ATEEL | ACEA

Study on future sound limit values for type approval for vehicles of category M & N

Final Report 27.01.2022
**Project Details**

**Report:** Study on future sound limit values for type approval for vehicles of category M & N

**Version:** FinalReport V01.00

**Duration:** 01.10.2020 – 30.06.2021

**Client:** ACEA – Association des Constructeurs Européens d’Automobiles
Avenue des Nerviens 85
1040 Brussels
Belgium

**Contractor:** ATEEL S.à r.l.
14, Op Huefdréisch
6871 Wecker
Luxembourg

**Authors:**
Kitesh Patel, M.Sc.
Marcus Feld, M.Eng.
Dipl.-Ing. Rüdiger Kubis
Dipl.-Ing. Tobias Meinhard
Florian Maus, B.Eng.
Abstract

The objective of the ATEEL-ACEA study is to investigate the current vehicle sound emission levels of category M and N in order to evaluate the potential and the feasibility of limit value reductions in the UN Regulation No. 51. Furthermore, the translation of the limit value reductions in type approval conditions to real road traffic conditions is investigated. Finally, the study aims to assess the efficiency of alternative measures and compare them to the ones achieved through limit value reductions in type approval testing.

The project is based on a combination of evaluation steps involving the analysis of a type approval database (provided by OICA), a consultation with the vehicle and tyre industry as well as an impact analysis of various measures to reduce road traffic noise. A calculation tool developed in-house provides the ability to clarify the complex transfer of the type approval test results to real traffic conditions. The resulting output from the tool in form of efficiencies of powertrain and tyre measures on the vehicle allow a comparison with available alternative measures to reduce road traffic noise and thus the selection of the most suitable solution.

The study confirms that the sound emission level of all vehicle categories has decreased over the past ten years. The simulated improvements in relation to the introduction of stricter limit values have an effect with a considerable time delay due to the market penetration of new vehicles. Moreover, limit reductions without significant improvements and contribution from the tyre/road side is considered critical and would not provide the desired improvements in real driving conditions. Furthermore, an introduction of limit values beyond phase 3 is regarded as technically unachievable given the current state of technology.

In conclusion, a number of recommended further investigations are proposed in order to determine more precisely the current status quo of vehicle sound emissions in real traffic and the necessary conditions for restoring the effectiveness of the limit value reductions are explained.
Content

Abstract........................................................................................................................................6

1  Introduction..................................................................................................................................7
   1.1  Background and Objectives.................................................................................................7
   1.2  Current Vehicle Sound Emission Certification Procedure ...............................................7

2  Type Approval Database Analysis.............................................................................................11
   2.1  Vehicles of Category M (Vehicles carrying Passengers)......................................................11
       2.1.1  Category M1.................................................................................................................12
       2.1.2  Category M2.................................................................................................................17
       2.1.3  Category M3.................................................................................................................19
   2.2  Category N (Carriage of Goods)..........................................................................................23
       2.2.1  Category N1.................................................................................................................23
       2.2.2  Category N2.................................................................................................................25
       2.2.3  Category N3.................................................................................................................28
   2.3  Representativeness of the Type Approval Data Composition..............................................31
   2.4  Overview and Conclusion ....................................................................................................33

3  Industry Consultation ..................................................................................................................35
   3.1  Vehicle Industry....................................................................................................................35
       3.1.1  Evolution in vehicle sound technology .........................................................................35
       3.1.2  Vehicle Lifecycle...........................................................................................................36
       3.1.3  Challenges by future Limit Value Reductions ..............................................................36
   3.2  Tyre Industry ........................................................................................................................40
       3.2.1  Technical Aspects ........................................................................................................40
       3.2.2  Regulatory Aspects and Conflict with future Requirements ........................................41
       3.2.3  Original Equipment (OE) vs Replacement Tyres .........................................................42
       3.2.4  Opportunities for lowering the Rolling Sound .............................................................43
   3.3  Conclusion.............................................................................................................................44

4  Impact Analysis on Real Traffic - Calculation Tool.................................................................45
4.1 Demands on the calculation tool ................................................. 45
4.2 Limit Value Scenarios ...................................................................... 46
  4.2.1 Limit Value Scenario 1 ................................................................. 46
  4.2.2 Limit Value Scenario 2 ................................................................. 47
  4.2.3 Limit Value Scenario 3 (fictional) ............................................... 47
4.3 Model Description ............................................................................. 48
  4.3.1 Model Structure .............................................................. 48
  4.3.2 Parameters in the Calculation Tool ............................................. 50
  4.3.3 Sound Split in Calculation Tool .................................................. 55
  4.3.4 Sound Pressure Output Value Equivalent ................................. 60
4.4 Conclusion ....................................................................................... 62
5 Impact Analysis on Real Traffic - Simulation Results .......................... 64
  5.1 Calculations based on the Limit Value Scenarios ................................ 64
    5.1.1 Impact of Limit Value Reductions – Comparison of Scenarios ....... 64
    5.1.2 Impact of Driving Speed ......................................................... 66
    5.1.3 Impact of Market Penetration ................................................... 69
    5.1.4 Impact of Pure Electric Vehicle Share ........................................ 70
    5.1.5 Impact of Acoustic Vehicle Alerting System (AVAS) ................. 72
    5.1.6 Impact of Tyre/Road Interaction ................................................ 75
    5.1.7 Impact of Traffic Density ........................................................ 78
  5.2 Analyses of Alternative Measures ................................................... 79
    5.2.1 Impact of Speed Limits ............................................................. 79
    5.2.2 Potential of Geofencing ........................................................... 80
  5.3 Calculated Efficiency of Measures ................................................... 81
5.4 Conclusions ..................................................................................... 87
6 Additional Aspects .............................................................................. 89
  6.1 Regulatory Aspects ......................................................................... 89
    6.1.1 Measurement Uncertainties (MU) .............................................. 89
6.1.2 Specific Needs for Alternative Propulsion Types ........................................... 92
6.1.3 Real Driving Additional Sound Emission Provisions (RD-ASEP) ....................... 94
6.1.4 Harmonisation with other Regulations ................................................................ 96
6.2 General Context and Noise Psychology .................................................................. 97
6.3 Analysis of the Phenomena Assessment Systematic ............................................... 99
7 Conclusion and Recommendations ............................................................................ 103
  7.1 Limit value reductions – what does it mean? ......................................................... 103
  7.2 Current situation – vehicle (powertrain) side: ..................................................... 103
      7.2.1 Vehicles tested according to Annex 3 Sub-paragraph 3.1.3.1 ......................... 103
      7.2.2 Vehicles tested according to Annex 3 Sub-paragraph 3.1.3.2 ......................... 104
  7.3 Recommendations and Observations .................................................................... 105
      7.3.1 Prerequisite for new Limit Values and Investigations of the Status Quo ........ 105
      7.3.2 Alternative Opportunities for an efficient Reduction of Road Traffic Noise .. 106
      7.3.3 Considerations regarding Electro Mobility ................................................... 106
      7.3.4 Further Considerations regarding Niche Segment Vehicles ....................... 107
8 Explanation of Abbreviations, Acronyms and Terms ................................................. 108
9 List of Tables ............................................................................................................ 111
10 List of Figures .......................................................................................................... 112
11 List of Sources ......................................................................................................... 114
1 Introduction

1.1 Background and Objectives

In the framework of vehicle type approvals, it is obligatory for all vehicle manufacturers to prove the compliance of their products to exterior vehicle sound emission provisions. So-called pass-by-noise (PBN) tests have been used and evolved over the years to provide representative vehicle sound emission values that must remain under a specified limit. The limit values for the sound emission type approval procedure of the various vehicle categories have continuously been reduced over the years, becoming more and more challenging for the automotive industry to achieve. This study aims to shed some light on the specific trade-offs and challenges that come along with potential further limit reductions.

While vehicle manufacturers understand and support the necessity to lower the environmental road traffic noise, it is becoming more important to carry out an in-depth investigation into the complex aspects of road traffic noise, before any revision of future vehicle sound limits can be agreed upon. In this context, the European Automobile Manufacturers Association (ACEA) has tasked ATEEL to perform a study to investigate current sound emission levels of M- and N-category vehicles and if deemed feasible to propose new sound level limits and/or alternative measures to improve environmental road traffic noise.

The first part of this study aims to investigate the technical progress on sound emission levels of M- and N-category vehicles over the past decade. An additional fundamental aspect consists in building an understanding of the technical feasibility and financial expenditure for the automotive industry related to potential further limit value reductions. Furthermore, the effect of the current limit values in place and possible new reduced limit values are analysed over a 20-year period and compared to alternative measures related to sound emission reductions.

1.2 Current Vehicle Sound Emission Certification Procedure

As stated in Directive 2007/46/EC, category M includes “motor vehicles with at least four wheels designed and constructed for the carriage of passengers” whereas category N vehicles are defined as “motor vehicles with at least four wheels designed and constructed for the carriage of goods”.

Page 7
The categories M and N are each separated into 3 vehicle classes M1, M2, M3 and N1, N2, N3 respectively, with each vehicle class differing in vehicle characteristics. The corresponding criteria are shown in table 1-1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver’s seat.</td>
</tr>
<tr>
<td>M2</td>
<td>Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver’s seat, and having a maximum mass not exceeding 5 tonnes.</td>
</tr>
<tr>
<td>M3</td>
<td>Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver’s seat, and having a maximum mass exceeding 5 tonnes.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>Vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes.</td>
</tr>
<tr>
<td>N2</td>
<td>Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes.</td>
</tr>
<tr>
<td>N3</td>
<td>Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 12 tonnes.</td>
</tr>
</tbody>
</table>

Table 1-1: Classifications according to Directive 2007/46/EC [1]

To respect different vehicle concepts, the categories are split into further subcategories according to UN Regulation 51. For each of the vehicle subcategories, varying vehicle exterior sound emission limit values are in force. The subcategory definitions are dependent on the vehicle main category:

- Power-to-mass-ratio (PMR) for M1
- Technically permissible laden mass (M) for M2 and N1
- Rated maximum engine power (Pn) for M3, N2 and N3

The current regulation specifies a reduction of the limit values in three subsequent phases. Phase 1 had to be applied for new types starting 01.07.2016, phase 2 from 01.07.2020 onwards (with exception for N2 from 01.07.2022) and phase 3 is foreseen to be applied from 01.07.2024 (respectively 01.07.2026 for M3, N2, N3). For vehicle types designed for off-road use, the limit values are increased by 1 dB(A) for categories M1, M2, N1 and N2 as well as 2 dB(A) for categories M3 and N3. The different limit values in accordance to UN Regulation 51 are shown in table 1-2.
<table>
<thead>
<tr>
<th>Vehicle category</th>
<th>Vehicles used for the carriage of passenger</th>
<th>Limit Values [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phase 1</td>
</tr>
<tr>
<td>M1</td>
<td>PMR ≤ 120</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>120 &lt; PMR ≤ 160</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>PMR &gt; 160</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>PMR &gt; 200, no. of seats ≤ 4, R-point height &lt; 450 mm from the ground</td>
<td>75</td>
</tr>
<tr>
<td>M2</td>
<td>M ≤ 2.5 t</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>2.5 t &lt; M ≤ 3.5 t</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>M &gt; 3.5 t; Pn ≤ 135 kW</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>M &gt; 3.5 t; Pn &gt; 135 kW</td>
<td>75</td>
</tr>
<tr>
<td>M3</td>
<td>Pn ≤ 150 kW</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>150 kW &lt; Pn ≤ 250 kW</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Pn &gt; 250 kW</td>
<td>80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vehicle category</th>
<th>Vehicles used for the carriage of passengers</th>
<th>Limit Values [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phase 1</td>
</tr>
<tr>
<td>N1</td>
<td>M ≤ 2.5 t</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>M &gt; 2.5 t</td>
<td>74</td>
</tr>
<tr>
<td>N2</td>
<td>Pn ≤ 135 kW</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Pn &gt; 135 kW</td>
<td>78</td>
</tr>
<tr>
<td>N3</td>
<td>Pn ≤ 150 kW</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>150 kW &lt; Pn ≤ 250 kW</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>Pn &gt; 250 kW</td>
<td>82</td>
</tr>
</tbody>
</table>

Table 1-2: Limit values according to UN Regulation 51[2]

Currently, the certification test procedure according to UN Regulation No. 51 includes two pass-by noise (PBN) test conditions: a wide-open-throttle (WOT) and a cruise (CRS) test. The final test result value, which is intended to be representative for urban conditions, is a weighted combination of these two PBN tests for the categories M1, M2 (M ≤ 3500 kg) and N1. This approach according to subparagraph 3.1.3.1. of the regulation is often called “passenger car principle”. For categories M2 (M > 3500 kg), M3, N2 and N3 the final test result is only determined with wide-open-throttle testing. Accordingly, this approach according to subparagraph 3.1.3.2. is often called “truck principle”.

The test speed for vehicles tested according to the “passenger car principle” is 50 km/h ± 1 km/h. The gear(s) to be tested is (are) determined on the basis of the acceleration capabilities of the individual gears.
In detail, the test acceleration(s) are compared with reference values, which in turn depend on the PMR of the tested vehicle. One is the reference acceleration $a_{\text{wot-ref}}$, which defines the required acceleration for the test. The other is the target acceleration $a_{\text{urban}}$, which defines the typical acceleration in urban traffic and is derived from statistical investigations. Chapter 6.1.2 discusses the selection of gear ratio in more detail. In contrary, the test speed for vehicles tested according to the “truck principle” is 35 km/h ± 5 km/h. The gear(s) to be tested is (are) determined based on the target rotational engine speed and the target vehicle speed. Regardless of the test principle applied, in the case where two gears are tested, the test results are weighted depending on the deviation of the test accelerations of each gear from the reference acceleration.

In addition to the PBN tests, the current certification procedure includes a test to determine the sound level of the stationary vehicle. In this respect, the regulation specifies a target engine speed, which is dependent on the rated engine speed. Contrary to the PBN tests, where only one mode, namely the mode with the acceleration being closest to the reference acceleration $a_{\text{wot-ref}}$, has to be tested, stationary sound levels is required to be measured for all driver selectable modes.
2 Type Approval Database Analysis

In order to elaborate the progress made by vehicles in terms of sound noise emissions during the past ten years, two databases containing type approval (TA) data from various vehicle types of categories M and N are analysed in the course of this study. The databases are provided by ACEA and OICA. The ACEA TA Monitoring database from 2010 and the OICA TA database from 2020, provide the foundation of the subsequent analysis.

The ACEA TA Monitoring database, also used in previous studies [3] [4] [5], contains data sets from 1186 vehicle types. The recent OICA TA database 2020 provides an increased number of datasets of 2076 vehicle types. 1816 datasets are approved according to the "passenger car principle", 260 according to the "truck principle".

The content of the databases can be filtered regarding vehicle characteristics (e.g. propulsion type, rated power, vehicle test weight, etc.) and type approval values / regulation specific values (e.g. sound emission test results, related limit values, etc.).

In comparison to the ACEA database from 2010, the OICA database from 2020 includes significantly more datasets for vehicles with alternative propulsion types such as pure electric vehicles (EVs) or hybrid electrical vehicles (HEVs), which are analysed in further detail in this chapter. The knowledge gained by tracking the progress of vehicles in terms of sound emissions over the past ten years provides valuable contribution to the subsequent feasibility analyses regarding further limit value reductions for UN Regulation No. 51, addressed in the upcoming chapters.

Since both databases did not provide the data in an identical format and data in the databases were partially unusable (e.g. duplicates, obvious mistakes, and typing errors), a significant effort was invested to make an efficient comparison and analysis possible

2.1 Vehicles of Category M (Vehicles carrying Passengers)

The characteristics and the various limit values of category M vehicles are explained in chapter 1.2. The graphs on the following pages are only a small extract of the most interesting findings.
2.1.1 Category M1

Category M1 is represented in the OICA TA database 2020 with 1655 datasets and 611 datasets in the ACEA TA Monitoring database 2010 respectively. The OICA TA database 2020 contains vehicle types with alternative propulsion types, which are not present in the older ACEA TA Monitoring database from 2010. In total 27 pure electric (EV), 141 hybrid electric (HEV) and 4 natural gas (NG) vehicles are included within the M1 vehicle category datasets.

The following figure shows the statistical distribution of the characteristic sound level $L_{urban}$ of all M1 datasets, plotted as cumulative and Gaussian distribution curve. Both plots of the 2020 data reveal a shift towards lower values in comparison to the 2010 data, indicating a trend towards reduced sound levels. The median reduction of $L_{urban}$ at the 50% cumulative point can be quantified to 1.5 dB(A) compared to the 2010 data. While the minimum value for $L_{urban}$ has decreased by 1 dB(A) from 64 to 63 dB(A), the maximum $L_{urban}$ value remained constant at 76 dB(A), but with a decrease in the number of samples as illustrated by the Gaussian distribution.

![Statistical distribution of $L_{urban}$ - Category M1](image)

Figure 2-1: Statistical distribution of $L_{urban}$ - Category M1

To allow a more detailed analysis, the datasets are split into their respective subcategories according to UN Regulation 51. The subcategory M1-a represents approximately 79% of the total datasets in the OICA TA database 2020 for category M1. Subcategories did not exist in 2010. The data of the ACEA TA database are categorised according to the new subcategories to make a fair comparison possible. The graphs clearly illustrate the progress of the specific subcategories.
It is noticeable that high performance vehicles of subcategory M1-c have become over-proportionally more quiet with an improvement of approximately 2.5 dB(A) over 2010. A few possible explanations for this observation is the increased use of hybridisation, full electrification and extensive gearbox developments in this vehicle category.

![Statistical distribution of Lurban - Category M1](image)

Figure 2-2: Statistical distribution of $L_{urban}$ - Category M1 (Subcategories)

The improvements for the four subcategories at 50% cumulative (median) range from 1.5 dB(A) to 2.5 dB(A) compared to 2010, shown in table 2-1.

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Improvement</th>
<th>Datasets available</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1-a: PMR ≤ 120</td>
<td>1.6 dB(A)</td>
<td>1306 (2020) vs. 522 (2010)</td>
</tr>
<tr>
<td>M1-b: 120 ≤ PMR ≤ 160</td>
<td>1.5 dB(A)</td>
<td>181 (2020) vs. 54 (2010)</td>
</tr>
<tr>
<td>M1-c: PMR &gt; 160</td>
<td>2.5 dB(A)</td>
<td>109 (2020) vs. 23 (2010)</td>
</tr>
<tr>
<td>M1-d: PMR &gt; 200</td>
<td>1.5 dB(A)</td>
<td>59 (2020) vs. 12 (2010)</td>
</tr>
</tbody>
</table>

Table 2-1: Median improvements of $L_{urban}$ - Category M1

At this point, a compliance analysis of the 2020 and 2010 data against the limit values of the current regulation can further underline the progress made. Although the vehicles in 2010 referred to higher limit values that were in force at the time, the comparison of both datasets to current limit values enables an alternative perspective into the progress made by modern vehicles. The table 2-2 illustrates the percentage of limit value compliant vehicles with respect to the limit phases 1, 2 and 3 as prescribed by UN Regulation No. 51.
<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Compliance 2020</th>
<th>Compliance 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
</tr>
<tr>
<td>M1-a</td>
<td>100.0%</td>
<td>92.7%</td>
</tr>
<tr>
<td>M1-b</td>
<td>100.0%</td>
<td>89.3%</td>
</tr>
<tr>
<td>M1-c</td>
<td>100.0%</td>
<td>96.5%</td>
</tr>
<tr>
<td>M1-d</td>
<td>100.0%</td>
<td>98.3%</td>
</tr>
</tbody>
</table>

Table 2-2: Limit value compliance analysis - Category M1

All datasets in 2020 for category M1 are 100% compliant with the phase 1 limit values which came into force in the middle of 2016. A compliance percentage of 89.3% up to 98.3% can be seen with respect to the phase 2 limit values, whereas 50.9% to 60.3% are already compliant to a future phase 3 limit value depending on the vehicle subcategory.

The figure above demonstrates that the vehicles do not strictly lean towards the specific limit values that were in place during the date of type approval. A high percentage of vehicles are noticeably below their binding limit values with a fraction already pre-compliant to future limit values.

Another area of interest is the shift in the power-to-mass ratio of vehicles, also used as a criterion for differentiating between the various sub-categories of vehicles in class M1. Figure 2-3 shows a clear shift towards vehicles with a higher PMR. The PMR increase at the median point is in the range of approximately 10 kW/t. A small number of datasets for vehicles with a PMR above 300 kW/t is also available in the 2020 database.
Figure 2-4 shows the dependency between $L_{\text{urban}}$ vs. PMR. The plot displays a general reduction of $L_{\text{urban}}$ sound values for the 2020 data, with significant improvements realised at the higher end of PMR range. In the event that several datasets have identical PMR values, the average $L_{\text{urban}}$ value is calculated and displayed and therefore the elevated values of 76 dB(A) are no longer visible in the 2020 dataset on the plot. At the lower end of the spectrum, less improvement is visible and the $L_{\text{urban}}$ values remain closer to those seen in the 2010 database. This is hinting to a potential technological feasibility limit for further sound level reductions. A further reason may be the lack of constraint from the limit values because the vehicles are already compliant with future limit values (e.g. phase3). The linear averages of the two scatters indicate the same decrease in terms of $L_{\text{urban}}$ values as illustrated on figure 2-1.

