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The future of urban sound environments: Impacting mobility trends and insights for noise assessment and mitigation

1 **Abstract**

2 The degradation of the sound environment contributes significantly to the external costs of mobility
3 and is an obstacle to the development of cities. Action plans aiming at fighting traffic noise often take
4 a long time to reach mature implementation. Therefore, it is advantageous to envisage how societal
5 and urban changes and associated changes in mobility practices will modify the urban sound
6 environment of tomorrow. In this article, an interdisciplinary team of seven researchers, whose work
7 focuses on different fields of acoustics and mobility, reviews the potential impact of ongoing mobility
8 and society changes on sound environments. First, the team identified the trends dealing with urban
9 renewal, societal changes and new mobility drivers that have the greatest influence on sound
10 environments, and analyzed in detail. From this analysis, insights emerged for urban noise impact and
11 innovative noise mitigation solutions in the light of improved assessment of the links between mobility
12 and urban sound environments.

13 **1. Introduction**

14 Awareness of the health effects of noise progressively increased in the second half of the 20th century
15 (Rueb, 2013). Noise refers to any acoustic phenomenon producing a generally unpleasant or disturbing
16 sensation (ISO, 1996). The high noise levels, combined with the growing aspiration of city dwellers for
17 a pleasant and environmentally friendly city, have quickly made noise a first-rate nuisance, to
18 characterize and mitigate (WHO, 2011). Metropolitan urban areas, since they are both the place with
19 highest noise levels and the highest population densities, concentrate the highest exposures and
20 therefore most of the current efforts to contain noise.

21 City dwellers aspire for both calm sound environments and lively neighborhoods. These aspirations are
22 in contrast with the increasing urbanization observed, which is inseparable from movement and
23 therefore sound environments dominated by road traffic noise. The concentrated demand for mobility
24 inherent in the development of cities is a potential vector for the degradation of sound environments.
25 In practice, the urban planning decisions – including *laissez-faire* policies – of the second half of the
26 20th century left a significant place for the automobile in the city (Buchanan, 1963; Mumford, 1968;
27 Kenworthy and Laube, 1999), and road traffic is as a result now regularly cited as the most annoying
28 source of noise (Science for Environment Policy, 2017).

29 The urban and societal changes observed can also have a significant impact on sound environments.
30 The fluidification of living rhythms (Bauman, 2000), the urban development, sprawl and intensification,
31 or the changes in individual mobility practices modify the intensity and temporality of sound sources,

32 and thus shape sound environments. Studying the impact on the sound environments of these urban
33 and societal changes is crucial because they will make the urban sound environments of tomorrow.
34 Anticipating and adapting noise mitigation methods and modeling approaches to this evolution is also
35 essential.

36 This article intends to highlight the key factors in the on-going changes in mobility practices that will
37 shape the urban sound environments of tomorrow. More specifically, a prospective analysis aims to
38 target factors that are a threat to urban sound environments, and to deduce from it the likely evolution
39 of urban sound environments. Insights are then provided for the mitigation of noise environments in
40 terms of actions to be taken, models to develop, and modes of governance to encourage. The article
41 is based on an interdisciplinary discussion, at the interface between several disciplinary fields dealing
42 with mobility and acoustics, and a review of the emerging noise abatement solutions. The discussion
43 aims to stress the levers for improved future sound environments. The paper is intended for
44 researchers in both disciplinary fields, and recalls some basic knowledge to promote their
45 rapprochement.

46 Section 2 describes the followed methodology and the framework of this work. Section 3 reviews
47 several on-going mobility and society changes and highlights their potential impact on sound
48 environments. Section 4 underlines the methodological shortcomings in current methodologies for
49 assessing the impacts of mobility on sound environments, and points out new insights for noise
50 assessment and mitigation. Section 5 concludes on the findings from this discussion, and identifies the
51 most promising current avenues of research for improving future sound environments.

