REVIEW ARTICLE

Technology-forcing to reduce environmental noise pollution: a prospectus

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BACKGROUND: Environmental movements of the late 20th century resulted in sweeping legislation and regulatory actions to reduce the prevalence of diverse pollutants. Although the consequences of noise pollution to public health, environment, and the economy have been recognized over the same time period, noise has received far less policy attention. Correspondingly, even while evidence of the diverse and detrimental effects of noise pollution on human health has grown, solutions and actual reductions in environmental noise remain seemingly out of reach.
OBJECTIVE: To address this shortcoming, we developed a prospectus for environmental noise reduction through technology-forcing policies. Technology-forcing describes intent to encourage technological solutions for pollution control through policy and regulations, and has been a critical component of national and global progress in reducing environmental pollutants.
METHODS: We take advantage of the unique policy history for noise in the United States - which initially enacted, but then abandoned federal noise regulation. We compare this history against outcomes from contemporaneous environmental legislation for air, water, and occupational pollution control, to demonstrate the potential for technology-forcing to reduce noise pollution. Our review then identifies promising solutions, in the form of existing technologies suitable for innovation and diffusion through technology-forcing regulations and incentives.
RESULTS: Based on this review, we outline a program for noise policy development to support efforts to reduce environmental noise pollution worldwide. The proposed program consists of three steps, which are to (i) identify dominant sources of noise pollution, (ii) combine legislative or regulatory provisions with suitable systems of enforcement and incentives, and (iii) anticipate and prepare for stages of technological change.
IMPACT STATEMENT: Analysis of noise policy often focuses on justifying the need to reduce noise pollution. In this article, we demonstrate how technology-forcing regulations could also promote much-needed innovation and diffusion of technologies to reduce environmental noise pollution. We first establish the potential for technology-forcing by comparing technology outcomes from environmental legislation passed contemporaneously to the inactive US Noise Control Act. We next review promising innovations available for diffusion in multiple sectors to reduce environmental noise. Lastly, we recommend a program to support development of technology-forcing noise policies, to help ensure that the benefits of reduced noise pollution are distributed equitably.

Keywords: Noise; Technology-forcing; Innovation; Policy; Public health; Economy

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INTRODUCTION

"The state of the art has tended to meander along until some sort of regulation took it by the hand and gave it a good pull." - U.S. Health, Education, and Welfare Secretary John Gardner, Congressional Hearing regarding automotive emissions, 1967.

The environmental movements in the latter half of the 20th century led to passage of national legislation and regulations to reduce many forms of pollution. Comprehensive legislation that was passed in the United States in the early 1970s included the Clean Air (1970), Occupational Safety and Health (1970), Clean Water (1972), and the Toxic Substances Control (1976) Acts. These pieces of legislation - which were considered highly progressive - helped spur adoption of legislation and policies in other regions and nations over the next several decades aimed at reducing public exposure to environmental pollutants. During this period, the hazards that noise pollution posed for public health were similarly recognized in the United States by passage of the Noise Control Act (NCA) of (1972). The NCA assigned the responsibility of setting noise product standards to the Environmental Protection Agency (EPA), along with other mandated responsibilities including providing technical, regulatory, enforcement, and educational support to states and localities. The initial implementation of the NCA led to the identification of noise thresholds for public health and safety, and issuance of noise standards for some products

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Box 1. Glossary of terms

noise pollution: unwanted sound that is considered harmful to human health
occupational noise: noise in or at a workplace, typically resulting from use of required machinery and equipment
environmental noise: ambient noise in any environment, from single or aggregate sources
invention: the first practical demonstration of an idea [123]
innovation: the first commercial application of an invention to the market [123]
diffusion: the spread of the innovation into the market [123]
technology-following: laws and regulations that encourage or require adoption of existing pollution control technologies [124]
technology-forcing: first appearing in judicial decisions related to the Clean Air Act (ca. 1975), refers to Congressional intent in creating laws and regulations to induce rapid improvements in pollution control technologies, often to reduce public health or environmental risks [125]
incremental innovation: adaptation of existing technologies or processes, to improve efficiency or broaden application [52]
transformative technologies: innovations that shift dominant technology, technology platforms, and infrastructure in industries [52]

within a relatively short time period. However, unlike its legislative contemporaries, the NCA was dogged by weak policy structure, lack of strong Congressional support, and eventual defunding of the administrative office tasked with implementation [1, 2]. Thus, despite a long understanding of the consequences of noise for public health, noise has not received the same regulatory attention. In fact, by defunding rather than repealing the NCA, Congress created regulatory gridlock, since states may not set competing standards for products that were federally regulated. At the time the Office of Noise Control was defunded, the EPA had promulgated standards for three products (motorcycles, medium/heavy trucks, and air compressors), preempting states from doing anything other than enforcing these now decades-old standards. Although the NCA does allows states to set environmental noise limits and regulate use, operation, or movement of products to reduce noise exposures, the wording of the Act specifically precludes competing regulation of interstate railroad or motor carrier noise [3, 4]. By defunding implementation and enforcement of the NCA, Congress limited states' abilities to address several dominant sources of transportation noise (trucks and railroads) and created regulatory confusion, while removing the federal resources that could support noise reduction and enforcement efforts at state and local levels [3].