![Lurban vs. PMR - Category M1](image)

Figure 2-4: $L_{\text{urban}}$ vs. PMR - Category M1

Figure 2-5 uncovers the potential benefits of alternative propulsion types in terms of vehicle sound emission reduction for category M1. Both HEVs and EVs show a substantial benefit over the equivalent ICE powered vehicles under type approval conditions, populating the lower end of the spectrum in terms of sound emission. Moreover, a considerable benefit is also visible for higher PMR vehicles with both alternative propulsion types, realising lower $L_{\text{urban}}$ values compared to equivalent ICE powered vehicles. With the emergence of electrification, the subject of tyre/road interaction is gaining increased attention. In the context of rolling noise, the sound pressure value by constant speed $L_{\text{crs}}$ is a reliable indicator. Approximately 90% of $L_{\text{crs}}$ can be related only to the tyre/road interaction and only 10% (depending on vehicle characteristics and propulsion type) comes from differing sound sources, but primarily from powertrain.
Figure 2-5: Lurban vs. PMR - Category M1 (Propulsion types)

Figure 2-6: Lcre vs. tyre width - Category M1

Figure 2-6 shows the $L_{cre}$ value vs. tyre width. The resulting graph confirms the tendency shown on the previous figures towards lower sound levels for the 2020 datasets of approximately 1.5 to 2.0 dB(A). The linear average indicates a rising sound level with increasing tyre width.
It must be noted that the limit values for tires increase with increasing tyre widths according to UN Regulation No. 117, which could explain the increase in the $L_{crs}$ sound level. The steady increase in PMR and/or vehicle weight and the consequential requirement for wider tyres must also be considered as contributing factor towards higher vehicle sound levels.

2.1.2 Category M2

With 23 datasets for 2020 and 47 for 2010, the number of available datasets for the vehicle category M2 is significantly lower, compared to category M1. Any reliable and meaningful analysis and resulting observations and conclusions must be handled with caution. Nevertheless, the following analysis will attempt to highlight the main divergences and findings between the provided data of the years 2020 and 2010.

Figure 2-7 shows the statistical distribution of $L_{urban}$ values for the complete category M2, analogous to category M1. A shift of the curve towards lower $L_{urban}$ values can be noted in comparison to 2010, especially at the lower end of the spectrum. The median decrease in terms of $L_{urban}$ is 0.4 dB(A).

![Statistical distribution of $L_{urban}$ - Category M2](image)

**Figure 2-7: Statistical distribution of $L_{urban}$ - Category M2**

Figure 2-8 illustrates the statistical distribution of $L_{urban}$ values separated into the various subcategories. It is important to consider that M2 vehicles with a technically permissible maximum laden mass higher than 3.5 tonnes have to be tested using the “truck principle” in accordance with 3.1.2.2 of the regulation. The absence of data for the subcategory M2-a in the 2020 datasets may be explained by the integration of M2-a vehicles into the M2-b category.
Moreover this would explain the considerable improvement of approximately 3 dB(A) for the M2-b category in 2020 over both M2-b and M2-a categories in 2010, see table 2-3.

![Statistical distribution of Lurban - Category M2](image)

**Figure 2-8: Statistical distribution of Lurban - Category M2 (Subcategories)**

Unfortunately, due to the absence or limited amount of data in both databases, no resulting and reliable trends for this category can be concluded.

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Improvement</th>
<th>Datasets available</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2-a: M ≤ 2.5 t</td>
<td>NA</td>
<td>0 (2020) vs. 37 (2010)</td>
</tr>
<tr>
<td>M2-b: 2.5 t &lt; M ≤ 3.5 t</td>
<td>3.0 dB(A)</td>
<td>14 (2020) vs. 10 (2010)</td>
</tr>
<tr>
<td>M2-c: M &gt; 3.5 t; P_n ≤ 135 kW</td>
<td>NA</td>
<td>9 (2020) vs. 0 (2010)</td>
</tr>
<tr>
<td>M2-d: M &gt; 3.5 t; P_n &gt; 135 kW</td>
<td>NA</td>
<td>0 (2020) vs. 0 (2010)</td>
</tr>
</tbody>
</table>

**Table 2-3: Median improvements of Lurban - Category M2**

Table 2-4 shows the limit value compliance of the subcategories concerning the current limit phases 1, 2 and 3. Due to the significant improvements realised for the M2-b subcategory, the limit compliance of the 2020 data is 100% for phase 2 and 64.3% for phase 3. M2-c achieves a compliance value of 50% for phase 2 and 33.3% for phase 3. Due to the lack of data, any further comparison and conclusions from 2010 data is not possible.
Table 2-4: Limit value compliance analysis - Category M2

2.1.3 Category M3

The vehicle category M3 represents vehicles for carriage of persons with a maximum mass above 5 tonnes as defined in chapter 1.2. With 44 (2020) vs. 45 (2010) both datasets are comparable. While the data of category M2 in 2020 was limited to ICE vehicles, the 2020 data for M3 consists of 38 ICE vehicles, 4 NG and 2 EVs.

Figure 2-9 shows the statistical distribution of $L_{urban}$ for the complete datasets for category M3. The graph indicates a clear shift towards lower type approval values with the median $L_{urban}$ value decreasing by 3.3 dB(A) in comparison to 2010. Furthermore, the minimum and maximum $L_{urban}$ values display substantial reductions: the maximum decreases by 3.0 dB(A) from 81 dB(A) to 78 dB(A) and the minimum value decreases by 5.0 dB(A) from 72 dB(A) to 67 dB(A).

Figure 2-9: Statistical distribution of $L_{urban}$ - Category M3
Figure 2-10 shows the statistical distribution of $L_{urban}$ separated into the various subcategories. It can be observed that both subcategories M3-b and M3-c have the same lowest type approval value in 2020 and in 2010. Also noticeable is that up to 50% cumulative the 2020 subcategories M3-b and M3-c are quieter than the 2010 subcategory M3-a. This improvement can be linked to the presence of electrified vehicles in the 2020 data. Due to the contribution of the subcategory M3-a in the 2010 data, the improvements of the single subcategories are higher than the previous mentioned average improvement for the complete category M3.

![Statistical distribution of Lurban - Category M3](image)

**Table 2-5: Median improvements of $L_{urban}$ - Category M3**

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Improvement</th>
<th>Datasets available</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3-a: $P_n \leq 150$ kW</td>
<td>NA</td>
<td>0 (2020) vs. 18 (2010)</td>
</tr>
<tr>
<td>M3-b: $150 &lt; P_n \leq 250$ kW</td>
<td>3.4 dB(A)</td>
<td>19 (2020) vs. 14 (2010)</td>
</tr>
<tr>
<td>M3-c: $P_n &gt; 250$ kW</td>
<td>4.3 dB(A)</td>
<td>25 (2020) vs. 13 (2010)</td>
</tr>
</tbody>
</table>

Figure 2-11 shows the statistical distribution of $L_{urban}$ values, divided into subcategories for ICE vehicles only.
Without the contribution of the pure electric vehicle types the improvements at the lower end decreases significantly from 67 dB(A) to 71 dB(A) for both subcategories in 2020. As mentioned above, the electrification demonstrates a significant potential to reduce sound emissions levels of M3 vehicles under type approval conditions especially considering that these vehicles are only testing under WOT condition. Table 2-6 shows the limit value compliance of the subcategories concerning the current limit phases 1, 2 and 3.

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Compliance 2020</th>
<th>Compliance 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
</tr>
<tr>
<td>M3-a</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>M3-b</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>M3-c</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 2-6: Limit value compliance analysis - Category M3

The distinguishing criterion for the subcategories of the vehicle category M3 is the rated engine power. Figure 2-12 shows the evolution of the rated engine power between both 2020 and 2010 datasets. The investigation is limited to subcategories M3-b and M3-c due to the lack of data for subcategory M3-a in the 2020 data. With the exception of a larger spread, no significant changes in terms of rated engine power can be extracted from the plot apart from the addition of engine power values in the range between 150 kW up to 200 kW.
Figure 2-12: Statistical distribution of rated engine power - Category M3 (Subcategories)

Figure 2-13 compares the relation between L_{urban} vs. rated engine power for both datasets. The differentiation between propulsion types clearly illustrates the high potential of alternative propulsion technologies, which provides significant benefits in terms of sound levels under type approval conditions.

Figure 2-13: L_{urban} vs. rated engine power - Category M3
2.2 **Category N (Carriage of Goods)**

In analogy to the previous analysis of category M vehicles, which are mainly designed and constructed for the transport of passengers as well as their luggage, the following chapter deals with the analysis of the evolution concerning category N vehicles, which are primarily used for the carriage of goods.

2.2.1 **Category N1**

The vehicle category N1 contains classical pick-up trucks and vans not exceeding a mass of 3.5 tonnes. 159 datasets (2020) vs. 125 datasets (2010) are available for further analyses. In the 2020 dataset vehicles with alternative propulsion types are available with 3 EVs and 2 NGs.

Figure 2-14 shows the statistical distribution of $L_{urban}$ values of both databases. The graph indicates a sound level improvement of 2 dB(A) at the upper end, whereas no improvements can be observed at the lower end. Surprisingly the minimum value remains at 66 dB(A) even with the presence of EVs in the 2020 data. This observation could suggest a potential technological limit for this category of vehicles at the lower end of the spectrum with alternative propulsion technologies not being beneficial at type approval conditions. Furthermore, the minor improvement level of 0.4 dB(A) at the median point could represent a confirmation of this finding. However, in order to confirm this finding more datasets for alternative propulsion types are necessary.

![Statistical distribution of $L_{urban}$ - Category N1](image)

*Figure 2-14: Statistical distribution of $L_{urban}$ - Category N1*
Analysing the sub categories in detail, figure 2-15 highlights a significant improvement for category N1-b from 2010 to 2020. Due to the lack of data for category N1-b in 2010 (only 10 datasets) conclusions need to be analysed with caution and may not reflect the reality precisely.

![Statistical distribution of Lurban - Category N1](image)

Figure 2-15: Statistical distribution of Lurban - Category N1 (Subcategories)

Moreover, it can be noticed that the subcategory N1-b in 2020 is very close to the values of subcategory N1-a of 2010. The median value of Lurban at the 50% cumulative point is reduced by 0.5 dB(A) whereas the subcategory N1-b has made considerable improvements of 1.9 dB(A) over 2010.

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Improvement</th>
<th>Datasets available</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1-a: M ≤ 2.5 t</td>
<td>0.5 dB(A)</td>
<td>95 (2020) vs. 115 (2010)</td>
</tr>
<tr>
<td>N1-b: M &gt; 2.5 t</td>
<td>1.9 dB(A)</td>
<td>64 (2020) vs. 10 (2010)</td>
</tr>
</tbody>
</table>

Table 2-7: Median improvements of Lurban - Category N1

Similar conclusions can be drawn when analysing limit value compliance concerning phase 2 and phase 3 for both subcategories, summarised in table 2-8.

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Compliance 2020</th>
<th>Compliance 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
</tr>
<tr>
<td>N1-a</td>
<td>100.0%</td>
<td>75.3%</td>
</tr>
<tr>
<td>N1-b</td>
<td>100.0%</td>
<td>92.2%</td>
</tr>
</tbody>
</table>

Table 2-8: Limit value compliance analysis - Category N1
Figure 2.16 shows a scatter plot of $L_{urban}$ vs. mass $M$ values for the 2020 datasets with a distinction in propulsion types.

![Figure 2.16: $L_{urban}$ vs. technically permissible maximum laden mass $M$ - Category N1](image)

Based on figure 2.16, it is observed that vehicles with higher technically permissible maximum laden masses tend to be equipped with compression ignition engines. In terms of sound levels, no clear differences between vehicles equipped with positive ignition (PI) and compression ignition (CI) engines can be identified. Despite the low amount of available datasets for EVs, these vehicles show a tendency towards higher technically permissible maximum laden masses and indicate an improvement in terms of sound emissions in comparison to the average ICE powered vehicle of category N1.

### 2.2.2 Category N2

The vehicle category N2 covers the medium commercial trucks. The databases contain 76 datasets (2020) vs. 63 datasets (2010) for the N2 category. While the 2010 data only consists of compression ignition powered vehicles, the 2020 database also includes datasets for EV (2 datasets) and NG vehicles (4 datasets).

Figure 2.17 illustrates the comparison of the statistical distribution concerning $L_{urban}$. The graph shows a significant improvement for the 2020 data with an improvement of 3 dB(A) at 50% cumulative over the 2010 data. In the 2020 database, the maximum value decreases by 1 dB(A) from 79 dB(A) to 78 dB(A), with the minimum value considerably decreasing by 3 dB(A) from 70 dB(A) to 67 dB(A).
From figure 2-18, it can be seen that the progress made by the subcategories N2-a and N2-b is inferior in comparison to the overall improvement illustrated in figure 2-17.

This result is caused by the following two reasons. Firstly, it can be noted that subcategory N2-a has made more progress than N2-b according the provided data, with improvements at mean distribution amounting to 1.6 dB(A) for N2-a and 1.0 dB(A) for N2-b.
Secondly, it has to be noted that the 2020 data is much less balanced in terms of available datasets between sub categories (see Table 2-9). While the 2010 data contains a similar amount of datasets for both subcategories, the 2020 data set contains an increased number of entries for subcategory N2-a. Accordingly, the contribution of subcategory N2-a, is much higher to the average improvement of the complete category N2 in 2020 shown Figure 2-17.

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Improvement</th>
<th>Datasets available</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2-a: $P_n \leq 135 \text{ kW}$</td>
<td>1.6 dB(A)</td>
<td>62 (2020) vs. 31 (2010)</td>
</tr>
<tr>
<td>N2-b: $P_n &gt; 135 \text{ kW}$</td>
<td>1.0 dB(A)</td>
<td>14 (2020) vs. 32 (2010)</td>
</tr>
</tbody>
</table>

Table 2-9: Median improvements of $L_{eqAnn}$ - Category N2

Table 2-10 illustrates the limit value compliance to the future limit value phases. It should be noted that phase 2 for category N2 will not apply before 01.07.2022.

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Compliance 2020</th>
<th>Compliance 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
</tr>
<tr>
<td>N2-a</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>N2-b</td>
<td>100.0%</td>
<td>71.4%</td>
</tr>
</tbody>
</table>

Table 2-10: Limit value compliance analysis - Category N2

Figure 2-19 shows the evolution of the rated engine power, which highlights a trend towards lower rated engine power. As mentioned above, this observation is in line with the imbalance in 2020 data in terms of their subcategories. Whether this imbalance is due to a technical explanation and reflects the distribution in terms of registration data or merely the lack of input data for the 2020 database for category N2-b, cannot be clarified at this stage.
Figure 2-20: $L_{urban}$ vs. rated engine power - Category N2

Figure 2-20 shows the relation between $L_{urban}$ and the rated engine power as scatter plot. The trend line for the 2020 ICE data shows a clear improvement over 2010 confirming the findings in the previous figures. The values for EVs are approximately 1 dB(A) below the quietest ICE engine. Analogous to N1, the findings need to be examined with caution due to data inconsistencies and the limited amount of data for alternative propulsion types.

2.2.3 Category N3

The final vehicle category analysed in the course of this report is category N3 representing heavy commercial trucks with 127 (2020) vs. 224 (2010) datasets available for analysis. The 2020 database also includes datasets for electric (6 datasets), hybrid electric (2 datasets) and natural gas powered vehicles (6 datasets).

Figure 2-21 shows the statistical distribution of $L_{urban}$ values for the complete datasets of category N3. The graph shows an improvement of 1.1 dB(A) for the 2020 data at median point. Progress at both, lower and upper end, are noticeable with a reduction by 2.0 dB(A) from 86 dB(A) to 84 dB(A) at the maximum level. The minimum value is reduced by 10.0 dB(A) from 79 dB(A) to 69 dB(A). The substantial improvement at the lower end of the spectrum can be explained by electrified versions of heavy commercial vehicles and the benefits they bring in type approval testing in terms of sound level, especially considering that N3 vehicles are only testing under WOT condition.
Figure 2-21: Statistical distribution of $L_{\text{urban}}$ - Category N3

Figure 2-22 shows the statistical distribution of $L_{\text{urban}}$ separated into the subcategories N3-a, N3-b and N3-c. While the median improvement is 1.3 dB(A), the most significant improvements in terms of sound level can be seen at the upper and the lower end of the $L_{\text{urban}}$ spectrum.
Table 2-11 illustrates issues regarding the available number of datasets per subcategory. A meaningful and reliable analysis cannot be performed for category N3-a due to the lack of data. Similarly, the small number of available data sets compared to the 2010 database may affect the subcategory N3-b and therefore any findings must be examined with caution.

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Improvement</th>
<th>Datasets available</th>
</tr>
</thead>
<tbody>
<tr>
<td>N3-a: P_n ≤ 150 kW</td>
<td>3.0 dB(A)</td>
<td>2 (2020) vs. 4 (2010)</td>
</tr>
<tr>
<td>N3-b: 150 &lt; P_n ≤ 250 kW</td>
<td>1.7 dB(A)</td>
<td>19 (2020) vs. 74 (2010)</td>
</tr>
<tr>
<td>N3-c: P_n &gt; 250 kW</td>
<td>1.3 dB(A)</td>
<td>106 (2020) vs. 146 (2010)</td>
</tr>
</tbody>
</table>

Table 2-11: Median improvements of $L_{eq,1h}$ - Category N3

Table 2-12 shows the limit value compliance to current and future limit value phases.

<table>
<thead>
<tr>
<th>Subcategory</th>
<th>Compliance 2020</th>
<th>Compliance 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
</tr>
<tr>
<td>N3-a</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>N3-b</td>
<td>100.0%</td>
<td>84.2%</td>
</tr>
<tr>
<td>N3-c</td>
<td>100.0%</td>
<td>92.5%</td>
</tr>
</tbody>
</table>

Table 2-12: Limit value compliance analysis - Category N3

Figure 2-23 shows the evolution of the rated engine power, which indicates a tendency towards higher engine power in the 2020 data with the median increase amounting to approximately +20 kW.

**Figure 2-23: Statistical distribution of rated engine power - Category N3**
Figure 2-24: $L_{urban}$ vs. rated engine power - Category N3

Figure 2-24 illustrates the relationship between $L_{urban}$ and the rated engine power by means of a scatterplot. The polynomial averages confirm the trend to lower type approval values within the 2020 database. Additionally, the differentiation of propulsion types allows for a detailed look of their effects and advantages in terms of sound levels in type approval conditions. From the graph, we can see that NG and HEV vehicles do not show a real benefit and behave similar to regular ICE vehicles. On the other hand, EVs show substantial potential to reduce the type approval values of category N3 vehicles. This can be explained through the WOT procedure of the type approval testing where the use of the EVs provide significant benefits in terms of sound level.

2.3 Representativeness of the Type Approval Data Composition

The intention of the following investigation is to evaluate the representativeness of the composition of both type approval databases in comparison to the fleet composition in real traffic. It should be stressed that both databases, OICA TA Database 2020 and ACEA TA Monitoring Database 2010, contain type approval values of selected vehicle types that are available on the market without claiming to be exhaustive. As explained in the previous sections, the provided information allows for the detailed analyses of the progress made by various vehicle categories over a specific period.
On the other hand, both databases do not provide any further information concerning the detailed vehicle composition in real traffic. In order to verify and evaluate the representativeness of the individual data sets of the databases, a comparison with the European Environment Agency (EEA) [6] registration database is performed. This database provides information about the registered vehicles within the European Union from the years 2011 up to 2019. This EU Registration database contains approximately 15 million datasets for the year 2019 and permits a comparison for the representativeness of the OICA and ACEA databases in terms of real traffic composition. Similar to figure 2-3 in chapter 2.1.1, the below figure 2-25 illustrates the evolution of the PMR value for vehicle category M1. Furthermore, the EU registration database allows for a comparison of this parameter between different countries.

![Figure 2-25: EU registration data vs. Type approval data - Category M1](image)

Contrary to the findings in figure 2-3 of chapter 2.1.1, the graph above illustrates a decrease in terms of PMR for EU registrations in 2019 compared to 2011. This suggests that even though more vehicle types with a higher PMR value are available on the market, consumers are purchasing more vehicles with a lower PMR value. Interestingly, the subcategory M1-a with a PMR ≤120 kW/t makes up to 98% of the total registered vehicles in 2019. The remaining subcategories with a PMR above 120 kW/t merely contribute with 2% of total registrations to make up the entire fleet share.
A further interesting aspect is the classification according to different EU member states. The graph illustrates a significant spread and difference in distribution between different countries in terms of PMR of registered vehicles. In order to allow an EU wide representation, the remainder of the study will focus on the average PMR values of all EU member states rather than for a specific country. The data illustrated in figure 2-25 in conjunction with the values of the TA databases form the basis for the calculation tool, described in further detail in chapter 4.

2.4 Overview and Conclusion

The comparison of the OICA TA database 2020 and the ACEA TA database 2010 permits an in depth look into the progress made by the various vehicle categories over the past decade in terms of sound level. In summary, it is evident that all categories have seen improvements in terms of their sound noise emissions in type approval conditions although noteworthy differences exist within a vehicle category.

For the M1 category it can be concluded that the subcategory M1-c has made substantial improvements in comparison to subcategories M1-a, M1-b and M1-d. Interestingly, the data reveals that certain vehicle categories such as M1 and N1 have not improved in their minimum $L_{urban}$ value over the past ten years despite the introduction of alternative propulsion technologies within both categories, suggesting a technical feasibility limit already having been reached. The subject of technical limits and feasibility is investigated in further detail in chapter 3.

Additionally, it is concluded that the introduction of alternative propulsion types such as EVs and HEVs have a considerable benefit in terms of sound emission in type approval conditions, especially for the vehicle categories tested under the “truck principle” in accordance with 3.1.2.2 of the regulation. The effect and real benefits of these propulsion types in real traffic scenarios is further assessed in chapter 5. Figure 2-26 outlines the above mentioned findings using statistical distribution and allowing the graphical display of variations for each vehicle category.
Unfortunately, the lack of data does not allow for an in-depth look at the progress made by several vehicle sub-categories and certain tendencies need to be analysed with caution.

An important conclusion can be extracted from the limit value compliance. In contrast to the general assumption that vehicles are situated exactly on their respective limit value, the data reveals that vehicle categories already partially present a pre-compliance towards future limit value phases. This signifies that the introduction of lower limit values in the future would potentially have less of an impact on sound emission levels in real traffic compared to the assumption that all vehicles are compliant and positioned on their respective limit value.

Finally, the analysis of the EU registration data for the vehicle category M1 indicates that the PMR of vehicles registered in 2019 has reduced since 2011. The vehicle category M1-a represents 98% of the registered vehicles in Europe (average) in 2019 with the remaining subcategories making up merely 2%.
3 Industry Consultation

In an effort to understand the current state of the art for vehicle sound reduction technologies in further detail and to better comprehend the technical challenges related to upcoming limit value reductions, numerous interviews were conducted with vehicle manufacturers representing the concerned vehicles. The information gathered in these interviews is processed with the purpose of identifying common points and predicaments shared by the majority of interviewed OEMs and highlight specific points relevant to individual vehicle categories.