52 **2. Methods and materials**

53 **2.1. Methods**

54 The prospective exercise on urban sound environments presented here required an interdisciplinary
55 discussion at the interface of the fields of mobility and acoustics. The diversity of the experts'
56 disciplinary fields of research, whose works focus on physical acoustics, soundscapes, noise and health,
57 mobility, air pollution, indicators and urban planning, allowed a perspective to approach this question
58 from various angles. The study partners met physically on 27/02/2019 for a discussion on the impact
59 of changes in mobility practice on noise environments. The methodology was as follows:

- 60 • Two weeks prior to the meeting each expert received a short description of the scope of this
61 prospective study and was asked to prepare a 10 minute presentation on their view on
62 emerging trends and methodologies;

- 63 • During the meeting, each participant highlighted his or her viewpoint followed by a generative
64 discussion that resulted in an accumulation of ideas;
- 65 • At the end of the meeting a discussion was started that aimed at reaching consensus between
66 the experts;
- 67 • After the meeting, a first draft of the consensus document circulated. This document was
68 further amended and discussed over several months.

69 The selection of trends in societal change and mobility practices was based on literature, notably on
70 the deliverable D2.1 of the MOBILITY4EU project (L'Hostis et al., 2016). The selection of innovative
71 noise mitigation solutions resulted both from literature and the expertise of the participants. The
72 confrontation of sound and mobility knowledge highlighted the most impactful trends, which are those
73 presented here. In section 3, the impacting trends are analyzed in the light of current knowledge in
74 acoustics, in order to deduce the likely changes in urban noise environments in the coming years. These
75 trends point to insights in terms of modelling and noise mitigation policies, which are discussed in
76 section 4.

77 The empirical part is largely drawn from European countries, thus it directly applies to cities whose
78 mobility trends are part of this context. However, the disparities between cities are such that applying
79 the results of the general analysis proposed here for a given city requires that local specificities be
80 taken into account, as each city's needs, context and aspirations are different (Anderton et al., 2015).

81 **2.2. Material: foreground on urban sound environments**

82 This section provides some background knowledge on urban acoustics and traffic noise, which is
83 necessary for assessing in a prospective angle the links between mobility and urban sound
84 environments. Most of the examples will be drawn from road traffic noise, which is generally declared
85 as the most annoying source of noise in urban areas (Science for Environment Policy, 2017).

86 The noise impact of changes in mobility can be approximated on a macroscopic scale on the simple
87 basis of the estimated increase or decrease in the number of vehicles (cars, airplanes, etc.) on a
88 territory. Due to the decibel scale used in acoustics, emissions related to a traffic flow are proportional
89 to the logarithm of the vehicle flow. It is for instance common to state that doubling the vehicle flow
90 increases sound levels by 3 dB. This simple relation gives some insight into the links between the
91 number of vehicles and the average sound level:

- 92 • Reducing the number of vehicles by 10% will only reduce noise levels by up to 0.5 dB, which is
93 hardly noticeable to listeners;

- 94 • A strong reduction in the number of vehicles, for instance by 90% (for example in the context
95 of a strong modal shift towards bicycles in traffic free city centers), will make average noise
96 levels decrease by 10 dB.

97 The spatial distribution of noise is of great importance when assessing noise impacts. The spatial
98 variability of noise levels is indeed very high (Aumond *et al.*, 2018), and closely linked to both urban
99 spatial characteristics (Liu *et al.*, 2013) and the road network (Barrigon Morrillas *et al.*, 2005). In
100 addition, links between sound levels and large scale urban spatial attributes can be found in the
101 literature. Salomons and Berghauer Pont (2012) showed that road traffic noise increases with the
102 road network density and the travelled distances by car per surface unit, but decreases as the building
103 density increases, resulting in a sound level decrease with increasing population density. A negative
104 correlation between sound levels and building densities is also found in Ryu *et al.* (2017).

105 The temporal evolution of noise is also a key element in the assessment of the impacts. The aggregated
106 indicator promoted by the Directive 2002/49/EC, the L_{den} , underlines the specificity of noise exposure
107 over evening and night periods by introducing respectively a 5 dB and 10 dB penalty for these periods.
108 This specificity must thus be taken into account when assessing the impact of increased traffic flows
109 during these periods.

110 **3. On-going society and mobility changes and their impact on sound environments**

111 The close links between society and mobility are widely accepted in the scientific literature (Urry,
112 2007). The observed trend of increased mobility is likely to continue: by 2050 passenger mobility
113 should increase by 200-300 % and freight activity by as much as 150-250 % (Wilson 2011). In parallel
114 with this increase, the forms of mobility are changing. L'Hostis *et al.* (2016) addressed the societal
115 needs and requirements for future transportation and mobility, and listed the societal drivers that
116 have an impact on mobility and logistics. Four identified trends in mobility are discussed in this section
117 from a sound environments point of view.