The consequences of this action for public health, environmental sustainability, and the economy were far-reaching, not only for the United States but potentially worldwide. This is because stringent environmental regulations have the unique potential to result in technology-forcing, which can shape invention, innovation, and diffusion of technologies, often in rapid timeframes (Box 1). Technology-forcing is important not only for the capacity to substantially reduce pollution, but to incentivize and support transformative technologies, new markets and industries, and sustainable development [5–7]. Previous analyses of the consequences of defunding the NCA have assessed its policy limitations or issues with implementation, and emphasized the need for reinstatement to protect public health [2, 8, 9]. In this prospectus, we focus on illustrating the NCA as a critical missed opportunity to reduce noise pollution through innovation and diffusion of technologies over several decades. As we will describe, many of these innovations could help address the growing global issue of noise pollution and also offer co-benefits toward other environmental goals like reducing carbon emissions.

In the five decades since passage of the NCA, justification for addressing environmental noise pollution through regulation has strengthened, with increasing and indisputable evidence of the diverse and detrimental effects of noise on human health. Disparate studies have assessed or estimated that 15-20% of workers are exposed to harmful occupational noise [10], and globally, occupational noise exposure is estimated to account for 16% of all hearing losses [11]. Although hearing loss is too often disregarded as symptom of aging or a mere nuisance [12], it has dramatic repercussions on quality of life through reduced productivity [13], increased risk of accidents [14], social isolation, depression, and anxiety [15–17]. The impacts of noise on public health through increased annoyance and sleep disturbance have been directly measured for decades, and can even be predicted with some level of certainty for communities that are exposed to different noise sources and levels [18]. Noise is also strongly associated with development of cardiovascular diseases and impaired mental health [10, 19]. These and other health outcomes have been long demonstrated through cross-sectional studies, but are increasingly supported by more robust longitudinal studies. For example, 10 dB incremental increases in transportation noise exposure have now been shown to increase risk for developing hypertension [20], stroke and cardiovascular disease [21], severe postpartum depression and other mental disorders [22]; night-time aircraft noise exposure has been recently implicated even in increased risk of acute cardiac events and death [23, 24]. The diverse impacts of noise on communities also extend far beyond epidemiology; among the most poignant are the demonstrated impacts of noise on childhood learning, through impaired memory, comprehension, and delayed reading [25].

In this prospectus, we first demonstrate the missed opportunity for innovation and diffusion related to noise control, by comparing outcomes of technology-forcing in other sectors (i.e., air, water, and toxic substances) where legislation was passed and remained intact. We next identify and summarize technology and design opportunities that await sustained research attention and industrial development. We close by presenting a program to develop technology-forcing strategies and policies for noise pollution, based on key lessons drawn from implementation of other environmental legislation. Our goal is to support global efforts to reduce environmental noise pollution in ways that not only reduce costs for public health and environmental sustainability, but ensure that these benefits are distributed equitably. Although the focus in this article is on environmental noise (Box 1), we wish to note that our technology-forcing concepts and the process we develop is equally applicable to reducing noise exposure from any source, including occupational noise or noise from consumer products.

TECHNOLOGY-FORCING WORKS

Technology-forcing - defined as the use of laws or regulations to promote innovation or diffusion of technologies (Box 1) - is a widely accepted policy concept today, in part due to the environmental movements and legislation described above. The terminology first appeared in the course of legal challenges to the Clean Air Act (1970), and represented a judicial interpretation of Congressional intent [26]. Although it is well understood that regulation cannot actually force invention [27], numerous analyses of industry responses to environmental legislation over the last 50 years leave no doubt that regulation - or even anticipation of regulation - can stimulate innovation and diffusion of existing technologies. These can shift industries toward use of more effective and efficient pollution-control methods, or even development of entirely new technologies [5–7, 28, 29].

