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The Influence of Pavement Degradation on Population Exposure to Road Traffic Noise

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Abstract: Road pavement develops distresses over time, which increase tyre/road noise. This work focuses on the impact of these distresses on environmental noise. To calculate the environmental noise, a method to transform Close ProXimity (CPX) measurement results into the required input for traffic noise models was defined and used. The tyre/road noise levels were determined by the CPX method for three types of pavement, with three types of distress, at three different speed levels. The study was carried out in the city center of Guimarães, a medium-sized Portuguese city. Using the NMPB model, 18 noise maps were produced for the passing of one single vehicle, taking into account two levels of distress (50% and 100%) for the pavement. The presence of distresses increased the noise, calculated at control points, by up to 7.1 dBA, and the percentage of the population exposed to levels over 45 dB was more than 11%. It was shown that pavement maintenance at early stages of distress development is, particularly for low-speed roads, very important to reduce environmental noise and population exposure. A comprehensive selection of the type of surface and speed control policies can mitigate the impact of a lack of maintenance.

Keywords: environmental noise; pavement distresses; CPX; alligator cracking; raveling; road traffic noise exposure

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1. Introduction

Motorized traffic is nowadays recognized as the major contributor to environmental noise in urban areas. The main noise sources are engine noise and rolling noise from tyre/road surface interaction [1], where typically noise levels increase with higher traffic volumes and speeds. The exposure to noise is responsible for a number of health issues, such as increased risk of cardiovascular health disorder, sleep disorders, psychological impact, cognitive dysfunction for children, and more generally, annoyance and stress [2–4].

Environmental noise studies, performed to date, indicate road traffic noise as the major noise source, which includes both engine noise and tyre/road noise components [5].

In general, studies concerning the characterization of road traffic noise are mostly related to factors, such as vehicle speed, and the number and type of vehicles [6]. Some studies address the tyre/road components of road traffic noise, focusing on pavement characteristics, such as texture and porosity [7–9]. Besides these factors, the behavior of the driver, the characteristics of the tyres [10] and also the weather conditions [11,12] affect tyre/road noise and consequently the overall environmental noise.

The condition of the pavement itself, however, changes over time due to (heavy) traffic, the impact of weather conditions (freeze–thaw cycles in winter time, high temperatures during summer, ageing due to UV-radiation, etc.) and also due to maintenance operations. After a period of time, usually several years, the surface of the pavement starts exhibiting distresses, such as rutting, raveling, cracking and, eventually, alligator cracking, among others [13]. Together with other pavement discontinuities, like bumps or potholes [14–16], these distresses are expected to affect tyre/road noise generation mechanisms, mainly by increasing the tyre vibrations [16,17]. This in turn, will increase the noise levels and therefore population exposure and annoyance.

The effect of changes in pavement surface characteristics on its acoustic performance has captured the attention of several researchers. An extensive review on the effect of those characteristics and also ageing on tyre/road noise was done by [18], where the increase of noise level (without the effect of the traffic volume) is reported to be associated with wearing on the pavement. However, many studies focus on the first years of the pavement's lifetime, before the development of distresses [19,20].

However, limited research has been performed where pavement surface degradations are related to the corresponding tyre/road noise levels. In [21], the noise generated by the tyre/road interaction was used to obtain a Pavement Condition Index (PCI), a measure to indirectly assess the pavement condition and detect distresses. More recently, a method to help road surveyors to identify the many distress conditions of localized defects was developed by [22,23]. Nonetheless, a clear relation between tyre/road noise measured over specific distresses at different speeds, and the analysis of the impact on population exposure is still missing. Moreover, budgetary restrictions lead more often to late interventions in pavement maintenance, and consequently, the population is exposed to higher levels of noise, influenced by distresses. In this context, the assessment of the impact of distresses on environmental noise will provide environmental and road agency managers with a tool to support their decisions and actions.

Road traffic noise levels can be assessed by two different means: measurements and prediction. The measurement method is only feasible when applied to existing situations. The prediction method is often used from the very start of the planning process until the final detailed design of noise abatement measures [1,24]. For the assessment of the impact of pavement distresses on environmental noise, both methods are necessary. Recently, attention has shifted towards measurement methods, such as CPX (Close ProXimity), that allow the noise emission of road surfaces to be characterized at the source, at different speeds. This technique has the advantage of a continuous high-speed measurement [25,26]. On the other hand, the modelling of outdoor acoustic propagation in urban areas must integrate all the parameters that may influence noise propagation, including, among others, the topography of the site, noise screens (if present), the nature of the ground, and in certain cases, the wind and the heterogeneousness of the atmosphere. In this context, the main objective of this work is the evaluation of the impact of road pavement distresses on environmental noise and, consequently, on population exposure.

The paper is structured as follows. In Section 2, the main methodology is explained, followed by details regarding the case study, the measurement method used, and the development of the noise maps. The actual results are discussed in Section 3. This includes, firstly, the influence of the pavement type, vehicle speed and distress type on the different acoustical parameters and, secondly, the corresponding noise maps and resulting noise exposure. Finally, some conclusions and limitations of the current study are provided in Section 4.

2. Materials and Methods

2.1. Methodology

To achieve the main objective, the CPX method was used to collect tyre/road noise at three speed levels on several pavement types, with different distresses. In this study, only alligator cracking and raveling are investigated. These results will be used as inputs for a calculation model of the environmental noise. Macrotexture levels were determined at the same time.

Next, several scenarios were defined, taking into account the combination of the traffic speed with the pavement type, distress type and distressed surface. The following step consists of the transformation of the CPX data into the required input for the traffic noise model. The developed methodology includes a propagation filter as the main improvement, compared to other attempts to study the tyre/road noise evolution and annoyance [27,28].

Finally, based on the traffic data and site physical characteristics for the selected case study, noise maps were created and combined with the population distribution layers from a GIS (Geographical Information System) model. The scientific toolbox, adopted to develop these studies, included a noise simulation model in the CadnaA software (version 2018) and a GIS platform. This combination was the basis for the identification of the people's exposure to certain road traffic noise levels.

An overview of the methodology is shown in Figure 1.

