Chapter 10
Future Developments in Noise from Transport

Antonio J Torija Martinez

Abstract The world is currently undergoing a significant transition towards cleaner and more sustainable energy sources. The transportation sector is gradually moving away from fossil fuels and electric vehicles, both on the ground and in the air (e.g., drones), are more and more common. The introduction of these electric vehicles will bring new sources of transportation noise, which might lead to the largest shift in soundscapes in living memory. This soundscape shift could be detrimental to the public health and well-being if appropriate actions are not taken. This chapter presents the state-of-the-art of the fast-developing field of transportation noise, and discusses current practice gaps and recommendations.

> We need to start imagining (and asking ourselves) what the future is going to sound like above and under water,
>
> What do we want our future to sound like and how do we get there?.
>
> Spence in https://planetforward.org/story/marine-ecologists-sound-pollution/

10.1 Introduction

The world is currently undergoing a significant transition towards cleaner and more sustainable energy sources. During this energy transition, there is a gradual move away from fossil fuels and an increased reliance on renewable energy technologies such as wind, solar, and hydroelectric power. This energy transition is expected to bring substantial environmental and socioeconomic benefits; but it is important to also account for the impact of the noise generated by these renewable energy installations on human' and wildlife's health and well-being.

Wind turbine noise has been a focus of environmental noise research for several years (Hansen and Hansen 2020). The impact underwater noise produced by offshore

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wind farms has on wildlife has been investigated. For instance, Madsen et al. (2006) reported that high sound levels during construction activities are likely to disrupt the behaviour of marine mammals at ranges of many kilometers. However, Mooney et al. (2020) suggest that further research is needed to have a comprehensive understanding of the effects of offshore wind farm noise on wildlife. The noise generated by wind turbines is frequently a cause of complaints from communities living near wind farms due to noise annoyance and sleep disturbance (Nguyen et al. 2021). The noise annoyance due to wind turbine noise has been usually associated with several acoustic features, such as the presence of infrasound, a low-frequency dominated spectrum (Zajamšek et al. 2016), tonality (Liu et al. 2012), and amplitude modulation (Nguyen et al. 2021). Noise annoyance due to wind turbine noise is correlated to sound levels; but is also associated with several non-acoustic factors, e.g., both objective and subjective factors of wind turbine visibility (Pedersen and Waye 2007). Due to these acoustic and non-acoustic factors, some studies (Pedersen and Waye 2004) have found wind turbine noise to lead to a higher percentage of highly annoyed people than expected from the existing dose–response relationships for transportation noise (Miedema and Oudshoorn 2001).

Decarbonising heating and cooling is one of the main goals of the European Environment Agency (EEA 2023). Heat Pumps have been suggested as a key technology for the decarbonisation of heating in households. In the UK, the Government's Net Zero agenda is planning a wider deployment of Heat pumps, at a rate of 600,000 a year from 2028. However, these technologies do not come without drawbacks and challenges. Noise has been regularly suggested as one of the main barriers to the wider adoption of heat pumps. Some of the acoustic features of heat pump noise have been comprehensively studied, such as vibration-induced noise, low-frequency noise, and tonal noise (Waye and Rylander 2001; Yonemura et al. 2021). There are also some important challenges still to be further investigated, such as how communities will respond to a sound environment with multiple heat pumps operating under different regimes; and what the contribution is of transient behaviours (e.g., de-frosting) on noise annoyance. This further research is a key priority of the working group Annex 63 of the Heat Pump Technologies (HPT) Technology Collaboration Program (TCP) of the International Energy Agency (IEA).

The transportation sector is also in a process of transition towards more electric and autonomous technologies. Transportation noise is usually reported to be the most important source of environmental noise (Clark and Stansfeld 2007). Therefore, the remaining of this chapter focuses on expected developments in transportation, and their implications on environmental noise and its effects.

This chapter presents the state-of-the-art of the fast-developing field of transportation noise, and discusses current practice gaps and recommendations.

10.1.1 Transportation Noise: Towards Electric Mobility

The soundscapes in which we live and work affect us in several ways, every moment of every day; and these soundscapes are expected to change dramatically in the coming years, whether we like it or not, as part of a major shift towards electric-driven mobility. Imagine a city in 2030, electric vehicles have taken over and the sky is inundated with drones and other novel aircraft; on the ground, electric vehicles and two-wheeled transport are dominating (see Fig. 10.1).

Electric mobility (or e-mobility) will lead to vehicles with entirely new sound sources. On the ground, the move away from internal combustion engines and towards e-drives would, in principle, lead to quieter vehicles as engine noise will be significantly reduced. However, a noticeable reduction in the overall noise reduction of Electric Vehicles (EV), compared to combustion engine cars, happens only at low speeds (i.e., lower than 30 km/h) where engine noise is dominating (Iversen et al. 2013). The overall noise reduction at higher speeds is less certain, and even a small increase in rolling noise caused by tire-road contact might happen due to an increase in EV weight consequence of carrying heavy batteries. Even with a quieter EV, this could be actually more annoying than a louder combustion engine vehicle, partly because the EV is different in noise spectrum and character (e.g., more high-frequency noise), but also because the quieter e-drive can reveal other vehicle sounds which were previously masked (e.g., tonal noise).

Fig. 10.1 Illustration of an urban scene with electric scooters and drones flying over. *Image generated by Midjourney [Large data model], (2024) from A man riding a scooter, by Pony (@getapony), 2022. (*https://unsplash.com/photos/a-man-riding-a-scooter-OHxsu4HTz5c*). Unsplash licence*

On the other hand, quieter EVs at low speeds could go undetected, and probably form a risk for pedestrians nearby. Therefore, these EVs must generate sound artificially to alert other road users, with potentially non-harmonious consequences for local communities. If not properly designed, this mixture of artificial alert sounds from different vehicles could be a factor of significant community noise annoyance.