To demonstrate the potential for technology-forcing for noise pollution, we first generated timelines of technology-related provisions for influential legislative contemporaries of the NCA, which were the Clean Air Act (CAA), Clean Water Act (CWA), and Occupational Health and Safety Act (OSHA). To these, we conducted a literature review to map innovation and diffusion of pollution control technologies attributed to the legislation and regulatory schemes (i.e., system of enforcement and incentives) (Supplemental Figure S1). In doing so, we focus on what are generally considered successes in technology-forcing, while fully acknowledging that not all provisions influence technology development and that specific regulations can and have resulted in mixed or indifferent outcomes [26]. We then developed a similar policy and regulatory trajectory for noise pollution, and compared this against the timeline for the CAA (Fig. 1a-b), which is widely considered to have had far-reaching and influential impacts on technology development. Some amendments of the CAA also established mandates to monitor emissions; as a result, progress toward meeting National Ambient Air Quality Standards has been systematically tracked since the 1990s [30] (Fig. 1c). Although there is no national monitoring for noise - and, indeed, very few sources of long-term monitoring for noise at all - we generated a surrogate estimate of noise trends for the period of 1995-present, using available data from airport noise monitoring stations [31–33] (Fig. 1d).

Over the past 50 years, it is evident that the CAA amendments have resulted in multiple industrial transformations (Fig. 1a), which have included both substantive upgrades to the dominant technologies (i.e., the internal combustion engine) as well as supporting more revolutionary innovations and diffusion of battery-electric vehicles or BEVs [6, 34]. The initial technology advancements that reduced automotive emissions ultimately improved power and fuel efficiency of motor vehicles, which benefitted automakers [27]; similar benefits accrued to innovators and early adopters of clean technologies for stationary sources [35]. As with other types of industrial learning, the costs of pollution control have consistently come down with investment, use, and industry learning and knowledge transfer (i.e., progress ratios) [35–37]. Feedbacks such as these are common to the regulatory-innovation process, which can make it challenging to accurately determine and compare costs of compliance [36, 38]. However, economic analyses of the CAA generally conclude that the costs of compliance have been largely neutral over the long-term, resulting in net positive assessments when the immense societal benefits are considered [37]. Most importantly, despite increases in numbers and use of non-stationary (i.e., vehicles) and stationary (i.e., power plants) sources of air pollutants, emissions of a majority of air quality indicators regulated under the CAA have been strongly reduced over time (Fig. 1c).

In contrast with the CAA, we see the relatively stark progress in noise policy or regulations leading to innovation or diffusion of technologies over the same time (Fig. 1b). The contrast also demonstrates the fragmented nature of noise policy, which is implemented as a patchwork of legislation, implemented by multiple agencies. As discussed previously, the rapid Congressional abandonment of the NCA meant that the initial product standards identified and promulgated by the EPA were barely implemented or enforced [2]. The only non-aviation noise policy that can be considered technology-related is the Federal Aid to Highway Act of 1970, which banned federal funding for highways without plans and specifications for noise abatement. Since then, this criteria has largely been addressed through the construction of noise barriers [39].

The primary sector where noise policy has had some influence on technology is in aviation. In the US, early legislation authorized the Federal Aviation Administration (FAA) to create noise measurement standards and regulations for noise abatement; these have included developing processes to certify aircraft noise stages, land use recommendations, and noise mitigation programs (i.e., soundproofing) around civil airports. However, the FAA mandate to regulate and promote civil aviation for safety and efficiency, not environmental impact, is long recognized and criticized as a bottleneck to reducing aviation noise [2, 40]. Furthermore, aircraft are certified based on noise emission specifications set by the International Civil Aviation Organization (ICAO), with increasing noise reduction over time for specific aircraft classes. Therefore, the FAA (and other national ICAO members) are largely involved through establishing certification schedules for new aircraft, which are referred to as Stages by the FAA. Currently, new aircraft must meet Stage 5 requirements (corresponding to ICAO Chapter 14).

The FAA also applies these Stages to phaseouts of aircraft. For example, the legislated phaseouts of Stage 2 aircraft in the 1990s resulted in substantial noise reduction during this period, as reported by studies [41] and shown in our analysis of airport noise data (Fig. 1d). Today, the challenge facing the aviation industry is that phaseouts of Stage 3 or even Stage 4 aircraft would not result in appreciable reductions in overall noise levels, since a majority of Stage 3 certified aircraft would also meet Stage 4-5 requirements [41]. This corresponds with ICAO modeling that future scenarios based on even the most advanced aircraft technology and operational improvements will not keep pace with increases in air traffic [42]. Barring dramatic and unprecedented changes in aircraft noise policies related to technology development, noise from air traffic over time is predicted to increase [43].

Although availability of long-term noise data are limited, the history of relatively weak regulatory activity to reduce noise is borne out by monitored (Fig. 1d) or modeled data that do exist. Aviation and other transportation noise are readily modeled based on routing and operations data. e.g., [44]. Although efforts to assess change over time are challenged by lack of high-resolution spatial data and historical operations data, analyses that have been done indicate that community noise is generally increasing [45, 46]. Here, we want to acknowledge that although we make this comparison and assessment based on US policy, we believe that it is fairly representative of the current potential for noise policies to influence technology development worldwide. While research has shown that the social and political barriers to addressing noise pollution are higher in the US than in some nations and regions [47], stringent noise policies (i.e., with aggressive product standards or low environmental thresholds) of the type that incentivize innovation or diffusion of technologies are still the exception rather than the norm [48–50].