118 **3.1. Distribution of wealth and labour market developments**

119 Direct consequence of the global economic growth will be an increase in flows, particularly freight. At
120 the individual level, economic growth usually converts into more mobility, as illustrated by the growth
121 of tourism (Dubois *et al.*, 2011). The number of air passengers carried worldwide grew for instance by
122 6.3% in 2016, and this trend is likely to continue as this increase has been during the past 40 years
123 continuous and resilient to oil-price shocks or recessions (EC, 2017). This increase in flows is likely to
124 result in an increase in noise emissions, whose the Advisory Council for Aeronautics Research in Europe

125 (ACARE) is aware as it fixes the goal of reducing by 65% the perceived noise per passenger kilometer
126 by 2050 relative to the year 2000 (ACARE, 2015). This objective is however vague since the selected
127 indicators are not mentioned in the report.

128 In addition, the working arrangements are being restructured. Observations show that average daily
129 travel-time expenditures are stable over time (Stopher *et al.*, 2017), giving credit to the idea of travel
130 time budget (Zahavi, 1976). It appears that increases in transport modes speed or new improvements
131 in mobility are spent into more kilometers travelled and hence more mobility. Telework and part-time
132 work are the two major foreseeable trends already happening that are expected to grow further in the
133 future. This trend leads to a drop in the number of trips to work and thus to a decrease in the peak
134 hour travel. On the other hand, these new working arrangements favorize urban sprawl, or even
135 commuting from one city to another, with a probable associated increase in the number of trains
136 operating and the related noise. This trend is therefore a potential vector for a modification of the
137 temporal and spatial structure of urban sound environments.

138 **3.2. Inclusive society, personalization, accessibility**

139 Life rhythms are changing. There is an emerging consensus among social scientists (Clegg and
140 Baumeler, 2010) around the idea of *liquid modernity* introduced by Z. Bauman (Bauman, 2000), but
141 also on the acceleration of the social life (Rosa, 2003). Acceleration and flexibility provide an
142 explanation to the increase of leisure time and its associated mobility pattern, which tends to
143 desynchronizing the existing rhythm of mobility at the risk of exceeded noise annoyance over evening
144 and night periods. The flexibility in rhythms can also modify diurnal noise temporal patterns, with
145 longer rush hours and less breaks. For example, the average daily travel time for non-work or studies
146 activities increased from 40 min in 2001 to 52 min in 2010 in Île de France region, Paris (Courel &
147 Gloagen, 2016). The evolution towards instant delivery also affects logistics. For example, by 2025,
148 20% of retail sales are expected to be online, which will imply an increase in the demand for urban
149 parcel deliveries and smaller but more frequent shipments (Vidyasekar and Frost & Sullivan, 2013).
150 This might favor noise at sensible periods of the day. However, this depends on the modes of transport
151 chosen, which were at first mainly operated with bicycles (Dablanc *et al.*, 2017). The example of
152 individual meal delivery companies, initially provided by cyclists but increasingly turning to motorized
153 deliveries and longer delivery distances, illustrates the potential danger to urban sound environments
154 of this trend (Aguilera et al., 2018). The arrival of drones for delivery, which might deteriorate sound
155 environments, is also subject to caution.

156 In addition, the move of city dwellers towards more active and healthy lifestyles implies a shift to soft
157 modes of transport (Davis *et al.*, 2012) that are also known to be quieter. However, mobility trends
158 vary greatly from one segment of the population to another. Young generations are likely to use the
159 car less, but active mobility may be less plausible for all people within the older segments of society,
160 which may result in more public services close to where people live (Anderton *et al.*, 2015). Finally, car
161 ownership has been a status symbol since the introduction of mass production of private vehicles. But
162 in large cities, and among younger generations (Deloitte *et al.*, 2015; McKinsey *et al.*, 2012), mobility
163 is increasingly seen as a service that not necessarily includes private car ownership (Kamargianni *et al.*,
164 2018).