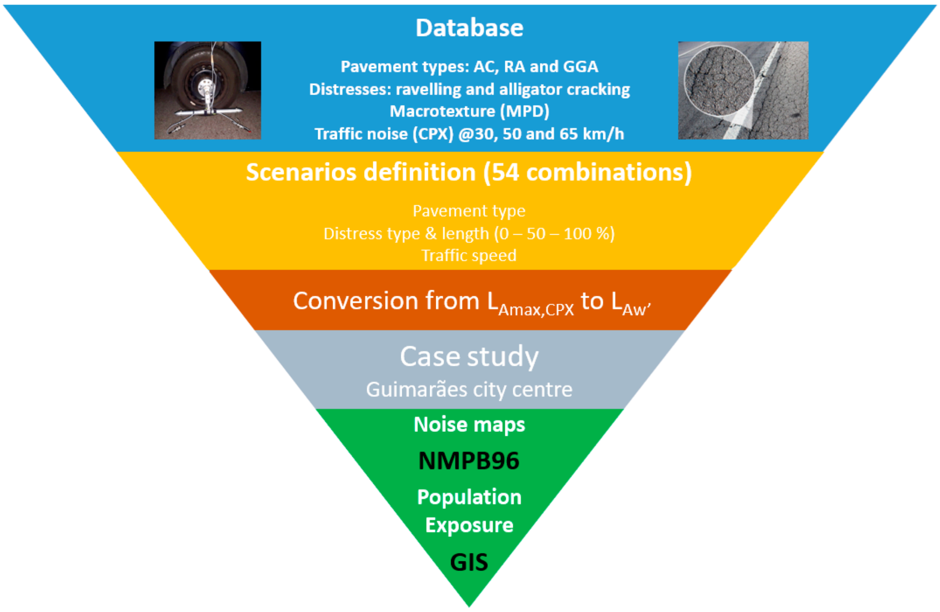

Figure 1. Study methodology. AC: asphalt concrete; RA: rubber asphalt; GGA: gap-graded asphalt; GIS: Geographical Information System.

2.2. *Case Study*

The study was carried out in the city center of Guimarães. This municipality is located in the Ave sub-region of the Braga district in North-Western Portugal. The city of Guimarães, located at the center of the municipality, has approximately 52,000 inhabitants [29]. The streets used in the noise maps are illustrated in Figure 2, and their characteristics are included in Table A1 (Appendix A). The current pavement surfaces in the center of Guimarães consist mainly of asphalt concrete (AC) and cobble stones. However, for the present study, two other types of road pavement surfaces, frequently used in Portuguese urban areas, specifically, rubber asphalt (RA), and gap-graded asphalt (GGA), were added. Therefore, to widen the study results and for better measurement conditions, a database was constructed with information collected from other sites, located outside the city center.

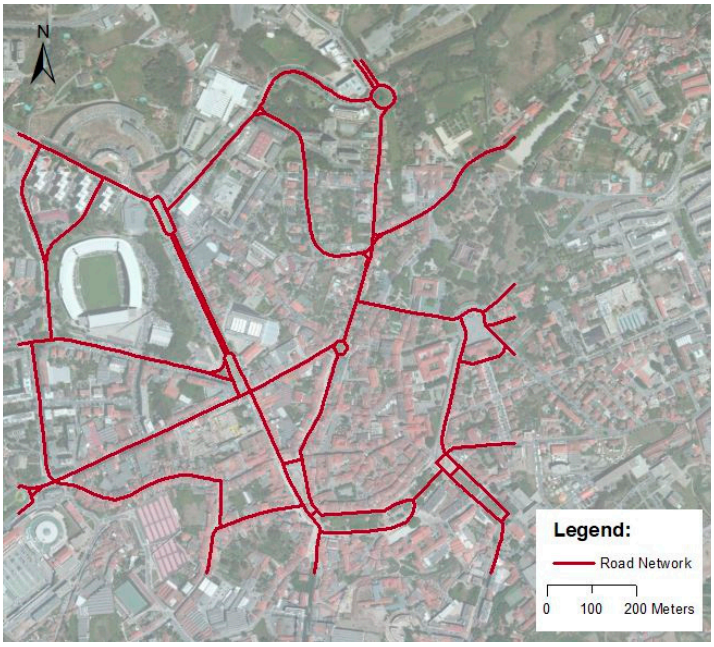

Figure 2. City center of Guimarães and the streets included in the noise maps.

2.3. Database

Seven regional roads in the region of Minho, with either AC, RA, or GGA, encompassing, in total, 16 test sites (5 to 6 sites per distress type), were selected (see Table A2, Appendix A). At these locations, both tyre/road noise and macrotexture measurements were performed.

Information included in the database was collected from asphalt pavement surfaces exhibiting two of the most common distresses that are present in urban areas: alligator cracking (ACR) and raveling (R). For comparison, sections without distresses (N) were analyzed as well. According to [30], ACR is an area of interconnected cracks that characteristically form a complete chicken wire/alligator pattern, which usually occurs in the wheel paths due to repeated traffic loadings. R is the wearing away of the pavement surface, caused by the dislodging of aggregate particles and a loss of asphalt binder. In Figure 3, examples of these distresses are shown.

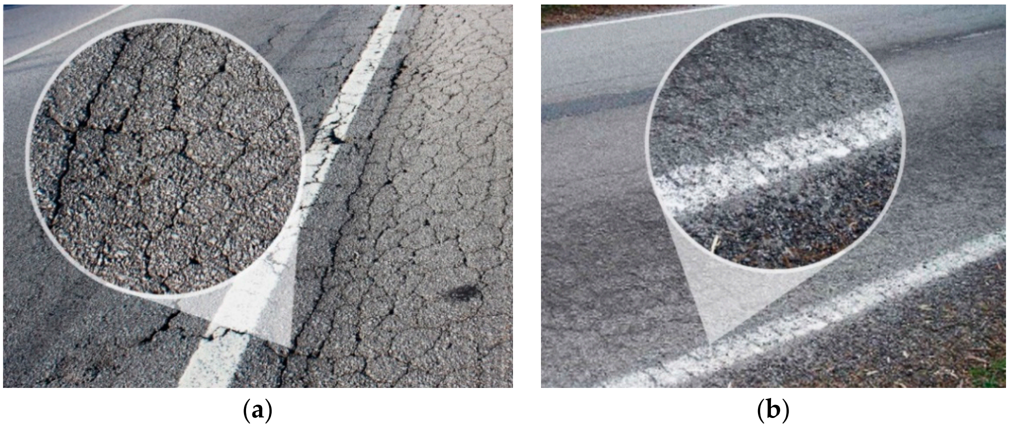

Figure 3. Examples of the distresses: (**a**) alligator cracking (ACR) and (**b**) raveling (R).