TECHNOLOGY SOLUTIONS TO REDUCE ENVIRONMENTAL NOISE

In engineering systems, noise is typically a symptom of design inefficiencies, resulting in air pressure fluctuations that propagate into the surrounding environment. In this section, we provide a comprehensive review of environmental noise sources, and specific noise control targets, with promising innovations that could be diffused under technology-forcing policies (Table 1). We also summarize the potential noise reduction offered by these innovations. However, we note that, more broadly, the inefficiencies in design that lead to noise often have other negative consequences, such as reduced output power relative to energy input (i.e., performance) or increased vibration and wear. For this reason, noise control solutions often offer synergistic benefits such as improved power efficiency, or reduced need for product maintenance.

Our review is intended to bring focus to opportunities for controlling major sources of environmental noise pollution, which are dominated by transportation platforms such as aircraft, vehicles, and trains [51]. For transportation platforms, there are two major types of noise, propulsion and aerodynamics (aero-acoustic). Propulsion noise is emitted mostly from the engine and exhaust systems, while aerodynamic noise is generated from the shape and geometries of the frame and wheels of a vehicle. Inefficiencies in design are manifested as vibrations of the moving parts, explosion in combustion or jet engines, or turbulent flow from suboptimal aerodynamics.

It is remarkable that even limited federal and industry investments in noise control research and demonstration have resulted in invention and innovation of feasible technologies that

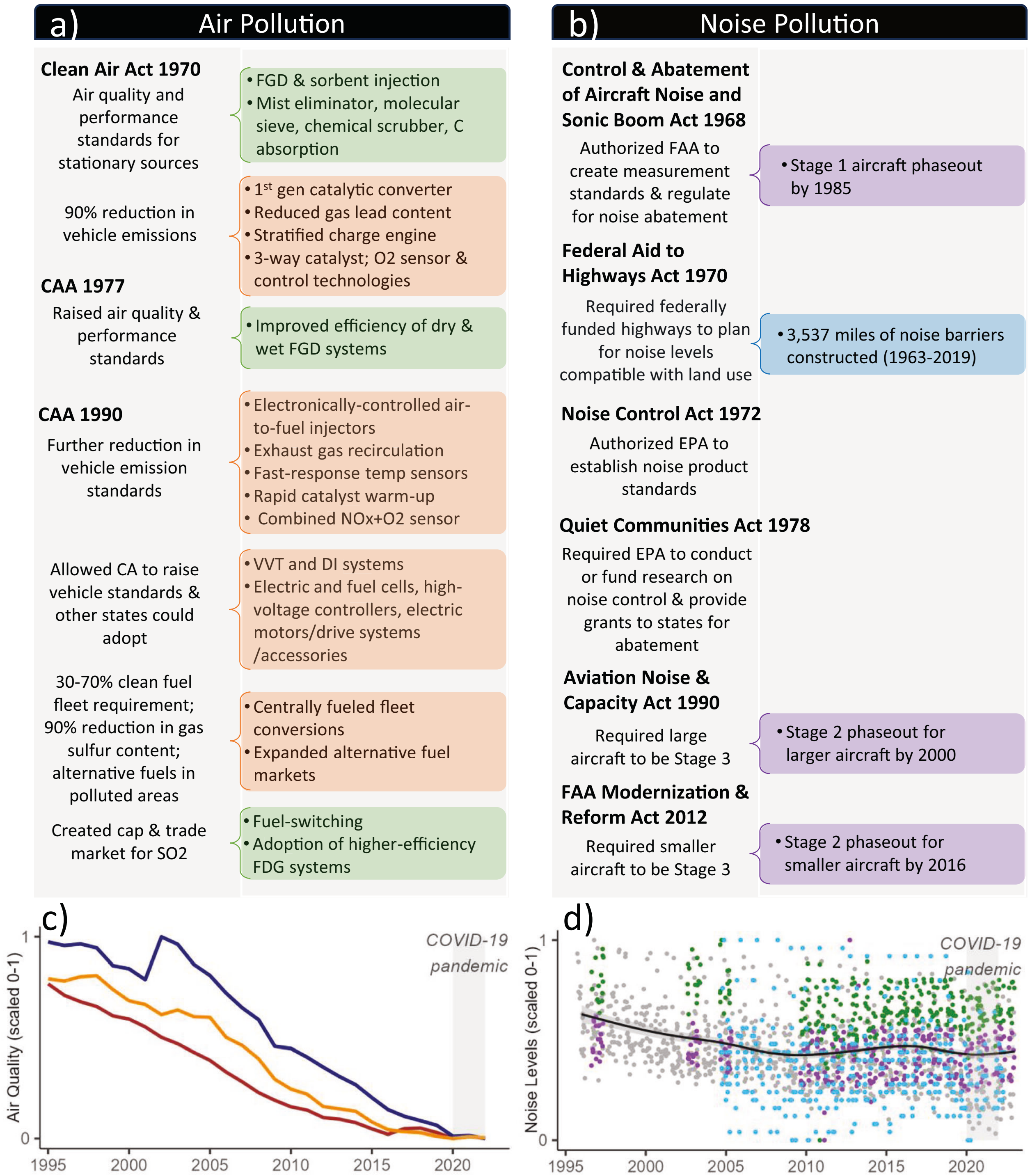

Fig. 1 Policy and technology development histories for (**a**) air and (**b**) noise pollution in the United States since 1965. Legislative provisions with the potential to impact innovation or diffusion of technologies are listed, with corresponding technology development that reduced emissions or exposure to pollutants from sources (colors: orange=vehicles, green=power plants, blue=highways, purple=aircraft). Comparison of (**c**) air pollutant and (**d**) noise levels based on available monitoring data between 1995-2023. Air quality data from national monitoring for CO (brown), NOx (dark blue), and SO2 (orange) from 1990-present [30] were normalized (scaled 0-1) to show trends. Noise measurements were compiled from networks of fixed noise monitoring stations maintained by ORD (grey) [33], IAD (green) [32], DCA (purple) [32], an LAX (light blue) [31] airports; as such, they reflect realized community noise levels over time, from aircraft as well as other noise sources. Annual noise level data for monitored locations were normalized within each airport dataset, and the combined trend is represented by a LOESS smoothing curve (black line); points are jittered to avoid overplotting.

Table 1. Noise control technologies suitable for innovation or diffusion, arranged by the source of noise environmental pollution.

Noise Source	Noise Control Targets	Technology-forcing opportunities	Potential noise reduction
Commercial Aircraft	Propulsion (includes engine, exhaust, auxiliary power unit)	Installing engining above wing or fuselage [64]	20–30 dB
		Hybrid power [94]	30 dB
		Active noise control algorithms [59], source identification [58]	Varies with application
		All-electric power [95–97]	50% at takeoff
	Airframe (includes landing gears)	Blended/Hybrid Wing Bodies [64]	30–50%
		Fairings, metamaterials, metasurfaces [98, 99]	Up to 10 dB
		Nano-composite materials [100, 101]	20%
		Slat-Gap Filler [102]	Up to 8 dB
		Energy Harvesters [103]	20%
Helicopters	Rotorsystem	Nano-composite materials [100, 101]	20%
		Airfoil with fringes [104]	3–5 dB
Unmanned aircraft		Phase synchronization [105], genetic algorithm for blade power management [56], location mapping [53], and feedback control [57]	12–30 dB
Civil airfield	Flight operations	Reduction or re-allocation of night flights, runway extensions, graded sound insulation, flight path optimization [106]	Up to 20% in population exposure
Military airfield	Flight operations	Multi-objective algorithms to optimize flight paths for reducing population exposure [54, 55]	Up to 50% in population exposure
Vehicles and Roads	Propulsion (includes engine, exhaust, auxiliary power unit)	Electrification [95–97]	3–15 dB
		Non-flow restriction silencers and materials selection (similar to aircraft) [107–109]	20–40 dB
	Tires	Tire tread pattern, air pumping, pipe resonance, Helmholtz resonance, and horn effect [110–112]	5–14 dB(a)
		Acoustic network resonators [113]	4–7 dB
	Pavement	Poroelastic pavement [114]	7–12 dB
		Embedded resonators [114, 115]	7–10 dB
Rail Transport	Rails	Structured polymer concrete sleepers [116]	2–4 dB
		Rubber-spring floating slab track [69]	15 dB
	Trams	Rail lubrication [117]	26 dB
	Elevated trains	Acoustic board and steel spring floating plate [118]	1–5 dB
		Track acoustic absorber, track side noise barrier [119]	1–5 dB
Construction/ Maintenance	Home maintenance equipment	Electrification [120]	6 dB
	Construction zones	Active noise barriers [60]	9–16 dB(a)
Industrial	Wind turbines	Condition-based maintenance of mechanical components [121]. Blade aerodynamic optimization [66]	Up to 9 dB
	Manufacturing & Power Plants	Retrofitting noise barriers, absorption materials, and condition-based maintenance [122]	2–50 dB

Examples of specific targets for noise control that can reduce noise emission from sources are selected, and corresponding opportunities to develop or diffuse existing innovations through technology-forcing. The potential source reduction (in dB or %) is shown, based on comparison with dominant technology; a range in dB reduction may reflect lack of consensus between studies, or size and velocity-dependent variation.

can substantially reduce noise. This is especially true in aviation. While the solutions shown in Table 1 have not yet been adopted by the industries responsible for the noise emissions, they show the significant potential noise reductions in many applications, which could be developed into less polluting products. It is useful to distinguish that these opportunities can represent incremental innovation as well as more transformative technologies (Box 1). For example, substantial noise from cars and trains is due to the inefficiency of their internal combustion (IC) engine. The primary solutions available are application of metamaterials, nonrestrictive flow to the exhaust system, or the use of an electric motor. Metamaterials and restricted exhaust flow would be considered incremental innovations, as they will only attenuate the noise produced by the existing source; however, they can be implemented with minimal modifications of the IC engine. Replacing the IC engine with an electric motor is a transformative technology, as it eliminates the existence of noise sources but may also require broader changes in accessories or supporting infrastructure [6, 28, 52].

Naturally, noise cannot always be eliminated or feasibly reduced through mechanical source control. However, technological opportunities are not only limited to mechanical source control, but include dynamic optimization methods that can reduce emissions and exposure of people to noise. Table 1 includes promising examples of computational advancements in data-driven, multi-physics, optimization algorithms, particularly for establishing flight path planning and routing that is optimized for noise mitigation. These algorithms can reduce exposures by incorporating location management to reduce exposures based on population size or noise-sensitive areas [53–55], vehicle power management [56], feedback control [57], and source identification [58]. Active noise control (i.e., anti-phase noise 'canceling') shows promise and has been explored for application in diverse contexts, including use in open spaces such as construction zones and highways [59–61]. However, as with mechanical source control solutions, these advancements also require investment and development for improving their efficiency and predictive reliability.

Clearly, the simple existence of these innovations does not mean they are or will be diffused into the marketplace. Many of the barriers are not technical, but rather political, or due to limited economic incentives [43, 62, 63]. The three major barriers revealed in this review are: (i) economic and political power of incumbency, (ii) limited entry points for diffusion; and (iii) structure of the certification process. For example, one of the major available transformative technologies that offers to reduce aircraft noise and fuel consumption by 30-50% is the Blended Wing Body and Hyper-blended Wing Body, developed and demonstrated by NASA [64, 65]. Incumbency is the primary barrier for diffusing these two engineering marvels, stemming from the dominating airline manufacturers' fear of disrupting the current economic ecosystem. This is based on the industry assumption that the minimum aircraft lifespan is 25 years before an overhaul. The reliance on large manufacturers to produce both aircraft - and the airport infrastructure to support them - correspondingly limits the entry points for technology diffusion.

Understanding and overcoming diffusion barriers is vital not only for addressing current noise sources, but for a growing suite of new sources. The innovations outlined in Table 1 are applicable to traditional noise sources and designs (e.g., cars, trains) as well as expanding and emerging systems. Fifty years ago, emerging and expanding noise sources came from the rise in recreational vehicles (e.g., power boats, ATVs, jet skis, snowmobiles) and personal devices or tools (e.g., boombox, leaf blowers, weed whackers) [9]. Today, new sources of concern include wind turbine farms [66], supersonic and hypersonic vehicles [67], drone swarms [68], and vertical takeoff and lift for urban travel and air-taxis [69]. The noise reduction innovations we describe are equally applicable to these new platforms, but are most effectively considered in the earliest stages of the design process. Lack of policies to incentivize noise control engineering means, however, that new noise sources are likely to be designed using the same engineering principles, and suffer from the same inefficiencies as traditional ones. Expanding or new sources simply means more noise, in new spaces.

Because noise control often addresses inefficiencies that also improve aerodynamics, performance, and vibration (i.e., wear), they represent exciting potential for spillovers into diverse industrial sectors and markets. Technology spillovers are not always well-documented, but recent strong trends in development of BEVs (Fig. 1a) offer examples of the potential for such transformative technologies to alter multiple sectors. For BEVs, these have included application to grid storage e.g., [70], improvement of BEV components for multiple industrial uses [71], and cross-sector incentives that drive co-adoption (e.g., BEVs and solar energy) [72]. In Table 1, the innovations having strong potential to diffuse across sectors include high-energy storage batteries, energy harvesters, and improvement in electric motors. Although slow, some diffusion of high-energy storage batteries and energy harvesters is already occurring in the energy, packaging, and satellite industries [73]. Better performing electric motors have the potential to substantially improve and expand multiple industries including automotive, aerospace, marine transport, and robotics [74].

Among these diverse and exciting cross-sector opportunities, we believe that there are particularly strong synergies between noise control engineering and any industries oriented toward decarbonization. Because noise control addresses and improves design inefficiencies, there is a strong coupling of innovations that reduce both noise and overall carbon emissions [43, 75]. We advocate that engineering and policy efforts to reduce environmental noise should cultivate partnerships with similar groups working to reduce carbon emissions and combat climate change, to simultaneously advance two agendas for sustainable development [7].

TECHNOLOGY-FORCING TO REDUCE NOISE POLLUTION: A WAY FORWARD

To outline how a technology-forcing approach differs from a general strategy of noise reduction, we developed a program for noise policy development that draws from the fifty-year histories of US legislation for air, water, and occupational safety (Fig. 1, Supplemental Fig. S1). Our purpose is not to detail the complex and dynamic responses of industry to regulation (e.g. [5, 34, 35]), or to evaluate the effectiveness of specific legislative provisions or regulatory structures, which has been done elsewhere [52, 76, 77]. It is rather to translate key lessons within these histories to inform strategic, pragmatic technology-forcing programs for noise. The proposed process consists of three steps or strategies: (i) identify dominant sources of noise pollution, (ii) combine legislative or regulatory provisions with suitable systems of enforcement and incentives, and (iii) anticipate and prepare for stages of technological change.

The first of these strategies is that technology-forcing is not generic, but *takes aim at dominant sources of a pollutant*, either in terms of the highest contributions to ambient levels or the most widespread impacts. This often has the uncomfortable result of focusing political and regulatory attention on a limited number of industries and manufacturers, as occurred with the automotive industry and power-plant generation under the Clean Air Act [5, 26, 27] or water treatment facilities under the Clean Water Act [52, 78]. However, this also results in focused (and sometimes coordinated) attention and investment - by both industry and government - toward innovation for specific control targets. An example of this was industry-led refinement of catalytic converters for internal combustion engines under the CAA, which was supported by government-led regulation of fuel content [52]. Importantly, a narrowed focus on specific control targets can also support regulators in countering information advantages held by industry and prevail against inevitable legal and political opposition [26, 27, 76].

A technology-forcing approach to noise pollution would therefore target the noise sources impacting the largest numbers of people, which is vehicle and road noise [79]. A secondary target would be aircraft noise, which impacts smaller proportions of the population, but results in the highest levels of annoyance and well-documented health consequences e.g., [80]. Review of design and engineering opportunities then offers a way to estimate the relative noise reductions that are available through innovation, whether through single or combined noise control targets. For example, although modifications to vehicle engines are an important target to reduce vehicle noise, quieter tires and pavements also offer substantial noise reduction (Table 1). An optimal technology-forcing strategy would therefore include vigorous product standards for engines and tires (e.g., through a reinstated EPA Office of Noise Control). However, it might also require use of quiet pavements in federally-funded (e.g., through amendment to the Federal Aid to Highways Act) or state-funded projects. Such criteria could be usefully refined around the idea of 'nonattainment' (noisy or noise-sensitive) and 'attainment' (quiet) areas, as was used under the Clean Air Act to target use of better control technologies in areas with dirty compared to cleaner air (Supplemental Fig. S1).

A second lesson is that *technology-forcing is not the outcome of a single law or regulation, but legislative provisions combined with a suitable system of enforcement and incentives, which collectively create an environment that favors innovation and diffusion of technologies*. It is important to recognize that technology-forcing can stem from a menu of possible policy options that include command-and-control approaches (i.e., enforcement of standards) as well as market-based approaches (i.e., incentives) (Supplemental Fig. S1). In the case of both automotive emissions and stationary sources of air pollutants, initial command-and-control was effectively followed by market-based regulations (e.g., cap and trade) [35, 37].

This flexibility allows tailoring of technology-forcing strategies to specific noise sources and contexts. It is also important to point out that technology-forcing strategies are not limited to national or federal action, but may be implemented by states, member countries, or other local jurisdictions (e.g., cities). This is particularly true in countries or regions where federal policies – whether by design or neglect - leave room for local promulgation and enforcement of noise standards [8, 47, 49]. For example, the current approach to reducing noise from aircraft is through international certification standards (i.e., product standards), with regional tailoring of operations by national agencies (e.g., the FAA). However, there is substantial scientific consensus that the potential to reduce noise through ongoing modification of existing aircraft designs has plateaued. Newer stages of aircraft are producing incremental noise reductions [81], and not at a pace to counter increasing air traffic [41, 42]. Rather than spend political and social capital pressuring ICAO and national agencies to make these incremental changes, a technology-forcing strategy might instead incentivize airlines and consumers toward adopting more impactful innovations (Table 1) through a typical "polluter pays" model, which is currently lacking for aircraft noise. One avenue to accomplish this is airport noise taxes [82], which can be enacted locally and revenues distributed based on local priorities (e.g., toward noise and/or carbon emissions abatement or research). Sufficient number of airport noise taxes could put pressure on airlines and consumers to support and advocate for more transformative aircraft that can considerably reduce both noise and carbon emissions [43, 65].