In the air, drones (or other novel aircraft such as electric Vertical Take-Off and Landing—eVTOL—vehicles) will bring unconventional noise signatures. In these vehicles, the sound will be eminently tonal and high-pitched (Torija and Clark 2021). Tonal noise has been found to be strongly associated with noise annoyance, while high-frequency content has been found as one of the most important contributors to aircraft noise annoyance (Torija et al. 2019). There is enough evidence to suggest that the sounds of these novel air vehicles do not resemble the sounds of conventional aircraft (Christian and Cabell 2017). Neither will be the operating characteristics. Drones and eVTOLs will operate closer to communities (than conventional aircraft), and over urban (and possibly rural) communities not usually exposed to aircraft noise. All these new sources will certainly lead to the largest shift in soundscapes in living memory.

This soundscape shift could be detrimental to the public health and well-being if appropriate actions are not taken. However, there is also a scenario where drones move rapidly and quietly through the air; and electric surface transportation provides a pleasant background hubbub. To do this, manufacturers and decision-makers need the tools for carefully designing the sound of e-mobility vehicles so that they produce an optimal sound, taking citizens' requirements into consideration.

To realise this scenario, new perceptually driven engineering methods are needed. The concept of perception-influenced (or perceptually-driven as referred to in this chapter) engineering was first introduced by Davies and colleagues at Purdue University, to integrate the ways people perceive, or are affected by, machinery outputs into the design of engineered systems (Davies 2007). These perceptually-driven methods allow putting the public at the centre of engineering decisions to ensure responsible innovation. With these perceptually driven methods, manufacturers could listen to the effects of early design changes in their prototypes, and optimise the product sound for the user and their environment. This would allow manufacturers to fully realise the benefits of industrial strategies, such as Industry 5.0 in the European Union (Cotta and Breque 2021), pushing for a translation to a sustainable and human-centric industry.

The challenges are several and complex, including:

- A better understanding of the noise emission characteristics of e-mobility vehicles (as compared to their equivalent ground and aerial vehicles);
- New or updated sound emission and propagation models able to account for the unconventional noise signatures and operating conditions of e-mobility vehicles;
- Psychoacoustic knowledge to understand the human response to the sound generated by e-mobility;
- New or updated policy and guidance to inform vehicle and operation development to limit the impact of these new sound sources on communities.

But, at the same time, the introduction of e-mobility provides an excellent opportunity to change the way we have traditionally addressed the problems of environmental noise, and therefore allows us the opportunity for a fresh start to shape future soundscapes the way citizens want.

10.2 Drones and Other Novel Aircraft as New Sources of Environmental Noise

Several recent studies have found drones reported to be more annoying than other transportation vehicles, at the same sound level. A pioneering study by Christian and Cabell (Christian and Cabell 2017) compared the annoyance of a series of drone flyovers with road vehicles passing-by. They found the drones evaluated (with the number of rotors varying from 4 to 8, and weight from 1.6 to 8 kg) to be equally annoying as road vehicles with a 5.6 dB higher sound level; in other words, road vehicles had to be 5.6 dB louder to be perceived as equally annoying as drones. The authors hypothesised that this offset in annoyance is due to the specific sound characteristics of drones (i.e., tonal and high-frequency noise), and also due to the different flight operations (e.g., flying closer to people). Similar findings have been found by other researchers. Torija and Li (2020) found a small quadcopter 33% less preferred than a conventional civil aircraft taking-off (at the same sound level, 65 dBA); Gwak et al. (2020) found hovering drones equally annoying as a jet aircraft taking-off with a 4–10 dB higher sound level, depending on the size of the drone. It should be noted that drone and propeller technology is advancing rapidly, so these offset values might be soon obsolete and further research would be required.

There are several reasons why drones are more annoying than other transport vehicles at the same sound level, related to the ‘sound signature’ of drones. To start with, the concentration of acoustic energy in the high-frequency region (see Fig. 10.2) is one of the main differences between the noise signature of drones and other conventional civil aircraft (Gwak et al. 2020). The sound produced by a drone is very particular. In the case of multirotor drones, the propellers usually rotate at slightly different velocities which causes the presence of a multitude of discrete tones at specific frequencies. This makes the sound of a drone highly tonal; but also ‘rough’ as the multitude of discrete tones can interact with each other leading to fast modulation phenomena (equivalent to the sound of a ‘sporty’ car). The interaction between rotors, and between rotors and fuselage, produces unsteady pressure fluctuations causing high-frequency noise (Hubbard 1991). The operation of electric motors also produces the generation of high-frequency noise (Cabell et al. 2016).

Drone noise is also highly influenced by ambient weather conditions (Alexander et al. 2019). The flight control system of a drone varies individual rotor speeds to maintain vehicle stability, and creates an unsteady noise signature with rapid temporal fluctuations of the tonal components. Small variations in the frequency of the different rotors lead to large variations at higher frequencies (see Fig. 10.3). Together with

