verify the tyre performance at later stages of the development process a larger number of prototype tyres will be built in order to perform a larger number of relevant indoor and outdoor measurements to verify the different performances. Besides indoor tyre noise measurements on a drum under free rolling and torque conditions, possible measurements could be outdoor pass-by noise measurements (UNECE R117 and/or UNECE R51.03) and/or wet grip and rolling resistance tests according to UNECE R117. After completion of the prototypal test track in Nantes carved prototype tyres reflecting the latest state of

action B7 will be delivered to UNI EIFFEL for measurements on the prototype test track (action B2). The obtained data will be used for further development and/or validation within action B7.

6. Based on (5) and if necessary further subsequent optimisations, moulded test tyres reflecting the latest state of action B7 will be delivered to Florence for testing on the optimized asphalt (action B3) after this has been built. The obtained data will be used for further development and/or validation within action B7. The delivered tyres will also be used for the EV festival in Florence.

6 Acknowledgments

The work presented in this report has been financially supported by the European Commission research project *LIFE E-VIA*, grant no. LIFE18 ENV/IT/000201.

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