The third component of a technology-forcing strategy for noise is the recognition that *technology-forcing occurs over time and in stages, which includes initial industry opposition, followed by periods of innovation and diffusion that can shift industry trajectories in new directions*. The initial stage immediately following regulation (i.e., 5-10 years) is largely defined by opposition from industry (or environmental advocates) on technical and legal grounds [26, 34, 78]. Legislative and administrative responses may be required to adjust, clarify, or strengthen standards (Supplemental Fig. S1). Examples of these adjustments abound, such as when Congress and regulators delayed the initial time frame allowed to meet automotive standards under the Clean Air Act [27, 76], or reiterated initial deadlines under the Clean Water Act [78]. The outcomes of legal challenges and regulatory adjustments can have very important implications for technology-forcing [8, 26, 76]; however, the overarching point is that this stage is likely to be a period of high contention and sluggish innovation, when social and political support can wane.

Following stages of opposition and clarification, we can begin to see innovation and diffusion [34, 35], which can follow diverse and often exciting trajectories for both technology development and reduction of pollutants. The first of these consist of process changes and product substitutions that simply reduce use and exposure to pollutants, as occurred when standards under the Occupational Health and Safety Act led to process innovations that reduced worker exposure to asbestos, lead, and vinyl [52]. Regulation, however, can also lead to more transformative technological change, as when similar restrictions on cotton dust prompted both broad process innovation and diffusion of technologies that automated and modernized the cotton industry [52]. Technology-forcing histories not only offer abundant and rich examples of technology innovation and diffusion, but also strong evidence of net benefits to industry resulting from compliance. These benefits include increased efficiency, reduced operating or capital costs that emanate from systems review and research [35, 36], or competitive advantages in early adoption [34]. As with other types of industrial learning, pollution control costs consistently come down with investment, use, industry learning and knowledge transfer (i.e., progress ratios) [35].

Ideally, technology-forcing strategies for noise would be informed by and anticipate stages of opposition, innovation, and (potentially) transformative change. This could include actions like modeling scenarios based on alternative industry responses [34, 83], process vs. product innovations [52], and innovation efficiencies that accrue to industries [35, 36, 38]. Other preparation could include communicating realistic timescales for change to policymakers and the public.

CONCLUSIONS

Despite the meandering attention to noise policy, recent decades have seen social, economic, and technical changes that suggest renewed will to address noise pollution. The first of these is simply a growing public awareness of the extent of noise pollution and its impacts, in part due to growth of urban areas and transportation networks that have increased noise exposures for more people. Further, as noise monitoring costs have come down - even readily done by community scientists with smartphones - numerous studies have drawn attention to pervasive noise impacts for both people and wildlife, including in wilderness and protected areas [84, 85].

In parallel, evidence of the negative impacts of noise for both public health and the economy has amassed. Even as the US has retreated in its leadership of noise, environmental policies enacted elsewhere have spurred research on noise pollution [50]. A key example is the European Environmental Noise Directive of 2002, that has required and supported development of systematic methods to monitor, map, and plan for noise abatement [51]. Research in these areas has led to methods that can reliably estimate population exposures to noise, while research into specific health consequences has supported development of exposure-response relationships that can be translated into population health risks [80, 86]. Collectively, these advancements mean that we can not only assess the prevalence of noise at large scales, but also quantify health risks e.g., [87] and the economic costs for public health e.g., [88], use of public spaces e.g., [89] and property values e.g., [90].

From a technology-forcing standpoint, one of the most important outcomes of this recent research is awareness that, like other forms of pollution, noise and its impacts are disproportionately borne by socioeconomically disadvantaged people [91]. While much remains to be understood in how noise impacts different demographic groups and intersects with other types of environmental stress [92], we assert that the environmental justice implications elevate the need for technology-forcing noise policies. Although technology should never be considered a panacea for pollution control [36], it does offer equitable solutions that make the benefits of noise control and abatement available to all, not only those who can afford them. Recent decades have seen many calls for reinstatement of the Noise Control Act in the United States [8, 93], and for new or strengthened policies worldwide [50]. We recommend that these efforts should focus on technology-forcing strategies that can tap enormous potential to reduce noise equitably, while also supporting economic growth through creation of new markets, jobs, and industries that are oriented toward sustainable development [7].

DATA AVAILABILITY

All data used in this manuscript are publicly available, and appear as citations in the References.

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AUTHOR CONTRIBUTIONS

LMK, EH, and TME conceived and designed the work, acquired data, interpreted results, drafted and revised the manuscript. SJO assisted with manuscript development, interpreted results, assisted with drafting and revision, and approved the final manuscript. All authors are accountable for the accuracy and integrity of the work.

COMPETING INTERESTS

The authors declare no competing interests.

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