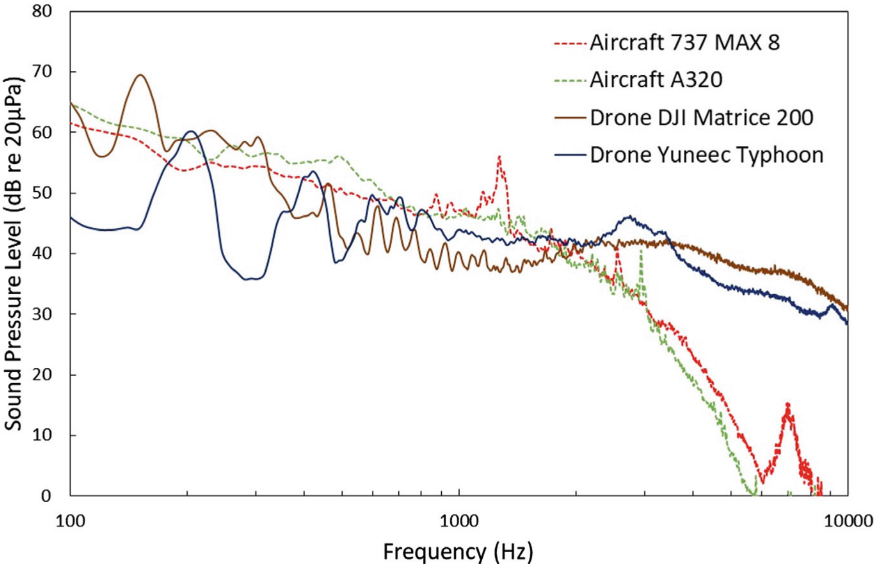

Fig. 10.2 Frequency spectra of two civil aircraft (Airbus A320 and Boeing 737-8MAX) and two small multi-copters (DJI M200 and Yuneec Typhoon), with an overall sound pressure level normalised to 65 dB(A) for comparison. Modified from (Torija and Clark 2021), licensed under CC-BY 4.0

the high-frequency sound of the motor, this creates a very noticeable high-frequency sound.

Another reason why drones are more annoying is that drones operate in a significantly different manner to conventional civil aircraft and on most occasions over

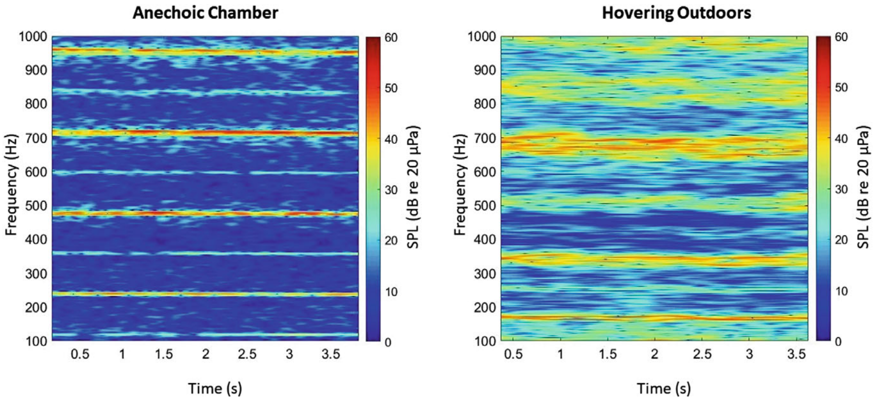

Fig. 10.3 Spectrogram of a DJI Phantom 2 quadcopter measured in an anechoic chamber (left) and measured outdoors while hovering (right). Modified from (Torija et al. 2019), licensed under CC-BY 4.0

communities not currently exposed to aircraft noise. In conventional civil aviation operations, flight profiles are designed to quickly move aircraft far away from exposed communities. Thus, in communities living around airports, aircraft height about ground would be about 6,500–7,500 ft (around 2–2.3 km). Drones will operate much closer to exposed communities, i.e., not higher than 400 ft (i.e., 120 m) above the ground. In a typical operation for a parcel delivery, a drone would approximate the property of destination, would descend, stay hovering for several seconds, then ascend and fly away again. This implies that the drone operation close to citizens can lead to noise annoyance. Christian and Cabell (2017), suggest that a 'loitering' penalty would account for some, if not all, the differences in noise annoyance between drones and road vehicles.

In summary, noise annoyance from drone operations has been found to be primarily influenced by how loud the sound is perceived, the presence of high frequency (or high pitch) noise, and the presence of amplitude-modulated sound due to the interaction between rotors (Gwak et al. 2020; Torija and Nicholls 2022); and the presence of tonal noise (Torija and Li 2020).

10.2.1 Urban Air Mobility

A new aviation sector is also expected to expand in the next few years: Urban Air Mobility. The main motivation here is to contribute to a multimodal mobility system, enabling the exploitation of urban skies for people's transportation. Building upon the ongoing development of electric powertrains and battery technology, a new generation of aircraft is under research and development. These novel aircraft include several configurations, although the main designs pivot around eVTOL vehicles. Most of these eVTOLs are based on multi-rotor configurations, which produce a noise significantly different from the conventional rotorcraft and propeller-driven aircraft. As for the drones, these novel aerial vehicles bring significant acoustic challenges due to their unconventional noise signatures, with more tonal, high-frequency broadband and time-varying noise; and also unconventional maneuvers such as the transition from hover to forward flight. If not appropriately considered and managed, these noise emissions and operating characteristics will likely lead to important problems of environmental noise.

10.3 Change in Soundscape with e-Mobility

The transition to electric mobility could have detrimental effects on the soundscape of cities, such as a shift towards high frequencies which are usually perceived as more annoying and unpleasant. Urban soundscapes are currently dominated by road traffic noise, which has been traditionally generated by fossil fuel or internal combustion engine vehicles. There is a significant difference between internal combustion engines and electric powertrains and so their sound generation mechanisms are different. The sound emission of electric powertrains can be up to 20 dB lower (in A-weighted sound level) in full acceleration mode than conventional internal combustion powertrains. However, their sound signature is dominated by high frequencies and tonal components in the frequency range from 1 to 10 kHz (Muender and Carbon 2022). The human auditory system is particularly sensitive to these high frequencies. By being very quiet, and with the absence of the typical broadband noise spectrum of internal combustion engine vehicles, other disturbing noises are unmasked. These include switching noise caused by power electronics, with frequencies ranging from 250 Hz to 20 kHz, which has been found to be experienced as quite unpleasant. For the specific case of vehicle interior sound quality and comfort, electric powertrains are potentially more annoying than internal combustion powertrains due to their acoustic profile with higher frequencies and tonal components (Muender and Carbon 2022; Lennström and Nykänen 2015; Swart et al. 2016; Lennström et al. 2013).