For each pavement surface and distress type, Table 1 presents the maximum aggregate size (D_{max}) and the average Mean Profile Depth (MPD), measured every 10 m on the surfaces. Due to their grading, AC and GGA have a positive texture, while RA exhibits a negative texture. It is clear that the presence of a distress increases the MPD, but no difference is found between ACR and R for the MPD-values.

Table 1. Mean profile depth (MPD) and maximum aggregate size for each pavement condition.

Pavement Type	**MPD [mm]**			**D_{max} [mm]**
	N	**ACR**	**R**	
AC	1.0	1.8	1.8	16
RA	1.1	1.8	1.8	10
GGA	1.0	1.4	1.4	7

2.4. *Tyre/Road Noise Measurements*

The method selected for the measurement of the tyre/road noise was the Close ProXimity Method (CPX), following the ISO 11819-2:2017 standard [31] The noise levels were measured by two $\frac{1}{2}$ inch Free-Field microphones (B&K type 4190, see Figure 4) connected to a portable platform (Pulse type 3460-C) through B&K AO-0419 cables and, finally, to a laptop. The tyre/road noise was registered as audio data files in the DAT format and manipulated later to extract the necessary noise indicators. The tyre used for testing was a Continental ContiEcoContact3 195/65-R15.

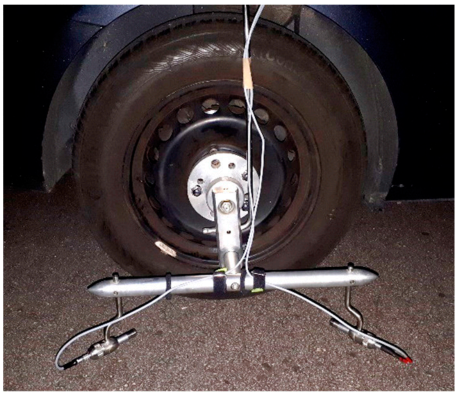

Figure 4. Set-up of the microphones (B&K type 4190) assembled on a vehicle.

The data acquisitions were made at least twice for three different speeds (30, 50, and 65 km/h) at each test site. The audio files were then cut into time fragments, equivalent to 50 m (6.00; 3.60; 2.77 s), which is a length in the range of those used in road engineering for performance assessment of the pavement condition. Only those respecting the speed level and free of unwanted noises were considered. Finally, the A-weighted maximum noise level ($L_{A\text{max,CPX}}$) of each microphone was calculated using the *Psysound3* software [32], which is run in Matlab®.

2.5. *Noise Modelling*

The noise modelling procedure starts with the transformation of the A-weighted maximum noise level ($L_{A\text{max,CPX}}$) into noise emitted by a single vehicle, the sound power level per unit length from the tyre/road noise (L_{AW}'). In its turn, the L_{AW}' will be used as the input in a validated simulation model to produce noise maps and, at last, calculate the population exposure.

2.5.1. Calculation of the Sound Power Level per Unit Length from the Tyre/Road Noise

The A-weighted sound power level per unit length (L_{AW}') by road segment is the sound input required for the environmental noise calculation models. Therefore, a method to transform the tyre/road noise, measured by the CPX method, into a L_{AW}' was defined, involving two main phases.

First, the $L_{A\text{max,CPX}}$ values are converted into values corresponding to the statistical pass-by method ($L_{A\text{max,SPB}}$). For this purpose, the CPX/SPB filter, proposed by [33], was used. In practice, it corresponds to a reduction (ΔL_r) of 21.6 ± 0.9 dB. This filter can be applied between the frequencies of

100 to 5000 Hz. Because noise levels outside of this range are very small in terms of tyre/road noise, the filter was applied to the full spectrum.

Subsequently, the $L_{A\max,\mathrm{SPB}}$ is transformed into $L_{AW}{}'$. In this phase the three-step procedure, presented in *Guide du Bruit* [34], was adopted.

First step: calculation of the power level L_w (Equation (1)).

$$L_W = L_{A\max} + 20\log\sqrt{7.5^2 + 1.2^2} + 10\log(2\pi) \tag{1}$$

where 7.5 is the distance between the microphone and centerline of the road, 1.2 is the height of the microphone, and both values are in meters.

Second step: calculation of the emission E (Equation (2)).

$$E = L_w - 10\log(v) - 50 \tag{2}$$

where v is the velocity in km/h.

Third step: calculation of $L_{AW}{}'$ (Equation (3)).

$$L_{Aw}{}' = [E_{lv} + 10\log(Q_{lv})] \oplus [E_{hv} + 10\log(Q_{hv})] + 20 \tag{3}$$

where E_{lv}, E_{hv} are the emissions of the light and heavy vehicles, respectively (L_{eq} per hour), and Q_{lv}, Q_{hv} are the number of light and heavy vehicles that pass by, respectively.

For this work, only one light vehicle was considered.

2.5.2. Calculation of Horizontal Noise Maps

The modelling of outdoor acoustic propagation in built-up urban areas must integrate all the parameters that influence the noise propagation. A geographical model of the area was developed by [35]. A full survey, including the topographic characteristics, location of reception points (calculation grid), sound absorption characteristics of the ground, presence of natural and artificial barriers, and the specification of the emission sources (profile, cross section and pavement types of streets) were the primary data for the construction of the geographical model. With the data gathered, the noise simulation model was used to produce horizontal noise maps for the defined scenarios. The New Method for Forecasting the Traffic Noise (French method-NMPB 96) was used to develop noise maps using the CadnaA (Computer Aided Noise Abatement) software. The NMPB 96 method was developed in France in 1996. This method is the recommended interim computation method for road traffic noise calculation by the European Parliament Directive 2002/49/EC and the Council of June 25, 2002 (Directive 2002/49/EC, 2002), which addressed the assessment and management of environmental noise. According to [35], the following calculation parameters should be adopted:

- Grid spacing: software-generated variable grid spacing (less than 10 m);
- Height of the maps: 4 m;
- Occurrence of favorable meteorological conditions: in compliance with WG-AEN (2006), day period 50% ($p = 0.5$); evening period 75% ($p = 0.75$); night period 100% ($p = 1$);
- Reflection order: 2nd.