As it turned out, a major concern shared by all vehicle OEMs is the conflict of targets between sound and safety characteristics on the tyre side. Therefore an interview with an OE tyre manufacturer representing the tyre category was conducted in addition, which confirmed the statements previously gathered. The following chapter aims to give insight in the challenges faced by the industry and highlights some of the aspects pinpointed in the manufacturer interviews.

3.1 Vehicle Industry

In the beginning of the year 2021 Europe’s major OEMs were as well interviewed as some from overseas and some smaller manufacturers with limited and very specific product ranges. Together they stand for more than 30 brands covering the whole range from small M1 cars to the biggest N3 trucks as well as from niche products to mass production in large scales. In preparation for the interviews, a common questionnaire had been sent to the manufacturers. In addition to that, the interviews gave much room for any individual topic highlighted by the OEMs.

3.1.1 Evolution in vehicle sound technology

Manufacturers have stated that the change from Method A to Method B as defined in UN Regulation No. 51 and the introduction of the phase 1 and phase 2 limit values according to UNR51 have certainly delivered the desired positive impact in terms of lowering noise emissions from vehicles. This positive trend showing the achieved improvements is clearly visible in figure 2-26 under chapter 2.4.

The technology implemented in most recent vehicles of category M1 is such, that in type approval conditions, the sound emission values for ICE vehicles are comparable to the values achieved by full electric vehicles. This statement is further underlined in chapter 2.1.1.
For an electric vehicle the dominating noise source is the tyre/road interaction, contributing to almost 85% of the overall sound of the vehicle. In order to further reduce the sound levels of this type of vehicle, the part source contribution of the tyre/road interaction needs to be addressed. The increased weight of the vehicles and the resulting use of wider tyres with a higher load index may have a negative influence on the sound emission of an electric vehicle. Vehicle manufacturers are already forced to equip certain vehicles with superior tyres in terms of sound levels in order to pass the limit values as defined in UN Regulation No. 51. This trend will become more widespread and more extreme over all vehicle categories with further decreasing limit values. Manufacturers have stated that certain electrified vehicles of the category N1 would not only be affected from a reduction in technically permissible laden mass due to the increased weight, but also struggle to even comply with the upcoming phase 3 limit value reduction, if tyre/road interaction sound level does not contribute efficiently.

3.1.2 Vehicle Lifecycle

A vehicle lifecycle is defined as the amount of time required from start of development until the end of life and recycling. Within this timeline, there are defined stages of development that a vehicle will undergo. During the stage of pre-development, all aspects from research & development, conceptualisation, styling and packaging are considered. This includes the decisions about how long the vehicle is supposed to be available on the market. This in turn means, that potential changes in regulations that will occur during this time frame have to be considered. In terms of sound emissions, a vehicle manufacturer is already forced at the beginning of the development, to consider a future phase of limit value reduction that will come into force in the later stages of the vehicle lifecycle. Therefore, many vehicles on the market already have a pre-compliance to future phase limits. This phenomenon is validated with data analysed in the compliance analysis for each category in chapter 2.

3.1.3 Challenges by future Limit Value Reductions

**Dominant Partial Sound Source**

For M1 and N1 vehicles, the permanent developments towards lower powertrain sound levels and the introduction of increasingly complex exhaust aftertreatment systems (e.g. particulate traps) have reduced the powertrain sound level to such an extent that the tyre / road interaction has become the dominant partial sound source contributor at type approval conditions.
For EVs, this theoretically extends further down to lower speeds due to the absence of combustion noise from the engine. The tyre/road interaction has therefore become the limiting factor for noise emission reductions at type approval conditions. Due to the logarithmic principle of summing up sound pressure levels of individual part sound sources, it is key and most efficient to reduce the dominant sound source in order to achieve a significant overall sound level reduction.

Due to the wide open throttle testing procedure for vehicle categories M2 (M > 3500 kg), M3, N2 and N3, the powertrain still remains the main contributing sound source under type approval testing conditions. The test procedure for these categories is designed to highlight the powertrain contribution and cannot be translated one to one into real life conditions. The electrification of city busses implemented in many bigger cities has shown a significant positive impact in terms of sound levels already. Unfortunately, the electrification of heavy commercial vehicles and the corresponding technology is mostly in the conceptualisation phase. The resulting lack of TA data does not allow a reliable impact assessment of this technology in real traffic conditions.

**Limited Packaging Space and increased Vehicle Weight**

A further reduction in powertrain noise emissions would necessitate an increased silencer system volume. An encapsulation of the engine, wheel arch housing, underbody and the engine compartment itself, is also considered as an option in combination with a reduction in tyre/road noise. All these solutions demand an increase in packaging space. By contrast, the striving towards a near-zero emission compliance forces manufacturers to use the silencer volume for its exhaust after-treatment system. With the packaging space being further limited, new solutions need to be developed, which are not available to manufacturers for now. The ICE engines of vehicle categories M2 and M3 are already encapsulated to a high level and would therefore require currently non-existent technology to further lower the overall sound level. For heavy commercial vehicles, the powertrain thus far is not fully encapsulated in most cases. A complete encapsulation of the powertrain would be beneficial to reduce the powertrain source contribution. However, this would bring considerable challenges, especially in terms of thermal conditions for the engine. Further encapsulation remains complicated with a lack of space to integrate additional coolers, since the limited length at the front-end is required for safety features. Furthermore, the extensive use of fibrous absorbent materials on the vehicle underbody is not appropriate and feasible for vehicles with extensive off road (e.g. building site) use.
In addition to the above-mentioned solutions being exposed to package constraints and underfloor protection, they also have the disadvantage of adding additional weight to the vehicle. This in turn results in implications for emission related aspects such as increased fuel consumption, exhaust gas emissions and the resulting decline in payload and vehicle range, which in turn are key criteria for the transport of goods.

**Measurement Uncertainties**

With ever more stringent limit values the measurement uncertainties are further gaining in importance. The measurement uncertainties are created by many influence factors such as measuring equipment, test sites, ambient conditions and run-to-run variability. The measurement uncertainties for type approval test runs can reach up to 1-2 dB(A) for which no correction factors are foreseen in the UN Regulation No 51. Vehicle manufacturers are therefore forced to take these measurement uncertainties into consideration and develop their vehicles up to 1-2 dB(A) below a certain limit value in order to pass the type approval or conformity of production tests under any circumstances. This further strengthens the presented data in chapter 2 illustrating that the vehicle sound levels do not strictly lean against a specific limit value, but mostly over deliver in terms of sound level reductions.

**Possible Conflicts with future Emission Regulations**

With future emission regulations becoming ever more stringent, vehicle manufacturers have reached a point where certain trade-offs need to be taken into account. On the one hand, the measures taken to lower sound emissions lead to higher weight and thermal challenges, which in turn have a negative impact on exhaust gas emission levels. On the other hand, measures required to fulfil the stringent emissions criteria could lead to higher sound emissions from the powertrain side. Equipping vehicles with low rolling resistance tires could be unfavourable for lowering the overall sound emission of a vehicle due to increased rolling sound levels.

Furthermore, manufacturers expressed a concern about the seemingly disorderly introduction of regulations that can indirectly affect the efforts and work done by manufacturers to type approve their vehicles. A coordinated and aligned introduction of upcoming regulations such as EU7 or GSR would be welcomed by the industry. Chapter 6.1.4 takes a detailed look into this subject matter.
Lack of existing Technology and Portfolio Reduction

Manufacturers have stated that no technologies are available or in development for their portfolio of vehicles, especially with ICE engines, to achieve limit value reductions beyond phase 3. Numerous aspects contribute to the verdict that a technological limit has been reached to significantly reduce noise emissions from the powertrain to reach limit values beyond those of phase 3. Chapter 4.2 of this study investigates this aspect in detail.

Budget or economy cars risk to be the first affected by further sound limit reductions as these type of vehicles are generally designed to be small, lightweight and inexpensive. Due to these requirements, the technologies and measures used in more premium vehicles to reduce sound emissions cannot be implemented into this category of vehicles. On small vehicles, the available space for additional encapsulation or silencers is commonly more limited than on larger and more expensive cars. Both of these factors could lead to the risk that these vehicles are unable to pass the limit values beyond phase 3 and subsequently risk being the first type of vehicles to be discarded from the manufacturer’s portfolio. Figure 2-25 illustrates that the majority of vehicles registered in 2019 have a PMR value equal to or below 75 kw/t. Vehicle manufacturers stressed that this topic needs to be addressed and taken into consideration before any future limit value reduction is decided. This problem could have severe consequences on the buying options for the end consumers and on the overall CO2 emissions of transportation sector due to customers being forced to buy bigger cars with increased exhaust gas emission levels.

Significant Change in Mobility Concept and Cost Statements

The data analysed in chapter 2 highlights certain vehicle subcategories reaching a potential technical limit in terms of sound level reduction. Manufacturers further state that a limit value reduction beyond phase 3 is not feasible with technologies available or in development. Lower limit values beyond phase 3 would potentially lead to a significant change in current vehicle mobility concepts with the extent of the change unknown at this time.

Unlike in the past, where a certain cost estimate could be associated with the efforts needed to reach future limit values, the industry is facing the challenge of technical feasibility at this stage, which cannot be quantified in terms of cost. In addition, compliance with the limit values is obligatory for the vehicle industry and the question of cost is out of focus in view of the technical feasibility issues destined to be witnessed with the introduction of limit values beyond phase 3. Consequently, a cost-benefit analysis cannot be carried out for this study.
Special Purpose Vehicles

Many special purpose vehicles are based on and derived from vehicle types developed for the consumer market. Terminating the development of the base vehicle, as they fail to pass future sound limit values, could have significant consequences to the special vehicles market as well. Manufacturers further raised the question whether it is necessary and useful to impose the same limit value reductions to this special category of vehicles even though the majority of special purpose vehicles operate outside of urban areas and restricted to very specific environments e.g. heavy equipment transport trucks.

3.2 Tyre Industry

A common subject mentioned in all interviews with the tyre experts of the vehicle manufacturers of category M1 & N1, was the limited potential and the contribution of the tyre/road interaction towards achieving lower vehicle sound levels. Therefore, it was decided to interview a tyre manufacturer in order to confirm the statements made during vehicle manufacturer interviews and to further understand the challenges faced by the tyre industry.

3.2.1 Technical Aspects

A vehicle tyre plays an integral role in the proper functioning of key vehicle performances. The tyre is a complex structure incorporating up to 20 components that can be tuned in order to achieve the desired performances such as safety, tread wear or fuel saving. During tyre development, up to 14 key tyre attributes have to be considered. Tyres are separated into three distinct categories:

- C1: passenger car tyres
- C2: light commercial vehicle tyres
- C3: heavy vehicle tyres

Depending on the tyre category and field of deployment, certain attributes and performances are adjusted and emphasised in order to achieve the desired functionality. High performance vehicle tyres highlight the safety, cornering and wet performances, whereas a tyre for heavy-duty commercial vehicles is designed with focus on mileage and fuel economy performance. A vehicle manufacturer will prioritise the aspects which provide the greatest benefit in order to satisfy the characteristics of the vehicle and to meet or exceed end consumer’s expectations.
Unfortunately, a tyre that fulfils all performances to the best level cannot exist since tyre development is a compromise of different attributes and requires a blending and balancing of various characteristics in order to achieve the desired performance characteristics. Consequently, the improvement of certain attributes will naturally lead to the deterioration of other performances.

Figure 3.1: Tyre performance trade offs - Regulated and non-regulated

Figure 3.1 illustrates an example of the performance balance change for the optimisation towards wet performances and the undesired effects towards other performances. It can be clearly seen that certain key attributes such as abrasion and comfort degrade post tyre optimisation.

3.2.2 Regulatory Aspects and Conflict with future Requirements

The UN Regulation No. 117 defines the requirements and specifies the limit values for the rolling sound of tyres as described in the test procedure. The prescribed limit values increase in terms of permitted sound level with increasing tyre widths. It is worth noting that there exists a discrepancy between UN Regulation No. 51 and UN Regulation No. 117 with regard to the prescribed test speed. Whereas vehicle manufacturers test the vehicles at lower speeds where the powertrain is dominant, the UN Regulation No. 117 specifies higher speeds where the tyre rolling sound becomes dominant.
Nevertheless, the tyre industry does not consider an alignment of the two regulations to be useful, as the optimal potential for noise reduction is given at speeds where the tyre is the dominant sound source [7]. It is not clear to what degree the optimisations made at higher vehicle speeds are transferred to lower speeds of 50 km/h.

The electrification of vehicles has brought further challenges to the tyre industry. The increased weight in combination with considerable higher torque and acceleration performances of EVs, as well as their requirement for reasonable driving range and the wish for lower interior noise forces the tyre manufacturer into a peculiar position. As mentioned above, the tyre performance is a compromise of many attributes. A low rolling resistance tyre positively affects energy consumption and tread wear but negatively impacts exterior tyre noise due to the use of harder tread compounds.

Moreover, new safety regulations could have a negative impact on the sound performance of tyres. With the future GSR (General Safety Requirements) planning to regulate the worn tyre wet grip, tyre manufacturers are forced to improve the aquaplaning attributes by increasing the groove opening on the tread patterns, which in turn negatively affects the exterior noise performance of tyres.

In addition, the need for lower CO2 emissions will force the vehicle manufacturers to request tyres with lower rolling resistances. This indirect requirement will also lead to the above described target conflict in terms of tyre properties and will most likely deteriorate the rolling noise accordingly.

### 3.2.3 Original Equipment (OE) vs Replacement Tyres

OE tyres are fitted when the vehicle initially is delivered to the end consumer. In addition to the requirements of the UN Regulation No. 117, these tyres must also fulfil the performance requirements specified by the vehicle manufacturers. Thus, OE tyres are in most cases specifically designed and tuned in cooperation with the vehicle manufacturer to highlight certain performance characteristics of the vehicle. With the UN Regulation No. 51 limit values becoming tougher to meet, vehicle manufacturers increasingly request the OE tyre to be designed for lower exterior sound levels.

Replacement tyres on the other hand should offer an all-around performance that any vehicle can take advantage of. Unlike OE tyres, the replacement tyres do not benefit from the co-development and input from vehicle manufacturers.
As a result, the tyre manufacturers can concentrate on certain key performance characteristics without being pressured by the vehicle manufacturers to meet lowest sound emission levels. The tyre manufacturers are only required to meet the sound limits of UN Regulation No. 117. A tyre can be developed for improved tread wear, fuel efficiency, low interior noise, etc. This allows the end consumer to choose a particular tyre best suited for their driving style. Replacement tyres can also be tuned for lower external sound noise of class A according to the revised EU tyre label. Many manufacturers provide such tyres but the majority of end-consumers do not consider this an important buying argument but rather decide on performances such as increased grip/safety, lower fuel consumption and increased tread wear life. [8]

It is up to the consumer to either choose to replace worn tyres with identical OE tyres that provide identical performances to when the vehicle was initially delivered, or chose replacement tyres of any make and type that may focus on alternative tyre attributes, potentially exposing inferior noise emission levels.

### 3.2.4 Opportunities for lowering the Rolling Sound

For tyre categories C1 and C2, the best available tyres on the market in terms of noise emission levels are approximately only 1-2 dB(A) worse in comparison to slick tyres. With the knowledge that the shape of a slick tyre is the superlative in terms of sound emission levels but for safety reasons prohibited for road use, a significant reduction for road legal tyres cannot be expected with currently available technologies. A reduction of 1 dB(A) (based on UN Regulation No. 117 testing) on the sound level is likely to be attained on the tyre side in order to achieve phase 3 of UN Regulation No. 51. With the tyre being a compromise of multiple attributes, any further improvement is not expected due to the negative impact on the safety performances of the tyre. Moreover, a breakthrough in technology solving these conflicts is not to be expected. For C3 tyres, the opportunities for an improvement in sound level are expected to be insignificant due to the limited design parameters of ribbed tyres.

Similar to type approval testing of vehicles, the testing according to UN Regulation No. 117 suffers from measurement uncertainties. Although certain correction factors have been implemented, a measurement uncertainty of 1-2 dB(A) still persists and needs to be considered during the development of the tyre.
3.3 Conclusion

From the conducted interviews, it is clear that the technical feasibility has become a serious issue in order to fulfil future and more stringent noise emission requirements. Especially considering M1/N1 vehicles, the powertrain sound levels have been decreased over the last years to such an extent that the tyre/road interaction has become the dominant part sound source in type approval testing. Options such as encapsulations for N3 vehicles provide opportunities to lower the powertrain noise level even further but have an opposing effect to aspects such as vehicle weight, engine cooling, package space, etc. In order to further improve the overall sound level of vehicles, the tyre is forced to provide a significant contribution. The tyre is a balancing act of numerous parameters with the safety performance of a tyre being of paramount importance. The sound level can only significantly improve with an unacceptable deterioration of the safety or other critical performance aspects of a tyre.

The information presented and gathered during the manufacturer interviews provides invaluable data that is implemented into the calculation model presented in the subsequent chapter. The combination of the evaluated data provided by both ACEA and OICA databases in combination with the realisable improvements provide the necessary backbone for the calculation of future limit value scenarios that are analysed and evaluated in chapter 5 of this study.

A limit value reduction for UN Regulation No. 51 without significant improvements in the contribution from the tyre/road side would render the technical feasibility of a limit value reduction unachievable and will not provide the expected improvements under real driving conditions. With the tyre/rolling sound becoming the dominant part source in type approval testing for certain vehicle categories, it is all the more important to consider aligning a reduction in limit values for both Regulation No. 51 and No. 117. It needs to be ensured that an alignment of Regulation No. 117 is technically feasible, reasonable and safe for the operation of the vehicles, bearing in mind that the tyre is a key component for safety and performance with multiple performance tasks to fulfil
4 Impact Analysis on Real Traffic - Calculation Tool

In order to evaluate the impact of particular measures on the overall real traffic sound level, a calculation tool is established. Numerous parameters need to be assumed correctly with many of them not obvious and small deviations leading to a significantly changed end result. In several studies, the conclusions are based on assumptions and boundary conditions that are unclear, questionable or impossible to follow.

The focus of this study lies in the investigation of the impact of potential further limit value reductions with the decisions to concentrate all the efforts on the vehicle level and specifically considering only M and N category vehicles. The focus is placed on the investigation of the current limit value reductions concerning phase 1, phase 2 and phase 3 of UN Regulation No. 51, further limit value reductions beyond phase 3 and alternative measures besides the ones on the vehicle side. The following chapter focuses on the structure of the calculation tool.

4.1 Demands on the calculation tool

In order to get a clear understanding of the effects, consequences and efficiencies of the limit value reductions, the tool needs to take a number of input parameters and variables into account. The main requirements are summarised in the subsequent points with a detailed description of the calculation tool included in 4.3:

- Vehicle (powertrain) and tyre model for each category, differentiating between ICE powered and BEVs where applicable to calculate vehicle sound level on ISO track surface over the entire vehicle speed range, extracted from type approval values (OICA TA 2020 database).
- Offsets to PTR noise level can be added depending on driving conditions: Differentiation of cruising conditions (low part load) and intermittent traffic (higher powertrain contribution, individual for vehicle category and vehicle speed).
- Offsets on rolling noise level can be allocated to consider different road surface types (different from ISO track used during type approval), weather conditions and tyre sound levels (Class-A to Class-C labelled).
- Individual vehicle share rates (distribution) can be assigned depending on street type, variable distribution of vehicle types for day vs. night, share rate of BEV vehicles over time, number of vehicles (frequency), etc.
Ability to investigate the effects of market penetration rate (how fast new vehicles with reduced sound levels are introduced into the market). Mainly based on assumptions for average vehicle age (individual values per category) and starting date for new limit values.

- The sound models per vehicle category are based on TA values of the 2 databases (OICA and ACEA) in conjunction with EU registration data. Tyre/road sound levels based on literature sources and best guess assumptions (e.g. axle configurations for N3 category), explained in further detail on the subsequent chapters.

- Exclusion of fudge factors in the calculation model that cannot be explained by physics or updated once more recent or more precise data becomes available.

Remark: Unfortunately, precise data for certain driving conditions such as cruise or rolling sound levels for N3 / M3 category cannot be obtained from databases or literature sources.

### 4.2 Limit Value Scenarios

The focus of the calculations with the tool is to predict the potential environmental impact of different limit value reductions in terms of vehicle exterior sound emissions under certain real driving conditions and street types. In order to investigate the effects and efficiencies of different levels of limit reductions, so-called limit value scenarios have been applied in the calculation tool. These limit value scenarios are presented and described in the following chapter.

#### 4.2.1 Limit Value Scenario 1

Scenario 1 is based on the assumption that the limit values will be frozen after the complete implementation of phase 2 for all vehicle categories as described under UN Regulation No. 51. This means that all new vehicles in the future need to comply with the current phase 2 limits and phase 3 of UN Regulation No. 51 will not enter into force. As previously described in chapter 2, most vehicles are compliant with the phase 2 limits. Thus, the required technical effort for reaching this scenario for all vehicle categories is considered low for the vehicle manufacturers. This scenario represents the baseline and reference for the simulations and is based on the 2020 data without any adoptions. Scenario 1 can be labelled as a “do nothing scenario”.

Page 46
4.2.2 Limit Value Scenario 2

Scenario 2 considers the launch and full implementation of phase 3 as given by the UN Regulation No. 51. Complying with the phase 3 limits, further improvements on vehicle (powertrain) and tyre in terms of sound emission levels are required from the manufacturers. In the calculation tool, sound level reductions of 0.5 dB(A) up to 1.0 dB(A) (selected individually per category) are assumed for the tyres, compared to the baseline scenario 1. The major efforts that are necessary to comply with the lower limits are assumed to come from the powertrain. Improvements of a similar magnitude are required, with the exception of the categories N2 and N3. Due to the powertrain being the dominant partial sound source, improvements of 2.0 dB(A) to 2.5 dB(A) are necessary to reach the limits of phase 3. As stated in chapter 3, technical solutions to comply with the phase 3 limits, are already in development and appear, based on the OEM interviews, challenging but still achievable for most vehicle categories.