165 **3.3. Urbanization and new city management forms**

166 Cities and city-regions are increasingly becoming the dominant forms of human habitat. They are
167 densifying and spatially extending. Growing cities lead to more intense and longer urban flows, both
168 for passengers and goods (Sena e Silva *et al.* 2013). Densification and urban sprawl are two processes
169 in progress and most likely to continue, which are factors of mobility and therefore potential noise
170 pollution. Density is generally associated with a decrease in road traffic noise levels, while urban
171 sprawl, by increasing the kilometers travelled, contributes to an increase in noise pollution. These
172 processes can also exacerbate environmental inequalities in noise, with: (i) gentrified city center
173 populations exposed to relatively low noise levels, as city centrums are marked by more and more
174 efficient public transport networks, traffic calming policies, and the development of active transport
175 modes, (ii) car-dependent populations on the inner periphery living in areas with high traffic density
176 and high noise levels exposure, (iii) external suburbs, despite being inhabited by heavy contributors to
177 traffic noise, remain relatively quieter than urban environments because of their lower density. Social
178 tensions could be exacerbated between these three urban configurations, that somewhat superposes
179 with the *three speeds city* model introduced by Donzelot: gentrification, periurbanisation and
180 marginalisation (Donzelot, 2006).

181 Regarding urban logistics, freight is an important component of traffic in cities (10 to 15 % of vehicle
182 equivalent miles), and this proportion is increasing due to the current spatial deconcentration of
183 logistics facilities (Dablanc *et al.*, 2016). The number of commercial vehicles increased by 32% from
184 2006 to 2014, and their contribution to both air and noise pollution is high. For instance, 10% of the
185 vehicles in London are commercial vehicles, and they contribute to 30% of the NO_x emissions
186 (McKinsey & Company, 2017). Night delivery is one of the targeted solutions, which would mean
187 degraded night sound environments, since an increase in flow rates inevitably entails an increase in

188 noise emissions. This effect could nevertheless be mitigated by using hybrid or electric mid-size
189 delivery vehicles.

190 In parallel, forms of city management are also changing. The development of the smart city aims at
191 articulating human and social development with information and communication technologies in
192 cities. These include actions for smart governance, economy, mobility, environment, people, and living
193 (Giffinger et al. 2007). As regarding mobility, Intelligent Transportation Systems and its related services
194 are a key lever to converge towards mobility efficiency. Environment-friendly solutions, including noise
195 mitigation, is also a targeted objective of the smart city.

196 **3.4. Environmental protection: climate change, pollution resource and energy efficiency** 197 **“sustainable consumption”**

198 Policies targeting the environmental impacts of transport are increasingly enacted, as an indirect
199 evidence of the rising awareness in society of environmental issues. Increased awareness of the impact
200 of local air quality (particulate matter) and the strengthening of EU emission regulations have urged
201 both regional and local initiatives to ban diesel vehicles and favor hybrid and electric cars. In addition,
202 climate change forces countries to act in favor of renewable energy, which will have a direct impact on
203 the choice of propulsion for private vehicles, public transport, and finally goods transport. Electric
204 vehicles are often seen as a solution to mitigate consumption issues. However, the resulting noise
205 reduction might be disappointing. Following the simple rules recalled in section 2.2, the effects of
206 introducing 10% of electric vehicles would be about 0.5 dB. The real effects might be even less since
207 they mainly reduce engine noise whereas rolling noise is the main source of vehicles at speeds above
208 30 km/h (Pallas et al., 2016). However, optimistic scenarios estimate that electric vehicles could
209 account for 48% to 76% of the car fleet by 2030 (Mc Kinsey & Company, 2014). This share becomes
210 significant from the point of view of noise emissions. This trend also modifies consumption and
211 logistics, with for instance the development of short supply chains aiming at reducing traffic flows and
212 thus noise.

213 Policies targeting the environmental impacts of transport also include speed reduction, which led to a
214 decrease in noise emission per vehicle. This measure, combined to the increase in the number of
215 vehicle kilometers travelled, led to a significant change in the ratio of peak levels to the constant hum
216 (Van Renterghem et al., 2012).

217

218

219 **4. Insights in noise impact assessment and mitigation**

220 **4.1. Insights in noise impact assessment**

221 **4.1.1. New noise assessment trends**

222 Noise impacts are first estimated in terms of exposure. Exposure calculations are often based on static
223 approaches, which cross-reference population density data with calculated noise maps to estimate the
224 number of people exposed to threshold levels. However, a recent work has shown the interest of
225 taking into account activity patterns to refine the calculation of exposures, showing that noise
226 exposures largely depend on the individual's within-day dynamics (Kaddoura *et al.*, 2017). The context
227 of exposure also plays an important role, in particular calm sound environments at the residence place
228 is a strong demand of city dwellers. Geography, particularly renewed by time geography (Hagerstrand,
229 1970), has been much more interested in movement than in its necessary counterpoint, rest (Seamon,
230 1979). The affirmation of the restorative character of the use of the home in social practices and its
231 corollary need for calm would deserve to be investigated in the light of new knowledge in the human
232 sciences.