In accordance with APA [36] and with NP ISO 1996, three long-term measurements were carried out over two typical days. The site selection of the measurement locations was undertaken according to the following criteria: predominant influence of one type of source, predicted values exceeding the regulatory requirements (hot spots) within the perimeter of the urbanized area closest to the source, and doubtful results. In each case, the measurement height was 4 m, measured away from the facade of buildings (≥4 m). The comparison between measurements taken on-site and the noise map has confirmed the generally good performance of the model. It was found that the measured levels were generally within 1.4 dBA of the predicted levels, as shown in Table 2, taken from [35].

Table 2. Validation of the Guimarães noise map [35].

Location	L_{den}/L_n [dBA] Measured	L_{den}/L_n [dBA] Modelled	Absol. Diff. [dBA]
MP1	45.9/40.3	46.1/41.1	+0.2/+1.2
MP2	65.7/55.4	67.1/55.2	+1.4/−0.2
MP3	67.3/55.3	67.8/56.0	+0.5/+0.8

2.5.3. Population Exposure to Noise

The 2011 population data were obtained from the Census Bureau CENSO2011 and were georeferenced to the smallest geographical spatial unit available—the census block. Population data were stored in a topological GIS coverage and overlaid together with the noise maps in order to determine the percentage of people subjected to relevant ranges of $L_{A,eq}$. For this purpose, a uniform distribution of the population within the blocks was assumed.

For the calculation of the relevant noise levels, to which the population is exposed, three hypotheses regarding the distressed length of the road were considered: 0%, 50%, and 100%. The first hypothesis will be considered as a reference, while the other two represent severe and very severe conditions. Due to budgetary restrictions felt all over Europe, long sections of pavement requiring maintenance will be more often the real condition of the road network.

3. Results and Discussion

In total, 54 ($3 \times 3 \times 3 \times 2$) scenarios were considered: three pavement surfaces (AC, RA, GGA), three speed levels (30, 50, 65 km/h), three distresses (N, R, ACR) and the distressed length of the road (50% and 100%).

3.1. Calculation of Tyre/Road Noise Emission

The L_{Amax} of all sound files was calculated using the Psysound3 software. Table 3 presents the $L_{Amax,CPX}$ in dBA for each speed, pavement and distress type.

Table 3. Measured $L_{A\text{max},\text{CPX}}$ [dBA], according to the speed, pavement and distress type.

Speed [km/h]	$L_{A\text{max},\text{CPX}}$ [dBA] Pavement Type			Distress Type
	RA	AC	GGA	
30	84.7	84.0	84.9	N
	85.1	90.4	84.8	R
	88.4	91.2	88.5	ACR
50	91.1	92.2	91.1	N
	94.9	97.5	91.4	R
	95.9	96.6	95.7	ACR
65	96.9	95.4	96.9	N
	97.5	101.3	97.2	R
	99.4	100.3	99.4	ACR

3.1.1. Analysis of Speed and Distress Effect

Noise levels usually increase with speed. As shown in Figure 5, this effect is also true for pavements with alligator cracking and raveling, with the pavement types under analysis in this study (AC, RA, and GGA) included as individual dots belonging to a certain distress type.

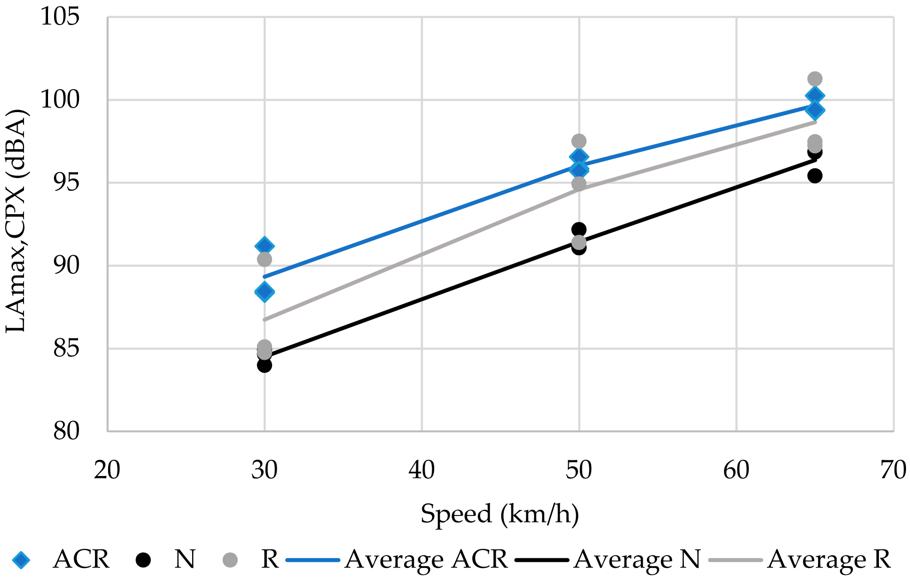

Figure 5. $L_{A\mathrm{max,CPX}}$ of all pavement types by distress type.

The statistical Kruskal–Wallis test was carried out to confirm if there were significant differences between the three conditions of the pavement (N, ACR, and R), regardless of the pavement type, and in this way, to confirm their effect on tyre/road noise levels. Statistically significant differences at a 10% significance level were found, with the following p-values: 0.079 at 30 km/h, 0.097 at 50 km/h, and 0.059 at 65 km/h. Therefore, the average $L_{A\mathrm{max,CPX}}$ of all the different pavements with alligator cracking (ACR) is on average higher than that of pavements with raveling (R), which in turn is higher than that of pavements without distress (N). At high speeds, the increase in the average noise level is equal to 3.3 dBA, while at low speeds, the effect of distresses raised the average tyre/road noise levels with up to 4.8 dBA.