4.2.3 Limit Value Scenario 3 (fictional)

Scenario 3 in the calculation model is based on the assumption of a further limit value reduction of 2.0 dB(A) below phase 3 values for all vehicle categories. In order to comply with reduced limit values beyond phase 3, further improvements on both tyre and powertrain would be necessary. Based on the feedback from vehicle manufacturers and an OE tyre manufacturer, a reduction of 2 dB(A) on the tyre, as assumed in several other studies in the past, appears to be absolutely unattainable. As concluded in chapter 3, such drastic reductions in tyre noise sound levels would lead to severe compromises on critical parameters and functions that the tyre needs to fulfil. Safety shall not be compromised by measures for sound level reduction of the tyre and remain second priority next to other top priorities like rolling resistance, wear resistance and comfort. Based on the feedback from the manufacturer interviews, no further sound level reduction on top of the 1 dB(A) assumed in scenario 2 can realistically be achieved. Consequently, all efforts in sound level reduction would need to be shifted to the powertrain leading to scenario 3 to become completely unrealistic. Henceforth, all further calculations related to scenario 3 are considered purely fictitious.

Hereinafter, in order to have a level playing field, it is assumed that the reduction on tyre side amounts to 0.5 dB(A) to 1 dB(A) on top of the improvement assumed in scenario 2. Considering that the tyres are the dominant partial sound source for most categories tested according to the “passenger car principle”, improvements of up to 3 dB(A) for the vehicle (powertrain) are necessary to reach the limits in scenario 3.
According to the vehicle manufacturers, these assumed reductions are not achievable with today’s available technology and vehicle concepts. As a result, all further analyses with the simulation tool, based on scenario 3, have to be considered as purely fictional and only for reference to be able to investigate the theoretical potential without any consideration of feasibility.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Baseline freeze after phase 2</td>
<td>Launch of phase 3 as given by UN R51.03</td>
<td>-2.0 dB(A) reduction beyond phase 3</td>
</tr>
<tr>
<td>Feasibility</td>
<td>Possible</td>
<td>Largely possible</td>
<td>Critical, fictional</td>
</tr>
<tr>
<td>Explanation</td>
<td>Already in place (N2 from 1st July 2022 onwards)</td>
<td>Already in development, but challenging</td>
<td>Technical limit already reached in phase 3</td>
</tr>
</tbody>
</table>

Table 4-1: Limit value scenarios in calculation tool

### 4.3 Model Description

The following section provides an overview of the structure of the calculation tool with all inputs and outputs. The operation principles of the tool are briefly explained, as well as the variable parameters that define the calculation scenarios. Additionally, the format of the result output and its meaning are explained.

#### 4.3.1 Model Structure

The baseline of the calculation tool consists, in a first step, of the type approval data from both databases in conjunction with the EU Registration data of the corresponding years. Since the vehicle distribution varies from country to country in terms of registrations, the EU average is considered as most representative for the further calculation. The combination of both data inputs are applied to extract the most representative sound level under type approval conditions according to UN Regulation No. 51 for every vehicle category. Correspondingly, the same procedure is applied to alternative propulsion types such as pure battery electric vehicle data. This provides the opportunity to investigate the potential of these vehicles in terms of traffic noise reduction compared to vehicles with conventional combustion engines.

The test procedure according to UN Regulation No. 51 is focusing on specific driving conditions and a very narrow vehicle speed window. To be able to evaluate the effectiveness and impact of the limit value reduction beyond those reached in type approval conditions, it is key to comprehend how each vehicle category behaves under “real driving” conditions.
The sound emission level of each vehicle category is determined, using realistic transfer functions for the powertrain and tyre/road interaction sound level over the entire operation speed of the vehicles. The applied transfer functions are based on a combination of type approval data, literature research, physical correlations according to literature and an educated guess approach for vehicle categories where recent data is unavailable (e.g. EV busses). The sound level of each category is calculated by logarithmic addition of the two part sound sources, the powertrain and the tyre/road interaction. Chapter 4.3.3 describes these sound models in detail.

Finally, the overall sound level of the vehicles is calculated based on:

- the share rate of the vehicles at a given condition (type of street, period of day)
- the vehicle speed (variable speed differences for individual vehicle categories independent of the speed limit for road type)
- street type (offset in sound level vs. ISO surface for different surface conditions)
- scenario (1, 2 or 3 with option to consider scenarios with or without tyre contribution)
- numerous other parameters that can be adapted (vehicle category share rates, BEV share rate, market penetration speed, traffic frequency etc.)

Figure 4-1 gives a simplified overview for the model structure of the calculation tool. Employing the various options and parameters included in the calculation tool, it is possible to investigate various effects against each other. A variation of parameters can be individually adapted, depending on the task that shall be observed. This permits different scenarios to be investigated in comparison to each other, providing helpful impressions about the efficiency of individual measures concerning the boundary conditions such as vehicle speed, road surface, tyre type etc. Chapter 4.3.2 focuses in further detail on the type of parameters and the options available in the tool. The final output of the calculation consists of a single value for the sound pressure, equivalent to the sound pressure level of all contributing vehicle categories under the given boundary conditions ($L_{Aeq}$). The definition and meaning of the $L_{Aeq}$ as used in the calculation model is subject of chapter 4.3.4.
4.3.2 Parameters in the Calculation Tool

As touched upon in previous chapters, numerous options and parameters are integrated in the calculation tool. The first layer provides the selection of the street type and driving condition (fluent traffic = cruise | alternating traffic with higher powertrain contribution = urban):

Street Types

Five main different street types are implemented in the calculation tool defined as residential street, urban main street, extra urban road, rural roads and motorways. Depending on the selected street type, the calculation scenario predetermines an individual driving speed for every vehicle category. E.g. the driving speed on motorway is configured to 120 km/h for categories M1 an N1, 110 km/h for category M2, 100 km/h for category M3 and 90 km/h for categories N2 and N3.
<table>
<thead>
<tr>
<th>Street Type</th>
<th>Typical Driving Speed / Speed Limit [km/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential Street</td>
<td>30</td>
</tr>
<tr>
<td>Urban Main Street</td>
<td>50</td>
</tr>
<tr>
<td>Extra Urban road</td>
<td>60 - 70</td>
</tr>
<tr>
<td>Rural Road</td>
<td>60 - 90</td>
</tr>
<tr>
<td>Motorway</td>
<td>90 - 120</td>
</tr>
</tbody>
</table>

Table 4-2: Street types in calculation tool

For all pre-configured street types (except motorway), a distinction can be made between cruise and urban conditions. For urban conditions, the powertrain and tyre sound levels is raised by a pre-defined amount depending on the individual vehicle category and the driving speed. The offset varies between a maximum of 2 dB(A) for powertrain (PTR) and 0.5 dB(A) for the tire at vehicle speeds below 70 km/h, down to 0 dB(A) on motorway. The offset for urban conditions vs. cruise conditions is implemented for the purpose of reflecting the increased contribution of powertrain and tyre noise caused by the accelerations under intermittent traffic conditions.

Driving Conditions

The values for the vehicle sound levels under urban conditions have been aligned to the $L_{\text{urban}}$ values obtained from type approval data, whereas the values for cruise conditions have been derived from the corresponding $L_{\text{crs}}$ values wherever available.

<table>
<thead>
<tr>
<th>Driving Condition</th>
<th>Characteristic</th>
<th>Based on Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermittent Traffic</td>
<td>Accelerating/Deaccelerating</td>
<td>$L_{\text{urban}}$</td>
</tr>
<tr>
<td>Free Flowing Traffic</td>
<td>Constant Speed</td>
<td>$L_{\text{crs}}$</td>
</tr>
</tbody>
</table>

Table 4-3: Driving conditions in calculation tool

Traffic Density

A further parameter for variation in the simulation tool is the traffic density respectively traffic volume. This parameter simply follows the physical basis of logarithmic addition. E.g. a doubling of the traffic density increases the simulation result that represents the sound pressure equivalent $L_{\text{eq}}$ by 3.0 dB(A). With the focus of the simulation tool being placed on the analysis of the sensitivity of the sound level vs. various boundary condition variations, the influence of potentially increasing traffic density is omitted, implying that the traffic volume is constant over the years.
This hypothesis prevents the risk of mixing several effects, therefore enabling the investigation of the effects for each individual parameter and change. The absolute value generated by the calculation tool has to be considered with care when used for the comparison with study results from other sources.

Besides the main focus being on the comparison between different scenarios and measures, this study aims to provide an understanding on the level of improvement to be expected in real traffic, for the considered limit value reduction under one specific condition at a time. The relative improvements calculated in this study are completely independent from the offsets that may result from variations in traffic volume. These type of effects add an offset to the absolute value but have no influence on the variation (delta) between the scenarios.

**Tyre/Road Interaction**

In the majority of real traffic scenarios, a difference between real road and ISO track conditions can be observed in terms of tyre/road sound. Numerous parameters can have a significant impact on the level of tyre sound level caused by the tyre/road interaction. The rolling sound can significantly be reduced by the use of specific road-surfaces or by fitting all vehicles with the most quite tyres available on the market, resulting in lower tyre/road sound levels compared to ISO track. Adversely, there is a high risk that the sound level from tyre/road interaction in real traffic is considerably higher than the reference level encountered in type approval conditions. These offsets can be caused by the road surface type itself, wear on the street (deformations, potholes and patches on surface), noisy tyres (C-Label), worn out tyres, rain, etc. In the calculation model, offsets to the tire/road interaction sound level can be assigned in both directions and individually per vehicle category, to consider all these different aspects affecting the tyre/road interaction and the resulting sound level.

The parameters of the second layer deal with the vehicle share rates between different vehicle categories as well as within the vehicle category itself:

**Vehicle Shares per Street Type**

Initially, the share rates of the respective vehicle categories are defined depending on the selected street type. E.g. the share of passenger cars on residual roads exceeds that of heavy commercial trucks. Additionally, the share varies depending on the period of day, namely day and night, which are implemented in the calculation tool. Both periods of the day are weighted differently for the calculation of $L_{Aeq}$: 80% for day and 20% for night, considering the ratio of vehicles that typically use the street in the given time slot. It is important to keep in mind that these shares may vary significantly across road types and countries.
These values intend to be in line with an average distribution in Europe and based on best engineering practice assumptions and estimations established on statistical values acquired from recognised sources e.g. BASt website [9].

<table>
<thead>
<tr>
<th>Street Type</th>
<th>Vehicle Category</th>
<th>Share – Day (80%)</th>
<th>Share – Night (20%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Main Street</td>
<td>M1</td>
<td>81.5%</td>
<td>88.2%</td>
</tr>
<tr>
<td>- 50 km/h</td>
<td>M2</td>
<td>1.0%</td>
<td>0.1%</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td>1.1%</td>
<td>1.3%</td>
</tr>
<tr>
<td></td>
<td>N1</td>
<td>14.6%</td>
<td>9.7%</td>
</tr>
<tr>
<td></td>
<td>N2</td>
<td>1.9%</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td>N3</td>
<td>0.1%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

Table 4-4: Share of vehicle categories - Urban main street

**Share Rate of Electric Vehicles**

Furthermore, the share rate of electrical vehicles within the relevant categories is considered and increased over time. The exact market penetration speed of these vehicle types being unclear and varying depending on the respective country, three different BEV market penetration speeds are implemented in the calculation model, defined as Slow, Medium and Fast. Medium represents the current forecast in accordance with the latest Bloomberg EVO 2021 study. The BEV market penetration speed defined as Slow assumes 50% of Medium and share rate model Fast assumes a penetration speed of 200% respectively. It must be noted that the BEV share rate of category N2 and N3 is set to 0.0% or “non applicable” for all street types as there is not sufficient data available to build reliable transfer functions for these type of vehicles. Moreover, it is unclear what the forecast for both categories realistically look like in the future. Table 4-6 illustrates the BEV share rate with a Medium penetration speed over time for an Urban Main street type:

<table>
<thead>
<tr>
<th>Street Type</th>
<th>Year</th>
<th>Vehicle Category</th>
<th>Share – Day</th>
<th>Share – Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020</td>
<td></td>
<td>ICE, HEV</td>
<td>BEV</td>
</tr>
<tr>
<td>Urban Main Street</td>
<td></td>
<td>M1</td>
<td>80.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>- 50 km/h</td>
<td></td>
<td>M2</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M3</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N1</td>
<td>14.4%</td>
<td>0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N2</td>
<td>1.9%</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N3</td>
<td>0.1%</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 4-5: Share of vehicle categories incl. BEV share rate - Urban main street (2020)
<table>
<thead>
<tr>
<th>Street Type</th>
<th>Year</th>
<th>Vehicle Category</th>
<th>Share – Day</th>
<th>Share – Night</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Main Street – 50 km/h</td>
<td>2040</td>
<td>M1</td>
<td>53.8%</td>
<td>27.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M2</td>
<td>0.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M3</td>
<td>0.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N1</td>
<td>10.8%</td>
<td>3.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N2</td>
<td>1.9%</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N3</td>
<td>0.1%</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 4-6: Share of vehicle categories incl. BEV share rate – Urban main street (2040)

**Market Penetration Rate**

In a further step, the market penetration speed of new vehicle types is implemented and considered as a variation parameter of considerable importance. Since the exchange rate for new vehicles cannot be perfectly predicted for the coming years, four different market penetration speeds are considered in the calculation tool defined as Slow, Medium, Fast and Very Fast. The calculation of the exchange rate is based on the average age of the whole vehicle fleet. Medium represents the scenario that is considered most realistic in terms of market penetration speed established on data extracted from ACEA [10] and KBA [11]. Based on the analysis of data, the current average age for vehicles of category M1 is set to 10 years. This leads to a vehicle exchange rate (new vehicle replaces oldest vehicle) of 5% per year in the calculation model. The other penetration speeds are based on slightly lower average ages (M1 Fast – 8 years / M1 Very Fast – 5 years) or higher average age (M1 Slow - 12 years).

The calculation tool does not consider the phenomenon of an increasing vehicle fleet age over time. The exchange rates for the other categories are determined in the same way. They are adapted to the “real” average age of the vehicles as extracted from the data sources and the individual dates when new limit phases come into force. Being aware that this model is not perfectly reflecting reality, esp. considering the differences between individual countries and all over Europe, the model is still capable of providing a very reasonable prediction concerning the needed period until the limit reductions will be visible.

The possibility to bias the exchange rate in the calculation provides interesting insights on the dependency of the effectiveness of future limits on the “real distribution” of new vehicles and the corresponding impact on the sound emission level. Table 4-7 displays the Medium market penetration speed for category M1 with a constant whole fleet age of 10 years over a period of time:
<table>
<thead>
<tr>
<th>Year</th>
<th>Baseline Phase 1 &amp; older</th>
<th>Scenario 1 Phase 2</th>
<th>Scenario 2 Phase 3</th>
<th>Scenario 3 Beyond Phase 3</th>
<th>Whole Fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Share</td>
<td>Ø Age</td>
<td>Share</td>
<td>Ø Age</td>
<td>Share</td>
</tr>
<tr>
<td>2019</td>
<td>100%</td>
<td>10.0</td>
<td>0%</td>
<td>--</td>
<td>0%</td>
</tr>
<tr>
<td>2020</td>
<td>95%</td>
<td>10.5</td>
<td>5%</td>
<td>0.5</td>
<td>0%</td>
</tr>
<tr>
<td>2021</td>
<td>90%</td>
<td>11.0</td>
<td>10%</td>
<td>1.0</td>
<td>0%</td>
</tr>
<tr>
<td>2022</td>
<td>85%</td>
<td>11.5</td>
<td>15%</td>
<td>1.5</td>
<td>0%</td>
</tr>
<tr>
<td>2023</td>
<td>80%</td>
<td>12.0</td>
<td>20%</td>
<td>2.0</td>
<td>0%</td>
</tr>
<tr>
<td>2024</td>
<td>75%</td>
<td>12.5</td>
<td>20%</td>
<td>3.0</td>
<td>5%</td>
</tr>
<tr>
<td>2025</td>
<td>70%</td>
<td>13.0</td>
<td>20%</td>
<td>4.0</td>
<td>10%</td>
</tr>
<tr>
<td>2026</td>
<td>65%</td>
<td>13.5</td>
<td>20%</td>
<td>5.0</td>
<td>15%</td>
</tr>
<tr>
<td>2027</td>
<td>60%</td>
<td>14.0</td>
<td>20%</td>
<td>6.0</td>
<td>20%</td>
</tr>
<tr>
<td>2028</td>
<td>55%</td>
<td>14.5</td>
<td>20%</td>
<td>7.0</td>
<td>20%</td>
</tr>
<tr>
<td>2029</td>
<td>50%</td>
<td>15.0</td>
<td>20%</td>
<td>8.0</td>
<td>20%</td>
</tr>
<tr>
<td>2030</td>
<td>45%</td>
<td>15.5</td>
<td>20%</td>
<td>9.0</td>
<td>20%</td>
</tr>
<tr>
<td>2031</td>
<td>40%</td>
<td>16.0</td>
<td>20%</td>
<td>10.0</td>
<td>20%</td>
</tr>
<tr>
<td>2032</td>
<td>35%</td>
<td>16.5</td>
<td>20%</td>
<td>11.0</td>
<td>20%</td>
</tr>
<tr>
<td>2033</td>
<td>30%</td>
<td>17.0</td>
<td>20%</td>
<td>12.0</td>
<td>20%</td>
</tr>
<tr>
<td>2034</td>
<td>25%</td>
<td>17.5</td>
<td>20%</td>
<td>13.0</td>
<td>20%</td>
</tr>
<tr>
<td>2035</td>
<td>20%</td>
<td>18.0</td>
<td>20%</td>
<td>14.0</td>
<td>20%</td>
</tr>
<tr>
<td>2036</td>
<td>15%</td>
<td>18.5</td>
<td>20%</td>
<td>15.0</td>
<td>20%</td>
</tr>
<tr>
<td>2037</td>
<td>10%</td>
<td>19.0</td>
<td>20%</td>
<td>16.0</td>
<td>20%</td>
</tr>
<tr>
<td>2038</td>
<td>5%</td>
<td>19.5</td>
<td>20%</td>
<td>17.0</td>
<td>20%</td>
</tr>
<tr>
<td>2039</td>
<td>0%</td>
<td>--</td>
<td>20%</td>
<td>18.0</td>
<td>20%</td>
</tr>
<tr>
<td>2040</td>
<td>0%</td>
<td>--</td>
<td>15%</td>
<td>18.5</td>
<td>20%</td>
</tr>
</tbody>
</table>

Table 4-7: Medium market penetration speed - Category M1

### 4.3.3 Sound Split in Calculation Tool

As touched upon in chapter 4.3.1, the vehicle exterior sound emission is calculated by logarithmic addition of the two main partial sound sources, the powertrain and the tyre/road interaction. Both sound models (transfer functions) are established by means of available databases, engineering approaches and literature research. It needs to be taken into account that these models are an estimation and attempt to predict an extremely wide range of vehicles using one single model. For particular categories with no available real data from realistic configurations, the model quality would benefit from additional data provided by OEMs or test institutes.
Overall, the sound models reliably cover the differences between the individual categories without ignoring the fact that individual vehicles may behave outside the spectrum given by the sound model. The occurrence of these deviations is understood, covered by the approach and considered according their share rate in the overall model.

**Specific consideration of category M1**

Figure 4-2 displays the sound split model used for the calculation model for vehicle category M1 with internal combustion engine, based on the 2020 type approval data weighted with EU registration data of 2019. In the following example, the emitted exterior noise is calculated using ISO track road surface and cruise conditions (free flowing). The powertrain contribution over the driving speed range is primarily driven by engine speed. The typical effects of gearshift peaks that one would expect when looking at a single vehicle are evened out due to the fact that a wide range of very different vehicles are represented by this “average” approach. The tyre/road sound level model is driven by driving speed and follows generic physical rules. The shape of the curve is evaluated and adjusted by means of measurement data and literature sources where available.

![Graph](image)

**Figure 4-2: Sound split in simulation tool - Category M1 (ISO track | Cruise condition)**

As illustrated in the figure above, the powertrain is the dominating source for the emitted vehicle sound at low driving speeds. Under type approval conditions on an ISO track surface, the balance between powertrain and rolling sound is reached at approximately 48 km/h. Beyond this speed level, the tyre/road sound increasingly becomes the dominant contributor to the overall sound level of the vehicle.
Following the rules and the principles of logarithmic addition, it can be seen that at the crossing point (identical sound level of both part sources) the overall vehicle sound is 3 dB(A) above the level of both part sources. Once either of the two part sources is 10 dB(A) below the more dominant one, its respective contribution to the overall sound level can essentially be neglected. From this point onwards the overall sound level is primarily following the dominant sound source. This principle behaviour and conclusion is valid for all vehicle categories and propulsion types.

![Sound Split in Simulation Tool - Category M1 (Real Road | Cruise)](image)

**Figure 4-3: Sound split in calculation tool - Category M1 (Real road | Cruise condition)**

Figure 4-3 demonstrates the effect of a +3.0 dB(A) offset for tyre/road interaction to the sound model in the simulation tool. This offset is intended to represent a more realistic average of a “real road” tyre/road sound level compared to an ISO track, which is used for type approval. These types of offsets are applied in several studies around the topic of vehicle sound emissions and are of a similar magnitude to the ones used in the CNOSSOS [12] model. The powertrain curve remains identical while the rolling noise curve is shifted upwards by 3 dB(A).

Under these boundary conditions, it can be seen that the crossing point between both sound sources is shifted to the left side towards lower driving speeds by approx. 10 km/h. This indicates that the tyre/road interaction becomes the dominant partial sound source at a lower driving speed compared to ISO track conditions.
This model and calculation illustrates that only a fraction of the limit value reductions achieved on the vehicle side, as recorded during type approval, will be translated to a “real” driving scenario considering the applied offset to the tyre/road interaction. Under these conditions, the tire is already contributing by approximately 75% to the overall vehicle sound level.