A literature survey about noise from electric vehicles (Marbjerg 2013) described the frequency content of noise from electric vehicles under different speeds, and for different electric and hybrid electric vehicles. The common finding was that the frequency spectra of electric vehicles have much less content in low-frequency noise, and much more content in high frequency noise. For instance, Fig. 10.4 (modified from (Wachter 2009)) shows sound levels of electric vehicles at frequencies between 1 and 2 kHz higher than the sound levels of internal combustion engine vehicles at a speed of 50 km/h.

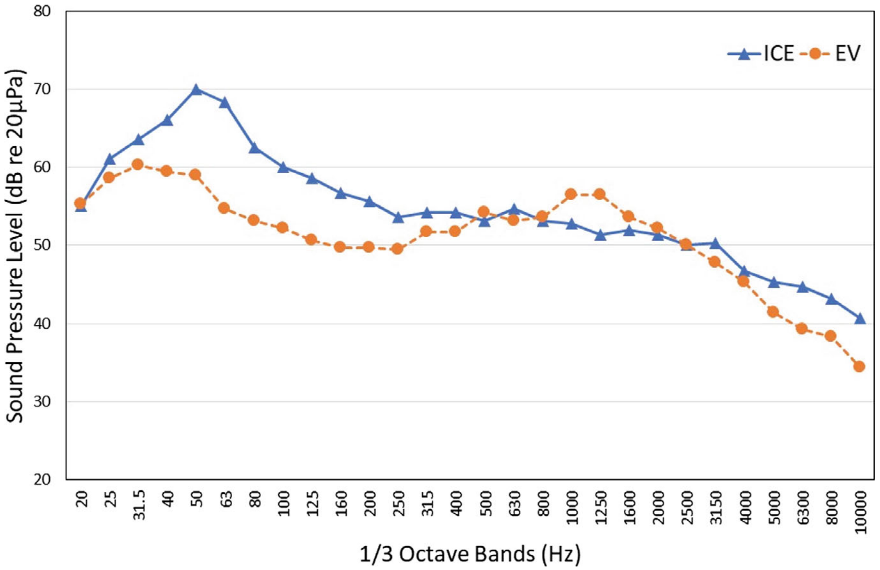

Fig. 10.4 Frequency spectra of an internal combustion engine (ICE) vehicle and Electric vehicle (EV) at a constant speed of 50 km/h. Modified from (Wachter 2009)

The literature on the perception of noise from electric vehicles is scarce and focuses mainly on vehicle interior sound quality. A study conducted by Govindswamy and Eisele (Govindswamy and Eisele 2011) investigated what parts of the frequency spectrum are more important for sound perception in electric vehicles from the driver's perspective. Using an electrified version of the Fiat 500, and varying the sound level at different frequency regions,[1] the authors found that: (i) reducing the low-frequency content had no effect on noise perception ratings; (ii) reducing the mid-frequency content improved the reported pleasantness and dynamic impression rating; and (iii) reducing the high-frequency content lead to the biggest improvements in reported pleasantness and preference. Similar findings were reported by Lennström et al. (Lennström et al. 2011). In their sound quality evaluation of EVs in vehicle's interior, the authors found that increasing the sound levels of tonal components at high frequencies led to high values of reported sharpness (i.e., sensation based on the amount of high pitch noise), annoyance, toughness/aggressiveness, and powerfulness; while a reduction of sound levels of tonal components at high frequencies yielded high rankings in the overall satisfaction of the sound produced by the EV. The understanding of changes in environmental noise perception with the introduction of EVs is rather limited and must be further investigated.

Regarding changes in noise pollution in the environment, the introduction of e-mobility vehicles can lead to an overall reduction of sound levels, as EVs are significantly quieter than internal combustion engine vehicles (Marbjerg 2013). A report by the National Institute for Public Health and the Environment in the Netherlands (Verheijen and Jabben 2010) estimated a fully electrified fleet of road vehicles to lead to an overall reduction of sound level between 3 and 4 dB. The main assumption was that 90% of passenger cars and light freight cars, and 80% of heavy trucks were electric. The report also suggested that the largest reduction of 4 dB will be on secondary urban roads and intersections (with lower average speeds); and also that for speeds above 50 km/h, EV and hybrid vehicles were not quieter than conventional internal combustion engine vehicles. This is because rolling noise (or tire-road noise) is the dominant noise source at high speeds, in contrast with engine noise which is dominant at low speeds. Campello-Vicente et al. (Campello-Vicente et al. 2017) investigated the effect of the replacement of internal combustion engine vehicles with EVs on the overall sound levels presented in strategic noise maps. The authors also considered the effect of the Acoustic Vehicle Alerting System (AVAS) on the overall sound emission. Assuming all passenger cars to be electric and no heavy vehicles in traffic, and an average speed of 30 km/h in a free field lane, an overall sound level reduction of 2 dB was found. This overall reduction of sound level dropped to 1 dB, if the use of the AVAS in electrics passenger cars was assumed.

With a decrease in noise in urban environments due to EVs replacing internal combustion engine vehicles, other noise events can become more noticeable, and therefore, lead to an increase in community noise annoyance. This is the case with novel aircraft concepts operating in the skies of our cities, such as drones. A study

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[1] The authors presented the original recording of the electrified version of the Fiat 500 vehicle, and also the original recording with the different part of the frequency spectrum attenuated.

based on laboratory simulations found that at locations with dominant road traffic noise, the presence of a drone led to an increase in the reported annoyance 1.3 times the annoyance without the drone; while at locations with low road traffic noise, the annoyance due to the presence of the drone increased 6.4 times (Torija et al. 2020). In these locations with low traffic noise, the noise annoyance was always about 7 (on a scale from 0 to 10), regardless of the overall A-weighted Energy Equivalent Sound Pressure Level (L_{Aeq}) in the location. This suggests that the L_{Aeq} is not an appropriate metric for assessing the annoyance due to drone operations. Since A-weighted time-integrated sound level metrics are widely used in environmental noise mapping, assessment and planning, this is an important finding. LAeq based metrics may not be the most appropriate ones to assess new urban soundscapes with more clearly noticeable sequences of noise events, both on the ground and in the air. Other metrics might be worth consideration, such as the Intermittence Ratio (Wunderli et al. 2016) accounting for the acoustic energy contribution of individual noise events above a threshold; or other acoustic or psychoacoustic metrics accounting for unconventional frequency and temporal characteristics.

10.4 Challenges in AVAS for e-Mobility

As discussed above, EVs might be almost silent at low speeds (i.e., below 30 km/h) due to the significant reduction of mechanical sounds produced by the vehicle powertrain. Although this can lead to a reduction of environmental noise, and therefore, minimise adverse health outcomes due to noise exposure (Campello-Vicente et al. 2017), it could pose a growing threat to pedestrians (and other users of the public space) in the form of collisions. Several associations of the blind and visually impaired, including the Royal National Institute of Blind People in the UK, have advocated for the addition of artificial acoustic signals to increase the detectability of EVs. The hazard of ‘near-silent’ EVs has been widely featured in mass media (Fiebig 2020).

The US National Highway Traffic Safety Administration (Hanna 2009) found increased incidence rates of pedestrian and bicyclist accidents where EVs were involved, compared to internal combustion engine vehicles. The study also found an increased risk of collisions with EVs (compared to internal combustion engine vehicles) for visually impaired people. Karaaslan et al. (Karaaslan et al. 2018) found that the risk of road traffic near-misses and accidents involving pedestrians was around 25% more likely when comparing EVs with no AVAS to internal combustion engine vehicles. Several near misses have been recorded in Norway involving pedestrians with impaired vision when crossing roads. A third of the members of the Blind Union of Norway now say they are more afraid to move around in traffic (Berge 2018). Other studies in Norway also found EVs are more likely to collide with pedestrians and cyclists than internal combustion engine vehicles, possibly because of the low noise levels (Liu et al. 2022).

Electric scooters (or e-scooters) are now a common form of transportation in cities, with an estimated number of e-scooters across Europe of 520,000 in 2022. A study by the UK Department for Transport on road traffic collisions involving e-scooters found an increase from 484 in 2020 to 1,356 casualties in collisions in 2021 (DfT 2021). In a survey on perceptions of current and future e-scooters used in the UK (KANTAR 2021) 53% of the respondents suggested safety issues as one disadvantage of these vehicles.

These issues with the safety of pedestrians, and other users of the public space, including the blind or visually impaired, have led to the development of regulation for the design and use of AVAS in EVs. Currently, there is a range of regulations specifying the requirements of AVAS for EVs (Fiebig 2020). For instance, the United Nations Economic Commission for Europe (UNECE) Regulation 138 specifies the minimum required sound levels in one-third octave bands between 160 Hz and 5 kHz, and states that complying with alerting sounds requires minimum levels in at least two of the specified bands and with one of them below or within the 1600 Hz one-third octave band. There is a good degree of agreement between different regulations, although there are some differences. For instance, European regulation (No 138 of UNECE, U.E.R. 2017) requires the AVAS to operate up to 20 km/h, and include a pitch shifting with speed (not mandatory in US regulation); while the US regulation (NHTSA 2016) requires the AVAS to operate up to 30 km/h, and produce an alerting sound while the vehicle is stationary (not mandatory in European regulation).

To date, there is no regulation requiring AVAS for e-scooters, and therefore, there is no guidance on specifications of alerting sounds for these small vehicles. However, the UK Government has recently suggested e-scooter audibility as a key point to be included in future policy development (DfT 2022). To this end, Torija et al. (2023) and Walton et al. (2022) have conducted research into the detectability of e-scooters in a range of environmental noise conditions to aid the development of AVAS for micromobility transport.

The design of alert sounds for AVAS needs an appropriate consideration of the balance between detectability and annoyance. In other words, manufacturers want their vehicles to sound distinctive and identifiable, but do not want their vehicles to be associated with annoying sounds; at the same time, regulators want EVs to be detected to avoid risks of collision with pedestrians and other users of the public space, but do not want these vehicles to contribute to noise pollution in cities.

The addition of pure tones, and amplitude modulation and impulsive characteristics seem to be beneficial for increased detectability and localizability. A problem arises when a fleet of EVs of different types, and producing different alerting sounds operate at the same time and location. Each type of vehicle should have an appropriate alerting sound, that in addition to comply with regulation if existing, allows pedestrians to clearly associate the sound with the vehicle. For instance, the characteristics of the sound of an e-scooter (e.g., pitch) should be recognisable as a sound produced by a small vehicle operating at low speed (below 20 km/h), and therefore cannot be the same as the alerting sound for an electric bus.

Superposed alerting sounds, with different pitch, pitch-shift factor, and noise character can lead to dissonant and inharmonious urban soundscapes (Laib and

Schmidt 2019). Soundscapes composed of dissonant sound patterns caused by several 'untuned' superposed alerting sound signals could increase noise annoyance. Therefore, assuming a transition towards a fleet of electric vehicles operating in urban settings, from e-scooters to electric trucks, avoiding unintended effects such as an overall increase of noise annoyance due to different AVAS would require a close alignment between regulations for different types of vehicles, but also comprehensive studies investigating the acceptance of soundscapes with a range of AVAS in operation.

10.5 Research and Policy Gaps

10.5.1 Drones and Other Electric Novel Aircraft

In 2020, the NASA Urban Air Mobility (UAM) Noise Working Group published the white paper *'Urban Air Mobility Noise: Current Practice, Gaps, and Recommendations'* (Rizzi et al. 2020). Although the focus of the white paper was UAM vehicles, i.e., aircraft for public transportation in urban settings, part of the gaps and recommendations are also of application for small to mid-size drones (i.e., below 600 kg of total weight including payload). This white paper overviews the current practice, identifies gaps, and makes recommendations in four areas of interest: (1) tools for acoustic prediction; (2) ground and flight testing; (3) human response and metrics; and (4) regulation and policy. Areas (3) and (4) are of more interest for this book chapter.

There is currently some regulation and guidance on drone noise measurements, for instance, the Commission Delegated Regulation (EU) 2019/945 of 12 March 2019, amended by the Commission Delegated Regulation (EU) 2020/1058 of 27 April 2020. This regulation requires the calculation of Sound Power Level (L_W) for drones in the 'Open Category' to be measured during hover above one reflecting (acoustically hard) plane, according to EN ISO 3744:2010. Regulation 2019/945 also includes maximum Sound Power Level requirements, as a function of the weight of the drone (always below 4 kg). For outdoor conditions, other guidance currently in place includes: 'Guidelines on noise measurement of Unmanned Aircraft Systems lighter than 600 kg operating in the specific category' developed by the European Union Aviation Safety Agency (EASA), the 'NASA UAM ground and test measurement protocol', and the ISO 5305:2024—Noise measurements for UAS (unmanned aircraft systems). These guidelines specify detailed methods for an accurate characterisation of the noise produced by drones under actual operating conditions outdoors. However, what these guidelines do not include are noise limits for drone operations, as they are set for other aircraft and rotorcraft.

The lack of noise limits for drone operations is probably due to the scarce evidence on human response to drone noise. Although the evidence of drone noise effects on humans is very limited, some conclusions can be drawn from the literature (Schäffer et al. 2021). For instance, drone noise is reported to be more annoying than road traffic and aircraft noise (at the same sound level) due to particular acoustic characteristics such as the dominant presence of tonal and high-frequency noise. However, other factors such as the influence of factual and situational context, existing soundscape and audio-visual interactions on noise effects of drones have not been explored to date. The need for further research to better understand the effects of drone noise on exposed communities includes the development of noise metrics to assess the community noise impact of drones; the definition of acceptable levels for drone noise; the development of noise abatement procedures for drone operations; and the innovation in approaches to predict the long-term effects of drone noise exposure (Torija and Clark 2021). The latter is of particular importance, as it will allow to define exposure–response relationships for drone noise, as a key to carrying out an appropriate management of the noise produced by drone operations.

10.5.2 Electric Ground Mobility

There are two important issues associated with the replacement of internal combustion engine vehicles with EVs: (1) the shift in the frequency spectra of EVs toward higher frequencies (compared to internal combustion engine vehicles), leading to a potential increase in noise annoyance and (2) the need to add artificial alerting sounds to EVs to enhance noticeability at lower speeds, potentially increasing noise annoyance due to the use of acoustics features such as pure tones (at relatively high frequency) and amplitude modulation.

Some research has been done to be able to tackle these issues (Pallas et al. 2016). Further research is required, but this is not a simple task due to the change in the contribution of dominant sources (at different speeds) compared to internal combustion engine vehicles, the uncertainty of differences in rolling noise in EVs compared to internal combustion engine vehicles (Marbjerg 2013), and the quantification of the contribution of artificially added alerting sounds to the overall noise emission of an EV. In addition to this, it is unknown how communities will respond to a soundscape composed of a multitude of several alerting sounds with different characteristics. Comprehensive research is needed to better understand the potential change in noise perception of road traffic when conventional low-frequency propulsion noise is replaced by alerting sounds using tonal, amplitude modulation, and other acoustic features to increase the noticeability of EVs.

Another issue to address is the lack of regulation for artificial alerting sounds for micromobility (i.e., electric scooters). As for electric cars, specific requirements for the acoustic features of alerting sounds in e-scooters are deemed necessary for vehicle manufacturers to ensure that their vehicles do not create a risk for pedestrians and other users of the public space. The expectation is to provide minimum requirements of sound emission, frequency content, temporal characteristics, and directivity to ensure an appropriate balance between maximum noticeability and minimum noise annoyance. The use of psychoacoustic methods as suggested by

Fiebig (2020), or implemented by Walton et al. (2022) should allow the careful design of alerting sounds including key acoustic features to increase vehicle detectability for pedestrians without necessarily leading to an increase in noise annoyance.

10.6 From Noise Control to Perception-Driven Acoustic Engineering

Transportation noise has traditionally been managed using a noise control approach. This approach is mainly based on an assessment of decibels received at a receiver position, using a suite of noise metrics based on A-weighted equivalent sound pressure level integrated over a given time period ($L_{Aeq,t}$), or in some cases like sleep disturbance, event-based metrics like A-weighted maximum sound level (L_{Amax}). After an assessment has been done, appropriate (ad-hoc) interventions are designed and implemented to correct any exceedances of existing noise limits set by regulation. Such an approach usually provides a limited scope for solutions, as meeting a compliance level in dB does not consider the quality of the sound, and might not allow to address the core issue and meet communities' requirements and expectations.

The transition towards e-mobility, could offer policymakers and urban planners more scope for positive choices in the design of the urban sound environment. The acoustic design of the next generation of EVs and Advanced Air Mobility aircraft needs to incorporate not just models of sound emission and propagation, but also models of sound perception to understand how the sound will integrate into the overall soundscape. Embedding these models of sound perception into the design of novel vehicles can allow their optimisation to meet noise targets and psychoacoustic constraints at a conceptual level, and therefore avoid more costly and challenging ad-hoc solutions.

After being introduced by Davies and colleagues at Purdue University in 2007 (Davies 2007), several researchers and engineers have adopted a perception-driven engineering approach as a way to integrate human factors and perception into the design of engineered systems, and also have developed tools for its implementation to aid the design of vehicles and transport infrastructures. Examples of the transition towards perception-influenced engineering, or perception-driven engineering as proposed here, are the development (and consideration) of Sound Quality Metrics for a more holistic assessment of how sound is perceived (compared to A-weighted sound pressure levels) (Boucher et al. 2019); the development and implementation of psychoacoustic models (Fastl and Zwicker 2006; Torija et al. 2022); and the development of auralisation tools for the simulation of the noise produced by a given vehicle under expected operating conditions (Aumann et al. 2015). These auralisation tools have been suggested as a key element of perception-driven design of new aircraft (Rizzi and Sahai 2019); and road traffic (Finne 2016) and railway (Pieren et al. 2016) infrastructures.

This perception-driven approach has also proven to be useful for the design of alerting sounds for electric scooters (Walton et al. 2022), where a psychoacoustic model was used to optimise the design for maximum detectability and minimum annoyance. Further research and innovation for the continued development of perception-driven methods seem to be an inevitable requirement for shaping the future of mobility.

Therefore, if current methods are not optimised for better integrating human factors into the design of engineering systems and living spaces, the current energy transition will likely cause unintended effects in the form of decreasing human health and well-being due to new and unconventional noise sources.

References

Administration NHTS (2016) Minimum sound requirements for hybrid and electric vehicles: final environmental assessment (Document submitted to Docket Number NHTSA-2011–0100. Report No. DOT HS 812 347). National Highway Traffic Safety Administration (NHTSA), Washington, DC, 2016

Alexander WN et al. (2019) Predicting community noise of sUAS. In: 25th AIAA/CEAS aeroacoustics conference. Delft, The Netherlands

Aumann AR et al. (2015) The NASA Auralization framework and plugin architecture. 2015.

Berge T (2018) Experience and perception of AVAS on electric vehicles in Norway. In: Internoise and noise-con congress and conference proceedings. 2018. Institute of Noise Control Engineering

Boucher M et al. (2019) Sound quality metric indicators of rotorcraft noise annoyance using multilevel regression analysis. In: Proceedings of meetings on acoustics 177ASA. 2019. Acoustical Society of America

Cabell R, Grosveld F, McSwain R (2016) Measured noise from small unmanned aerial vehicles. In: Inter-noise and noise-con congress and conference proceedings. Institute of Noise Control Engineering

Campello-Vicente H et al. (2017) The effect of electric vehicles on urban noise maps. Appl Acoust 116:59–64

Christian AW, Cabell R (2017) Initial investigation into the psychoacoustic properties of small unmanned aerial system noise. In: 23rd AIAA/CEAS aeroacoustics conference

Clark C, Stansfeld SA (2007) The effect of transportation noise on health and cognitive development: a review of recent evidence. Int J Comparat Psychol 20(2)

Cotta J, Breque M (2021) Industry 5.0 - towards a sustainable, human-centric and resilient European industry. 2021, Directorate-General for Research and Innovation, European Commission

Davies P (2007) Perception-based engineering: Integrating human responses into product and system design. Bridge, Nat Acad Engin 37(3):18

DfT (2021) Reported road casualties Great Britain: e-Scooter factsheet year ending June 2021. UK Department for Transport

DfT (2022) Government response to the e-scooter trials evaluation report. UK Department for Transport

EEA, Decarbonising heating and cooling — a climate imperative. 2023, European Environment Agency.

Fastl H, Zwicker E (2006) Psychoacoustics: facts and models. Springer

Fiebig A (2020) Electric vehicles get alert signals to be heard by pedestrians: benefits and drawbacks. Acoust Today 16(4):20–28

Finne P (2016) Road noise auralisation for planning new roads. In: Inter-noise and noise-con congress and conference proceedings. Institute of Noise Control Engineering

Govindswamy K, Eisele G (2011) Sound character of electric vehicles. 2011, SAE technical paper

Gwak DY, Han D, Lee S (2020) Sound quality factors influencing annoyance from hovering UAV. J Sound Vibrat 115651

Hanna R (2009) Incidence of pedestrian and bicyclist crashes by hybrid electric passenger vehicles

Hansen C, Hansen K (2020) Recent advances in wind turbine noise research. In: Acoustics. 2020. MDPI

Hubbard HH (1991) Aeroacoustics of flight vehicles: theory and practice. volume 1. noise sources. 1991, National Aeronautics and Space Admin Langley Research Center Hampton VA

Iversen LM, Marbjerg G, Bendtsen H (2013) Noise from electric vehicles-'State of the art'literature survey. In: INTER-NOISE and NOISE-CON congress and conference proceedings. 2013. Institute of Noise Control Engineering

KANTAR, Perceptions of current and future e-scooter use in the UK: Summary report. 2021.