To control the traffic noise under operating conditions in urban areas, it is therefore important to control the level of distresses, particularly for roads with low traffic speeds.

3.1.2. Analysis of Pavement Effect

Figure 6 shows, for each pavement and distress type, the $L_{A\mathrm{max,CPX}}$ averaged for the three speed levels and the corresponding extreme values as an error bar. The road-type AC has a higher average tyre/road noise level than that of RA and GGA. This was expected due to the road-type's intrinsic characteristics and its influence on noise. AC pavement has the least favorable characteristics: the largest D_{max}, the lowest air voids content, and it is usually stiffer. The noise levels for RA and GGA are similar, however, the GGA provides slightly lower tyre/road noise levels.

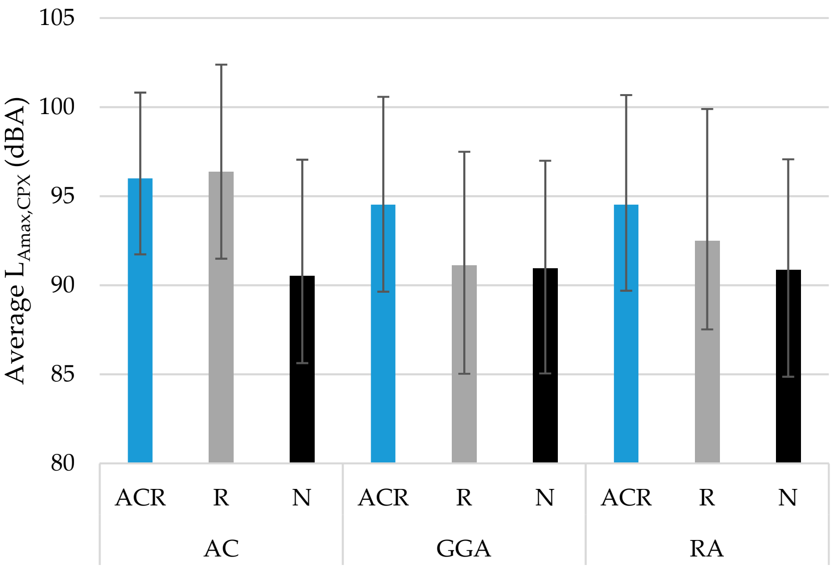

Figure 6. Average $L_{A\max,\mathrm{CPX}}$ for all speed levels for the pavement and distress type. The range is shown as an error bar.

3.2. Calculation of L_w and $L_{Aw'}$

The sound power level was calculated, as explained previously in Section 2.5.1., and is shown in Table 4. As expected, the increase of the vehicle speed results in an increase of noise levels, and this tendency is observed for all types of pavement and distress. The worst situation is observed for the passage of a vehicle at a speed of 65 km/h on an asphalt concrete pavement with raveling (57.1 dBA). The behavior of the RA and GGA types of pavement is comparable. The noise levels resulting from these two types of pavement, with and without distress and at the different measurement speeds, are very similar. Only the scenario for raveling at 50 km/h provides a difference larger than 0.3 dBA.

Table 4. Noise indicators for each speed and pavement type [dBA].

Speed [km/h]	Road Type	$L_{A\max,\mathrm{SPB}}$			L_w			E			$L_{AW}{}'$		
		N	**R**	**ACR**	**N**	**R**	**ACR**	**N**	**R**	**ACR**	**N**	**R**	**ACR**
30	RA	63.0	63.5	66.8	88.6	89.1	92.4	23.9	24.3	27.6	43.9	44.3	47.6
	AC	62.4	68.8	69.6	88.0	94.4	95.2	23.2	29.6	30.4	43.2	49.6	50.4
	GGA	63.3	63.2	66.9	88.9	88.7	92.5	24.1	24.0	27.7	44.1	44.0	47.7
50	RA	69.5	73.3	74.2	95.1	98.9	99.8	28.1	31.9	32.8	48.1	51.9	52.8
	AC	70.6	75.9	75.0	96.2	101.5	100.5	29.2	34.5	33.6	49.2	54.5	53.6
	GGA	69.5	69.8	74.1	95.1	95.4	99.7	28.1	28.4	32.7	48.1	48.4	52.7
65	RA	75.2	75.9	77.7	100.8	101.5	103.3	32.7	33.3	35.2	52.7	53.3	55.2
	AC	73.8	79.7	78.6	99.4	105.2	104.2	31.3	37.1	36.1	51.3	57.1	56.1
	GGA	75.2	75.6	77.8	100.8	101.2	103.4	32.7	33.1	35.3	52.7	53.1	55.3

In order to limit the number of possible scenarios for noise mapping, a selection was made based on these results. With respect to the type of pavement, the selection of AC and GGA will provide the biggest difference in overall noise results, as the noise results of the RA and GGA are similar, but the latter provides the lowest noise levels.

With respect to the distress type, as raveling provides intermediate noise levels, only the extreme values, without distress (N) and with alligator cracking (ACR), are used as the input for the noise maps. The development of distresses on the total area of the pavement occurs only in extreme situations of a lack of maintenance. Therefore, as mentioned before, two hypotheses were also considered for the distressed area of each pavement type, 50% and 100%.

3.3. Noise Mapping

In total, 18 different noise maps were calculated: two pavement types (AC and GGA) × three speeds (30, 50, 65 km/h) × three types of distress (N, 50% ACR and 100% ACR). For each noise map, a single pavement surface and the corresponding A-weighted sound power level per unit length (L_{AW}') were attributed to all the streets included in the noise map (approx. 9 km in total).

After generating these noise maps and calculating the noise levels at each control level point (receiver point), implemented as illustrated in Figure 7, two approaches were used during the analysis of the results. In order to make a comparative analysis of the noise maps, six receiver points were used. The location of each point met the following criteria:

- Spatial distribution;
- Proximity of roads with buildings on both sides;
- Proximity of roads with single-sided buildings;
- Open field.

Figure 7. Calculation area and the six selected receiver points.