233 In addition, environmental acoustics is increasingly turning away from approaches based solely on
234 quantitative approaches. Raymond Murray Schafer's work in the 1970s led to the notion of
235 "soundscape" (Murray Schafer, 1979), now widely used, which can be defined as "the sound
236 environment as perceived, experienced or understood by one or more persons, in its context" (ISO
237 12913-1:2014; Aletta *et al.*, 2016). Research in soundscape concentrates an increasing effort, as
238 underlined in Kang *et al.* (2016). In particular, research in sounds classification within urban sound
239 environments often highlights a distinction between mechanical, natural and human sounds. The
240 questions then arises as to the competition between the sources of these classes and their suitability
241 for a given environment. Interactions between road traffic noise, water and bird sounds have been
242 extensively investigated in the literature, the latter two being perceived positively and the former
243 negatively (Jeon *et al.*, 2010). As an example of the practical result in terms of urban planning,
244 fountains are sometimes advocated to improve sound environments dominated by road traffic noise,
245 although recent research shows the limitation of such practice (De Coensel *et al.*, 2011). In terms of
246 modeling, soundscape approaches target qualitative indicators, such as the sound pleasantness, which
247 better characterize the perceptual effects than the aggregated energetic indicators (Aletta, 2015;
248 Aumond, 2017), or the tranquility rating, which associates visual attributes such as the percentage of
249 natural features visible in the scene (Pheasant *et al.*, 2008).

250 Soundscape approaches also emphasize the importance of preserving quiet urban neighborhoods,
251 with modalities for their identification and preservation described in (EEA, 2004). The interest in

252 preserving places with high quality acoustic environments, referred to as restorative places, has been
253 demonstrated; they are proved to positively affect well-being and therefore require special attention
254 (Van Kamp et al., 2016). In that perspective, metrics have been proposed, such as the perceived
255 restorativeness soundscape scale (PRSS) introduced in Payne (2013) that is based on criteria such as
256 the appealing, attention, notion of refuge, etc. Such metrics help rating the restorativeness of different
257 soundscapes, which makes it possible to differentiate for example the soundscape of different urban
258 parks.

259 Finally, noise is increasingly taking part of global assessment, as long with other environmental
260 externalities, within integrated approaches. In particular, noise emissions are increasingly taking part
261 of Life Cycle Assessment (LCA), whose methods of consideration are still debated (Cucurachi *et al.*,
262 2012). Meyer *et al.* (2019) showed for instance that integrating the impact of noise into LCA can double
263 the estimated impact of road transport on human health.

264 **4.1.2. Assessing the noise impact of urban renewal**

265 Urban renewal, including densification and urban sprawl processes, requires revisiting noise modeling.
266 Urban-scale prediction and assessment of noise impacts faces several obstacles:

- 267 • First of all, estimating the road traffic demand in view of potentially disruptive modal shifts for
268 passengers and new distribution models for goods is a huge challenge. Not only, the L_{den} levels
269 may be affected, but also the number of noise peaks and quiet intervals. Today, we already
270 witness changes in exposure-annoyance relationships for railway noise and aircraft noise
271 (WHO, 2018) that may be caused by such modal shifts and increased traffic intensities in air
272 and rail traffic. Therefore, developing integrated modelling chains that combine mobility and
273 noise and include a modelling of transportation modal shifts is a crucial research challenge for
274 the coming years;
- 275 • Secondly, assignment of traffic to the road network has some uncertainty. The deterioration
276 of traffic conditions induced by an increase in travel demands on the main arteries can load
277 residential areas, which is very difficult to model. Since noise is a very local phenomenon
278 (propagation distances are short in a densely built network), this can result in breaking up quiet
279 areas and thus have significant consequences on the number of people exposed to traffic
280 noise. Moreover, reducing traffic in city centers, e.g. via low emission zones and traffic free
281 areas may result in increased traffic in the periphery rather than inducing the modal shift that
282 planners hope for. Urban planners need models able to highlight this spatial modification in
283 sound environments. More generally, the digital twin technology applied to the city

284 environment is increasingly seen as a potential way to facilitate decision making (Mohammadi
285 & Taylor, 2017), which could also apply to the context of sound environments;