As described in chapter 4.2, it appears unlikely that an equal reduction on both part sound sources can be achieved. A further reduction in the powertrain sound level will extend the shift of the crossing point of both sound sources towards lower speeds, resulting in an even lower impact of the powertrain reduction efforts at higher speeds. Consequently, the efficiency of reductions made on the powertrain side progressively declines for future scenarios with limit value reductions. Chapter 5.1 takes a closer look at this topic.

Figure 4-4 illustrates the comparison of the M1 ICE vehicle with a typical M1 pure electric vehicle as implemented in the calculation tool. The curve of the rolling noise is assumed to be identical for both vehicle types. Possible influences from the use of wider tyres with higher load indices on electric vehicles due to the increased weight from battery packs are neglected at this point but may well be present and would increase the BEV tyre/road sound emissions. Compared to ICE powered vehicles, the powertrain curve is differing with the overall powertrain sound of a BEV, which is assumed to be lower. Consequently, the combined BEV whole vehicle curve deviates significantly from the ICE curve. At very low driving speeds, the sound emitted by an electric vehicle is much lower.

For pedestrian protection purposes all new BEVs need to incorporate an on-board sound system (AVAS) which artificially increases the sound of the powertrain in the low vehicle speed range and is characterised as part of the powertrain part source. Since the sound emitted by electrical vehicles can be quite diverse and follows a minimum and maximum requirement for the sound level, it is challenging to transfer this into one powertrain model that represents the entire vehicle category.

The phenomenon of the crossing point shifting to lower speeds is further validated in figure 4-4 above. For BEV vehicles, the crossing point where the tyre becomes the dominant partial sound source further shifts to lower vehicle speeds (below 30 km/h) in comparison to the ICE vehicle model.
Figure 4-4 further highlights an aspect of achievable sound reductions at higher vehicle speeds. It can be seen that for the given street type, there is almost no improvement for the M1 BEV vehicle above 60 km/h in comparison to the ICE vehicle. Despite the fact that the BEV model assumes a lower powertrain sound contribution of more than 10 dB(A) compared to the 2020 ICE vehicle, it does not provide any noticeable difference in the overall sound level at speeds beyond 50 km/h since the dominant sound source is the tyre anyway.

**Specific consideration of category N3**

The type approval test procedure for vehicles of category N3 (heavy commercial trucks) is run in a configuration which is not representative for their operation in real traffic. Furthermore, the type approval test is performed in a configuration with 2 axels, with the intention to highlight the powertrain sound level and simultaneously keep the tyre/road sound level to a minimum. In contrast, the most frequently seen mode of operation for heavy commercial trucks in real traffic is a 5-axle configuration and the noticeable contribution of the tyre/road interaction, as highlighted in the previous sections, leads to the conclusion that a 5-axle configuration is representative for the N3 category in the calculation tool.

Figure 4-5 shows the sound split implementation of the calculation model under real road (+3 dB(A) offset vs. ISO) conditions:
Despite the use of a realistic vehicle configuration with 5 axles, the powertrain has a higher contribution to the overall sound level of the vehicle, compared to category M1. Consequently, the crossing point is situated at a higher driving speed (approximately 53 km/h). The powertrain curve also assumes a very low dynamic over the entire vehicle speed range since modern trucks are typically equipped with a high number of gears and a very small band of engine speeds where it works at its most efficient rate.

With regard to the implemented powertrain curves, it must be noted that very conservative sound levels are implemented in the calculation tool which presumably overemphasises the powertrain contribution of all category of vehicles. Subsequently, this implies that the conclusions drawn from the calculation tool should be considered as a “best case scenario” and the attainable benefits from further limit value reductions may in reality be lower than displayed in the graphs.

### 4.3.4 Sound Pressure Output Value Equivalent

As described in the previous chapters, the intention of the study and the calculation tool is to evaluate the state of the art in terms of vehicle sound emissions of categories M and N in 2021 and the potential for further limit value reductions and the consequence thereof. The effects of the calculated sound emissions of powertrain and tyre / road interaction for different scenarios is evaluated in order to get a better impression for obvious potentials and measures that are best suited to most effectively reduce traffic sound in real world conditions.
The extensive influence of the vehicles on the overall sound level at a given location is extremely complex and depends on the boundary conditions entered into a simulation tool. These tools only work appropriately if all relevant input parameters are known, valid and set accordingly and all conclusions from these type of calculations are valid for only a very specific scenario upon which the calculations centre on.

As a result, this study aims to reduce all calculations and conclusions back to the initial level. This implies that only values directly linked or derived from the type approval (limit) values/procedure and values that can be translated into different reasonable real world scenarios are considered. This in turn means that all the calculation steps described in chapter 4.3.1 (calculation of representative sound level over driving speed per vehicle category and vehicle type, weighted with various parameters e.g. share of vehicle categories) are leading to one single output value, the \( L_{A_{eq}} \).

All calculations are focused and limited to vehicles of categories M and N including all subcategories. The \( L_{A_{eq}} \) is based on the overall sound levels of vehicles as measured during the type approval testing meaning that specific measurement conditions (measurement distance, measurement height, etc.) are identical to the ones used for the type approval procedure. In the final \( L_{A_{eq}} \) value, all vehicle categories and subcategories are represented according their share to the overall composition of the entire M and N pool of vehicles under the given conditions and driving scenario.

Placing the focus purely on the emission side, subsequent acoustic effects such as reflections at the facades or the sound emission of other vehicles and forms of transport (e.g. category L, railway, planes, etc.) are not considered. The advantage of this approach is that all input parameters are transparent and easily comprehensible in their impact on the result (cross sensitivity) even with the intention of covering all relevant parameters using the model.

In a final stage, the model provides the possibility to implement a countless number of options and parameter combinations in order to investigate all kinds of scenarios and to perform an in-depth analysis of effects observed during the data processing. During the course of this study more than 100,000 data sets have been computed and analysed. The plots and graphs displayed in this report are a small extract of plots that have been generated and analysed in the framework of the study.
4.4 Conclusion

The approach taken in this study in combination with the calculation tool allows to determine the contribution of each respective partial sound source over the entire speed range for each vehicle category under realistic boundary conditions. A key aspect when attempting to reduce sound emissions of vehicles in real traffic situations is to address the dominant part source with the highest sound level. As presented in chapter 4.3.3, the dominant partial sound source varies over the complete vehicle speed range in all real traffic situations. At low driving speeds, the powertrain is the dominant partial point source while the tyre/road interaction becomes dominant at higher driving speeds. This observation is valid for all vehicle categories and for all propulsion types. The main difference between the categories and propulsion types is the vehicle speed at which the crossing point between the dominant sound sources occurs. Furthermore, the vehicle models allow an in-depth look into opportunities to reduce specific sound sources.

Comparing the calculation models for vehicle categories M1 and N3, it can be observed that the N3 category provides greater opportunities to reduce the overall vehicle sound level by reducing the powertrain sound level. Considering the fact that vehicles of N3 category are primarily designed to carry heavy goods, mainly over long distances on motorways, it can be questioned how much of this improvement will be recognised in real life situation.

Furthermore, it is questionable how big the impact of this reduction will be in reality, even if a reduction of 2 dBA could be achieved. In cities and areas with low driving speed, the share rate of these vehicles compared to other categories is typically minuscule, reducing the potential for a noteworthy reduction of the $L_{Aeq}$ value. On the other hand, trucks and buses designed for transportation over small distances provide maximum benefit once converted to electrical powertrains. This concept makes perfect sense in the appropriate environment but cannot be considered a suitable solution [at least not in the near future] for vehicles mainly operating on motorway conditions, where the benefit of electrification in terms of noise is negligibly low.

Another example, even if not included in this study, similar effects could be achieved by replacing scooters with combustion engines by battery electric versions. This would be a very efficient measure in cities and a practical solution as well, but of course it would not work equally well in other environments.
From the calculations, it can be deduced that all measures carried out on the powertrain side of the vehicles are strongly dependent on the level of the tyre/road interaction sound level. The data reveals that the efficiency in reductions realised for the powertrain in type approval testing will deteriorate with the use of road surfaces that are noisier than the ISO track.

Inversely, the use of low noise road surfaces would significantly increase the effectiveness of the efforts to reduce the powertrain sound level. Chapter 5 takes an in-depth look into the effectiveness of sound level reductions for each part source and specific vehicle categories in real traffic conditions and analyses the influence of various road surface offsets in detail.
5 Impact Analysis on Real Traffic - Simulation Results

The following chapter intends to provide a deeper insight into the outcome and findings of the calculations performed with the simulation tool described in the previous chapter. Since the tool provides a wide range of options for the variation and combination of parameters and scenarios, only an extract with the most interesting results is presented and explained in detail. It is essential to analyse the effects and efficiencies of various measures on the powertrain and tyres, which are subject to further limit value reductions as defined by scenario 2 and 3 (see chapter 4.2).

Since the measures to reduce both partial sound sources are only effective in a certain speed range and only under certain conditions for real world driving, the effects of alternative measures such as speed limits, road surface improvements, BEV share and market penetration speed, etc. are additionally evaluated.

5.1 Calculations based on the Limit Value Scenarios

In general, the calculations are performed under the assumption of “real road conditions” (+3 dB(A) offset vs. ISO track), and other main parameters like market penetration speed and BEV share rate set to medium or default as assumed to be realistic for most cases. In particular cases e.g. for the analysis of cross sensitivity against specific variation parameters, the deviating boundary conditions are explicitly mentioned. Since the effect of increasing traffic density and its consequences are difficult to predict precisely, this parameter is neglected in the majority of the calculations. This allows for an easier and more reliable interpretation of the results, since these are not influenced or biased by an unpredictable parameter. Nevertheless, the traffic density parameter can effortlessly be adapted or corrected in a further calculation step, if required.

5.1.1 Impact of Limit Value Reductions – Comparison of Scenarios

In a first step, the three different scenarios (defined in chapter 4.2) are evaluated and displayed in figure 5-1. This graph indicates the progression of the calculated $L_{Aeq}$ level over time under urban main street conditions using the respective vehicle category share rates and vehicle speed of 50 km/h as depicted in table 4-4.
It can be seen for scenario 1, that even without new limit values coming into force, the replacement of older vehicles by ones compliant to phase 2 of UN Regulation No. 51 will lead to a decrease of the L\text{Aeq} by 2.1 dB(A) in 2040. The reduction in sound level is just a result of the replacement of older vehicles by newer ones, as available in 2020, without any consideration of further progress made on powertrain or tyres over time. In this context, the introduction of new propulsion types over time is included e.g. electric vehicles as available in 2020 with powertrains significantly quieter than the average of vehicles in 2020.

![Impact of Limit Value Reduction Scenario - Urban Main Street](image)

**Figure 5.1: Impact of limit value reductions - Urban main street**

Scenario 2 considers the launch of phase 3 in accordance to UN Regulation No. 51. A relative improvement of 2.8 dB(A) can be seen from 2020 to 2040. This means a further reduction of 0.7 dB(A) in 2040 over the baseline scenario 1. In contrast to scenario 1, vehicles compliant with phase 3 enter the market as of 2024. The period of time in which vehicles compliant with phase 2 could enter the market is limited to 4 years only, before being replaced by the next phase 3 of vehicles. The market share rate of phase 2 vehicles is not expected to raise above approximately 20% due to the rapid introduction of phase 3, only 4 years later.

Scenario 3 is assuming a further reduction of the sound limit values by 2dB(A) compared to scenario 2. For this scenario, a value reduction of 3.5dB(A) is predicted in 2040. Since scenario 3 is considered to follow scenario 2 in terms of market share rate, vehicles compliant to phase 2 and phase 3 will be limited to approximately 20% market share due to the rapid sequential implementation steps of 4 years. However, scenario 3 is not considered to be technically feasible from today’s standpoint, as explained in chapter 3.
The calculated $L_{Aeq}$ reductions over time and between the three different scenarios are summarised in Table 5-1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Improvements [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020 vs. 2040</td>
</tr>
<tr>
<td>1 – Freeze after Phase 2</td>
<td>2.1</td>
</tr>
<tr>
<td>2 – Launch of Phase 3</td>
<td>2.8</td>
</tr>
<tr>
<td>3 – Beyond Phase 3 (fictional)</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 5-1: Improvements of limit value reductions - Urban main street

From figure 5-1 and table 5-1, it is concluded that the biggest share of the improvement originates from the replacement of old vehicles by newer vehicles compliant with phase 2 of UN Regulation No. 51. The implementation of scenario 2 leads to a further reduction of 0.7 dB(A), however with an extended delay before effects become perceptible. In contrast to scenario 3, which is considered purely fictional, the scenario 2 is already under development by vehicle manufacturers and appears to be feasible for most vehicle categories and subcategories. The theoretically achievable advantage of 0.7 dB(A) in 2040 already indicates, that the benefit of limit reductions beyond phase 3 would only have a minor impact on the overall sound level and would take about 20 years from implementation to become fully available.

5.1.2 Impact of Driving Speed

As mentioned in previous chapters, it is assumed for scenarios 2 and 3 that the tyre is not able to contribute to an equivalent level as the powertrain in terms of lowering sound levels. In various other studies [4] [13] [14] it is frequently assumed that the powertrain and tyre/road sound level can be equally reduced by 2 dB(A) which would result in a reduction of approximately 2 dB(A) all over the vehicle speed range. Concluding from chapter 3, it is extremely unlikely to achieve 2 subsequent reductions of 2 dB(A) from phase 2 vehicles onwards, without jeopardising safety parameters significantly. Subsequently, in order to be able to meet the requirements for both scenarios 2 and 3, the powertrain requires an over-proportionally high contribution towards lowering noise emissions in comparison to the tyre.

For vehicle categories measured according to the passenger car principle, this imbalance theoretically leads to a high potential for sound level reductions at lower vehicle speeds where the powertrain is still the dominant sound source. On the other hand, a significant opportunity is lost to improve the sound level at higher vehicle speeds as the entire potential for sound level reductions is mainly driven by the tyre/road interaction.
Moreover, the sound level of the tyre/road interaction has an impact on the efficiency of the sound level reduction that can be expected under real driving conditions, examined later on in this chapter. The above-described effects are illustrated in the subsequent graphs showing the benefits at lower and higher speeds.

Figure 5-2 shows the progression over time at low driving speeds typical for residential street conditions. The sound level reduction from 2020 to 2040 amounts to 2.6 dB(A). Comparing the calculation to the urban main street scenario at 50km/h, a further reduction of 0.5 dB(A) can be seen for residential street conditions. The imbalance in sound level reduction between powertrain and tyre/road interaction leads to a significantly lower sound level for residential streets in 2040 and a bigger improvement between scenario 2 and 3.

![Impact of Limit Value Reduction Scenario - Residential Street](image)

**Figure 5-2: Impact of limit value reductions - Residential street**

From the figure above it is noticeable that the overall sound level achieved by scenario 2 in 2040 is not far-off from the levels achieved by a BEV vehicle equipped with an AVAS as shown in figure 4-3 and figure 4-4. The influence of AVAS is investigated in detail in chapter 5.1.5.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Improvements [dB(A)]</th>
<th>2020 vs. 2040</th>
<th>2040 vs. previous scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Freeze after Phase 2</td>
<td>2.6</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2 – Launch of Phase 3</td>
<td>3.2</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>3 – Beyond Phase 3 (fictional)</td>
<td>4.2</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5-2: Improvements of limit value reductions - Residential street**
The calculated improvements over time and versus the baseline scenario 1 are summarised in table 5-2.

![Impact of Limit Value Reduction Scenario - Motorway](image)

**Figure 5-3: Impact of limit value reductions - Motorway**

As expected, the overall improvements for all three scenarios at higher speeds are lower in comparison to the simulations at lower driving speeds. The decline in improvements is due to the lower realised improvements on the tyre/road contribution in comparison to the powertrain contribution, combined with the dominant influence of the tyre/road interaction at higher vehicle speeds.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Improvements [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020 vs. 2040</td>
</tr>
<tr>
<td>1 – Freeze after Phase 2</td>
<td>1.7</td>
</tr>
<tr>
<td>2 – Launch of Phase 3</td>
<td>2.3</td>
</tr>
<tr>
<td>3 – Beyond Phase 3 (fictional)</td>
<td>2.8</td>
</tr>
</tbody>
</table>

*Table 5-3: Improvements of limit value reductions - Motorway*

Finally, it can be summarised that the efficiency of the measures taken to comply to the next levels of limit values, are strongly dependent on vehicle speed and the tires used in real driving scenarios. In figure 5-4, the relative improvements for all three limit value scenarios between the first implementation in 2020 and the end of the calculation at 2040 are shown. Additional scenarios where the tire is not able to contribute towards lower sound levels are simulated. It becomes obvious that significant reductions, related to powertrain improvements, can only be achieved in the very low vehicle speed range.
The simulations, where the tyre contribution is neglected, clearly highlight that above 60 km/h no significant reductions in sound level can be expected even with significant improvements made on the powertrain side.

![Impact of Limit Value Reduction Scenario - Driving Speed](image)

**Figure 5-4: Impact of limit value reductions - Driving speed**

### 5.1.3 Impact of Market Penetration

In the following section, further developments that could affect the expected improvements in real life traffic are calculated and evaluated. The assessment of future developments such as varying market penetration speed provides a visualisation of the model sensitivity against incorrect assumptions in terms of exchange rates of vehicles. As explained in chapter 4.3.2, all calculations are based on assumptions trying to reflect the reality as appropriately as possible. The calculations of chapters 5.1.1 and 5.1.2 are determined with the assumption of a “medium market penetration speed” which is based on recent statistical data [10] [11]. Four different scenarios for the market penetration of vehicles are implemented into the calculation tool and investigated in the following section.

For vehicle category M1, the “medium” market penetration is assumed to be 5% per year. The “slow” value is defined as 4.16% per year, “fast” is equal to 6.25% and “very fast” represents 10%. “Slow” and “very fast” are classified as purely fictitious and implemented in order to cover both extremities. Figure 5-5 summarises the impact of the variations in market penetration speeds over time and provides insight on the dependency of the results and improvements in real traffic on certain boundary conditions.
A reduction or increase of the vehicle exchange rate in the tool by approximately 20 - 25% leads to a significant deviation in the result. A reduction to the “slow” exchange rate deteriorates the scenario 2 curve almost to that displayed for scenario 1. In contrast, an accelerated vehicle exchange rate simulated by the “very fast” scenario significantly benefits from the introduction of new vehicles with lower sound levels. It also assists in reducing the delay until the implemented limit values present a noteworthy effect. The very fast scenario is considered completely unrealistic since the capacity to produce and sell twice the amount of vehicles per year remains implausible.

5.1.4 Impact of Pure Electric Vehicle Share

An additional effect to consider is the impact of the share of pure electric vehicles on the overall sound level. The previously calculated scenarios are considering a “medium” (realistic) BEV share rate, based on the forecast reported in the Bloomberg EVO Report 2021 [15]. The transfer function for the individual BEV share rate for all concerned categories is extracted from this report. In analogy to the market penetration, the share rate of pure electric vehicles is likely to vary in future due to multiple aspects, e.g. driven by future regulations or political initiatives in several countries pushing for a faster change towards the electrification of vehicles. Therefore, different BEV share rates are considered and simulated in order to approximate the potential impact on the overall vehicle sound emission level under certain conditions.
Figure 5-6 illustrates the comparison of Scenario 1 to 3 with the “medium” BEV share rate and variations of the BEV share rate towards faster and slower implementation of BEV vehicles for scenario 2. The figure shows the dependency of the outcome on various parameters that can result in significant variations in the overall calculation results. It is therefore of utmost importance to understand the relation of all input parameters and boundary conditions and their influence on the overall result and subsequent conclusions.

Table 5-4 summarises the output of the calculations performed with differing BEV penetration speed scenarios, starting from “no BEV” over “medium (default)” to “slow (50 % of medium)” and “fast (200 % of medium)”. The values in the table present the calculated differences vs. the “medium” scenario for the year 2040 for the urban main street scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>BEV Share Rate</th>
<th>Difference in 2040 to BEV Share Rate Medium [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – Launch of Phase 3</td>
<td>No BEVs</td>
<td>+0.6</td>
</tr>
<tr>
<td></td>
<td>Slow</td>
<td>+0.3</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

Table 5-4: Improvements of pure electric vehicle share in 2040 - Urban main street

Figure 5-7 demonstrates the simulation results with identical variations of BEV share rate and boundary conditions at higher vehicle speeds, as defined as motorway conditions in the tool.
As predicted in chapter 5.1.2, figure 5.7 reveals no noticeable improvement of the overall sound level at higher vehicle speeds for an increasing BEV share rate.

At higher vehicle speeds, the difference between the two part sources for vehicle sound is so large, that a further reduction of the powertrain sound does not provide any noticeable improvement. Consequently, this signifies that even BEVs, considered as a promising solution to reduce road traffic noise, cannot contribute efficiently to lower the sound emissions under certain real life driving conditions. Therefore, it is concluded that pure electrical vehicles do not significantly differ from internal combustion powered vehicles in terms of sound emission at high driving speeds. On the other hand, the contribution of electric vehicles to reduce vehicle sound emissions in urban or residential areas appears to be substantial and promising. Since the powertrain of an electric vehicle is quieter compared to that of an ICE powered vehicle, residential and urban areas can benefit considerably from an increased share of electric vehicles. Chapter 5.1.5 will address this subject in more detail.

### 5.1.5 Impact of Acoustic Vehicle Alerting System (AVAS)

The calculations in the following section intend to provide a deeper insight on individual vehicle categories and their specific sound split as described in chapter 4.3.3. Focus of this investigation lies in the improved comprehension of the individual vehicle categories and their potential for sound level reductions under different real driving scenarios.
Concerning audibility, quiet road transport vehicles (QRTV) such as pure electric and hybrid electric vehicles that are able to start/drive without a running internal combustion engine are obliged to fulfil the requirements of the UN Regulation No. 138. In this context, this regulation ensures pedestrian protection with specific requirements regarding a minimum sound level and frequency shifts at low driving speeds until 20 km/h [16]. Most QRTVs fulfil these requirements by means of an Acoustic Vehicle Alerting System (AVAS). Commonly, this system uses loudspeakers to produce the required sound. The impact of electrification and the corresponding use of AVAS is subject of the following simulations.