The first approach consisted of evaluating the impact of the pavement and distress type by general comparison of all noise maps, representing each one of the 18 scenarios. In this article, the results are presented only for the most critical scenarios and respective reference at the three speed levels. Figure 8 includes the noise maps, showing the calculated L_{Aeq} at three different speeds for the AC pavement type without distress, as a reference, along with that which was 100% distressed with ACR, as the most critical scenario.

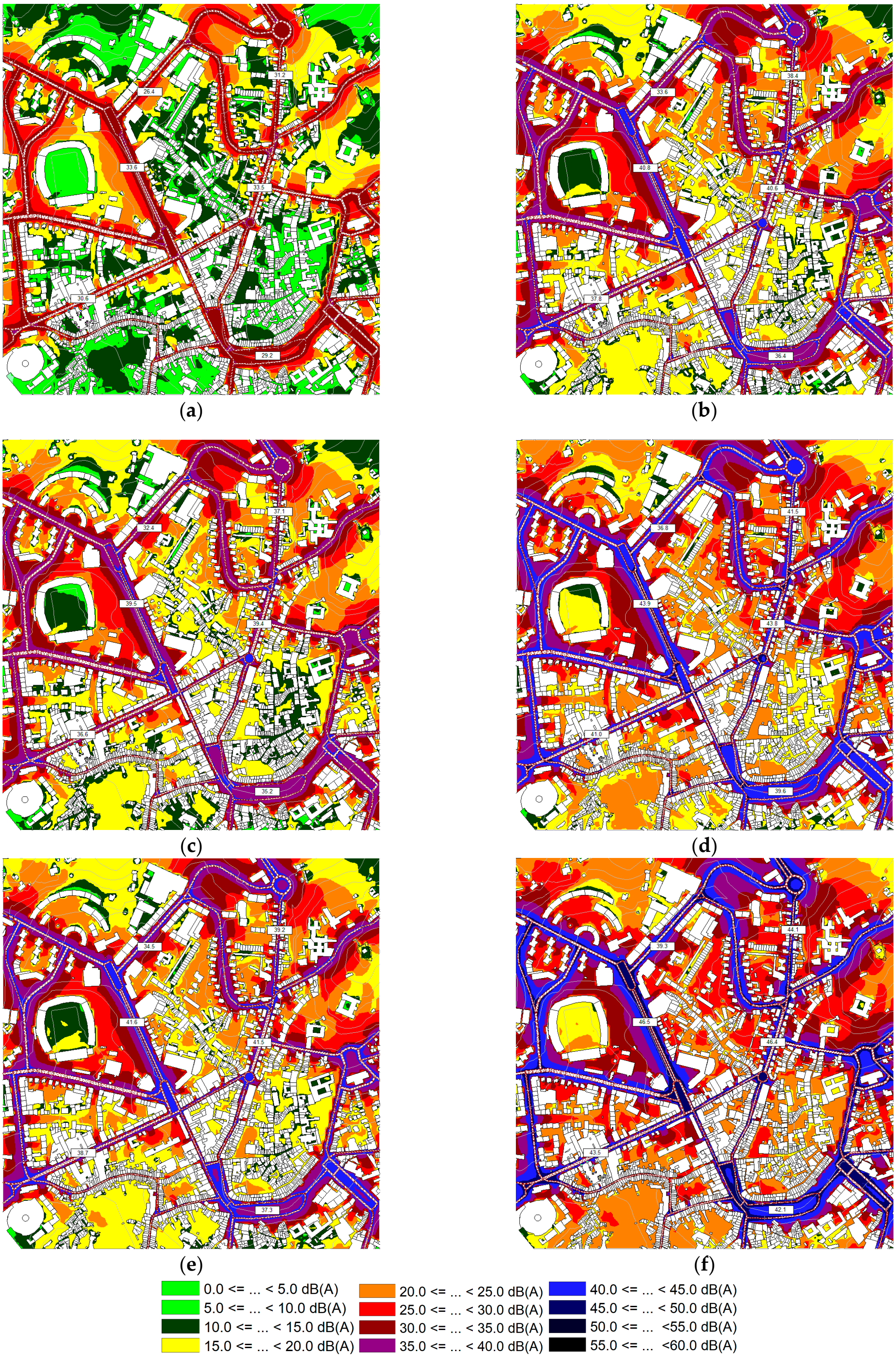

Figure 8. Noise maps for AC: (**a**) no distress, 30 km/h; (**b**) 100% ACR, 30 km/h; (**c**) no distress, 50 km/h; (**d**) 100% ACR, 50 km/h; (**e**) no distress, 65 km/h; (**f**) 100% ACR, 65 km/h.

From the visual analysis of the noise maps, illustrated in Figure 8, it is clear that the noise levels increase with the traffic speed. This happens in both scenarios, with and without distress. As expected, the best scenario is illustrated in Figure 8a and the worst in Figure 8f. Visually, the scenario with 100%

ACR at 30 km/h, shown in Figure 8b, is similar to the scenario without distress at 65 km/h, shown in Figure 8e. This means that the increase in noise levels due a pavement with 100% ACR at 30 km/h is equivalent to increasing the traffic speed from 30 to 65 km/h on an AC pavement without distress.

The second approach involved the evaluation of the impact using the control level points (see Figure 7). In Tables 5 and 6, the increase in the average noise levels (L_{Aeq}) is presented, calculated at the control level points for each selected scenario, and compared to the reference scenario (AC/N). For the studied scenarios, with distresses present, the average L_{Aeq} increased, ranging from 1.8 to 7.1 dBA. Furthermore, doubling the distressed area (from 50% to 100%) leads to an increase of between 0.8 and 1.6 dBA. When alligator cracking occurs, the noise levels clearly increase with the distress level. At 30 km/h and for AC, the ACR is responsible for a noise increase of 5.1 and 7.2 dBA, corresponding to 50% and 100% of the distressed area, respectively, which is double that of the GGA. At 50 km/h, the noise increase is similar for both types of pavement, at around 3.3 and 4.5 dBA. Again, at 65 km/h and for both distress levels, the AC is responsible for an increase in L_{Aeq}, which is double that of the increase for GGA.

Table 5. Noise levels [dBA] by speed and distress level for AC and GGA.

Speed	Distress Level	AC		GGA	
		AM *	SD **	AM *	SD **
30 km/h	N	29.9	2.0	30.8	2.0
	50% ACR	35.0	1.3	33.1	1.6
	100% ACR	37.1	2.0	34.4	2.0
50 km/h	N	35.9	2.0	34.8	2.0
	50% ACR	38.8	1.5	37.8	1.5
	100% ACR	40.3	2.0	39.4	2.0
65 km/h	N	38.0	2.0	39.4	2.0
	50% ACR	41.2	1.5	41.1	1.6
	100% ACR	42.8	2.0	42.0	2.0

* Arithmetic mean; ** Standard deviation.

Table 6. Increase of the average noise levels by distress percentage for AC and GGA [dBA].

Speed [km/h]	Distress	AC	GGA
30	50% ACR	+5.1	+2.3
	100% ACR	+7.2	+3.6
50	50% ACR	+2.9	+3.0
	100% ACR	+4.4	+4.6
65	50% ACR	+3.2	+1.7
	100% ACR	+4.8	+2.6

Speed control is one popular measure to reduce traffic noise. This kind of measure may be effective at low speeds to reduce environmental noise from pavement exhibiting distresses, such as alligator cracking or raveling. The presence of ACR on the pavement leads to noise increments of around 0.20 dB/(km/h) for the GGA and 0.17 dBA/(km/h) for the AC (Table 7). Regarding the reference scenarios, without distress, the highest changes occurred both at low and high speeds.

Table 7. Noise increments for AC and GGA by speed, in dBA/km/h.

Distress	Asphalt Concrete		Gap-Graded Asphalt	
	(30→50) km/h	(50→65) km/h	(30→50) km/h	(50→65) km/h
N	+0.30	+0.14	+0.20	+0.31
50% ACR	+0.19	+0.16	+0.25	+0.20
100% ACR	+0.16	+0.17	+0.25	+0.17

3.4. Population Exposure

Finally, the population exposed to specific L_{Aeq} levels is presented in Table 8 for the AC pavement and in Table 9 for the GGA pavement. This includes, in both cases, the scenarios without distress and those for 50% and 100% of ACR at 50 km/h. For this analysis, the maximum legal speed limit in urban areas was considered.

Table 8. Population exposed to noise, AC pavement—L_{Aeq} ranges.

Ranges of L_{Aeq} [dBA]	**No Distress**				**50 km/h, ACR Distress**			
	30 km/h		**50 km/h**		**50%**		**100%**	
	N	**%**	***n***	**%**	***n***	**%**	***n***	**%**
0–5	6	0.1	0	0.0	0	0.0	0	0.0
5–10	208	3.3	2	0.0	0	0.0	0	0.0
10–15	1108	17.4	125	2.0	16	0.3	5	0.1
15–20	1717	26.9	892	14.0	380	6.0	173	2.7
20–25	1108	17.4	1699	26.6	1276	20.0	1025	16.1
25–30	531	8.3	1289	20.2	1685	26.4	1721	27.0
30–35	570	8.9	576	9.0	919	14.4	1173	18.4
35–40	918	14.4	541	8.5	534	8.4	546	8.6
40–45	213	3.3	801	12.6	645	10.1	559	8.8
45–50	0	0.0	454	7.1	800	12.5	879	13.8
50–55	0	0.0	0	0.0	126	2.0	300	4.7
55–60	0	0.0	0	0.0	0	0.0	0	0.0

Table 9. Population exposed to noise, GGA pavement—L_{Aeq} ranges.

Ranges of L_{Aeq} [dBA]	**No Distress**				**50 km/h, ACR Distress**			
	30 km/h		**50 km/h**		**50%**		**100%**	
	N	**%**	***n***	**%**	***n***	**%**	***n***	**%**
0–5	2	0.0	0	0.0	0	0.0	0	0.0
5–10	128	2.0	7	0.1	0	0.0	0	0.0
10–15	902	14.1	221	3.5	31	0.5	10	0.2
15–20	1700	26.7	1131	17.7	533	8.4	274	4.3
20–25	1280	20.1	1717	26.9	1442	22.6	1204	18.9
25–30	574	9.0	1086	17.0	1602	25.1	1694	26.6
30–35	542	8.5	529	8.3	774	12.1	1025	16.1
35–40	806	12.6	574	9.0	534	8.4	523	8.2
40–45	444	7.0	925	14.5	711	11.1	586	9.2
45–50	0	0.0	190	3.0	701	11.0	941	14.8
50–55	0	0.0	0	0.0	52	0.8	122	1.9
55–60	0	0.0	0	0.0	0	0.0	0	0.0

According to [37], a maximum value of 53 dBA for road traffic noise is recommended for L_{den}, as above this level, adverse health effects can occur, and 45 dBA for night-time road traffic noise L_{nignt}, with higher values leading to possible adverse effects on sleep. For the present analysis, the night-time guideline value of 45 dBA (for a single car passing by) was used.

From the analysis of Table 8, it can be stated that 926 and 1179 people are exposed to levels above 45 dBA due to 50% and 100% ACR distress, respectively, for the AC pavement. However, according to Table 9, for the same conditions and GGA pavement, the number of exposed people is decreased by 20% and 10%, respectively (753 and 1063 exposed people).

It should be stated that the increase of the level of distress, depending on the pavement, can affect people in different ways, e.g., the population exposed to noise levels above 45 dBA increases by approximately 27% and 42%, when the level of distress increases from 50% to 100% on pavement types, AC and GGA, respectively. Finally, the noise produced by a single vehicle running at 50 km/h on a distressed pavement with alligator cracking in the city center of Guimarães exposes up to 18.5%

of the population to (night) noise levels above 45 dBA. On the other hand, in the case of non-distressed pavement at 50 km/h, such as the AC, 7.1% of the population is exposed, compared to a non-distressed low noise pavement, such as the GGA, where only 3% are exposed.

4. Conclusions

In this work, the evaluation of the impact of road pavement distresses on environmental noise and on population exposure was studied for the city of Guimarães, Portugal. The impact of the distresses is clear and stronger at low speeds and is dependent on the type of pavement.

To obtain the necessary results, a methodology was successfully applied to transform tyre/road noise, measured by the Close ProXimity method (CPX), into the required input for a traffic noise model (in CadnaA), which included a propagation filter as an improvement. The following conclusions may be extracted and generalized:

- Raveling and alligator cracking increase tyre/road noise levels and thus environmental noise;
- Noise levels are affected by the combination of pavement type and distress type. In this study, the worst condition was asphalt concrete with alligator cracking;
- For the studied conditions, the calculated average noise levels at the control points increased from 1.8 to 7.1 dBA due to the presence of distresses;
- Doubling the distressed area (from 50% to 100%) leads to an increase of the environmental noise of up to 1.6 dB;
- Alligator cracking leads to noise increments of around 0.20 dB/(km/h) for the gap-graded asphalt and 0.17 dB/(km/h) for the asphalt concrete;
- A single vehicle driving at 50 km/h (legal speed) in the city center of Guimarães on pavement with alligator cracking may increase the exposed population by more than 11%.

The increase of the number of people exposed to excessive (night) noise levels, above 45 dB, due to a single vehicle passing by is a good argument for better speed control, selection of pavement type, and most importantly, for a cost-effective maintenance policy. When noise maps are developed for a certain region/location, as part of or as a first step in a noise action plan, not only values for new roads should be included. An analysis should be conducted to determine how critical the acoustical quality of the pavement itself is. If the road traffic noise would increase by 3 or 6 dB, how would that affect the population exposure? How many people would be above a certain action value? If these maps and acoustical data are readily available, then the road administration can use them to determine when they need to take action, not solely because of the mechanical lifetime, but also because of the acoustical lifetime.

There are some limitations to this study that are of minor relevance for its aim, but which should be highlighted. The study was conducted for a single car with a specific tyre. While the tyre was selected among those representative of the current traffic, it is always a source of uncertainty that is very difficult to overcome. Differences can be expected when repeating these experiments with other tyres. Furthermore, the "filter" used to transform the noise from near field measurements (CPX) to the traffic noise input was adopted from the literature, and therefore the CPX measurement conditions could not be fully replicated.

In the future, the robustness of the results could be improved by increasing the database regarding the number of testing sites for each distress, type of distress and type of pavement. Additionally, increasing the amount of receiver points and replicating the scenarios in different cities, could provide some insight into the variation that might occur due to topography and geometrical effects. Moreover, to analyze the impact on population exposure of the degradation of high-speed roads inserted into the urban road network, this study should be repeated for higher operational speeds.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Asphalt concrete
ACR	Alligator cracking
CadnaA	Computer-aided noise abatement
CPX	Close-ProXimity method
CTAC	Centre for Territory, Environment and Construction (R&D unit of the School of Engineering of University of Minho)
DAT	Digital audio tape
EMIB	Energy and Materials in Infrastructure and Buildings (research group of UAntwerp)
GGA	Gap-graded asphalt
GIS	Geographical Information System
ISO	International Organization for Standardization
N	No/without distress
R	Raveling
RA	Rubber asphalt
SPB	Statistical Pass-By method
UAntwerp	University of Antwerp
UMinho	University of Minho
WHO	World Health Organization

Appendix A

Table A1. Roads included in the noise maps.

Street Name	Street Width [m]	Length [km]
ALAMEDA DE SAO DAMASO	7	0.82
ALAMEDA DA UNIVERSIDADE	8	0.13
ALAMEDA DR. ALFREDO PIMENTA	7	1.05
ALAMEDA MARIANO FELGUEIRAS	8	0.19
AV. ALBERTO SAMPAIO	8	0.29
AV. CONDE MARGARIDE	11	0.46
AV. CONEGO GASPAR ESTACO	8	0.08
AV. D. AFONSO HENRIQUES	8	0.03
AV. D. JOAO IV	8	0.12
AV. DE LONDRES	8	0.32
AV. DE S. GONCALO	10	0.55
AV. GENERAL HUMBERTO DELGADO	8	0.23
AV. NOSSA SR. DA CONCEICAO	10	0.33
AV. REPUBLICA DO BRASIL	9	0.35
LARGO CONDESSA MUMADONA	10	0.12
LARGO DO TOURAL	5.5	0.25

Table A1. *Cont.*

Street Name	Street Width [m]	Length [km]
LARGO MARTINS SARMENTO	10	0.07
LARGO NAVARROS DE ANDRADE	7	0.09
LARGO VALENTIM MOREIRA DE SE	8	0.06
PRACETA ROTARY CLUB DE GUIMARAES	10	0.17
RUA ALMIRANTE SOUSA VENTURA	10	0.12
RUA DR. JOSE PINTO RODRIGUES	10	0.24
RUA GIL VICENTE	5.5	0.22
RUA PROF. DR. ARNALDO SAMPAIO	7	0.46
RUA ANTONIO BARBOSA	10	0.06
RUA CAPITAO ALFREDO GUIMARAES	7	0.31
RUA CONEGO DR. MANUEL FARIA	9	0.33
RUA D. CONSTANCA DE NORONHA	8	0.08
RUA D. JOSE SAMPAIO	8	0.15
RUA D. TERESA	8	0.43
RUA DA LIBERDADE	6	0.11
RUA DE CAMOES	5,5	0.19
RUA DE S. GONCALO	8	0.55
RUA DE STO. ANTONIO	6,5	0.39
RUA DOM JOAO I	6	0.49
RUA DR. CARLOS MALHEIRO DIAS	7	0.06
RUA FERREIRA DE CASTRO	6	0.42
RUA PAIO GALVAO	6	0.36
RUA PICOTO	8	0.15
RUA SERPA PINTO	10	0.11
RUA TEIXEIRA DE PASCOAIS	9	0.29

Table A2. Roads where measurements were performed.

Pavement Type	Road	Distress Type		
		Alligator Cracking	Ravelling	Non-Distressed
Asphalt concrete	EN207-4	×		×
	EN105	×	×	×
	EN206 (1)		×	
	EN206 (2)	×		
Rubber asphalt	EN14 (1)			×
	EN14 (2)		×	
	EN103 (1)			×
	EN103 (2)	×	×	
Gap graded asphalt	EN310 (1)	×		
	EN310 (2)	×		
	EN310 (3)		×	×

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