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Review Article

“Noisy” issues in road acoustics: A white paper

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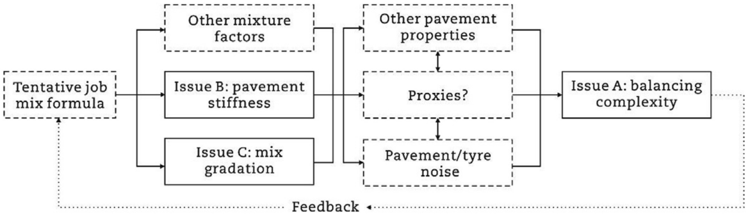
HIGHLIGHTS

- Optimal pavement design involves complex mix optimisation.
- High percentages of crumb rubber seem to optimise road acoustic response.
- Aggregate gradation is a reliable basis to predict surface texture and noise.

GRAPHICAL ABSTRACT



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ABSTRACT

Despite almost a century of studies dealing with traffic noise, researchers and practitioners still face old and new issues when designing a low-noise pavement. Given that, this manuscript aims at focusing on a number of unsolved questions, namely theoretical or technological. 1) Is it viable to balance diverse road-related needs (i.e., noise, expected life, texture levels, and friction)? 2) How much does the pavement material affect its acoustic performance (the remaining factors being constant)? 3) How much reliable is the relationship between road texture and mixture aggregate gradation? Based on the analysis of these issues, it emerges that: 1) optimal pavement design involves complex mix optimization and there are theoretical and practical bases to set up a balanced approach to address the complexity of pavement design; 2) high percentages of crumb rubber could optimise road acoustic response but this latter has a relationship with the tyre/road noise (expressed, for example, in terms of close proximity index) that calls for further investigation; 3) aggregate gradation appears to be a reliable basis to predict surface texture and therefore, under given boundary conditions, tyre/road noise; and 4) further studies and investigations are needed in terms of local calibration of deterioration curves and setting up of a sound method to assess the frequency response of asphalt concretes and to govern on-site noise indicators based on mixture properties.

1. Problem statement

This paper aims at providing insights and perspectives in the field of noise-related issues pertaining to tyre/road interaction and mainly builds on research work carried out by authors and their co-researchers (Praticò and Briante, 2020; Praticò et al., 2020a, 2021a, 2021b; Praticò and Fedele, 2021).

As is well-known, noise impacts human quality of life and health and this is well quantified in terms of disability-adjusted life-years (Fritschi et al., 2011).

How old are the studies about tyre/road noise? In 1969, Jonsson et al. (1969) focused on annoyance reactions to traffic noise in Italy and Sweden. In 1939, Kaye and Dadson (1939) focused on noise measurement and analysis in relation to motor vehicles and this paper is still mentioned in Sandberg and Ejsmont (2002) Tyre/road Noise Reference Book. Jones (1979) focused on noise in the human environment, mentioned in the study of Fwa (2005). Almost twenty years later, among more or less important changes, pavement role in mitigating traffic noise

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is unquestionable but how this impact should be considered as a part of a holistic vision is still to assess.

From a European perspective, traffic noise is a recurrent source of studies and projects as follows.

COMPETT. During the COMPETT project (2012–2015) (Iversen et al., 2013; Skov and Iversen, 2015), the following observations were made.

1) By comparing A-weighted frequency spectra of internal combustion engine vehicles (ICEVs) and electric vehicles (EVs), driven at 40 km/h (microphone at 7.5 m from the vehicles, placed 1.2 m far from the ground), absolute maxima for both ICEVs and EVs can be observed around 1 kHz, while only the ICE cars show supplementary peaks in the range 60–200 Hz. Note that the difference mentioned above is less relevant at 70 km/h. In both the cases (50 and 70 km/h), ICEVs are noisier (ΔSPL_{max} is about 27 dB) than EVs for the frequency range under consideration (20 Hz–6 kHz). It is important to underline that these differences in terms of frequency are clearly perceived by human ears.
2) By comparing the sound pressure level (SPL) of two electric "city cars" (Fiat 500 and Citroen C-zero), driven at 10 and 55 km/h (measured using the pass-by method and microphones 7.5 m far from the cars and 1.2 m above the ground), absolute maxima were observed at about 1 kHz at 55 km/h, while additional peaks at about 250 Hz were observed at 10 km/h.
3) By comparing the A-weighted 1/3 octave band spectra for noise levels measured at about 10 km/h and at about 60 km/h, light ICE- and EV-related spectra appear to have similar shapes but different amplitudes. Again, at 60 km/h, additional peaks can be seen in the range 30–60 Hz for ICE cars. These latter results are quite similar for decelerating cars, while during the acceleration (i.e., 0.7–4.8 m/s^2), ICEVs are noisier than EVs (65–75 dB(A) compared to 57–72 dB(A)) and the spectra show additional peaks for ICEVs in the range 50–150 Hz.

FOREVER. Pallas et al. (2015, 2016), within the project "FOREVER" (2013–2014), measured the noise produced by a small electric passenger car, a larger hybrid passenger car, and an electric truck. They found a difference of 4.5 dB(A) between the quietest and the noisiest vehicle at any speed in the range 20–50 km/h. In more detail, they measured the maximum sound pressure level (SPL_{max}; dB(A)) at 7.5 m from an EV (Citroen C-Zero) driven at constant speeds in the range 10–100 km/h. Furthermore, they found that the CNOSSOS-EU model (which is designed for the estimation of ICEVs noise emission in octave bands in the range 63 Hz–8 kHz (Kephalopoulos et al., 2012) overestimates the EVs noise (both propulsion noise component at speeds lower than 30 km/h and sometimes up to 50–60 km/h, and the rolling noise component) in most octave bands. Finally, they found that at low speeds (e.g., urban context, road sections with limited speed, traffic congestion on interurban or national networks) and for short source-receiver distances (i.e., at roadside), EVs allow reducing the traffic noise because of the fact that (unlike ICEVs) their engine noise is lower than rolling noise.

Additionally, they found that, for EVs, the SPL_{max} increases with the logarithm of the speed with a linear trend. A different trend was observed for low frequencies (63–250 Hz). They concluded that rolling noise and propulsion noise cannot be easily separated through the pass-by measurement approach and that some driving situations seem to reduce the acoustical benefit of EVs and hybrid electric vehicles (HEVs). Consequently, they found that strong accelerations significantly increase the global A-weighted SPL_{max} in the frequency bands over 500 Hz, while braking (probably because of the energy recovery system) increases the same parameter in all the frequency bands below 30–40 km/h.

SILVIA, SILENCE, PERSUADE, ROADTIRE, ROSANNE, E-VIA, SNEAK. A number of European research projects somewhat focused on and/or are going to refer to the impact of material-related properties on noise, such as SILVIA (sustainable road surfaces for traffic noise control, 2005), SILENCE (quieter surface transport in urban areas, 2008), PERSUADE (poroelastic road surface: an innovation to avoid damages to the environment, 2010), ROADTIRE (integration of end-of-life tires in the life cycle of road construction, 2010), ROSANNE (rolling resistance, skid resistance, and noise emission measurement standards for road surfaces, 2014), E-VIA (LIFE E-VIA: electric vehicle noise control by assessment and optimisation of tyre/road interaction, 2018), and SNEAK (optimized surfaces against noise and vibrations produced by tramway track and road traffic, 2020).

For example, PERSUADE aimed at developing a poroelastic road surface (PERS), mainly made of rubber granules from recycled car tyres, bound with a synthetic resin, such as polyurethane. PERS test tracks in Japan and Sweden were associated to extreme noise reductions (up to 12 dB(A)) in comparison to conventional dense asphalt concrete or SMA pavements. Despite the fact that their noise contribution is lower than the one of porous asphalts (from 1 to 7 dB(A)), PERS have a high risk of premature failure.

LIFE E-VIA. Tire-road noise for EVs is the main topic of the ongoing LIFE project "E-VIA" (2019–2023) (Fedele, 2021; Praticò et al., 2020a, b). In more detail, the E-VIA project aims at: 1) considering the contribution (i.e., both the noise and air pollution mitigation efficiency) of EVs and hybrid vehicles with respect to the current scenarios; 2) optimizing both road pavements and tires (durability and sustainability) for EVs (that in turn reduce the life cycle cost with respect to actual best practices); 3) contributing to the effective implementation of to EU legislation (directives 2002/49/EC and 2015/996/EC (The European Union, 2002, 2015)), and CNOSSOS-EU (Kephalopoulos et al., 2012); and 4) raising people's awareness of noise pollution and health effects.

E-MOPOLI. Another noteworthy example of EVs-related projects that aims at proposing strategies, guidelines and policy to accelerate EVs adoption is the Interreg Europe project "E-MOPOLI" (2018–2022, electro mobility as driver to support policy instruments for sustainable mobility (Kester et al., 2018; The European Union, 2018)).

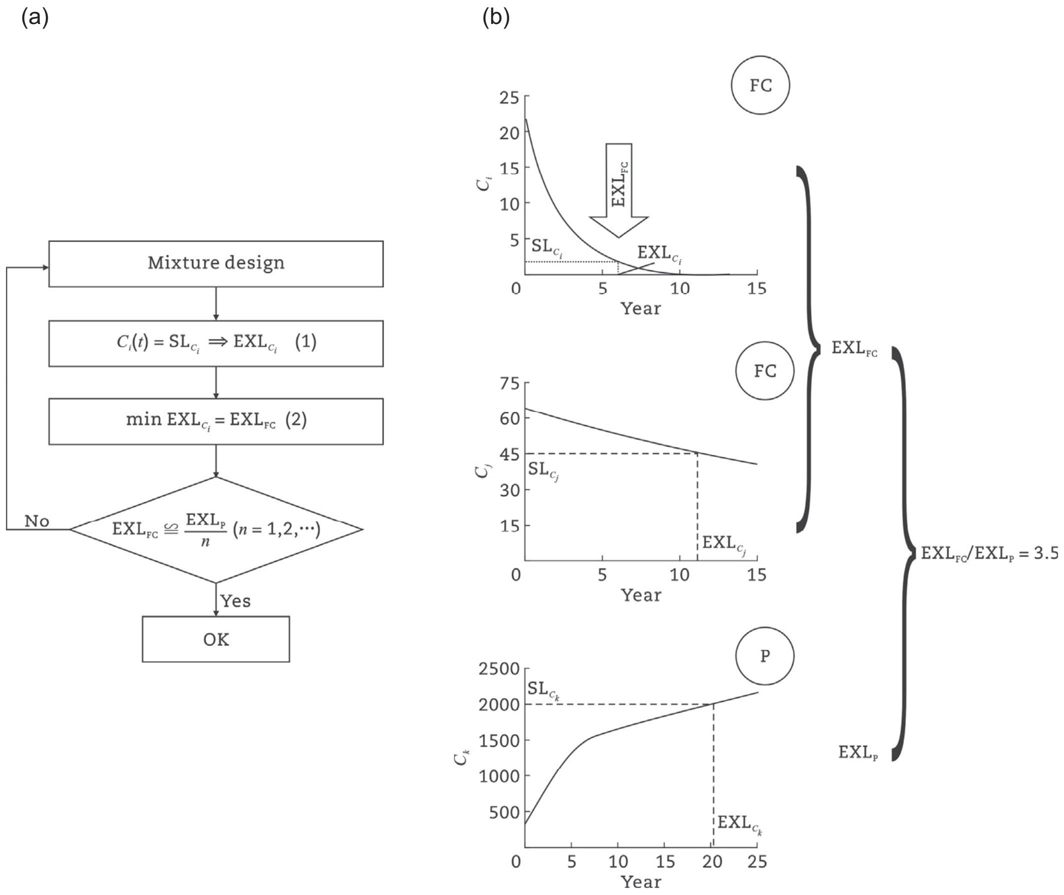
LIFE-SNEAK. SNEAK overall objective is the reduction of noise from roads inside densely populated urban areas, where tram and traffic noise and vibration superpose, by means of low-noise/vibration surfaces and retrofitting solutions having life cycle costs comparable to those of standard surfaces, while achieving a substantial noise reduction and global comfort. In more detail the main objects refer to the following.

1) Reducing the noise deriving from the superposition of air-borne noise and ground/structure-borne noise, where air-born noise derives from rail-wheel and pavement–tyre interaction, while ground-borne noise derives from the same interactions above with propagation through railway and road superstructure.
2) Reducing people annoyance due to noise and vibration generated by road and tram.
3) Contributing to the directive 996/2015/EC concerning the CNOSSOS noise assessment method.
4) Promoting the transferability/replicability of the implemented solutions against noise/vibrations.

2. Objectives

Although many studies and European Union (EU) projects were carried out, designing a quieter pavement is still a difficult task, far from having a set of physical-based equations. Different properties must be balanced and some of them are difficult to govern. For the reasons mentioned above, this manuscript aims at focusing on a number of unsolved questions in the domain of mixture design (Fig. 1), outlining their related research needs.

1) Issue A. Is it viable to balance diverse road-related needs (i.e., noise, expected life, and friction)?
2) Issue B. How much does a pavement material affect its acoustic performance (the remaining factors being constant)?



Note: $C_i(t)$ is the decay curve of the i-th property over time; SL_C is the specification limit of C; t is the time; EXL_{C_i} is the expected life of C_i; $\mathrm{EXL}_{\mathrm{FC}}$ is the expected life of the friction course (FC); $\mathrm{EXL}_{\mathrm{P}}$ is the expected life of the entire pavement; examples of $C_i(t)$, DR(t), drainability; $a_0(t)$, acoustic absorption coefficient; MTD(t), mean texture depth; PTV(t), pendulum test value; typical values for n, 2 or 3.

Fig. 1. Simplified schematic of method (Praticò et al., 2021a). (a) Design process. (b) Accessing the expected life.

3) Issue C. How much reliable is the relationship between road texture and mixture aggregate gradation? Can we really use it when designing a low-noise surface?

3. Issue A: framework and balance

Is there the possibility to set up and apply a method to design premium surfaces (e.g., porous asphalts) from a more comprehensive perspective, that is to say, considering traditional (e.g., crack percentage) and premium (e.g., acoustic absorption) properties?

As is well known, currently, the design of a bituminous mixture (as one of the layers of a pavement) aims at determining the quantities and quality of the components of the mix. It mainly builds on fulfilling workability, volumetric, mechanistic, and resistance-related properties over the expected life, based on plastic deformations, thermal cracking, and fatigue cracking.

In turn, the mechanistic properties depend on the quantities and quality of the components (Figs. 1 and 2). Finally, the design of the multilayered system is even more complex and ends up with an array of expected lives (one per layer), whose minimum is the expected life of the pavement ($\mathrm{EXP}_{\mathrm{P}}$).

Šernas et al. (2021) focused on maximising both acoustic absorption and resistance to traffic and climate conditions. In this case, the authors selected the most promising asphalt mixture through a developed analytic hierarchy process (AHP).

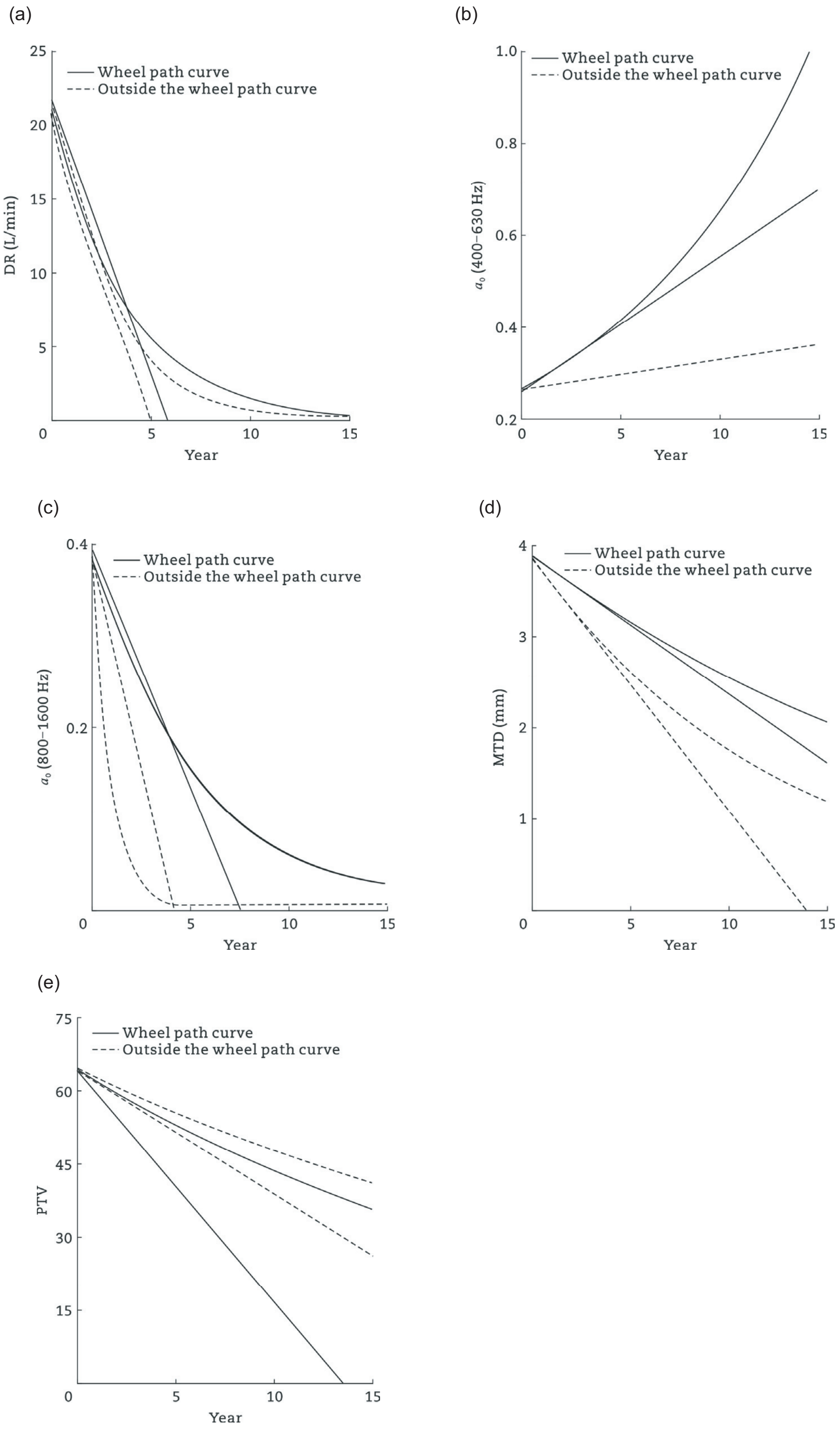
Cao et al. (2020) used a multi-objective optimization (MOO) decision-support system to take into consideration the following main objectives.

Low noise (maximizing the average close proximity (CPX) level reduction).

Low maintenance costs (minimizing the maintenance costs).

Low environmental impacts (minimizing the greenhouse gas emissions generated from the maintenance). They used the non-dominated sorting genetic algorithm II (NSGA-II) to search for the optimal intervention strategies.

The method proposed by Praticò et al. (2021a) aims at rationalizing the design of a pavement in terms of expected life and is based on the need of “intersecting” different classes of requirements. Indeed, for friction courses, surface properties (e.g., friction, surface texture, acoustic absorption, drainability) need for a concurrent design. As a result, each property (e.g., drainability) has an expected life ($\mathrm{EXP}_{\mathrm{D}}$) and the optimal solution is to have: 1) similar expected lives (in order to minimise economic losses); 2) expected lives that are not higher than the expected life of the remaining layers (same reason); and 3) expected lives that are possibly a natural sub multiple of the pavement expected life ($\mathrm{EXP}_{\mathrm{P}}$). This allows having a rehabilitation that coincides with the resurfacing. Based



Note: non-linear, $y = a\exp(bT) + c$ (T is the time in years; a, b, and c are coefficients to calibrate); linear,

$y = mT + q$ (m is the coefficient of variation; q is the intercept).

Fig. 2. Linear and nonlinear curves for the selected characteristics (Praticò et al., 2021a). (a) Drainability. (b) Acoustic absorption in 400–630 Hz. (c) Acoustic absorption in 800–1600 Hz. (d) Mean texture depth. (e) Pendulum text value.

on the above, the given equation to comply with is the Eq. (1) in Fig. 1(a), where $C_i(t)$ is the curve of the characteristic C_i as a function of time (t), SL_{C_i} is the concerned upper or lower specification limit, and EXL_{C_i} is the corresponding abscissa of $C_i(t)$ for $C_i(t) = \mathrm{SL}_{C_i}$, i.e., the expected life for the characteristic C_i. Note that while Fig. 1(a) illustrates the entire process, Fig. 1(b) focuses on the derivation of the expected life corresponding to different characteristics.

Furthermore, given the dependency of several surface properties on air voids content, AV, a supplementary condition could be considered for these properties, in order to have thresholds (SL_{C_i}) corresponding to a common value of air voids content (AV*), where SL_{C_i} is the specification value of the i-th characteristic and $C_i(\mathrm{AV}^*)$ is the value of C_i when the air void content approaches a common threshold of AV. This equation aims at having a consistent threshold system for the characteristics of the premium surface that have a sound dependency on AV, i.e., drainability, texture (outside the wheel path), and absorption coefficient. Indeed, this implies an economic advantage in terms of similar expected life.

The method applies as follows. 1) Based on the mix design of the friction course, the curves $C_i(t)$ (e.g., $C_i = \mathrm{DR}(t)$, drainability of FC; $C_j = \mathrm{PTV}(t)$, friction of FC; $C_k = \mathrm{CR}(t)$, longitudinal cracking of the entire pavement) are derived. 2) The intersection between each curve (e.g., $C_i(t)$) and the concerned specification limit (e.g., SL_{C_i}) is derived (expected life, EXL_{C_i}). 3) The minimum expected of FC life is derived ($\mathrm{EXL}_{\mathrm{FC}}$). 4) This value, $\mathrm{EXL}_{\mathrm{FC}}$, is compared to the expected life of the pavement, $\mathrm{EXL}_{\mathrm{P}}$. 5) If $\mathrm{EXL}_{\mathrm{FC}}$ approximates a natural submultiple (e.g., $n = 2$) of $\mathrm{EXL}_{\mathrm{P}}$ the process ends. If this does not happen (e.g., the ratio is about 3.5), a new mix design is required. The need for having n natural builds on the minimisation of agency and user costs, i.e., from having the rehabilitation of pavement (P) when not only the deeper layers but also the friction course (FC) are close to the end of their respective expected life.

In Fig. 2, where linear and exponential curves are included, for DR, the equation refers to areas outside the wheel paths and it is $\mathrm{EXL}_{\mathrm{DR}} \cong 7$ outside the wheel paths (OWP) and 10 in the wheel paths (WP) years. For a_0 in 800–1600 Hz, it results $\mathrm{EXL}_{a_0} \cong 5$ (WP) and 1 (OWP) year(s). Note that due the shift of absorption spectra towards low frequencies, for a_0 in 400–630 Hz, the expected life is theoretically infinite. For macrotexture, the expected life is $\mathrm{EXL}_{\mathrm{MTD}} \cong 43$ (WP) and 22 (OWP) years. For friction, it is $\mathrm{EXL}_{\mathrm{PTV}} \cong 4$ (WP) and 8 (OWP) years. The specification limits are 1.6 L/min (DR), 0.10–0.14 (a_0), 1.9 mm (MTD), and 45 (PTV, friction), respectively.

Finally, Fig. 3 offers a summary of the application of the method, where several characteristics (e.g., MTD) appear to overcome the optimal expected life, while some others appear unsatisfactory and quite far from the optimal range.

There remain some unsolved questions.

In summarising, achieving a balance among the different properties of a friction course is a quite obvious goal but studies demonstrate that there are uncertainties related to the algorithms to use and to the prediction of the decay over time of the main factors. Indeed, importantly, this depends also on a number of local and geographical variables (such as microtexture and macrotexture decay that depend on the particular type and mineralogy of aggregate). In order to improve the reliability and practical applicability of a synergistic design, an effort is requested to better study and characterise how the mixtures (using local materials) perform over time. This effort could be seen as a sort of local (regional) calibration of general purpose algorithms.

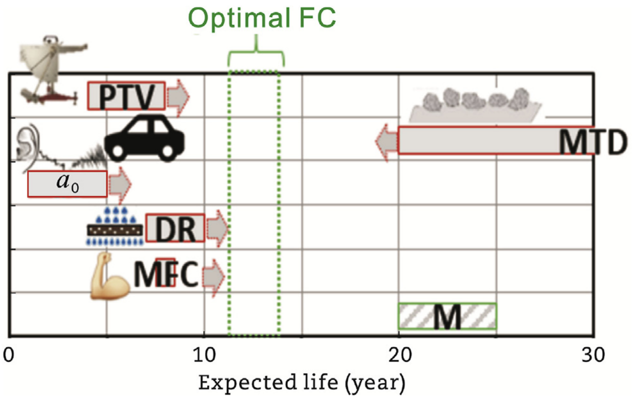


Fig. 3. Balancing different properties (Praticò et al., 2021a).

4. Issue B: materials and noise

The book “Harmonie Universelle Contenant la Théorie et la Pratique de la Musique” was published in Paris in 1636 (authored by Marin Mersenne). In this book, the author stated that the mass (per unit length) and the impact (stretching) force of a stretched string affect the corresponding frequency, being the force proportional and the mass inversely proportional to it. In 2004, Hamet and Kleine concluded that the reduction of pavement stiffness could reduce substantially the rolling noise. Overall, the theoretical and practical problem behind the demonstration of stiffness or/and density influence on noise is to isolate this factor from the remaining factors (e.g., surface texture, porosity, resistivity, tortuosity, and thickness).

Cesbron et al. (2009) studied the tire/pavement interface forces as a strategic factor in terms of noise assessment.

Vázquez and Paje (2016) focused on texture and dynamic stiffness impact on noise. The surface properties that could be the most important in controlling the acoustic performance (texture, acoustic absorption and dynamic stiffness or mechanical impedance) were measured for the characterization of a test track constructed with and without crumb tire rubber. Authors found that the parameters of roughness and texture could have a relevant role in the global tire/pavement sound emission, whereas dynamic stiffness influence could be relatively minor.

Chen et al. (2021) focused on the potential causal relationships between predictor variables and the CPX level. They included also the stiffness of the pavement. For stiffness, they observed that even if a stiffer surface is prone to cause more vibration and thus lead to more noise, due to the stronger impacts of tire types, road surface MTD, and porosity, the impact of stiffness is not clearly identifiable.

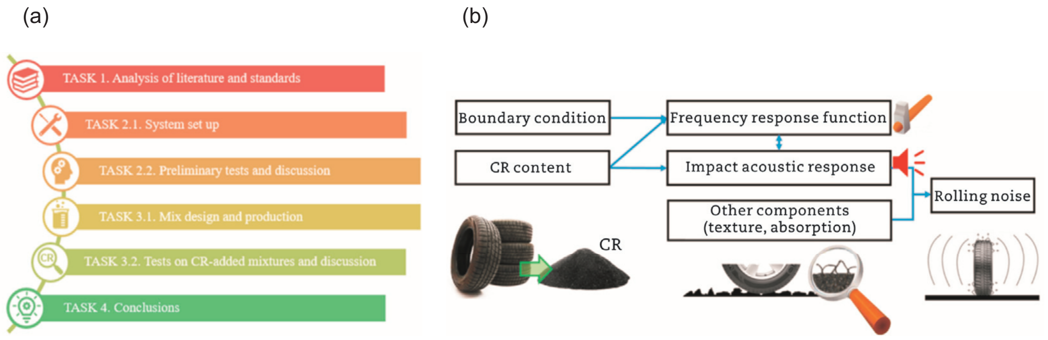
Praticò et al. (2021b) carried out experiments aiming at validating this assumption in the laboratory (Figs. 4 and 5). In this study, authors focused the attention on the relationships between road acoustic response (RAR or AR) and frequency response functions (FRFs) in the case of bituminous mixtures with the addiction of crumb rubber (CR).

Transfer functions (FRFs) can be defined as “the frequency domain relationship between an input (X) and output (Y) of a linear, time-invariant system” (SIEMENS, 2019). Examples of FRFs are the mechanical impedance (MI, i.e., the ratio between the force applied on a body, X, and the velocity of the body excited by the force, Y), and the dynamic stiffness (K, i.e., the ratio between the force applied on a body, X, and the displacement of the body excited by the force, Y).

It seems relevant to highlight that the hardness of the road surface (and its FRFs) could affect: 1) tyre vibration and consequent noise (structure-borne sound in the tyre (Vaitkus et al., 2016)); 2) the transmission of power from the tyre to the pavement and consequently the possible sound radiation from the road; and 3) the dependency of such phenomena on the natural frequency of the road (especially for bridge decks).

Based on results and data interpretation, the following conclusions were drawn in the study mentioned above.

1) Many parameters affect the FRF estimates (e.g., sample geometry, air voids, and under-layer materials).
2) In the literature, different standards are reported in order to obtain FRFs (e.g., dynamic stiffness, K, and mechanical impedance, MI). Nevertheless, there are no standards that refer to the tests on asphalt concrete cylindrical samples/specimens and this is a weak point.



Note: no acoustical measurements of “rolling noise” were carried out.

Fig. 4. Tasks performed and rationale behind (Praticò et al., 2021b). (a) Task. (b) Rationale.

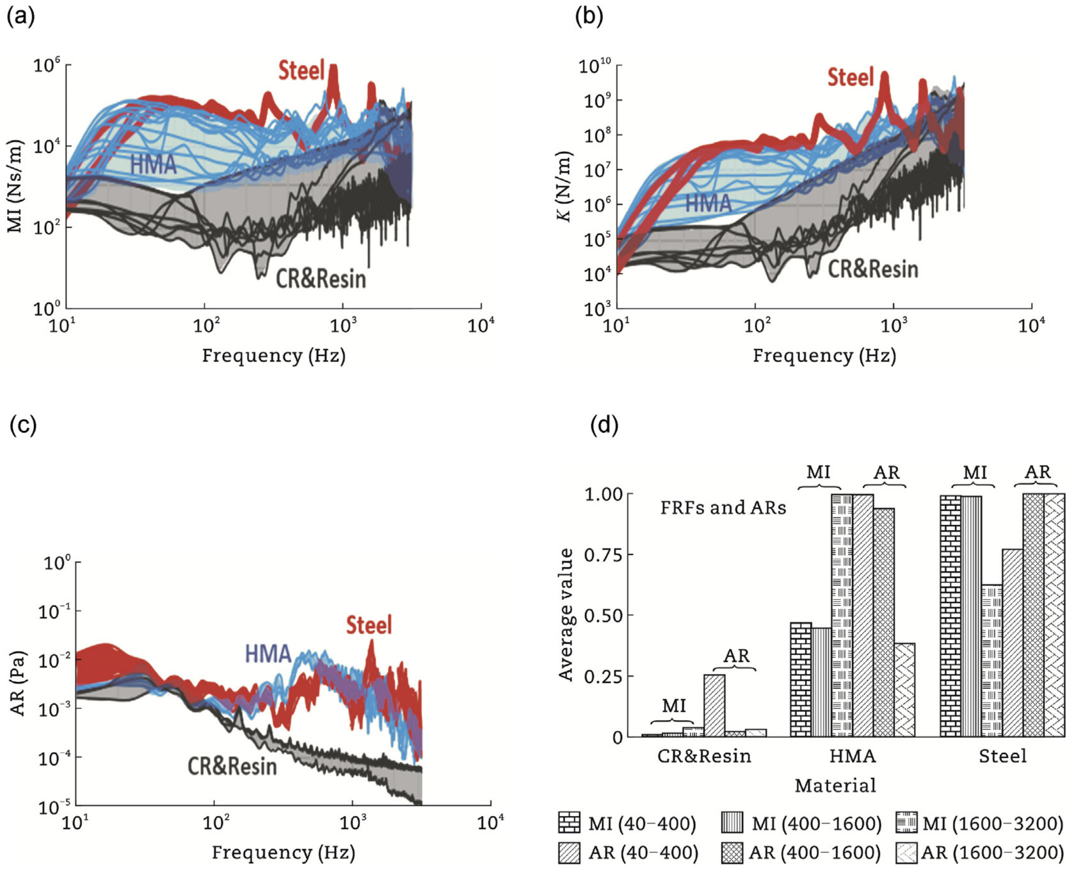


Fig. 5. Mechanical impedance (MI), stiffness (*K*), and acoustic response (AR) (Praticò et al., 2021b). (a) MI. (b) *K*. (c) AR spectra. (d) Average values for different materials.

3) The EN 29052-1 (acoustics, determination of dynamic stiffness, materials used under floating floors in dwellings) seems to provide quite sound estimates of resonant frequencies for cylindrical samples, especially in case of crumb rubber-added mixtures, where their weakest mechanistic properties positively impact estimates. Multiple degrees of freedom (MDoF) systems are useful to control experimental results.
4) For the mixes investigated and for the highest impact energy under investigation, an increase of crumb rubber (CR) percentage and the corresponding variations in terms of air voids imply the decrease of MI, of stiffness, and of max RAR.
5) In more detail, the synergistic influence of the hammer drop height (Hh) and the corresponding equations (RAR as a function of %CR and Hh) have been studied. Other experiments are needed to support these results.
6) Based on measurements, MI and *K* appear to be sound indicators to evaluate the RAR for frequencies in the range 400–3200 Hz. It should be underlined that the RAR could be influenced by the air void content of the samples.
7) The CR-related “mechanistic” contribution to low RARs appears to be scientifically supported. For low percentages of CR, the assessment of CR actual impact on RAR calls for further research.
8) Based on results, the mixtures with high percentages of CR outrank the remaining ones in terms of minimisation of the RAR. It is noted that many issues still call for further investigation, such as CR gradation, optimal binder percentage and type, technology

used, and environmental balance. These factors, together with the increase of cost with quite high CR percentages, add complexity to the selection of the best solution.

9) By referring to RAR-based versus CPX-based inferences and analogies, the relationship between the RAR, herein defined and measured, and the on-site CPX emerges as mainly unknown and probably quite complex. Nevertheless, other research reported in the literature has indicated that pavement stiffness has a substantial influence also on CPX noise levels, provided that CR percentages are quite high. Importantly, at least for small or moderate impact energies, the actual effect of low percentages of CR on common asphalt rubber pavements when impacted by tyre treads calls for further research and investigation.
10) Further investigations are required to have a higher accuracy of the results and to better understand CR actual impact on tyre/road noise and remaining properties. The RAR studied here could have an effect on tire/road emissions from vehicles or test tires, but, unfortunately, this effect cannot be fully determined from the results presented in this study. Thence, either a further theoretical model or a complex set of experiments are required for having a single-factor approach and controlling different known or suspected sources of variation (including texture and air voids).

Unsolved questions still remain.

The idea of a theoretical relationship between material properties and how they impact noise pollution is suggestive but still quite far from becoming an engineering tool. Too many conundrums hinder the transition from the studies and investigations to a tool for better designing, namely the following.

- The choice of the right characteristics to consider as the most representative ones (e.g., stiffness or mechanical impedance).
- The choice of the best material and strategy to decrease noise pollution.
- The uncertainties in the best method to assess the selected FRFs.
- The complexity of the experimental set up and the difficulty of proving the relationship noise-material, due to a number of boundary factors to control. Furthermore, this issue is even more complex to solve because noise indicators are usually referred to on-site tests and not to in-lab tests.

Based on the above, future studies are needed into the main weaknesses above, i.e., best characteristic, best material, best method, best experimental set up, and strategy to consider a widespread noise indicator, such as, for example, the close proximity index.

5. Issue C: practical solution?

When Sir Francis Bacon published in his work, the saying: “knowledge itself is power”, probably he wanted to transmit the idea that having and sharing knowledge is the cornerstone of reputation and influence, and therefore power. By referring to the need for setting up practical solutions for quiet pavement technologies, many studies were carried out (Cafiso and Taormina, 2007; Chen et al., 2017; Gunay and Woodward, 2007; Masad et al., 2007; Miljkovic et al., 2014; Noyce et al., 2005; Praticò and Vaiana, 2015; Praticò et al., 2010; Sollazzo et al., 2016).

Licitra et al. (2019) focused on acoustic aging and they considered also pavement type with its properties.

Chen et al. (2018) set up a a prediction model correlating the tire-pavement noise level with macrotexture and short wavelength of mega-texture of pavement, using a multivariate non-linear regression analysis.

Losa et al. (2010) defined a rolling noise prediction model for a reference tyre, as a function of speed, on dense asphalt surfaces with medium-low macrotexture levels. They used texture levels of pavement profiles and rolling noise levels recorded at different speeds.

Praticò and Briante (2020) focused on the prediction of surface texture starting from mixture composition and namely from aggregate gradation (Figs. 6 and 7).

In the pursuit of assessing how composition affects surface texture for the sake of designing surface properties, analyses were carried out and models were set up.

Based on the results obtained the following conclusions were drawn.

- Nominal maximum aggregate size (NMAS) concept confirms to be very important, even if minor adjustments may be needed to enhance its ability to predict texture levels and noise impact. Further research is here needed because of the need for exploring new composition-based ideas to model sphere packing.
- ISO gradation (ISO 10844) confirms to constitute a benchmark when predicting texture levels and ISO-like surfaces have low NMAS and low texture levels. Related information on this type of surface can be found in ISO 10844 (2014): acoustics-specification of test tracks for measuring noise emitted by road vehicles and their tyres. Geneva, Switzerland: international organization for standardization and in project: strengthening the effect of quieter tyres on European roads (STEER).
- The one-peak model set up by Praticò and Briante (2020) yields *R*-square values close to 0.8. It builds on having a maximum for (λ^*, L_{tmax}), where L_{tmax} is the maximum L_{tx}, and a quite constant slope in a semi-log plot. Its strength is due to the outstanding relevance of the maximum over the remaining parts of the spectrum. This notwithstanding, from a practical standpoint further studies are needed to enhance the potential of this model and to apply to a wider set of mixtures for friction courses.
- For the packing-based model presented by the same authors above, note that the choice of NMAS70 (i.e., a different NMAS concept where instead of 90%, 70% is considered) enhances its potential even if the overall performance is worse than the one of the one-peak model.
- For the model broken up (other model considered), it performs the best. It is quite easy to apply and builds on having a matrix that summarises the relationship between each wavelength-level with each sieve percentage.
- Although the model broken up with constant (other model considered) exhibits the best results in terms of explained variance, the potential of the peak models appears remarkable because they build on the concept of sphere packing and because a better estimate of the maximum could enhance the percentage of variance explained to more than 90%.

  Some unsolved questions are as follows.

  The logical flow from health (noise pollution) to road design may include many steps, namely the following.
- The choice of the best health-related noise indicator.
- The choice of the best indicator to consider for pavement texture.
- The study of the best balance between generation factors (i.e., texture) and absorption factors (e.g., air void content).
- The selection of the most powerful mixture-related predictors (e.g., NMAS).

To this end, the following unsolved questions arise.

- What is the best choice for the indicators and predictors above?
- Apart from NMAS, what are the remaining secrets behind the job mix formula that can make the difference?

6. Conclusions

Different and concurrent requirements are essential for friction courses and particularly for premium ones. This poses theoretical and practical problems that merge with more specific issues in the field of low-noise properties design. Here different skills and competences are needed that span from the design of aggregate gradation to the image-

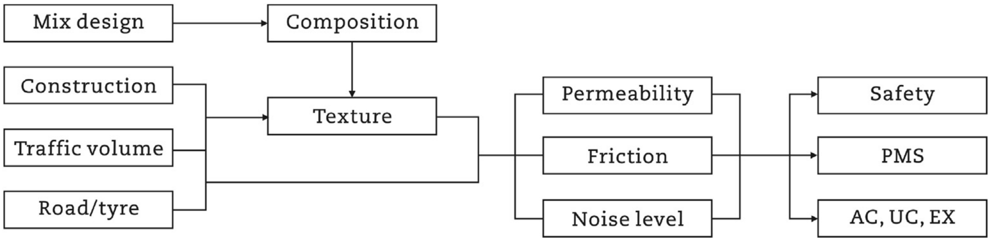
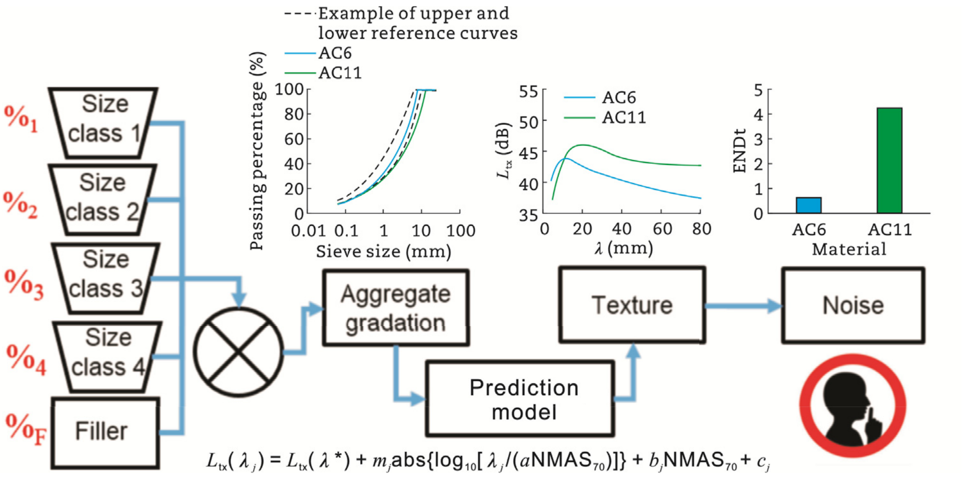


Fig. 6. From mix design to transportation instances (Praticò and Briante, 2020).



Note: L_{tx} means texture level (dB); λ means wavelength (mm); ENDt means expected pass-by noise level difference (dB) from texture level variation of road surface (ISO 10844).

Fig. 7. Simplified procedure for the selection of the aggregate gradation (Praticò and Briante, 2020).

source model. These aspects make having a holistic model quite difficult.

Based on the analysis of the issues above, it emerges that: 1) optimal pavement design involves complex mix optimization and there are theoretical and practical based to set up a balanced approach to address the complexity of pavement design; 2) high percentages of crumb rubber could optimise road acoustic response but this latter has a relationship with the tyre/road noise (expressed, for example, in terms of close proximity index) that calls for further investigation; and 3) aggregate gradation appears to be a reliable basis to predict surface texture and therefore, under given boundary conditions, tyre/road noise.

From the studies carried out, it emerges that further studies and investigations are needed as follows.

1) Local calibration of deterioration curves: this is crucial to allow a robust design, balancing the required properties.
2) Setting up of a sound method to assess the frequency response of asphalt concretes and of a suitable strategy to lower rolling noise.
3) Setting up of a reliable method to derive and govern on-site noise indicators based on mixture properties. Studies above can benefit researchers and practitioners involved in different research fields such as pavement surface design and psychoacoustics.

Declaration of competing interest

The authors do not have any conflict of interest with other entities or researchers.

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