286 • Finally, the assessment of environmental injustices in noise exposure is an exercise that
287 requires knowledge of both the spatial distribution of noise levels and the populations
288 affected, in terms of social conditions, age, etc. This necessarily entails the reinforcement,
289 already at work, of research groups involving environmental economists, epidemiologists,
290 geographers and acousticians. First findings on how noise influences urban landscape show
291 that the spatial noise distribution has a significant impact on the property market. Kim *et al.*
292 (2007) showed that a 1% highway traffic noise increase is associated with a 1.3 % decline in
293 land price. Such numbers are however hardly transferred to urban context, where a very low
294 association between price market and noise exposure is found in Brandt & Maennig (2011)
295 due to confounding factors. The spatial noise distribution also correlates with living spaces and
296 thus social groups, so that strong social inequalities in environmental noise exposure are
297 observed. Its processes are reviewed in Dreger *et al.* (2019): groups with lower socioeconomic
298 position suffer from a higher noise exposure, combined with an inability to afford more
299 effective noise insulation and an increased vulnerability to the effects of exposure (EC, 2016).

300 At the microscopic scale, the urban planning efforts in city centers are moving towards a more global
301 reflection on health and quality of life that is in line with the on-going research on soundscape, which
302 promotes holistic approaches (see section 4.1.1). The integration of soundscapes approaches into
303 modeling frameworks shared by architects and acousticians is an important challenge to progress
304 towards the design of high quality sound environments.

305 **4.1.3. Assessing the noise impact of societal changes**

306 The societal changes described by sociologists, which are a move towards more flexibility and an
307 acceleration in life rhythms, have begun to disrupt relationships with mobility, with predictable
308 consequences for urban sound environments. The individualization of living patterns, and the
309 increasing instantaneous nature of deliveries, increase the number of trips during evening or even
310 night periods, which are traditionally conducive to calm. These new noise nuisances question the
311 indicators and models to evaluate them.

312 The acoustic indicators commonly used to describe night annoyance are criticized for not taking into
313 account the impulsive nature of the noise associated with awakenings (Basner, 2018). In addition,
314 evidences show the interest of taking into account the number of noise events when assessing
315 perceptual effects of noise, in terms of the sound pleasantness of a scene (Gille et al., 2016; Ricciardi

316 et al., 2015). As a result, noise indicators to assess the impacts of noise, both in terms of annoyance
317 and health effects, are still under discussion (Lercher, 2018), with the aim to include the temporal
318 structure of sound environments. Indicators have recently been proposed to summarize the temporal
319 variations of noise, such as the Harmonica index which accounts for the sound levels amplitude
320 (Harmonica, 2013), or the Intermittency Ratio (Wunderli et al., 2015), which highlights the proportion
321 of the sound energy contained in noise peaks.

322 However, the estimation of noise event indicators remains difficult because the usual modelling
323 frameworks for road traffic noise prediction do not adapt well enough to the dynamics of noise induced
324 by road traffic, and even less so to the random nature of noise events. Recent modeling approaches,
325 which rely on microscopic road traffic models, seem promising for estimating acoustic indicators
326 characterizing noise peaks or calm periods (Can *et al.*, 2007; De Coensel *et al.*, 2016; Estevez-Mauriz &
327 Forssen (2018).

328 **4.1.4. Assessing the noise impact of new mobility drivers**

329 Mobility is also changing in terms of nature. The development of smart cities and new transportation
330 devices can have a very beneficial effect on sound environments. The deployment of electric vehicles
331 contributes to a reduction in noise levels since they attenuate propulsion noise. However, their impact
332 on urban sound environments will remain limited, until a massive spread. The probable future
333 emergence of autonomous vehicles can also be a lever for reducing noise levels, with the
334 implementation of driving modes that are economical in terms of the noise pollution generated
335 (reduction of high accelerations and congestion). However, some rebound effects are under study,
336 these vehicles can for instance induce empty trips and even congestion (Millard-Ball, 2019).

337 On the other hand, the development of new modes of transport, in particular drones, person-carrying
338 drones or urban helicopter transport, can lead to a significant deterioration in sound environments.
339 Initial researches have focused on the characterization of drones' emissions (Kloet *et al.*, 2017), or in
340 showing their increased annoyance compared with cars or trucks (Christian & Cabell, 2017 ; Torija et
341 al., 2020). It seems crucial to intensify the efforts on researching the potential noise impact of new
342 modes of transport, including beyond noise levels a research on the additional cognitive load induced
343 by these new vehicles.