Figure 5-8 presents the relative improvement by comparing the emitted sound of a representative pure electric and an internal combustion engine powered vehicle per category over a speed range as calculated in the simulation tool. Unfortunately, for several vehicle categories the values for the powertrain and tyre/road sound level may not be perfectly representative due to the lack of data. The powertrain models are derived from literature research combined with well-founded assumptions where applicable.

The data displayed in figure 5-8 provides information about the impact that an electric driven version can offer to potentially decrease the sound level of the vehicles of the concerned category compared to its ICE driven equivalent. Simulations are performed for cruise conditions over the relevant vehicle speed range.

![Figure 5-8: Relative improvement BEV vs. ICE and Impact of AVAS](image)
The AVAS sound emission is assumed as an average between the minimum and maximum legal requirement up to 20 km/h and ramped down zero at 40 km/h. As mentioned before, the potential increase in tyre rolling noise due to higher vehicle weight of HEVs and BEVs is neglected in the simulations.

Figure 5-8 reveals that the biggest improvements are achieved at the lowest driving speeds. Significant improvements can be realised for categories M2 and M3 due to the dominant nature of the powertrain contribution of the ICE engine in that vehicle speed range. It is assumed that this also correlates for the categories N3 and N2, but due to the lack of data, no BEV model could be implemented into the calculation tool for these categories.

In contrast to the potential improvements that electrification may bring to certain vehicle categories, it must also be considered that it may not be the most beneficial and reasonable solution for all vehicles of one specific category. E.g. for buses of category M2 and M3 that are mainly used in cities, the electrification of these vehicle categories has been introduced to most major cities and provides a proven solution for the future resulting in a constantly increasing share of electric city buses.

In contrast, the electrification of long haul coaches and trucks with the aim to reduce their sound level does not provide the same benefits as these vehicles mostly operate on motorways and outside of cities. The limited driving range and the lengthy recharging times as well as the loss of payload due to the increased weight of batteries are providing a significant challenge for these type of vehicles. Moreover, as highlighted in previous chapters, a reduction in the powertrain level through electrification will not bring any benefits at higher vehicle speeds. As reviewed in chapter 5.1.4, the advantages of electric vehicles in terms of sound emissions are practically neutralised from 70 km/h onwards.

A further aspect concerning the AVAS system at low vehicle speeds needs to be taken into consideration. In the range up to 40 km/h where BEV vehicles theoretically have the highest potential for improving sound levels, the regulatory requirement of the AVAS system can lead to a reduced benefit in terms of noise reduction of QRTVs. As shown in figure 5-8, the improvement for the vehicle category M1, as assumed in the calculation model, experiences a deterioration of the sound level at 30 km/h.

In reality, the magnitude of the impact from the AVAS is determined by the individual configuration of the AVAS itself and the range in which the system is programmed to operate (minimum or maximum sound level).
In summary, the electrification of vehicles provides a certain potential to reduce vehicle sound emissions at lower driving speeds, especially for light commercial trucks and buses at lower driving speeds. Conversely, the requirement for the Acoustic Vehicle Alerting System (AVAS) for BEVs can, depending on the configuration, significantly reduce the benefit to lower vehicle sound at driving speeds of around 20 to 40 km/h in comparison to scenario 2 (phase 3) ICE vehicles.

5.1.6 Impact of Tyre/Road Interaction

In contrast to type approval testing that is conducted on ISO surface test tracks, there are numerous effects in real traffic that can affect the tyre/road interaction and the resulting sound level. Environmental factors such as rain, snow or dirt can have a considerable impact on the tyre/road sound level leading to sizeable increases of sound levels compared to the levels obtained in type approval testing. Road surface wear, damaged or patched asphalt surfaces lead to highly increased tyre rolling sound levels when compared to new road surfaces of the same type or specific asphalts with noise-reducing properties (whisper concrete).

On the tyre side, sound level deviations depend on parameters like amount of tyre wear, tread distortion like flat-spotting or saw tooth wear, tyre inflation pressures and tyre age (rubber hardness). An additional aspect to be considered is the replacement of quieter OE tyres that can lead to a significant increase of the rolling sound level once the worn OE tyres are replaced by new “aftermarket/replacement tyres”. As examined in chapter 3, replacement tyres are still in line with the requirements of UN Regulation No. 117 but they can noticeably differ in terms of sound emission levels. A spread of several decibel for different tire makes within one specific tyre dimension class is possible between the quietest and loudest tyre. The impact of this tyre/road interaction offset on the vehicle sound emission is the subject of the following analysis.

The calculated $L_{Aeq}$ value over changing tyre/road conditions (sound level offsets) is illustrated in figure 5-9. Similar to the analysis of the driving speed in figure 5-4, additional scenarios with the assumption of no further tyre optimisation compared to the previous scenario are simulated. While a negative offset represents better conditions for the tyre/road interaction in terms of rolling noise compared to ISO track in combination with OE tyres, a positive offset represents a rolling sound level with a louder than ISO track road interaction.
As previously explained, the “real tyre/road interaction condition” is assumed to be +3 dB(A) louder (analogous to CNOSSOS) compared to type approval conditions on an ISO track and applied to the tyre/road interaction sound level to reflect “real world” conditions. From figure 5-9 it can be seen that an average increase of 1.8 dB(A) of the emitted sound level is simulated for the five different scenarios for real road conditions vs ISO. The conditions in real world driving scenarios are very specific and can be significantly worse than the assumed “real road” offset of 3 dB(A) vs. ISO conditions, e.g. worn aftermarket tyres in combination with patched roads or rainy conditions may certainly increase the offset to +8 dB(A) or more [17][18][19].

![Impact of Tyre/Road Interaction - Urban Main Street](image)

**Figure 5-9: Impact of tyre/road interaction - Urban main street**

In average, an offset of +8 dB(A) leads to an increase in $L_{Aeq}$ of 5.7 dB(A) compared to the type approval conditions. In contrast, the potential for improvements realised from limit value reductions is minimal and limited to scenarios with improved tyre/road offsets compared to ISO. The graph demonstrates that the measures taken to lower the powertrain sound are only effective where the road conditions are improved compared to type approval conditions. In scenarios with inferior road conditions, the positive impact of the powertrain measures can be discarded as the tyre/road interaction is particularly dominant. The figure proves that in order to see a considerable improvement in real road conditions or worse, the tyre/road interaction needs to be improved.

The equivalent calculations performed for motorway conditions once more shows a strong dependency of the overall sound level to the tyre/road sound level.
Similarly, figure 5-10 highlights the effect that the overall reduction of sound emissions of vehicles cannot be significantly improved by measures taken on the powertrain optimisations. Furthermore, the graph shows that all measures applied to improve the tyre/road sound emission levels, directly translate to a very high degree into reductions of the calculated $L_{Aeq}$ for each selected scenario.

The combination of silent asphalts coupled with quiet tyres provide a very effective measure to reduce traffic noise [17]. A further benefit of improved asphalt is the immediate effect on the overall sound level since it applies to vehicles of all categories and age with no delay in time because of slow market penetration.

![Impact of Tyre/Road Interaction - Motorway](image)

Figure 5-10: Impact of tyre/road interaction - Motorway

Figure 5-11 further highlights the tyre sound level in relation to the considered limit value reduction scenarios. As pointed out in previous chapters, it is not clear to which degree the sound level of the tyres can be further reduced over time. Additionally, figure 5-11 displays a hypothetical scenario where the improved tyres used from scenario 3 would become available in 2022 and could quickly enter the market via new cars and replacement of tyres on older cars. Due to the wide spread of sound emission levels between the quiet and loud tyres (Class-A to Class-C labelled), this scenario can be classified as realistic. The feasibility of this scenario relies on excluding the loudest tyres from the market, introducing the most quiet tyres (Class-A) with an appropriate performance criteria on new vehicles and replacing all old tyres of fleet vehicles with new class-A labelled tyres. The potential of using quiet tyres is investigated in a study requested by the BAFU (Bundesamt für Umwelt – Switzerland) [17].
The calculated scenario demonstrates the significance and the impact of the tyre noise level in urban main street scenarios. This alternative measure leads to a much faster and more efficient reduction of the calculated $L_{Aeq}$ compared to future limit value reductions where the effects are extremely time delayed. On top of that, the sound level of the vehicles in the fleet is strongly depending on the tyres being used on the vehicles. The calculated improvements for scenario 2 and 3 are already considering improvements on the tyres vs. scenario 1. Moreover, the figure shows that vehicles of scenario 3 running on louder tyres are not necessarily quieter than scenario 1 vehicles equipped with quiet tires.

![Impact of Tyre - Urban Main Street](image)

**Figure 5-11: Impact of tyre - Urban main street**

### 5.1.7 Impact of Traffic Density

The impact of traffic density is not considered in the study since it is very difficult to predict the change in traffic density over the next years. The study mainly focuses on understanding the improvements that can be realised by simulating different scenarios and alternative measures. Moreover, it investigates all effects individually making it easier to draw clear conclusions. As an alternative to determining the noise level on a specific street, the study lays emphasis on the relative changes/improvements. The traffic density becomes relevant when determining the level of the calculated sound pressure shifts, whereby the absolute shift remains identical for all scenarios. Doubling or reducing the amount of vehicles by 50% will lead to a shift of approximately $\pm 3 \text{ dB(A)}$. Multiplying traffic volume tenfold or reducing it to 10% will shift the values by approximately $\pm 10 \text{ dB(A)}$. 
5.2 Analyses of Alternative Measures

The following chapter investigates the introduction of alternative measures and compares the corresponding efficiencies to the ones achieved by introducing vehicle sound limit value reductions.

5.2.1 Impact of Speed Limits

The reduction of the traffic speed is becoming an increasingly popular and wide spread measure for areas concerned by traffic noise.

![Image: Impact of Speed Limits - Urban Main Street]

Figure 5-12: Impact of speed limits - Urban main street

Figure 5-12 shows the $L_{Aeq}$ over time for an urban main street condition with a driving speed of 50 km/h in comparison to a reduced driving speed of 30 km/h, signifying a speed limit reduction by 20 km/h. The immediate improvement, due to lower driving speeds is on average 4.1 dB(A). In addition to the speed limit being effective immediately once put in place, this measure affects vehicles from all categories and age. Furthermore, speed limits can be adapted to specific times of the day where traffic noise becomes critical e.g. night-time.

Depending on the street type, the application of different speed limits depending on vehicle categories can be a further possibility. This measure can be realised on motorways and easily adapted to the needs in terms of traffic density, time of the day and vehicle share (trucks vs. passenger cars) to achieve an improved overall sound level. The reduction in traffic speed is the only measure that can be adapted to individual conditions and needs without affecting the traffic flow during times where noise levels are less critical.
Additionally, the introduction of speed limits is independent from boundary conditions and is effective under all weather and road conditions.

As described above, figure 5-13 displays a speed reduction of 20 km/h for each vehicle category. The reduction of the overall sound level follows similar tendencies to urban main street scenario but with a minor reduction in efficiency.

![Impact of Speed Limits - Motorway](image)

**Figure 5-13: Impact of speed limits - Motorway**

### 5.2.2 Potential of Geofencing

A technology identified as an alternative measure is the implementation of “geofencing” which can be especially interesting for commercial vehicles of category N3. Rarely do such vehicles enter into residential areas or noise sensitive areas, as they are mainly designed to transport heavy goods over long distances on motorways or the outskirts of cities. Occasionally, when such vehicles are forced to enter sensitive areas, geofencing can provide a powerful solution.

Geofencing is a software function that defines geographical borders based on the Global Positioning System (GPS) or Radio Frequency Identification (RFID). By means of geofencing, specific vehicle categories could be restricted from entering certain noise or emission sensitive areas altogether or only enter during specific times of the day, if required. Hybrid vehicles and heavy-duty trucks could be allowed to enter these areas only in electric mode or in a specific engine operating mode beneficial to sound and exhaust emission levels respectively.
The introduction of stricter limit values targets a very specific driving condition in which certain vehicle categories do not spend most of their time and forces unreasonable efforts into powertrain sound level reduction measures, which could potentially harm the utility and performance aspects of the vehicle. Geofencing provides an alternative solution for vehicle manufacturers to proactively implement sound reduction methods in sensitive areas, providing more efficient sound level reductions than the implementation of stricter limit values.

5.3 Calculated Efficiency of Measures

From the previous chapters it becomes clear that various measures are available to reduce vehicle sound emissions. It is essential to understand that a simple reduction of 2 dB(A) equally on both powertrain and tyre can no longer be assumed. Particularly on the tyre side, the potential for further reduction is very limited for type approval testing and new vehicles with OE tyres as manufacturers are already forced to equip the vehicles with quieter tyres. Scenario 2 and 3 clearly demonstrate that this misbalance in sound level reduction between powertrain and tyres, leads to lower than expected overall sound level reductions resulting from stricter limit values at type approval conditions. The subsequent graphs illustrate the effectiveness and efficiency of the powertrain and tyre sound reduction measures over the vehicle speed range and in dependency of street conditions.

In this study, the efficiency is defined as the level of vehicle sound reduction achievable through measures taken at the powertrain or tyre part source in relation to the total effort applied to achieve the limit values for scenarios 2 and 3. The vehicle sound level is calculated by applying either the powertrain or the tyre sound level reduction to the sound model. As shown in figure 5.14, at low vehicle speeds, the powertrain is the sole (at 0 km/h) or dominant sound source in the model. Consequently, all improvements on powertrain sound level translate up to 100 % to the reduction of the overall vehicle sound level at lower vehicle speeds. In contrast, the efficiency of the tyre efforts starts at 0%, increasing to ≈ 100 % at higher vehicle speeds and especially at roads noisier than ISO track (positive offset vs. ISO).
Figure 5-14 shows the efficiency of powertrain (left) and tyre (right) optimisations at urban conditions (intermittent traffic conditions) for limit values scenario 2. In general, the efficiency of powertrain measures strongly depends on the vehicle speed and fades with increasing driving speed and deteriorating road conditions. Furthermore, the graph demonstrates that the improvements made on the powertrain are only efficient and promising in conjunction with improved road surfaces. Under real world conditions e.g. poor roads, bad weather or in combination with tyres worse than the ones used in type approval, the efficiency of the powertrain measures are immediately reduced.

In contrast, all measures to reduce the tyre/road sound level are preferential for most real world conditions and scenarios. As reviewed in chapter 5.1.6, a further benefit of improvements made on roads or tyres is the comparable positive impact on older vehicles in terms of efficiency.

Figure 5-15 allows a more accurate and easier comparison of both characteristics. Depending on the road conditions, the crossing point of the efficiency curves shifts to higher or lower vehicle speed. Assuming high rolling noise due to bad road conditions, the crossing point when tyre measures become more efficient then powertrain measures is already at approximately 30 km/h. This observation clearly shows that tyre / road optimisation measures have the bigger potential to reduce vehicle noise in most driving situation.
The effect of the efficiency shift for the both partial sound sources is shown in detail in figure 5-16. Since both part sources are unable to be lowered by the same amount, the efforts required from the powertrain side to meet new limit values are progressively increasing, therefore, a mandatory reduction of 2 dB(A) achieved under type approval conditions cannot be obtained under all driving conditions. In order to achieve a 2 dB(A) reduction of the sound level under all conditions, an equal level of improvement of the two contributing part sources is necessary. The above findings for category M1 are valid for other categories as well.
Figure 5-17 to figure 5-19 show the efficiency of measures for the vehicle category N1 model. The tendencies and findings are similar to the ones of category M1 but with higher efficiency rates for the powertrain measures. This means that the new limits can theoretically be achieved with less efforts on the powertrain side compared to category M1 for which the powertrain sound level is already very low in scenario 1.

Figure 5-17: PTR/tyre measures efficiency - Category N1 (Scenario 2 | Urban cond.)

Figure 5-18: PTR/tyre measures efficiency - Category N1 (Scenario 2 | Urban cond.)
For vehicle category N3, the conclusions remain valid, but have shifted significantly towards higher efficiency rates for powertrain measures. This denotes that all improvements to the powertrain are greater in terms of efficiency compared to other categories. Considering that the majority of N3 vehicles typically spend the better part of their operating time on motorways or outside of towns and cities, their contribution to lowering the overall sound level in the concerned areas is still extremely limited. In motorway or rural conditions, the contribution of the powertrain measures remains very limited.
Figure 5.21: PTR/tyre measures efficiency - Category N3 (Scenario 2 | Urban cond.)

Figure 5.22: PTR/tyre measures efficiency - Category N3 (Scenario 2 & 3 | Urban cond.)
5.4 Conclusions

In this chapter, the type approval values and scenarios leaning on reduced limit values as well as the impact and efficiency of these measures have been investigated under all kind of speed ranges and changes in boundary conditions. Additionally, the introduction of alternative measures to reduce the overall sound level in real traffic conditions have been examined. It shall be noted that all calculations carried out for scenario 3 are purely hypothetical and disregard the fact that the technical feasibility to reach these limit values is not given by the current state of the art technology, therefore no conclusions are drawn from the simulation of this scenario.

The simulation of scenario 2 shows an improvement of the overall sound level $L_{Aeq}$ in year 2040 by 2.8 dB(A) compared to 2020 for M1 in urban driving conditions and 2.3 dB(A) for motorway conditions respectively. The simulation does not consider the predicted increase in traffic volume over time, resulting in a potential decrease in the improvement of the overall sound level.

The variation of market penetration speeds of newer vehicles and alternative propulsion types (e.g. BEV) influence the delay until the implemented limit values begin to have a noteworthy effect. The analysis of an increased fleet share for pure electric vehicles of category M1 reveals a potential deterioration of the overall sound level at a vehicle speed of 30km/h due to the implementation of the AVAS system for these types of vehicles.

On the other hand, the electrification of certain vehicles categories shows a considerable potential to lower sound levels at lower vehicle speeds, but depending on the their operating conditions, e.g. city-buses. At high speeds such as motorway conditions, BEVs of all categories show no benefits over conventional ICE powered vehicles due to the tyre/road interaction being dominant.

The goal of future reductions shall result in the improvement of traffic noise in real life and especially in conditions and areas where people are significantly affected by elevated noise emissions. Comparing the effort required to reduce the powertrain sound with the effects and the impact on the overall sound emissions, it can be concluded that there are several other options and measures that offer a faster and significantly higher potential to reduce sound levels under real world conditions. These alternative measures are available without significant development efforts. E.g. a reduction in speed of 20km/h in urban and motorway conditions results in an immediate improvement of approximately 3 to 4 dB(A) on the overall sound level.
A similar magnitude in reduction can be realised by improving the road surface. Both alternative measures show the benefit of delivering an immediate impact on all types of vehicle categories irrespective of the vehicle age without any delay. A further advantage is the possibility to apply the measures locally in critical areas with acute noise emission concerns.
6 Additional Aspects

This chapter addresses further issues concerning the process of vehicle exterior sound emission certification in the context of traffic noise reduction. In addition to the analysis of various regulatory aspects such the potential of RD-ASEP or the handling of measurement uncertainties, a comparison between the systematic of the recent Phenomena study and this current study is included. Furthermore, as part of this chapter, the investigations and findings of this study are put into a larger context.

6.1 Regulatory Aspects

Several aspects of the current type approval testing procedure prescribed in UN Regulation No. 51 are highlighted in the interviews with the OEMs as critical. With increasing discussions about a further reduction of the limit values, certain aspects of the legislation are increasingly coming into focus and require a closer examination. The following chapter gives insight into some of these aspects.

6.1.1 Measurement Uncertainties (MU)

The subject of measurement uncertainties in the type approval of vehicles according to UN Regulation No. 51, briefly touched upon in chapter 3.1.3, is investigated in more detail in the subsequent chapter. The task force measurement uncertainty (TF MU) of the working party on noise and tyres (GRBP) of the UN ECE has carried out extensive research in this area.

![Figure 6-1: Uncertainty “Bubble” regarding UN Regulation measurement procedure [20]](image)
According to measurement technology, a measured result shall be understood as an approximation of the actual result, which by itself is unknown. Every measurement procedure is subject to several uncertainties, which cause variations in the measurement result, even if performed on the same subject. It is important to minimise the measurement uncertainties in order to ensure repeatability of test results. This can be realised by selecting a measurement method with sufficient accuracy, which is reasonable from an economic point of view and by reducing the dependency on environmental conditions. The impact of changing environmental conditions can be minimised, either by narrowing the test conditions or by applying corrective measures in form of correction factors, where applicable.

The UN Regulations No. 51.03 and 117.02 already provide provisions concerning the accuracy of the measurement equipment and the test conditions to ensure precise testing. However, the measurement uncertainties remain on a critically high level. The TF MU applies the “guide to the expression of uncertainty in measurement” (GUM – ISO/IEC Guide 98-3) to quantify the overall uncertainty CI 95% of both regulations. Table 6-1 illustrates that the overall uncertainty is higher in UN R51, mainly for vehicles of the categories M1, N1 and M2 (M ≤ 3500 kg) [20].

<table>
<thead>
<tr>
<th>Regulation</th>
<th>Vehicle / Tyre Category</th>
<th>Overall Uncertainty CI 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN R51.03</td>
<td>M1, N1, M2 (M ≤ 3500 kg)</td>
<td>± 2.7 dB(A)</td>
</tr>
<tr>
<td></td>
<td>N2, N3, M3, M2 (M &gt; 3500 kg)</td>
<td>± 2.2 dB(A)</td>
</tr>
<tr>
<td>UN R117.02</td>
<td>C1, C2</td>
<td>± 2.2 dB(A)</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>± 2.3 dB(A)</td>
</tr>
</tbody>
</table>

Table 6-1: Overall uncertainty according to GUM Assessment for UN R51 & UN R117 [20]

The level of uncertainties forces vehicle manufacturers to develop their vehicles significantly below their associated limit values in order to ensure compliance of the type approval test under any circumstances, in particular third party testing like in-use conformity and market surveillance. Particularly, the use of replacement tyres with inferior tyre noise attributes for market surveillance testing could further increase the measurement uncertainty and needs to be considered by setting specific rules. Conformity of production (CoP) is not mentioned as both regulations permit to exceed the limit value by up to 1 dB(A). However, as highlighted in table 6-1, the overall measurement uncertainty value exceeds this allowance.