Karaaslan E et al. (2018) Modeling the effect of electric vehicle adoption on pedestrian traffic safety: an agent-based approach. Transp Res Part C: Emerg Technol 93:198–210

Laib F, Schmidt JA (2019) Acoustic vehicle alerting systems (AVAS) of electric cars and its possible influence on urban soundscape. 2019: Universitätsbibliothek der RWTH Aachen

Lennström D, Nykänen A (2015) Interior sound of today's electric cars: tonal content, levels and frequency distribution. 2015, SAE Technical Paper

Lennström D, Ågren A, Nykänen A (2011) Sound quality evaluation of electric cars: preferences and influence of the test environment. In: Proceedings of the Aachen acoustics colloquium

Lennström D, Lindbom T, Nykänen A (2013) Prominence of tones in electric vehicle interior noise. In: International congress and exposition on noise control engineering: 15/09/2013–18/09/2013. 2013. ÖAL Österreichischer Arbeitsring für Lärmbekämpfung

Liu X, Bo L, Veidt M (2012) Tonality evaluation of wind turbine noise by filter-segmentation. Measurement 45(4):711–718

Liu C, Zhao L, Lu C (2022) Exploration of the characteristics and trends of electric vehicle crashes: a case study in Norway. Eur Transp Res Rev 14(1):1–11

Madsen PT et al. (2006) Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Mar Ecol Prog Ser 309:279–295

Marbjerg G (2013) Noise from electric vehicles–a literature survey. Report within Compett project, 2013

Miedema HM, Oudshoorn CG (2001) Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals. Environ Health Perspect 109(4):409–416

Mooney TA, Andersson MH, Stanley J (2020) Acoustic impacts of offshore wind energy on fishery resources. Oceanography 33(4):82–95

Muender M, Carbon C-C (2022) Howl, whirr, and whistle: the perception of electric powertrain noise and its importance for perceived quality in electrified vehicles. Appl Acoust 185:108412

Nguyen PD et al. (2021) Long-term quantification and characterisation of wind farm noise amplitude modulation. Measurement 182:109678

No, U.E.R., 138, Uniform provisions concerning the approval of Quiet Road Transport Vehicles with regard to their reduced audibility. Official Journal of the European Union, 2017. 13

Pallas M-A et al. (2016) Towards a model for electric vehicle noise emission in the European prediction method CNOSSOS-EU. Appl Acoust 113:89–101

Pedersen E, Persson Waye K (2004) Perception and annoyance due to wind turbine noise—a dose–response relationship. J Acoust Soc Am 116(6):3460–3470

Pedersen E, Waye KP (2007) Wind turbine noise, annoyance and self-reported health and well-being in different living environments. Occup Environ Med 64(7):480–486

Pieren R et al. (2016) Auralisation of railway noise: a concept for the emission synthesis of rolling and impact noise. In: Inter-noise and noise-con congress and conference proceedings. Institute of Noise Control Engineering

Rizzi SA, Sahai AK (2019) Auralization of air vehicle noise for community noise assessment. CEAS Aeronaut J 10(1):313–334

Rizzi SA et al. (2020) Urban air mobility noise: current practice, gaps, and recommendations

Schäffer B et al. (2021) Drone noise emission characteristics and noise effects on humans—a systematic review. Int J Environ Res Public Health 18(11):5940

Swart DJ, Bekker A, Bienert J (2016) The comparison and analysis of standard production electric vehicle drive-train noise. Int J Veh Noise Vib 12(3):260–276

Torija AJ, Clark C (2021) A psychoacoustic approach to building knowledge about human response to noise of unmanned aerial vehicles. Int J Environ Res Public Health 18(2):682

Torija AJ, Nicholls RK (2022) Investigation of metrics for assessing human response to drone noise. Int J Environ Res Public Health 19(6):3152

Torija AJ et al. (2019) On the assessment of subjective response to tonal content of contemporary aircraft noise. Appl Acoust 146:190–203

Torija AJ, Li Z, Self RH (2020) Effects of a hovering unmanned aerial vehicle on urban soundscapes perception. Transp Res Part D: Transp Environ 78:102195

Torija AJ, Li Z, Chaitanya P (2022) Psychoacoustic modelling of rotor noise. J Acoust Soc Am 151(3):1804–1815

Torija AJ, Li Z (2020) Metrics for assessing the perception of drone noise. In: e-Forum Acusticum 2020. 2020. Lyon, France: European Acoustics Association (EAA)

Torija AJS, Rod H, Lawrence Jack LT (2019) Psychoacoustic characterisation of a small fixed-pitch quadcopter. In: Inter-noise and noise-con congress and conference proceedings, InterNoise19. 2019. Madrid, Spain: Institute of Noise Control Engineering

Torija Martinez AJ et al. (2023) Generation and analysis of artificial warning sounds for electric scooters. In: Inter-noise and noise-con congress and conference proceedings. 2023. Institute of Noise Control Engineering

Verheijen E, Jabben J (2010) Effect of electric cars on traffic noise and safety

Wachter D (2009) Schallpegelmessungen an Elektrofahrzeugen („VLOTTE. Amt der Voralberger Landesregierung, Bregenz

Walton T, Torija AJ, Elliott AS (2022) Development of electric scooter alerting sounds using psychoacoustical metrics. Appl Acoust 201:109136

Waye KP, Rylander R (2001) The prevalence of annoyance and effects after long-term exposure to low-frequency noise. J Sound Vib 240(3):483–497

Wunderli JM et al. (2016) Intermittency ratio: a metric reflecting short-term temporal variations of transportation noise exposure. J Eposure Sci Environ Epidemiol 26(6):575–585

Yonemura M, Lee H, Sakamoto S (2021) Subjective evaluation on the annoyance of environmental noise containing low-frequency tonal components. Int J Environ Res Public Health 18(13):7127

Zajamšek B et al. (2016) Characterisation of wind farm infrasound and low-frequency noise. J Sound Vib 370:176–190