344 In view of the diversity of these new sources, estimating effects based on traditional subdivision on
345 transport modes (air, rail, road) can no longer be defended. The development of new impact indicators
346 that can lead to a unified theory for noise annoyance, sleep disturbance, and restoration is called for.

347 **4.2. Insights in noise mitigation**

348 **4.2.1. Insights in road traffic management**

349 The proximity between sources and exposed people in urban areas calls for a reduction of traffic noise
350 at source. The decibel scale recalled in section 2.2 draws direct conclusion in terms of road traffic
351 management. Indeed, a small proportion of noisy vehicles (for example logistic vans, motorcycles or
352 old vehicles), for instance 1% of vehicles that emit 20 dB more than the rest of the vehicle fleet, make
353 average sound levels increase by 3 dB. This result is a brake to legislating on vehicles noise limits to
354 reduce noise levels, as a small proportion of noisy vehicles, added to the inertia in the renewal of the
355 vehicle fleet, can contribute significantly to high ambient levels. But the opposite is true, a policy
356 targeting the 1% noisiest vehicles may reduce noise levels significantly. Acoustics radars are therefore
357 under testing and being deployed in some cities. They aim to identify noisy vehicles, pinpoint their
358 location and automatically ticket them. The sensor “Méduse” patented by BruitParif relies for instance
359 on an acoustic antenna composed of four microphones arranged in a regular tetrahedron (Mietlicki,
360 2018). Finally, the reduction of the engine component of vehicle noise, and the arrival of electric
361 vehicles on the market, bring out new opportunities for flanking noise control via quiet-tire policies
362 and road pavement choice and maintenance increase.

363 Acting on road traffic to mitigate noise requires the development of dedicated modeling chains. The
364 links between vehicle flows and sound power levels are indeed not trivial, since kinematics of single
365 vehicles is extremely important for noise emission. Thus, the effect of modifying the vehicle flow has
366 an effect on the vehicles kinematics and, consequently, on noise emissions. For example, reducing the
367 number of vehicles can be acoustically compensated by an increase in speeds that increases sound
368 levels. Recent advanced modelling approaches have been developed that rely on microscopic traffic
369 models, with the aim to capture the vehicle reassignments and the changes in traffic conditions, such
370 as traffic congestion, that may occur with acting on traffic management. These models work as follows:
371 the traffic model, originally designed for traffic management purposes, outputs vehicle trajectories on
372 an instantaneous basis, which feed noise emission models (De Coensel *et al.*, 2005; Can *et al.*, 2009).
373 The other advantage of this modelling approach is to enable the evaluation of sound level time series
374 and then the calculation of specific indicators that better describe sound environments (Can *et al.*,
375 2008). These models have been used to evaluate the impact of speed reduction or specific intersection
376 designs on the sound levels distribution. For example, the sound environments associated with
377 roundabouts are improved compared with traffic light intersections, as they smooth traffic and reduce
378 the number of acceleration phases (Chevallier *et al.*, 2009; Luo *et al.*, 2012). De Coensel *et al.* (2010)
379 demonstrated the interest of low speed green waves for reducing noise levels. Finally, integrated

380 approaches have combined noise and air pollution assessment within multi-criteria evaluations that
381 showed that the effects can vary from one externality to the other (Fernandes *et al.*, 2019; Sampaio *et*
382 *al.*, 2019). For example, De Coensel *et al.* (2012) proposed a case study in which a reduction in speeds
383 is slightly beneficial from an acoustic point of view, while NO_x emissions strongly decrease but the
384 number of particles emitted increases because vehicles operate in sub-regime speed.

385 **4.2.2. New modes of governance**

386 The emergence of new modes of governance and the growing diversity of stakeholders are changing
387 the way in which noise is being addressed. For instance, GPS applications available on the market,
388 whose objective is to optimize individual travel, shift traffic to residential streets, which can
389 significantly increase noise levels in initially quiet areas (Foderaro, 2017). This raises questions of
390 governance regarding sound environments in the smart-city context with private and public actors
391 (Courmont & Le Galès, 2019; Meijer & Bolivar, 2016). Decrease in private car ownership could also be
392 a lever to mitigate noise. Indeed, as soon as vehicles (cars, buses, trams, trains) are owned by a
393 limited number of operators, noise emission policy could take on new forms including stakeholder
394 negotiations and long-term planning.

395 In parallel, the rise of the soundscape approach, the deployment of urban sensor networks, and the
396 general trend towards greater participation of the various stakeholders in decision-making argue for
397 new modes of governance to mitigate urban sound environments. The association of different
398 stakeholders and methods in sound planning have been discussed in (Alves *et al.*, 2015) or (Gauvreau
399 *et al.*, 2016). The promoted holistic approach calls for instance for an active participation of city-
400 dwellers in the decision-making process, involving as well noise experts and city's players in focus
401 groups.

402 **4.2.3. Insights as concerning the smart city**

403 The smart city is already very present in the acoustics context, particularly via the development of
404 connected sensor networks (Sevillano *et al.*, 2016; Picaut *et al.*, 2017; Mydlarz *et al.*, 2019), which help
405 to monitor sound levels, but must be set to guarantee the privacy of city dwellers in response to
406 national laws. City-of-things distributed monitoring technology may be used directly in noise control
407 by adapting speed limits or variable access charging or tolling based on noise emission. However, the
408 smart governance dimension of smart cities, which could be defined as an hybrid governance
409 associating citizens to decisions made by public authorities, did not fully reached yet the acoustics
410 community. Sensor networks of the new generation might eventually participate in moving towards
411 an association of citizens in the decision-making process, and towards greater transparency in

412 governance models. Open data, such as the service offered by the New-York City that references and
413 shares on-line noise complaints (NYC, 2019), or smartphone noise applications that allow users to
414 measure and share the noise environment, such as Noisecapture (Picaut et al., 2019), can help to move
415 in this direction. This will in addition require the development of data visualization platforms that can
416 be easily interpreted, in order to test the impact of temporary policies.

417 Finally, the current development of intelligent measurement networks can be used to: (i) implement
418 noise reduction solutions (such as speed reduction) adapted to the noise levels measured, (ii) detect
419 noisy vehicles and decide on action concerning them, (iii) assess the benefits of local noise reduction
420 policies, by measuring their effects.

421 **5. Conclusions**

422 The degradation of sound environments is mainly attributed to the mobility demand and an obstacle
423 to the qualitative and quantitative development of cities. Societal and urban changes and the current
424 changes in mobility practices make it difficult to anticipate the sound environments of tomorrow.
425 However, this prospective analysis is essential to propose appropriate noise mitigation solutions.

426 The interdisciplinary discussion proposed in this article highlights the most influencing trends within
427 ongoing mobility and society changes on sound environments, and defines the consequences in terms
428 of noise assessment and mitigation. The selected trends that are likely to tend towards a deterioration
429 of sound environments are the global economic growth, the acceleration and fluidification of life
430 rhythms, the increase of freight traffic, the appearance of new aerial sound sources, and the spatial
431 growth of cities. The selected trends that are moving towards an improvement of sound environments
432 are the development of active mobility, the development of short supply chains, the emerging electric
433 vehicles and new forms of mobility. The article sets however limits in terms of anticipation, so the most
434 studied trends have been favored. Trends in urban sound environments may differ from those
435 predicted here if unanticipated external factors, such as technological disruptions or a collapse in
436 mobility, significantly alter mobility practices in the coming years (Urry, 2016; Scheel et al., 2015).

437 Finally, the paper builds on this discussion to propose and comment on insights for the assessment
438 and the mitigation of the noise impacts of mobility:

- 439 • The development of integrated modelling chains combining urban morphology, mobility and
440 noise is called for to assess the impact of the urban renewal on noise. In addition,
441 interdisciplinary researches involving environmental economics and geographers are required

442 to better retroactively describe the impact on society of the evolution of urban sound
443 environments;

444 • The proposal of unified noise indicators that can handle a variety of noise sources and specific
445 demands such as tranquility, restoration, and undisturbed sleep is required to better assess
446 the impacts;

447 • Research efforts on the potential impact of new modes of transport are crucial to anticipate
448 the acceptability of the evolution of future noise environments;

449 • The rise of new modes of governance associating all the stakeholders involved in the design of
450 urban sound environments is encouraged to mitigate noise. It could benefit from the
451 increasing amount of collected data as part of the smart city as long as decision-making
452 methods are developed in parallel.

453 These research insights and their further continuation is crucial to make the development of cities and
454 mobility compatible with sound environments of quality.

455

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