Table 6-2 shows the current calculated level of uncertainties in the UN Regulations No. 51.03 and 117.02. While most parameters are equally pronounced, some significant differences are present. Handling of the temperature influence on the test results is one of the major
differences between both regulations. The influence of temperature on the tyre/road sound level is recognised, for which the UN Regulation No. 117 provides a temperature correction to a reference temperature of 20°C and takes into account a tolerance range for the road surface temperature, whereas these aspects are missing in UN Regulation No. 51.

Additionally, the road surface structure can influence the rolling sound significantly. Although the test tracks used for type approval testing meet the requirements of ISO 10844:2014, each track surface differs in terms of acoustic behaviour [21].

<table>
<thead>
<tr>
<th>Area</th>
<th>Parameter</th>
<th>UN R117.02</th>
<th>UN R51.03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>Microphone</td>
<td>Type 1 microphone</td>
<td>Type 1 microphone</td>
</tr>
<tr>
<td></td>
<td>Calibrator</td>
<td>Class 1 calibrator</td>
<td>Class 1 calibrator</td>
</tr>
<tr>
<td></td>
<td>Calibration tolerance</td>
<td>+0.5 dB(A)</td>
<td>+0.5 dB(A)</td>
</tr>
<tr>
<td></td>
<td>Speed measuring device</td>
<td>±1 km/h at PP-line</td>
<td>±0.2 km/h or ±0.5 km/h</td>
</tr>
<tr>
<td></td>
<td>Engine speed measuring device tolerance</td>
<td>----</td>
<td>&lt; 2%</td>
</tr>
<tr>
<td>Test conditions</td>
<td>Air temperature</td>
<td>5°C to 40°C</td>
<td>5°C to 40°C</td>
</tr>
<tr>
<td></td>
<td>Road surface temperature</td>
<td>5°C to 40°C</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>Temperature correction</td>
<td>Normalise C1 and C2 tyres to 20°C</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>Preparation for the test</td>
<td>Tyre shall be warmed-up</td>
<td>Engine shall be brought to normal operation condition</td>
</tr>
<tr>
<td></td>
<td>Speed variation</td>
<td>±1 km/h at PP-line</td>
<td>±1 km/h at PP-line (WOT) ±1 km/h within AA' and BB'-line (CRS)</td>
</tr>
<tr>
<td></td>
<td>Wind speed</td>
<td>&lt; 5 m/s and suitable windscreen</td>
<td>&lt; 5 m/s and suitable windscreen</td>
</tr>
<tr>
<td></td>
<td>Background noise</td>
<td>&gt; 10 dB(A)</td>
<td>&gt; 10 dB(A) plus correction up to 15 dB(A)</td>
</tr>
<tr>
<td>Tolerances</td>
<td>Measuring instrument inaccuracies</td>
<td>Reduce test result by 1 dB(A)</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>CoP tolerance</td>
<td>+1 dB(A) allowance</td>
<td>Shall not exceed the limit by more than 1 dB(A)</td>
</tr>
</tbody>
</table>

Table 6-2: Difference in handling of uncertainties in current regulations [20]
A temperature correction and tolerance band for the test track temperature would allow for higher repeatability, consistency and reliability in test runs. Therefore, the TF MU proposes, among others, to use the same range of 5 °C - 50 °C for track temperatures, as defined in UN Regulation No. 117, and to prescribe a temperature-dependent correction of the tire rolling noise to compensate for the influence through ambient temperatures. Calculations conducted by the TF MU confirm the efficiency of the proposed measures. The total uncertainty CI 95% would decrease from ±2.7 dB(A) to ±1.7 dB(A) for M1, N1 and M2 vehicles (M ≤ 3500 kg).

The proposed adjustments to the regulation would ensure a reduction to the variability in readings during testing, thus allowing manufacturers to predict the type approval value more confidently and accurately during the vehicle development stage. Compliance has become increasingly challenging due to the progressive reduction of limit values. In order to have the opportunity to comply to reduced limits, it is essential to lower the measurement inaccuracies.

### 6.1.2 Specific Needs for Alternative Propulsion Types

With progress in technologies being able to enter the market, regulations have to be adapted to reflect the new needs and the actual state of the art. Due to the number of new vehicle types and propulsion technologies, especially the introduction of hybrid and pure electric vehicles, there is a need for a further revision of the regulation. In certain areas of the UN Regulation No.51, it is not clear whether the measured values from type approval testing will lead to the expected improvements under real traffic conditions. Further investigations are necessary to evaluate the behaviour of current vehicles outside of the current type approval conditions and revise the testing method accordingly. The following chapter aims to shed some light on how the UN Regulation No. 51 deals with the integration of HEVs and BEVs.

**Vehicles with multiple propulsion sources**

In contrast to the classic drive train concept with only one ICE engine, hybrids are per definition equipped with multiple propulsion sources. Exceptions are HEVs with a low degree of electrification, where the electric engine has no drive function, e.g. so-called micro- and mild-hybrids where the electric machines are only supporting the combustion engine. Commonly, BEVs are also equipped with two or more electric engines. The following section addresses both HEV and BEV technologies.
The current regulation foresees the following: “two or more sources of propulsive power operate at the conditions of test [...] the total engine power, \( P_n \), shall be the arithmetic sum of parallel propulsive engines on the vehicle” [2]. However, from a technical point of view, the trivial addition of the rated powers cannot reproduce what actually happens in real driving situations, even considering full load acceleration. This approach leads to exaggerated total engine power values, influencing the calculation of the PMR value, which in turn leads to the application of unjustifiably higher limit values.

In this context, it is more appropriate for the total engine power \( P_n \) to be represented by the consolidated total engine power of the multiple propulsion sources. This approach leads to realistic PMR values and supports the application of realistic limit values. The use of the consolidated engine power provides a better representation for real traffic behaviour of these vehicles.

**Gear Ratio Selection**

In contrast to pure electric vehicles, most hybrid electric vehicles have similar transmission characteristics (number of gears, gear ratios, etc.) to classic ICE powered vehicles. Therefore, the following section is only valid for HEVs.

As described in chapter 1.2, the test gear(s) is (are) determined on the basis of the acceleration capabilities in the individual gears of the tested vehicle. The test acceleration(s) in the respective gear(s) is (are) compared with the calculated reference accelerations \( \alpha_{\text{ref}} \) and if necessary the target acceleration \( \alpha_{\text{urb}} \) which in turn is also dependent on the PMR of the vehicle. In the simplest case, the test acceleration of a certain gear lies within the \( \pm 5\% \) tolerance of the reference acceleration and this gear can therefore be applied. However, there is a decisive restriction to this criterion. The test acceleration has to be below \( 2.0 \text{ m/s}^2 \).

Similar to high-powered vehicles, hybrids have impressive acceleration capabilities due to the immediate availability of high torque and the combination of both combustion and electric engines. In order to reduce the test acceleration, a higher gear is selected. As a consequence, the provision commonly leads to higher test gears for hybrid electric vehicles. Undeniably, testing in a high gear is more favourable in terms of sound emissions. From this evidence, the restriction of the test acceleration to \( 2 \text{ m/s}^2 \) could be reconsidered for HEVs.
**State of Charge (SOC) and ICE on/off**

The operating condition of a hybrid electric vehicle in real traffic highly depends on the driving speed, the requested acceleration and the state of charge (SOC) of the high voltage system. Many HEVs are able to drive in a pure electric mode up to a speed of 50 km/h and beyond, provided the SOC is sufficient. Accordingly, a proper charging and driving behaviour can enable purely electric driving.

In this context, no clear provisions are foreseen in UN regulation No. 51 for the operating conditions of a hybrid vehicle. Regarding SOC, no restrictions or ranges are specified. Considering the ICE engine, a general specification of “vehicle shall be representative of vehicles to be put on the market” and “the engine shall be brought to its normal operating conditions” [2] are detailed for the measurement procedures. However, it is not specifically stated that the combustion engine shall be running or not during the procedure. Indirect indications specified in the regulation could suggest the operation of the ICE engine during type approval testing but no clear statement is made. E.g. the regulation requires a mode “which achieves an acceleration being closest to \(a_{\text{wot, ref.}}\)” [2]. Accordingly, the ICE could be forced to start by this mode, provided the mode needs the ICE to be on at every driving condition. Furthermore, the WOT tests could trigger the running of the ICE for the majority of vehicles.

The regulation seems unclear and open to interpretation at this point. Testing with the ICE operating could lead to these vehicles failing to comply to the limit values although these type of vehicles make perfect sense in real traffic conditions, e.g. electric driving mode in sensitive areas and ICE operation in conditions where higher vehicle speeds are required. In contrast, tests in electric-only mode could distort the benefits achieved under real traffic conditions, especially if the end consumer does not charge the vehicle accordingly.

6.1.3 **Real Driving Additional Sound Emission Provisions (RD-ASEP)**

The main goal of the UN Regulation No. 51 intends to ensure that type approved vehicles demonstrate appropriate sound performance in the urban environment. However, as examined in previous chapters of this study, the type approval procedure of Annex 3 only covers a very limited and specific driving situation and condition. Unfortunately, the procedure does not allow to regulate operating conditions deviating from the test procedure, which, however, often occur in real traffic situations.
In order to ensure that type approved vehicles maintain a sound performance in line with the type approved sound character in every driving situation, the Additional Sound Emission Provision (ASEP) were introduced in Annex 7 of the regulation. In this context, the ASEP defined as an off-cycle criteria, aims to monitor the sound performance in a defined range. This range, otherwise known as the ASEP control range, monitors additional gears, engine speeds and loads. Each gear leading to results within the control range and fulfilling additionally target conditions, is forced to meet the ASEP requirements. This intends to reduce the resulting noise annoyances through single events related to vehicles.

The current ASEP procedure, developed between the years 2005 to 2010, is based on driving statistics from the 1990’s. Although still able to cover urban sound sources in a representative way, they are limited to full load test conditions at low gears and are not able to assess vehicle behaviour in higher gears. Furthermore, the current ASEP concept is non-transparent and time consuming for vehicle manufacturers. The progress and availability of new technologies permitting the design of sound independent from operation conditions has made it necessary to reconsider and update the ASEP concept. [22]

An updated concept defined as Real Driving-ASEP (RD-ASEP) has been under development in the IWG ASEP since 2017. The aim is to cover a wider operating range, simplifying and reducing the workload at the same time. The simulation model is able to estimate the sound under the majority of driving conditions using data gathered from type approval testing. The possibility to simulate various vehicle subcategories, propulsion types and road surface variations should provide considerable advantages over the current ASEP concept. The RD-ASEP are much more restrictive and complete, and thus more meaningful, as they cover all operating conditions, including all gears and even part load. At the same time, the provisions minimise the effort required for testing, which is applied as a computational verification. Further information concerning the model structure can be found on the “wiki.unece IWG ASEP” website. [23]

In terms of transfer into real traffic situations, the introduction of RD-ASEP and its extended operation range could provide a benefit in terms of lowering the occurrence of noise annoyances, especially through single events. Consistent with the launch of new limit phases, the introduction of RD-ASEP would be a requirement for new types of vehicles entering the market. Similarly, the impact observed by the introduction of RD-ASEP is heavily dependent on the market penetration of new vehicles and the resulting exchange rate with older vehicles. An additional aspect is the low sound dynamic of EVs under high engine load in comparison to regular ICE vehicles.
The share of EVs for the vehicle fleet in real traffic conditions is steadily increasing, whereas ICE vehicles are steadily being phased out. A neglected aspect in real traffic scenarios is the traffic violation through reckless driving and the replacement of OE exhaust systems with potentially louder aftermarket exhaust systems freely available on the market. These phenomena can significantly contribute towards increased noise annoyances and is not able to be covered by type approval testing according to UN Regulation No. 51 Annex 3 or RD-ASEP.

Considering these aspects, the introduction of RD-ASEP is likely to improve annoyances from single events from new vehicles placed on the market, but due to the decreasing volume of ICE vehicles coming onto the market it is not believed that RD-ASEP can solely contribute towards an overall lower sound level in real traffic.

6.1.4 Harmonisation with other Regulations

The automotive industry is currently undergoing a momentous evolution in terms of change in technology towards increased electrification as well as zero emission vehicles. Although the direction is set by political requests, there are still many uncertainties in terms of future regulatory changes. As already emerged in chapter 3, the different requirements from various regulations on the same vehicle systems but also the unsystematic introduction of regulations, are considerable challenges for the industry.

In particular, the challenge is generated by the unsynchronised introduction of different regulations (e.g. EU7, Noise, GSR) specifying interacting requirements on the same vehicle systems (powertrain and / or tyres). Consequently, not all requirements can be taken into account in one single development period. To enable the manufacturers to develop their vehicles to comply with all affected sets of regulations at the same time, a coordinated introduction of regulations would be appropriate. E.g. the development of new silencers in order to comply with new limits of UN R51, only to discover at a later stage that a complete new engine has to be developed to comply to a new set of emissions regulations. To this extent, vehicle sound is forced to be re-homologated due to the development of new components.

Illustrated in the previous chapters, the noise reduction potential has reached a critical level for many subcategories and the introduction of new regulations needs to be coordinated in terms of content. A harmonised enforcement is preferable to avoid unnecessary efforts through double-regulation of a system component. E.g. the regulatory challenges faced by tyre manufacturers due to requirements from UN Regulation No. 117 and indirect requirements from vehicle manufacturers for the compliance towards UN regulation No. 51.
Additionally, the improved rolling resistance and fuel economy performances required by emission regulations as well as the upcoming requirements of GSR (worn tyre wet grip) are in conflict to the requirements of UN Regulation No. 51. Similarly, as concluded from the industry consultation, the introduction of stricter exhaust emissions requirements and the striving towards zero-emission concepts will have a considerable impact on the sound behaviour of vehicles and will be in conflict with the noise requirements of vehicles. E.g. the requirement for increased combustion pressures and the resulting increase in vehicle weight due to the installation of after-treatment systems will result in increased noise emission from vehicles.

As concluded in chapter 3, in order to achieve compliance to future limit value scenarios for noise emissions, both powertrain and tyre/road interaction as partial sound sources need to be lowered simultaneously. Thus, a coordinated reduction of both UN Regulation No. 51 and UN regulation No. 117 is necessary for any future potential to reduce noise emissions.

Further limit value reductions for noise emissions need to be decided with caution with the increasing tendency to create a conflict between constantly improving ICE vehicles which risk to be quieter than QRTVs, which are forced to be louder at low speeds (see chapter 5.1.5).

An additional aspect is the exclusion of alternative technologies, showing encouraging improvements for other environmental properties, e.g. reduction of exhaust emissions through hydrogen vehicles or E-methane technologies, but eliminated due to non-compliance towards UN Regulation No. 51 that regulates a very specific driving condition.

6.2 General Context and Noise Psychology

The aim of this chapter is to place the performed investigations and calculated results into a larger context. Thus far, road traffic noise is perceived as an independent and stand-alone phenomenon in this study. However, it is of great importance to understand what contribution road traffic actually makes in the overall context of traffic noise and in comparison to other noise sources.

Taking into account that this study is strictly limited to vehicles of the categories M and N, as far as road traffic noise is concerned. However, regarding the complete transport noise section, there are numerous additional contribution sources. 2-wheelers of category L, sirens and horns as well as rail traffic and air traffic contribute significantly to the general noise level in real traffic.
As indicated in chapter 6.1.3, a high frequency of single events may significantly contribute to increased noise levels. Single events only last for a short period of time, but with growing frequency and increased sound levels they can have a noticeable effect on the calculated $L_{Aeq}$ values. According to Bruitparif [24], sirens and horns are the biggest contributors in terms of single events in Paris. 2-wheelers, trucks and garbage collection only play a minor role.

![Contribution of single events to $L_{Aeq}$ (Paris)](image)

Figure 6-2: Contribution of single events to $L_{Aeq}$ (Paris) [24]

It is important to keep in mind that the calculated $L_{Aeq}$ values do not match the subjective feeling of annoyance by noise. According to Bruitparif [24], sirens are also named, but here the 2-wheelers are annoying the people even more. Figure 6-3 shows the types of transport noise that are considered as the most annoying in Paris. It illustrates that this study is only covering 24% of all traffic annoyances since it is limited to the vehicle categories M&N.

Without simultaneously tackling other noise sources such as 2-wheelers of category L, no noticeable difference will be realised in terms of reduction in traffic annoyances. Furthermore, it is important to understand that the perception of “annoyance by noise” is context dependent and therefore cannot be generalised. Accordingly, the noise nuisance must be considered, to a certain extent, as predominantly subjective.
The types of noise considered as the most annoying among transport noise (Paris)

While sirens (29%) are important audible warning tools, the annoyance through 2-wheelers (32%) and M&N-vehicles (24%) are likely caused predominantly by inappropriate driving styles, reckless behaviour in road traffic or the installation of illegal replacement exhausts.

The statements above make pretty clear that the potential benefits shown on the previous slides have to be seen in context to other transport noise sources and single events since the contribution of M & N vehicles is rather low to the total “transport noise” and even lower to the overall noise.

6.3 Analysis of the Phenomena Assessment Systematic

The Phenomena Study [14] focuses on the investigation of the potential health benefits of noise abatement measures in the EU. One important characteristic is the alignment to the END (Environmental Noise Directive) and the noise management in the EU. Within the framework of END, several measures and policies have been implemented and adopted, relevant to reducing noise pollution at the source. The sources in this study are mainly road and rail traffic as well as aviation traffic. Besides the listed sound sources, it is obvious that the noise level in real traffic conditions strongly depend on the infrastructure conditions, driver behaviour and vehicle condition.
Section 3 “Analysis of noise action plans and stakeholder consultation” provides a list of possible noise solutions and measures to reduce road traffic noise. The first three items in the list are related to the vehicle itself, where the first two points are targeting noise from tyres and/or road surface. The third point is proposing a minimum 2 dB(A) reduction for the whole vehicle noise level. In theory, this approach is common, easy to understand and correct.

Translating this into the type approval procedure and subsequently into new limit values, it is clear that reductions made on road surface cannot contribute towards improvement in type approval conditions as the road surface quality in the regulation is fixed. The overall sound level consists of both part sources, powertrain and tyres. A reduction of 2 dB(A) under all conditions (vehicle speeds) requires an equal contribution of both part sources. A further 2 dB(A) - 4 dB(A) reduction on the tyres as mentioned in table 6.2 of the Phenomena study appears unrealistic with respect to type approval. The tyres used during current type approval testing are significantly below the current tyre noise limits [25].

A future limit value reduction on the “average tyre” may be feasible, resulting in the noisy but legal tyres to be excluded, leading to a very efficient and fast measure to improve the sound level for real traffic scenarios, as also explained in chapter 5.1.6 of the study presented here. Regarding type approval conditions under regulation UN R51, the potential to develop tyres with significantly lower sound levels than the ones currently in use appear to be low, as according to the industry consultations a technological limit seems to have been reached.

It was also pointed out that there is not necessarily a correlation between tyre label and real life measurements, just as recent studies have shown as well [17]. Based on consumer studies, the main criteria for tire selection are attributes such as performance (wet and dry grip), rolling resistance (fuel consumption) and durability [8]. Unlike the interior noise performance of a tyre, the exterior noise behaviour is an insignificant priority among the selection parameters, since the correlation of the noise label to the interior noise is not certain and guaranteed.

In the Phenomena study, the effect from solutions for the reduction of road traffic noise is often quantified using numbers provided by different parties and countries that frequently show a high variance. This confirms how difficult and challenging it is to quantify the benefit of a lower vehicle noise threshold with a single value. This is the reason why the present study focuses on all boundary conditions that can influence the sound level of the vehicle and investigates the sensitivity vs. changes in the assumption. This approach allows a better overview about the impact of the input parameters on the result.
Chapter 5.10 in the Phenomena study describes the model for the calculation of the road traffic noise. Several correction factors are listed and described that have been applied to the CNOSSOS model because of mismatches with other calculation models. From the description it is unclear what parameters are used for the calculation of individual vehicle categories in terms of sound emissions and where the baseline is set.

Looking at table 5.12, the baseline appears to be established on the assumption that all vehicles from 2015 are compliant and lean towards the limit values. In reality, most vehicles are already significantly below the limit value and some are already compliant with the next phase of limit values as illustrated in chapter 2 of this study. This denotes that in Phenomena the theoretical noise reduction is expected to be higher than what is actually possible in real traffic conditions. Moreover, the input and baseline parameters are unclear and it is difficult to evaluate what level of sound emissions is assumed for the individual vehicle categories.

Section 5.13 “Uncertainty in the model parameters and scenario parameters” touches upon the challenge faced by all conducted studies and the resulting conclusions that can be drawn. Any model or calculation is only as precise as the correct selection of the input parameters and the accuracy of the available data. Since this study and the Phenomena study aim to forecast the coming 15 – 20 years, it is important to get a correct understanding of the sensitivity against several parameters. This study focuses on the transparency and appropriate understanding of the variations of the results in response to modified inputs.

In line with this study, the paragraph 8.3.3 C – “Lower vehicle sound limits“ in the Phenomena report highlights that the sound emission reductions achieved under type approval conditions do not guarantee low sound levels for the whole operation range of a vehicle. Moreover, it is highlighted that further potential for lower limit values need to be derived from type approval test databases with focus on available technical potential and potential of electric and hybrid vehicles.

Based on the analysis in this study, it is illustrated that certain vehicle categories appear to have reached a limit of technical feasibility whereas some progress is still evident in other categories. This is indicates that the next level of limit value reductions needs to be limited to the vehicles situated on the upper end of the sound level range. For vehicles positioned on the lower end, the gap between the limit and the actual noise level is reduced and is becoming increasingly challenging to pass type approval tests without resulting in a significant reduction in noise levels under type approval conditions as well as real traffic conditions.
In this context, the Phenomena study presents an implementation of reduced vehicle sound limit by focusing on certain aspects such as the potential of EVs and HEVs and the potential of reduced tyre contribution especially in combination with road surfaces. It remains questionable what benefits a quieter surface for type approvals testing can bring, taking into consideration that the ISO track rolling sound level is 3 dB(A) – 4 dB(A) below a typical new standard road surface in real traffic conditions.

A lowering of the tyre noise during type approval testing by means of low noise road surfaces would allow a lowering of the limit values and expose the powertrain side slightly more but will never translate into any sound reduction in real traffic situations as long as the real roads remain in worse conditions. A road surface more silent than ISO track would make the procedure even less realistic compared to the current status quo. Furthermore, a reduction of 1 dB(A) - 2 dB(A) beyond 2026 (current “phase 3”) as mentioned in this chapter appears to be very challenging especially under the assumption that the progress on tyre side is limited by the multiple other performance criteria that tyres need to fulfil.
7 Conclusion and Recommendations

7.1 Limit value reductions – what does it mean?

A limit value reduction is oftentimes considered an appropriate noise abatement measure to reduce road traffic noise. The reductions of limit values in the past and the improvements in vehicle sound emissions achieved by the industry support this view. However, with ever lower limits, the question must always be answered anew as to what the effects of lower limit values would be in real traffic. Is a further reduction of the limit values in combination with the current test methods efficient in reducing vehicle noise emissions in real traffic? The main focus should be on how noise emissions from vehicular traffic can be reduced as efficiently as possible and how this can be implemented in the most sensible way without forcing regulations which may not lead to the promised improvements, but lead to undesired effects.

7.2 Current situation – vehicle (powertrain) side:

The sound emission level of most vehicle categories has significantly decreased over the last years and will be further reduced with phase 3 limits coming into force in the near future. The data examined in this study reveals that vehicle categories partially present a pre-compliance towards future limit value phases. In consequence, the introduction of lower limit values would potentially have less of an impact to sound emission levels in real traffic than the limit values suggest. A thorough investigation concerning the developments over the past decade is subject of chapter 2 and 3. The findings of the analysis of the current situation are summarised in the following section.

7.2.1 Vehicles tested according to Annex 3 Sub-paragraph 3.1.3.1.

UN Regulation No. 51 phase 3 limits appear to be the limit of technical feasibility with the current state of the art. A reduction of a further 2 dB(A) as assumed for scenario 3, would require an over proportional contribution from the powertrain side since a sound level reduction by 4 dB(A) vs. the level from 2020 is not realistic to achieve on tyre side. Currently no technologies are available to reach reduced limit values beyond phase 3. A drastic change in mobility concept would be required to achieve such limit values.

The contribution in terms of rolling sound level, even from modern tyres alone, is already reaching the limit for the scenario 3 vehicle limits, without considering any contribution of the powertrain part source. Accordingly, the tyre is becoming the dominant partial sound source under type approval conditions.
Compliance to phase 3 limit values is only possible with the very best available tyres in terms of sound emissions. Currently, a significant decrease in tyre noise is only possible by using narrower tyres, which represents a conflict with the objectives in terms of safety performances and the current market trends towards wider tyres.

Any further reductions realised for the powertrain is only effective at low vehicle speeds and in combination with road surface improvements and do not contribute to a reduction in noise at higher vehicle speeds such as rural conditions and motorways. Aiming for noise reduction by reducing limit values is subject to a significant time-delay in contrast to measures on tyres and/or the road surfaces. The measures on the tyres and/or road surface are effective under all circumstances as well as for vehicles from all categories and age with no delay for improved road surfaces and only a little market penetration time for tyres.

In contrast to some publications, the advantage of electric M1 vehicles is lower than expected, especially at high-speed conditions, and limited in real traffic conditions. A further investigation in combination with the effects of AVAS should be carried out. In general, a decrease of road traffic noise can be expected at lower driving speeds due to the electrification of certain vehicle categories, e.g. N1 and M2 (M ≤ 3500 kg).

Some vehicle types e.g. small city and budget cars will risk being abolished through reduced limit values due to the market need to keep these vehicles affordable and the limited packaging constraints to add further sound reduction systems.

7.2.2 Vehicles tested according to Annex 3 Sub-paragraph 3.1.3.2.

In contrast to passenger cars and light vehicles, the type approval procedure according to sub-paragraph 3.1.3.2 clearly highlights the drive train in the test procedure and the influence of the tyres are minimised. This is further highlighted through the 2-axle testing configuration used in type approval testing, whereas heavy commercial trucks in real traffic scenarios mostly operate with a 5-axle configuration, which in turn significantly increases the tyre contribution.

The compliance to stricter limit values can therefore solely be achieved through measures on the powertrain. Similar to light duty vehicles, the improvements made on the powertrain do not lead to a significant improvement in real traffic operation at higher speeds. Due to the dominance of the powertrain at lower speeds, both trucks and buses would theoretically benefit from electrification. It is acknowledged that it may not be the most beneficial and reasonable solution for all vehicles of one specific category.
In the case of buses and trucks, generally operating in cities and not restricted in their usefulness by limited vehicle range, the transition to electric drive is a very efficient means of reducing noise emissions and other gaseous pollution. For long haul coaches and heavy-duty commercial trucks, mainly operating over long-distance routes in rural or motorway conditions, the noise reduction potential due to electrification is limited and may have a significant impact on the utility value.

When selecting the best possible technology for the individual vehicle classes, the entire range of application must be taken into account and technologically sensible concepts should not be excluded from the market by noise limits without significant potential for improvement. In the case of commercial vehicles, the focus is on the utility value, which should not be sacrificed solely for noise reduction.

Many special purpose vehicles are built on an existing platform based on an off-road vehicle, a van or a truck. The development of such vehicles is only possible if the type approval regulations allow for the base vehicle to meet the specific requirements. If these requirements cannot be meet, the development of special purpose vehicles would not be financially viable due to their limited sales numbers. Questions have been raised whether it is necessary and useful to impose the same limit value reductions to this special category of vehicles even though the majority operate outside of urban areas and restricted to very specific environments e.g. heavy equipment transport trucks.

7.3 Recommendations and Observations

7.3.1 Prerequisite for new Limit Values and Investigations of the Status Quo

- A successful further reduction of limit values in UN Regulation No. 51 is only achievable if significant progress can be achieved on the quietest available tyres without sacrificing their performance attributes, especially with regard to safety.
- Before determining new limit values, production vehicles complying to phase 2 and phase 3 limit values should be extensively examined under various real traffic conditions in order to identify further potential concerning noise reductions.
- Prior to deciding new limit values beyond phase 3, the impact of vehicles homologated according to phase 3 limit values should be awaited and the resulting benefits in real traffic should be evaluated.
• Legislations should be adjusted carefully, in order to realise noticeable improvements in real traffic conditions and not cause undesired interactions between the various regulations in type approval compliance.
• Noise legislation should not lead to the elimination of promising technologies that may be useful in pursuing the reduction of exhaust emissions (e.g. ICE with H2 or E-methane).

7.3.2 Alternative Opportunities for an efficient Reduction of Road Traffic Noise

• In order to reduce traffic noise and achieve health benefits, a wide variety of alternative measures are available that can be implemented individually or in combination, e.g. speed limits, silent road surface asphalt, geofencing, etc.
• Due to the delayed effect of limit value reductions, developments on the tyre should be given priority as they can be applied to all vehicles in the field. Moreover, improvements can be realised without a long delay and are effective under all boundary conditions.
• It cannot be guaranteed that the latest generation of vehicles will show significant improvements over old vehicles once the OE tyres are replaced by tyres inferior in terms of noise emissions. Ensuring that all tyres available on the market are at equivalent levels to the best available tyres in terms of sound level would ensure that the benefits from newer vehicles will translate into real traffic conditions.

7.3.3 Considerations regarding Electro Mobility

• The development of the market penetration of electric vehicles in the coming future should be observed as well as upcoming alternative technological innovations that may need to be taken into account.
• Since the AVAS system for electric vehicles is permanently active at lower driving speeds, it is entirely possible that electric vehicles are noisier than regular ICE vehicles, depending on the individual AVAS configuration. A precise monitoring of the AVAS behaviour should be conducted in order to determine whether the increased spread of electric vehicles in real traffic will bring the desired improvement in overall noise levels.
• The scope for the AVAS configuration should possibly be reduced to avoid configurations being louder than necessary.
• The sound level of vehicles complying to phase3 limit values will be in the range of electric vehicles equipped with AVAS. A further reduction would result in conventional ICE vehicles forced to be equipped with AVAS to ensure pedestrian safety.
• The procedures and testing conditions for vehicles with hybrid propulsion should be precisely defined in order to be able to derive the most representative results from the type approval tests.

7.3.4 Further Considerations regarding Niche Segment Vehicles

• Also high-performance sports cars can be driven quietly and responsibly in urban and residential areas as long as the drivers of such vehicles obey the traffic rules. An increase in sound pressure levels cannot be completely prevented from such vehicles. However, this will not cause significant annoyances in road traffic conditions as long as the driver conducts the vehicle within the legal framework.

• Niche and special purpose/emergency vehicles shall not be neglected in new draft legislation in order to ensure their continued existence.
### 8 Explanation of Abbreviations, Acronyms and Terms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACEA</td>
<td>Association des Constructeurs Européens d’Automobiles</td>
</tr>
<tr>
<td>ASEP</td>
<td>Additional Sound Emission Provisions</td>
</tr>
<tr>
<td>AVAS</td>
<td>Acoustic Vehicle Alerting System</td>
</tr>
<tr>
<td>BEV</td>
<td>Electric vehicle using only batteries as energy storage</td>
</tr>
<tr>
<td>C1 Tyres</td>
<td>Tyres for passenger cars</td>
</tr>
<tr>
<td>C2 Tyres</td>
<td>Tyres for light commercial vehicle</td>
</tr>
<tr>
<td>C3 Tyres</td>
<td>Tyres for heavy vehicles</td>
</tr>
<tr>
<td>CI</td>
<td>Compression Ignition</td>
</tr>
<tr>
<td>CNOSSOS</td>
<td>Common Noise Assessment Methods in Europe</td>
</tr>
<tr>
<td>COP</td>
<td>Conformity of Production</td>
</tr>
<tr>
<td>DB</td>
<td>Data base</td>
</tr>
<tr>
<td>dB(A)</td>
<td>Unit for sound pressure – Decibel, A-weighted</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>END</td>
<td>Environmental Noise Directive 2002/49/EC specifying noise indicators</td>
</tr>
<tr>
<td>ETRTO</td>
<td>European Tyre and Rim Technical Organisation</td>
</tr>
<tr>
<td>EU 7</td>
<td>Stage 7 of exhaust emission restriction for M1 and N1 vehicles in the EU (in discussion)</td>
</tr>
<tr>
<td>EV</td>
<td>Electric vehicle – vehicle that uses only electric motor(s) for propulsion</td>
</tr>
<tr>
<td>GRPB</td>
<td>UNECE Working Party on Noise and Tyres (Groupe Rapporteur Bruit et Pneumatiques)</td>
</tr>
<tr>
<td>GSR</td>
<td>General safety regulation (EU) 2019/2144</td>
</tr>
<tr>
<td>GUM</td>
<td>Guide to the expression of the uncertainty in measurement</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid electric vehicle</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal combustion engine</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standardisation Organisation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>IWG ASEP</td>
<td>Informal Working Group ASEP</td>
</tr>
<tr>
<td>$L_{\text{Aeq}}$</td>
<td>Level A-weighted equivalent of sound pressure levels (weighted average max. pressure of different vehicle categories theoretically calculated as being one vehicle) [dB(A)]</td>
</tr>
<tr>
<td>$L_{\text{crs}}$</td>
<td>Vehicle sound pressure level at constant speed (cruise) [dB(A)]</td>
</tr>
<tr>
<td>$L_{\text{urban}}$</td>
<td>Vehicle sound pressure level representing urban operation [dB(A)]</td>
</tr>
<tr>
<td>$L_{\text{wot}}$</td>
<td>Vehicle sound pressure level at wide open throttle [dB(A)]</td>
</tr>
<tr>
<td>MU</td>
<td>Measurement Uncertainty</td>
</tr>
<tr>
<td>NG</td>
<td>Natural gas</td>
</tr>
<tr>
<td>OE</td>
<td>Original Equipment</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>OICA</td>
<td>Organisation Internationale des Constructeurs d’Automobiles</td>
</tr>
<tr>
<td>PBN</td>
<td>Pass-by-noise</td>
</tr>
<tr>
<td>Phenomena</td>
<td>Project assessing the potential health benefits of noise abatement measures in the EU</td>
</tr>
<tr>
<td>PI</td>
<td>Positive Ignition</td>
</tr>
<tr>
<td>PMR</td>
<td>Power to mass ratio [kW/1000 kg]</td>
</tr>
<tr>
<td>$P_n$</td>
<td>Nominal engine power [kW]</td>
</tr>
<tr>
<td>PTR</td>
<td>Powertrain, including engine, transmission, differential and axles</td>
</tr>
<tr>
<td>QRTV</td>
<td>Quiet Road Transport Vehicle</td>
</tr>
<tr>
<td>RD-ASEP</td>
<td>Real driving additional sound emission provisions</td>
</tr>
<tr>
<td>TA</td>
<td>Type approval</td>
</tr>
<tr>
<td>Test Track</td>
<td>UN R51 requires a test track in accordance with ISO 10844:2014</td>
</tr>
<tr>
<td>TF MU</td>
<td>Task Force Measurement Uncertainty</td>
</tr>
<tr>
<td>UN ECE</td>
<td>United Nations Economic Commission for Europe</td>
</tr>
<tr>
<td></td>
<td>World Forum for the harmonisation of vehicle regulations</td>
</tr>
</tbody>
</table>
UN R51  UN ECE Regulation No. 51
Uniform provisions concerning the approval of motor vehicles having at least four wheels with regard to their sound emissions – including:

Phase 1 of limits valid in UN R51
Phase 2 of limits valid in UN R51
Phase 3 of limits valid in UN R51

UN R117  UN ECE Regulation No. 117
Uniform provisions concerning the approval of tyres with regard to rolling sound emissions and/or to adhesion on wet surfaces and/or to rolling resistance

UN R138  UN ECE Regulation No. 138
Uniform provisions concerning the approval of Quiet Road Transport Vehicles with regard to their reduced audibility (defining AVAS)

WOT  Wide open throttle = full load acceleration
9 List of Tables

Table 1-1: Classifications according to Directive 2007/46/EC [1] .................................................. 8
Table 1-2: Limit values according to UN Regulation 51 [2] ................................................................. 9
Table 2-1: Median improvements of $L_{urban}$ - Category M1 .............................................................. 13
Table 2-2: Limit value compliance analysis - Category M1 ............................................................... 14
Table 2-3: Median improvements of $L_{urban}$ - Category M2 .............................................................. 18
Table 2-4: Limit value compliance analysis - Category M2 ............................................................... 19
Table 2-5: Median improvements of $L_{urban}$ - Category M3 .............................................................. 20
Table 2-6: Limit value compliance analysis - Category M3 ............................................................... 21
Table 2-7: Median improvements of $L_{urban}$ - Category N1 .............................................................. 24
Table 2-8: Limit value compliance analysis - Category N1 ............................................................... 24
Table 2-9: Median improvements of $L_{urban}$ - Category N2 .............................................................. 27
Table 2-10: Limit value compliance analysis - Category N2 ............................................................. 27
Table 2-11: Median improvements of $L_{urban}$ - Category N3 ............................................................ 30
Table 2-12: Limit value compliance analysis - Category N3 ............................................................. 30
Table 4-1: Limit value scenarios in calculation tool ............................................................................. 48
Table 4-2: Street types in calculation tool .......................................................................................... 51
Table 4-3: Driving conditions in calculation tool ................................................................................ 51
Table 4-4: Share of vehicle categories - Urban main street ................................................................. 53
Table 4-5: Share of vehicle categories incl. BEV share rate - Urban main street (2020) ....................... 53
Table 4-6: Share of vehicle categories incl. BEV share rate - Urban main street (2040) ....................... 54
Table 4-7: Medium market penetration speed - Category M1 ............................................................. 55
Table 5-1: Improvements of limit value reductions - Urban main street ............................................ 66
Table 5-2: Improvements of limit value reductions - Residential street .......................................... 67
Table 5-3: Improvements of limit value reductions - Motorway ....................................................... 68
Table 5-4: Improvements of pure electric vehicle share in 2040 - Urban main street ....................... 68
Table 6-1: Overall uncertainty according to GUM Assessment for UN R51 & UN R117 [20] ............ 71
Table 6-2: Difference in handling of uncertainties in current regulations [20] ................................. 91
10 List of Figures

Figure 2-1: Statistical distribution of $L_{urban}$ - Category M1 .........................................................12
Figure 2-2: Statistical distribution of $L_{urban}$ - Category M1 (Subcategories) ........................................13
Figure 2-3: Statistical distribution of PMR - Category M1 .......................................................................14
Figure 2-4: $L_{urban}$ vs. PMR - Category M1 .......................................................................................15
Figure 2-5: $L_{urban}$ vs. PMR - Category M1 (Propulsion types) .................................................................16
Figure 2-6: $L_{city}$ vs. tyre width - Category M1 ....................................................................................16
Figure 2-7: Statistical distribution of $L_{urban}$ - Category M2 .................................................................17
Figure 2-8: Statistical distribution of $L_{urban}$ - Category M2 (Subcategories) ........................................18
Figure 2-9: Statistical distribution of $L_{urban}$ - Category M3 .................................................................19
Figure 2-10: Statistical distribution of $L_{urban}$ - Category M3 (Subcategories) .....................................20
Figure 2-11: Statistical distribution of $L_{urban}$ - Category M3 (Subcategories | only ICE) ....................21
Figure 2-12: Statistical distribution of rated engine power - Category M3 (Subcategories) ...............22
Figure 2-13: $L_{urban}$ vs. rated engine power - Category M3 .................................................................22
Figure 2-14: Statistical distribution of $L_{urban}$ - Category N1 ...............................................................23
Figure 2-15: Statistical distribution of $L_{urban}$ - Category N1 (Subcategories) .....................................24
Figure 2-16: $L_{urban}$ vs. technically permissible maximum laden mass M - Category N1 ...............25
Figure 2-17: Statistical distribution of $L_{urban}$ - Category N2 ...............................................................26
Figure 2-18: Statistical distribution of $L_{urban}$ - Category N2 (Subcategories) .....................................26
Figure 2-19: Statistical distribution of rated engine power - Category N2 ..............................................27
Figure 2-20: $L_{urban}$ vs. rated engine power - Category N2 .................................................................28
Figure 2-21: Statistical distribution of $L_{urban}$ - Category N3 ...............................................................29
Figure 2-22: Statistical distribution of $L_{urban}$ - Category N3 (Subcategories) .....................................29
Figure 2-23: Statistical distribution of rated engine power - Category N3 ..............................................30
Figure 2-24: $L_{urban}$ vs. rated engine power - Category N3 .................................................................31
Figure 2-25: EU registration data vs. Type approval data - Category M1 ............................................32
Figure 2-26: ACEA TA Monitoring dB (2010) vs. OICA TA dB (2020) ..................................................34
Figure 3-1: Tyre performance trade offs - Regulated and non-regulated ..............................................41
Figure 4-1: Flow chart - Calculation model structure ..............................................................................50
Figure 4-2: Sound split in calculation tool - Category M1 (ISO track | Cruise condition) ....................56
Figure 4-3: Sound split in calculation tool - Category M1 (Real road | Cruise condition) ...............57
Figure 4-4: Sound split in calculation tool - Category M1 BEV (Real road | Cruise condition) ..........59
Figure 4-5: Sound split in calculation tool - Category N3 (Real road | Cruise condition) ...............60
Figure 5-1: Impact of limit value reductions - Urban main street .........................................................65
Figure 5-2: Impact of limit value reductions - Residential street .........................................................67
Figure 5-3: Impact of limit value reductions - Motorway.................................................. 68
Figure 5-4: Impact of limit value reductions - Driving speed........................................... 69
Figure 5-5: Impact of market penetration - Urban main street.......................................... 70
Figure 5-6: Impact of pure electric vehicle share - Urban main street............................... 71
Figure 5-7: Impact of pure electric vehicle share - Motorway .......................................... 72
Figure 5-8: Relative improvement BEV vs. ICE and Impact of AVAS ................................... 73
Figure 5-9: Impact of tyre/road interaction - Urban main street....................................... 76
Figure 5-10: Impact of tyre/road interaction - Motorway ............................................... 77
Figure 5-11: Impact of tyre - Urban main street ............................................................ 78
Figure 5-12: Impact of speed limits - Urban main street ................................................... 79
Figure 5-13: Impact of speed limits - Motorway.............................................................. 80
Figure 5-14: PTR/tyre measures efficiency - Category M1 (Scenario 2 | Urban cond.) .......... 82
Figure 5-15: PTR/tyre measures efficiency - Category M1 (Scenario 2 | Urban cond.) .......... 83
Figure 5-16: PTR/tyre measures efficiency - Category M1 (Scenario 2 & 3 | Urban cond.) .... 83
Figure 5-17: PTR/tyre measures efficiency - Category N1 (Scenario 2 | Urban cond.) .......... 84
Figure 5-18: PTR/tyre measures efficiency - Category N1 (Scenario 2 | Urban cond.) .......... 84
Figure 5-19: PTR/tyre measures efficiency - Category N1 (Scenario 2 & 3 | Urban cond.) .... 85
Figure 5-20: PTR/tyre measures efficiency - Category N3 (Scenario 2 | Urban cond.) ........... 85
Figure 5-21: PTR/tyre measures efficiency - Category N3 (Scenario 2 | Urban cond.) ........... 86
Figure 5-22: PTR/tyre measures efficiency - Category N3 (Scenario 2 & 3 | Urban cond.) ..... 86
Figure 6-1: Uncertainty “Bubble” regarding UN Regulation measurement procedure [20] ... 89
Figure 6-2: Contribution of single events to $L_{Aeq}$ (Paris) [24]....................................... 98
Figure 6-3: Most annoying types of transport noise (Paris) [24]....................................... 99
11 List of Sources

The following sources are taken into consideration though not all of them are cited directly in this report:


