Traffic noise and violence: empirical evidence from England

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ABSTRACT

Despite the vast research on traffic noise exposure's physical and mental outcomes, little was known about its effect on violent crimes. To address this question, We compared the number of violent crimes committed in areas targeted by the second-round noise action plans (adopted by DEFRA in 2014) to those committed in untargeted areas prior to and following the intervention from 2012 to 2017. The precise locations of noise action plan-affected areas and crime records were extracted from the Strategic Noise Mapping and Street-level Crime databases, respectively. We aggregated these data and other control variables at LSOA level (a small neighbourhood level) for England. The results of the Poisson random-effects models showed a 6.20% reduction in average ambient traffic noise category and 3.54% less violent crime after the intervention compared to untreated areas between 2012-2017. We found no reduction in violence in untreated areas with high traffic noise levels but no relevant noise-reduction interventions, and no evidence of any reduction in non-violent crimes after the interventions. We concluded that exposure to traffic noise was associated with an increased risk of violent crime.

INTRODUCTION

It is well recognised that exposure to traffic noise may disrupt daily activities, cause annoyance and affect sleep. The risk of developing hypertension, myocardial infarction and other health conditions has also been linked to noise exposure. However, the potential for noise exposure to have a detrimental effect on people's behaviour has not been appreciated, despite the fact that a sizable portion of the urban population is subjected to relatively loud traffic noise on a daily basis. It is plausible to suggest that noise annoyance and sleep disturbance may contribute to an elevated state of excitation and feelings of anger [1, 2]. Meanwhile, urbanisation has increased people's proximity to one another, making social interactions almost unavoidable. When these two factors are considered together, we hypothesise that exposure to traffic noise could result in an increased risk of violence in the population.

Some early experimental studies established that excessive noise can have a detrimental effect on participants' willingness to assist others [3, 4] and facilitate further aggression in previously angry individuals [5, 6]. While these studies focused on experimental environments with a relatively high noise threshold, the biomechanics of noise-induced annoyance and aggression via the release of stress hormones may be comparable in experimental and real-world settings. As a result, it was difficult to rule out the possibility that daily exposure to loud traffic noise may exacerbate hostility in some individuals, particularly those already involved in provocation, dispute, or hostility.

Despite the plausible theoretical link between noise exposure and violence, this subject has remained largely unexplored by empirical studies. The question did, however, have a significant policy implication, as the number of violent crimes committed in England has increased significantly in recent years. According to Home Office – Police recorded crime data, in 2011, police in England and Wales (excluding Greater Manchester Police) received reports of 15,377 assaults resulting in injury and assaults with the intent to cause serious harm. The same number increased by almost 26.9% to 19,511 in 2018. Street-level data showed that in 2017, violent and sexual crimes accounted for nearly 22.7% of all crimes reported to police. Home Office estimated in 2018 that violent crimes costed nearly three-quarters of all individual crime in England [7]. Given the high economic and social costs of violent crime, identifying potential predictors of violent crime was an important first step toward resolving the crisis.

This motivated us to conduct this interventional study in order to evaluate the association between exposure to traffic noise and violent crime. We used natural experiment that occurred in England from 2012 to 2017 to identify the relationship between noise exposure and violent crimes. The Department for Environment, Food and Rural Affairs (DEFRA) carried out England's second round of noise mapping in 2012 and then adopted a series of noise action plans in 2014 to address noise pollution caused by road and rail vehicles in 894 out of 1,974 Important Areas (defined as home to the top 1% of the population affected by the highest levels of road and railway traffic noise, as defined by noise action plans) in the country.

The assignment of treated IAs was contingent upon an investigation of the noise problem by relevant authorities and an evaluation of the financial viability and feasibility of measures advised by noise action plans. Specific strategies for reducing road traffic noise included tyre regulations, wall and fence installation, insulation, and road surface replacement with a less noisy material. The proposed measures for rail traffic noise reduction included the use of quieter train components, the installation of walls and fences, as well as compensation and insulation schemes. The treatment assignment and measurements appear to be exogenous to air pollution and socioeconomic conditions.

As a result, we took the advantage of this quasi-experiment to identify the association between traffic noise and violent crimes.

METHODOLOGY

We examined the second cycle of noise action plans, which spanned the years 2012–2017. Two rounds of noise mapping were conducted in 2012 and 2017, allowing for an assessment of the trend in noise exposure across the country. DEFRA has published precise locations of IAs that have been treated by relevant authorities. This led us to investigate the association between noise exposure and violent crimes using a difference-in-differences approach.

Study country and period

England was the research country. We focused on the period between 2012 and 2017, which covered the entirety of the round 2 noise action plan cycle. We excluded years prior to 2012 and after 2017 because interventions from the first (prior to 2012) and third rounds (since 2017) may introduce further endogeneity.

The geographic unit

We chose to analyse evidence aggregated at Lower Layer Super Output Areas (LSOAs) for the following reasons. In England, there were 32,844 LSOA areas with an average area of 3.97 km^2 and a population of between 1,000 and 3,000 people [8].

The treatment and control groups

We identified 1,924 LSOAs that overlay any of the 894 intervened IAs that were treated in whole or in part by relevant authorities (IAs classified as "A" or "AB"). According to Strategic Noise Mapping data, the letter "A" indicated that the action could be carried out and that the necessary financial resources were available. "B" indicated that action could be taken but funding would not be available immediately. "AB" denoted that both "A" and "B" were applicable; a portion of the IA may be treated due to readily available funding, but not the entire IA.

These treated LSOAs were primarily concentrated in major urban areas. Almost half of the treated LSOAs (N=950) were located in metropolises such as Greater London, Greater Birmingham and Greater Manchester as well as their surrounding regions such as Hertfordshire, Staffordshire, Central Bedfordshire and Essex. Our control group consists of the remaining 30,920 LSOAs.

Data

The measures of violent crimes

We obtained crimes from Street-level Crimes database, which provided detailed geographic information on types of crimes reported to police each year. The complete list of types of crimes and their definitions were available in Appendix Table 1. We used the number of violent and sexual crimes, a category of crimes that included all assaults on people [9], as our primary outcome due to its significant economic and social cost. We also examined public order and weapons offences, which encompassed a broad range of offences sometimes involving unlawful aggression but resulting in harassment and stress, among other consequences [10].

We also looked at other types of crimes that were likely to be less associated with aggression and anger than violent crimes. This included various financially motivated crimes such as burglary, drug offences, robbery, shoplifting, vehicle offences, and other thefts. We examined anti-social behaviour, which was a broad category that encompassed petty crimes such as begging, smoking in public places, graffiti, and littering, and criminal damage and arson, which included both intentional or reckless property damage and arson. We performed sensitivity analysis on these alternative types of crimes to better understand pre-existing trends in crimes in treated LSOAs compared to control LSOAs following the intervention.

Control variables

We attempted to account for as many socioeconomic variables as possible in our analyses. We obtained the annual fuel poverty rate at the LSOAs level. We used the annual unemployment rate for those aged 16 to 64 and the rate of people without any qualifications at the Local Authority District (LAD) level. We included total spending on social services per resident at the LAD level.

We extracted the rate of mental depression reported by NHS Clinical Commissioning Groups (CCGs).

To account for local demographic conditions, we included the male and 15–24-year-old population percentages.

We obtained DEFRA's background $PM_{2.5}$ and NO_2 concentration maps to control for air quality.

We controlled for the number of premises licences per 1,000 residents in each LAD, where premises licenced venues included supermarkets, pubs, bars, restaurants, and temporary events permitted to sell alcohol. The data on premium licences spanned the years 2012 to 2017, with the exception of 2015. We used the 2016 values as the data for 2015.

Annual police officer-to-1000 residents ratios by Police Force Areas were obtained to account for an individual's likelihood of being apprehended.

Finally, we used the 2011 rural-urban classification, which classified LSOAs into eight rural-urban classifications according to their physical settlement and associated characteristics. The complete list of classifications was available in Appendix Table 2.

These variables were either at LSOA, LAD, Police Force or CCG. Each LSOA uniquely belongs to a LAD, a Police Force level and a CCG. This allowed us to merge these variables in a file for analysis. The sources of these variables were presented in Appendix Table 3.

Basic specification

The econometric model was specified as following

$$crime_{it} = \alpha + \beta_1 post_{it} + \beta_2 treat_{it} + \beta_3 post_{it} \times treat_{it} + \Gamma \times X + \varepsilon_{it} \quad (1)$$

where i and t refers to LSOA, and year respectively. $crime_{it}$ was the annual total count of violent crimes reported. The $treat_{it}$ dummy was set as 1 if the LSOA was in the treatment group, and 0 vice versa. The $post_{it}$ dummy was set to 1 if $year > 2014$ and 0 otherwise. The difference-in-difference dummy was created as $post_{it} \times treat_{it}$. X denotes the control variable matrix. We controlled for Local Authority Districts fixed effects and year-specific fixed effects.

We analysed our data using Poisson random-effects because the number of violent crimes was count data. This was also because LSOAs were nested within higher-level administrative units such as Local Authority Districts and Police Areas, and random-effects models allowed for the use of this significant higher-level hierarchical variation [11]. On the other hand, the random effects model assumed that individual-specific effects were uncorrelated with the independent variables. Violation of such an assumption may result in an inconsistency in the estimator. As a result, we included results from a Poisson fixed-effects model that did not make this assumption to assess our findings' robustness.

When the dependent variable was the number of crimes, the exposure variable was set to the total population per LSOA, which converted the absolute count to a rate. The primary parameter of interest was β_3, which represented the difference in change in the number of violent crimes committed in the treatment group versus the control group prior to and following the adoption of action plans in LSOAs. We expected a negative value for β_3 due to the assumed effect of traffic noise on violent offences. We reported the incidence rate ratio, 95% confidence intervals, and significant levels.

Validating the identification assumptions

The difference-in-difference approach required the parallel trend assumption that there must have been no systematic pre-existing trend that could have resulted in a difference in the number of violent incidents in treated and untreated LSOAs. To check this assumption, we began by plotting the annual average of violent crimes committed per 100 residents by LSOAs in both treatment (red) and control groups (blue) from 2012 to 2017 in Appendix Figure 1. We observed that the total number of reported violent crimes was consistently higher in treated LSOAs than in untreated LSOAs. This was likely because treated LSOAs were more frequently found in England's major urban areas with high mobility and population density. While the distance between the two lines appeared to be unchanged prior to 2014, it noticeably narrowed thereafter. Thus, this plot suggested that there were perhaps no pre-existing trends that would close the violent crime gap between treated and untreated areas after 2014.

We also included leads and lags in Equation (1) by intersecting $treat_{it}$ by year dummies (2012–2017), rather than $post_{it}$, to compare pre- and post-treatment trends [13]. The graph was presented in Appendix Figure 2 but full results were available in Table 4. We discovered that all of the coefficients were positive, which was consistent with our previous findings that metropolitan areas experienced a higher rate of violent crime than suburban and rural areas. We observed a relative stable risk of violent crimes in treated LSOAs when compared to control LSOAs between 2012 to 2014, indicating that if the trend had continued, the difference in risk would not have decreased abruptly. As the interventions took effect, the risk of violent crimes in these treated LSOAs, compared with control LSOAs, declined significantly from 1.121 in 2014 to 1.043 in 2017. Our overall evidence thus supported the pre-trend common assumption might hold.

Sensitivity analysis

Given that treated LSOAs were more likely to be found in major metropolitan areas, there was a concern that other unobservable crime-related factors such as a lack of social integration [12], ethnic concentration and family disruption [13], and a change in general deterrence in a jurisdiction [14] etc. could occur concurrently during the same time in metropolitan areas in England. With this in mind, we conducted a series of sensitivity analyses to understand whether these unobservable factors could explain away the identified negative impact of noise intervention on violence.

Alternative treated LSOAs

We used the 1,080 second-round Important that fall into categories “B” “C'”, “D'” and ”E” as an alternative treatment group. “B” indicated that action could be taken but that funding was not immediately available. “C” and “D” were two types of IAs in which actions cannot be taken due to technical constraints or the possibility of causing adverse non-acoustics effects, respectively. IAs was classified as an “E” if the IAs do not require treatment, following an investigation.

This resulted in 1,954 LSOAs that contained noisy IAs, but the noise level within the unit should not be reduced in a systematic manner as a result of the lack of actual intervention. Due to the concentration of these LSOAs in urban areas and near busy roads and railway tracks, they should exhibit similar characteristics, such as urbanisation, socioeconomic conditions, and community structure to treated IAs. The findings from these untreated IAs could provide additional evidence regarding the general trend toward violence in urban and well-connected areas.

Alternative types of crimes

The second sensitivity analysis examined the association between noise intervention and all non-violent crimes, including those motivated by financial gain, anti-social behaviour, and criminal damage and arson. Unobservable risk factors were expected to be associated with a wide variety of types of criminal behaviour. If there were significant changes in these unobservable factors that could account for the negative relationship between noise intervention and violence, there would also be negative relationships between noise intervention and a variety of other types of crimes.

RESULTS

The descriptive statistics of the variables included in the analysis were presented in Appendix Table 2.

Main results

The main findings were summarised in Table 1, where Column (5) contained the results of a regression on a full specification, as specified in Equation (1). The coefficient indicated that the risk of violent crime had decreased by 3.54% in treated LSOAs since the noise action plans were implemented, compared to untreated LSOAs. Columns (1), (2), and (3) summarised the results of various specifications. The incidence risk ratio for treated LSOAs, compared to control LSOAs following 2014 were 0.925, 0.925 and 0.974 in (1), (2) and (3), respectively; all were statistically significant. Interestingly, the results in Column (4) used a fixed-effects model rather than a random-effects model. In contrast to a random effects model, a fixed effects model did not rely on the assumption that individual-specific effects were uncorrelated with the independent variables. The coefficient had a value of 0.965, which was very close to the value estimated using a Poisson random-effects model. The overall findings supported a robust conclusion that traffic noise intervention may be negatively associated with violence.

Table 1 The main results regarding the effect of noise action plans on violence

Dependent variable: violent crimes					
	(1)	(2)	(3)	(4)	(5)
Variables	Poisson RE	Poisson RE	Poisson RE	Poisson FE	Poisson RE
$Post$	1.645***	2.116***	1.011***	1.228***	1.270***
	(1.635 - 1.655)	(2.097 - 2.135)	(1.004 - 1.019)	(1.192 - 1.264)	(1.233 - 1.308)
$Treatment$	1.225***	1.151***	1.187***		1.118***
	(1.144 - 1.312)	(1.093 - 1.212)	(1.123 - 1.256)		(1.064 - 1.174)
$Post \times Treatment$	0.925***	0.925***	0.974**	0.965***	0.965***
	(0.904 - 0.947)	(0.904 - 0.946)	(0.952 - 0.996)	(0.944 - 0.986)	(0.944 - 0.986)
Constant	0.011***	0.013***	0.001***		0.002***
	(0.011 - 0.011)	(0.010 - 0.016)	(0.001 - 0.002)		(0.001 - 0.003)
Observations	197,056	197,056	179,125	178,924	179,125
Number of lsoa	32,843	32,843	32,066	31,882	32,066
Control variables	No	No	Yes	Yes	Yes
District FE	No	Yes	No	Yes	Yes
Year FE	No	Yes	No	Yes	Yes
Wald Chi2	958834	1.269e+06	1.014e+06	39105	1.364e+06

Incidence risk ratio and 95% CI in parentheses

*** p<0.01, ** p<0.05, * p<0.1

The association between noise intervention and noise exposure, poverty and air quality

We performed regressions on Equation (1) but replacing violent crimes with ambient $Lden$ traffic noise class, air pollution, and fuel poverty rate to determine the associations between noise intervention and these three variables. The noise data were obtained from Strategic Noise mapping via DEFRA. The description of noise data that were used in this analysis can be found in Appendix Table 2. Since traffic noise data were only available for 2012 and 2017, we matched these data to other variables for the same years.

Appendix Table 4 summarises the associations between noise intervention and noise exposure, poverty, and air quality. Column (2) showed that after 2014, the interventions cold be related to a nearly 6.20% reduction in the class of traffic noise in the treated LSOAs compared to the control LSOAs.

Interestingly, unlike noise pollution, the adoption of noise action plans seemed to have no negative relationship with air quality or poverty. The dependent variables in Columns (3)-(5) were $pm_{2.5}$, NO_2, and the fuel poverty rate, respectively. Instead of Poisson random-effects models, we used random-effects General Linear models with a log-link and a Poisson distribution because Poisson random-effects approach failed to converge. After 2014, treated LSOAs experienced increases in $pm_{2.5}$, NO_2, and fuel poverty of nearly 1%, 1.2% and 1.3%, respectively, compared to the control group.

The association between noise intervention and violence in untreated but identified IAs

There was concern that some unobservable factors might account for the relationship between noise intervention and violence. As a result, the sensitivity analysis was conducted, in which alternatively treated LSOAs were used in the regressions. These alternative treatment group included 1,954 LSOAs that covered 1,080 second-round Important Areas that were untreated by relevant authorities. In this paper, we referred to these LSOAs in the alternative treatment group as untreated but noisy LOSAs for convenience. These untreated but noisy LSOAs scattered in a broader area of England, in part because untreated IAs outnumbered treated IAs by 186. Approximately half of the LSOAs in this group (N= 825) were located in Greater Manchester, Greater London, Greater Birmingham, Leeds, and Southampton, as well as their surrounding regions such as Hampshire, West Yorkshire, Hertfordshire, Essex, Staffordshire, Surrey, and Kent.

Column (1) and (2) in Appendix Table 5 presented two separate regression on Equation (1) but using LSOAs containing untreated IAs as the treatment group.

The dependent variables were average ambient all-day traffic noise classes in (1) and violent crimes in (2). The results indicated that noise intervention was associated with an almost 8.11% increase in noise exposure in these untreated but noisy areas following 2014, when compared to control areas. This was consistent with our expectation that only treated LSOAs would experience a decrease in noise level as a result of intervention. As expected, there was no significant relationship between noise action plans and violence in these untreated but noisy LSOAs when compared to the control LSOAs.

The association between noise intervention and other categories of crimes

We examined the effect of noise intervention on financial crimes, anti-social behaviour, criminal damage and arson in order to gain a better understanding of the overall trend in crime in treated LSOAs.

Financial motivated crimes included drug offences, burglary, robbery, shoplifting, vehicle offences and other thefts. Our results in Appendix Table 6 illustrates the intervention has an insignificant correlation with drug offences, vehicle offences, burglary and other thefts. We observed an increase in robbery and shoplifting in treated LSOAs compared to control LSOAs after 2014. The direction of the association, however, was actually in the opposite direction of what we discovered for violent crimes.

We also looked at the association of the noise action plan with anti-social behaviour, and criminal damage and arson. The definitions of anti-social behaviour and criminal damage and arson implied a weak relationship with annoyance-induced aggression, we expected an insignificant association between noise action plans and these two types of crimes, which our results confirmed.

Interestingly, we discovered that after 2014, traffic noise interventions could be associated with a nearly 6.9% reduction in public order and weapon offences in treated LSOAs compared to control LSOAs. The magnitude of the correlation was greater than violent crimes. By definition, public order and weapons offences was a broad category of crimes that involve unlawful violence without an identifiable victim. Thus, the findings suggested that traffic noise may have a greater association with a less severe form of violent crime.

DISCUSSION

The purpose of our paper was to investigate the association between traffic noise produced by road and rail vehicles and violent crimes. The adoption of noise action plans in 2014 to reduce noise from road vehicles and trains in England's Important Areas provided an opportunity to examine the cause-and-effect relationship between noise intervention and violence using a difference-in-difference design. We aggregated street-level crime data and other control variables at LSOAs. This dataset contained information on approximately 5.4 million violent crimes that occurred in England between 2012 and 2017.

By using a Poisson random-effects model to analyse the data, results revealed that the implementation of the second round noise action plans could be associated with a nearly 3.54% reduction in risk for violent crimes in treated LSOAs compared to control LSOAs after 2014. This was consistent with our findings that treated LSOAs enjoyed nearly 6.20% lower in the average ambient all-day traffic noise exposure classes following intervention when compared to control LSOAs over the same period. We also found both air quality and poverty have deteriorated in these treated LSOAs over the same period, which implied that the decline in violence in these intervened areas might not be due to improved air quality or socioeconomic conditions.

We chose the difference-in-difference approach over other quasi-experimental designs, such as regression discontinuity and Instrument Variable (IV), because DEFRA has published high-quality data on the locations and timing of treatment of Important Areas. Relevant authorities' measures to treat noise pollution appear to have a very weak correlation with air pollution, socioeconomic status, and other broad crime-related factors. This may help disentangle the effects of noise pollution, air pollution, and poverty. Although we had noise exposure data for 2012 and 2017 derived from Strategic Noise Mapping, the accuracy of the noise data might be compromised due to the data being simulated using major road traffic flow only. As a result, both IV and regression discontinuity approaches that used noise exposure data may be unable to account for measurement error. Bakolis et al. (2016) used regression discontinuity to examine the short-term health effects of legislation by comparing the outcomes before and after an exposure window [15]. However, in our study, the intervention was introduced gradually into the treated IAs; establishing an exact exposure window was particularly challenging.

One source of concern was that these treated LSOAs were located in urban areas, close to railway or road networks. Unobservable factors that could negatively impact violent crimes might occur concurrently and lower the violent crime rate in the area. Our treatment group included 1,924 small neighbourhoods known as LSOAs (5.85% of all LSOAs in England) located throughout England. These LSOAs belonged to a variety of local governments, the majority of which were urban. Significant changes in urban-related factors such as social integration, ethnic concentration, family disruption, and general deterrence in the jurisdiction were unlikely to occur in these treated LSOAs only but not in adjacent untreated and noisy LSOAs (neighbourhoods that contained untreated IAs). However, we discovered no evidence of a link between noise intervention and untreated but noisy LSOAs. The primary distinction between treated and untreated but noisy LSOAs was that the former areas were subject to noise action plans, whereas untreated but noisy LSOAs were not. The contrast suggested that the decline in violence among treated LSOAs was not coincidental and could be attributed to the implementation of noise action plans that might have reduced the level of noise in treated areas.

Another important reason leading us to think there was a causal relationship between noise and violence was that we discovered a negative correlation between the adoption of noise action plans and violence and public order offences, but not with other types of crimes. We made no argument that financial crimes, anti-social behaviour, and criminal damage and arson had nothing to do with noise-induced annoyance and anger. Instead, we reasoned that they might have a weaker association with anger and annoyance than violent crimes do. A larger proportion of financially motivated crimes, anti-social behaviour, and criminal damage and arson could be categorised as controlled-instrumental aggression, which was defined by a relatively unemotional display of aggression directed toward accomplishing a goal [16].

Thus, other factors than annoyance and anger may have played a greater role in these types of crimes. For example, financially motivated crimes were more associated with economic activity [17, 18] and income inequality [17]. In particular, studies have concluded that drug offences were more likely to be motivated by an immediate economic need [19]. Anti-social behaviour was increasingly a problem of youth [20]. Factors such as availability of drugs, dysfunctional family, low educational attainment, a lack of community attainment, and disorganisation in the community may be important contributor to anti-social behaviour [21]. Criminal damage and arson were motivated behaviour [22].

These controlled-instrumental crimes were distinguished from violent crimes and public order offences by that the latter two types of crimes involved a greater proportion of impulsive emotional violence, which occurred suddenly in response to some perceived threat, provocation, or insult [16]. Several of the factors affecting controlled-instrumental aggression may also contribute to impulsive emotional violence. If impulsive emotional violence was not more strongly associated with annoyance and anger, its relationship with noise intervention would be similar to that between financial-motivated crimes, criminal damage and arson and anti-social behaviour – either insignificant or positive. We instead discovered a negative correlation between noise intervention and violent crimes as well as public order and weapon violations, suggesting that annoyance and anger, two negative emotions commonly associated with noise exposure, may contribute significantly to the identified negative association.

The release of stress hormones can explain the biological mechanism by which traffic noise-induced annoyance and anger cause violence. The biochemical response to noise exposure was the activation of emotional processing structures in the central nervous system, which may result in the release of certain stress hormones [23, 24, 25] such as cortisol and catecholamines [26, 27, 28, 29]. Stress hormones such as adrenaline and noradrenaline can be thought of as stress indicators [24], and some researchers discovered a significantly positive relationship between annoyance and stress hormone levels following noise exposure [29]. Moreover, a positive feedback loop between stress hormones and a brain-based aggression-control centre might exist, leading to a vicious cycle of stress and aggressive behaviour [30].

There was also a physiological explanation for how traffic noise may contribute to violent behaviour via negative emotions. Traffic noise was a frequent source of stress. The general strain theory explained that such a stressor could elicit negative emotions and a desire for a coping response [31, 32]. These negative emotions may then motivate the individuals to engage in criminal behaviours to terminate or escape from the stressor [31]. Anger is the most critical emotion that can heighten an individual's perception of injury, resulting in a desire for retaliation/revenge and a proclivity to self-justify aggressive behaviour [31]. While annoyance is the most common physiological response to noise pollution, it may also be associated with anger [33]. It was found in a psychological study to be a risk factor for aggression in daily family life [34].

To date, there was limited evidence of the association between noise exposure and violence. A working paper used daily variation in aircraft landing as an instrument variable concluded a 4.1 decibel higher background noise could be associated with a 6.6% increase in violent crime rate [35]. This study focused on real-world settings and presented some causal evidence between noise exposure and violence. Another study that focused on occupational exposure found a significantly positive relationship between noise intensity and verbal aggression, physical aggression, anger, hostility and overall aggression in workers [36]. Gomez-Azpeitia et al. (2006) found that inhabitants who lived in houses exposed to a higher level of noise were more likely to report domestic violence [37].

Our study had the advantage of analysing nearly 5.4 million violent crimes, the most costly type of crime economically and socially, that occurred in England between 2012 and 2017. The scale was the probably largest to the best of our knowledge, and as a result, the evidence may be more representative. We used a quasi-experimental design to examine the effect of a relatively abrupt decrease in noise exposure on violence. Treatment assignment was determined by exogenous variation that was likely unrelated to air pollution and local socioeconomic conditions. Thus, our study presented some evidence for a causal relationship between traffic noise and violence. However, ecological bias may still exist in our study as a result of unmeasured confounding and a lack of appropriate control groups [15], which was our first limitation.

This study has some other limitations too. The spatial autocorrelation was not taken into account in our study, which may introduce bias. We examined evidence from England, which had a total of 32,844 LSOAs. A spatial weight would be a 32,844 by 32,844 matrix that quantified the strength of the relationship between two spatial units. Due to our limited computing capability, it was difficult to create a weight matrix that size and fit our data into a spatial model. Secondly, because the air pollution data were collected in $1km$ background squares, they may not fully capture spatial variability, particularly in cities where $PM_{2.5}$ and NO_2 exposures were higher near roads. This was likely not a significant issue in our study, as there were few reasons to believe that air quality could have an effect on the assignment of treated areas.

CONCLUSION

Our research discovered a negative correlation between noise intervention directed at road and rail vehicle noise and violent and sexual crimes, and our findings suggested that noise reduction may play a role in this correlation. This study was perhaps one of the first study of its kind to examine the causal link between road and railway traffic noise and violent crimes.

This conclusion has a significant implication. The majority of people in developed countries and some developing countries live in urban areas that were densely populated and subject to chronic noise exposure. Road and railway noise were likely to affect a much larger proportion of the community's population than other sources of noise. As a result, traffic noise from road and rail vehicles could be a near-universal annoyance for a large proportion of residents. Our findings implied that, if the negative relationship between traffic noise exposure and violent crime was indeed causal, traffic noise-related violence may be a costly by-product of pollution in these societies that has largely gone unnoticed.

Between 2014 and 2017, the mean annual number of violent crimes committed by individuals with treated LSOAs (N=1,924) was approximately 38. We estimated that the implementation of traffic noise action plans was associated with an annual reduction of 1 incident of violent and sexual crimes per LSOA between 2014-2017. According to Atkinson et al. (2005), the cost of a violent crime was at least £5,300 [38]. Thus, assuming there was a causal relationship between traffic noise and violence, implementing noise action plans could save England at least £10 million per year from 2014 to 2017. This has not taken the cost of public order and possession of weapons into consideration, which was also found to be negatively related to noise intervention.

The significant economic and human costs associated with traffic noise related violence should serve as a stronger motivator for bolder action to address noise pollution. DEFRA has recommended a variety of measures to reduce exposure to traffic noise. Apart from the efficient approaches that DEFRA have taken, we suggested legislation should be introduced to regulate the speed of road and rail vehicles in densely populated areas, such as 20 mph zones, as a slower speed would significantly reduce the level of noise emitted by the engines [39]. A more pressing matter was to raise public awareness about the potential negative effects of traffic noise on behavioural problems, which has largely been neglected.

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APPENDIX

Figure 1 The mean violent crimes by treatment and control LSOAs

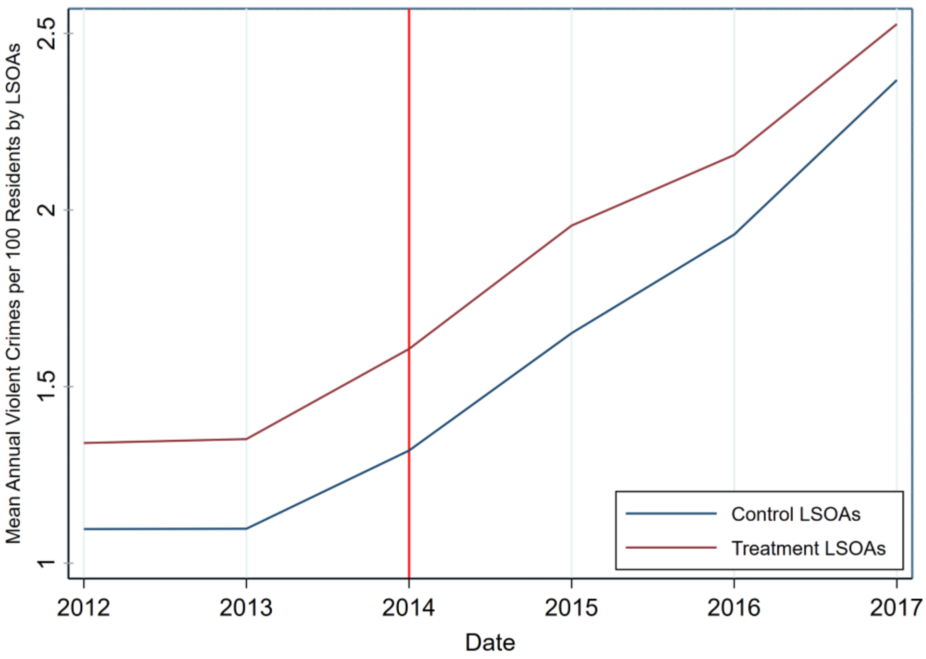

Figure 2 An event-study plot of the effect on noise action plans.

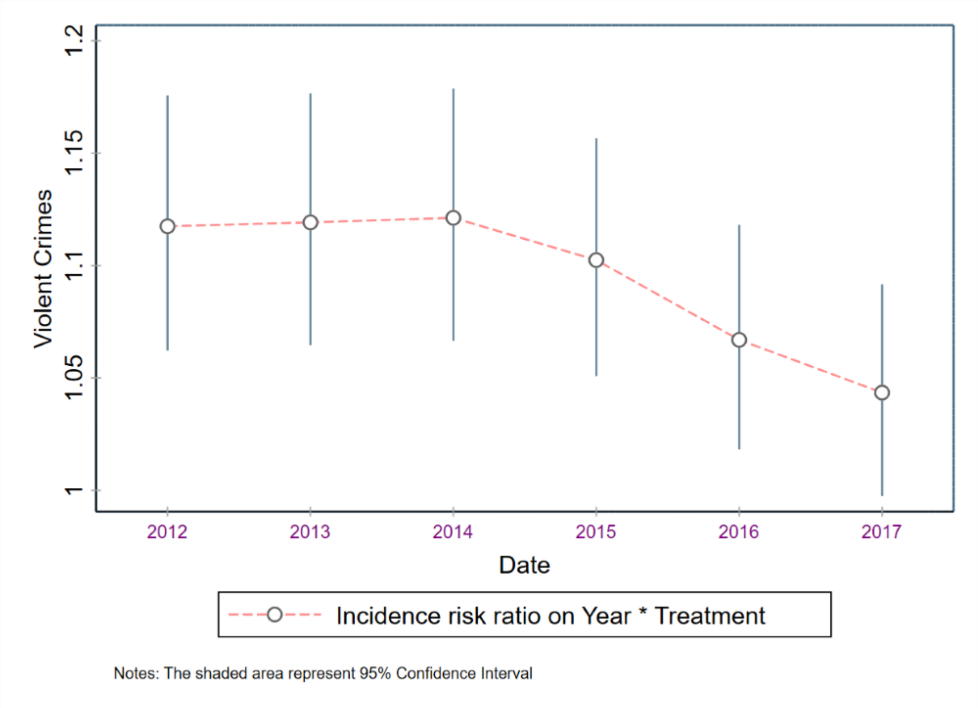

Table 1 The Definition of Types of Crimes

Type of Crime	Definition
Anti-social behaviour	Includes personal, environmental and nuisance anti-social behaviour.
Burglary	Includes offences where a person enters a house or other building with the intention of stealing.
Criminal damage and arson	Includes damage to buildings and vehicles and deliberate damage by fire.
Drug offences	Includes offences related to possession, supply and production.
other thefts	Includes theft by an employee, blackmail and making off without payment.
Public order offences and possession of weapons	Includes offences which cause fear, alarm or distress, and possession of a weapon, such as a firearm or a knife.
Robbery	Includes offences where a person uses force or threat of force to steal.
Shoplifting	Includes theft from shops or stalls.
Vehicle crime	Includes theft from or of a vehicle or interference with a vehicle.
Violent and sexual offences	Includes offences against the person such as common assaults, Grievous Bodily Harm and sexual offences.
Theft from the person	Includes crimes that involve theft directly from the victim (including handbag, wallet, cash, mobile phones) but without the use or threat of physical force.
Bicycle theft	Includes the taking without consent or theft of a pedal cycle.
Other theft crimes	Includes theft by an employee, blackmail and making off without payment.

Table 2 Descriptive summary of the variables

Variables	N	Mean	SD	Min	Max
Crimes:					
Violent and sexual crimes	197056	27.168	37.799	0	1794
Burglary	197056	12.34	10.35	0	293

Robbery	197056	1.753	4.787	0	383
Shoplifting	197056	9.466	39.31	0	1,997
Other thefts	197056	19.73	58.19	0	4,392
Vehicle offences	197056	11.09	10.9	0	329
Drug offences	197056	4.521	10.17	0	851
Anti-social behaviour	197056	55.79	73.09	0	2,956
Criminal damage and arson	197056	15.1	14.33	0	260
Public order and weapon offences	197056	6.365	13.93	0	1,087
Ambient Lden	65684	0.247	0.721	0	5
% Fuel poor	197056	11.326	5.245	0.9	56.8
% Unemployed aged 16-64	182014	6.447	2.826	1.3	16.5
% Male	197056	49.225	2.376	33.211	85.467
Total spending on social services per resident	197056	0.915	0.703	-0.144	4.725
% Population with no qualifications	191084	8.607	3.696	1.1	24.8
% Population aged 15 - 24	197056	12.078	6.064	0.406	88.732
Number of premium licence per 1000	194835	3.578	1.576	0.175	30.987
Police officers per 1000 persons	197056	2.172	0.875	1.229	22.856
Mean $PM_{2.5}$ background concentration	197056	10.407	1.879	4.705	19.591
Mean NO_2 background concentration	197056	17.295	7.005	2.409	59.160
Recorded depression prevalence (aged 18+) per 1000	196736	7.9	2.064	2.862	15.896
2011 rural-urban classification:					
was rural town and fringe	197056	0.089	0.285	0	1
was rural town and fringe in a sparse setting	197056	0.004	0.06	0	1
was rural village and dispersed	197056	0.072	0.258	0	1
was rural village and dispersed in a sparse setting	197056	0.006	0.074	0	1
was urban city and town	197056	0.44	0.496	0	1
was urban city and town in a sparse setting	197056	0.002	0.042	0	1
was urban major conurbation	197056	0.351	0.477	0	1
was urban minor conurbation	197056	0.037	0.188	0	1

Table 3 The source of the variables

Variable Name	Source
Annual number of violent and sexual crimes	Street-level crime database
Average ambient $Lden$ traffic noise level	Open data: strategic noise mapping
% Fuel poverty	Sub-regional fuel poverty data
% Unemployment male 16-64	Nomis official labour market statistics
Mean $PM_{2.5}$ background concentration	Modelled background pollution data
Mean NO_2 background concentration	Modelled background pollution data
Number of premium licences per 1000 persons	Alcohol and Late-night Refreshment Licensing England and Wales Statistics
Recorded depression prevalence (aged 18+) per 1000	Public Health Profiles
Population density	Office for National Statistics (ONS)

% population without qualification	Nomis official labour market statistics
% Male	Office for National Statistics (ONS)
% Population aged 15 to 24	Office for National Statistics (ONS)
Number of police officers per 1000 persons	Police Workforce, England and Wales Statistics database

Table 4 The effect of the adoption of noise action plans on violence for multiple periods, traffic noise, air quality and poverty

	(1)	(2)	(3)	(4)	(5)
	Poisson RE	Poisson RE	GLM RE Poisson distribution	GLM RE Poisson distribution	GLM RE Poisson distribution
Dependent variable	Violent crimes	Ave. ambient $Lden$	$PM_{2.5}$	NO_2	Fuel poverty
$Post$	1.276***	0.947*	1.032***	1.011***	1.013**
	(1.239 - 1.314)	(0.892 - 1.006)	(1.030 - 1.033)	(1.009 - 1.013)	(1.001 - 1.026)
$Treatment$		2.442***	0.993***	0.995***	0.986***
		(2.176 - 2.740)	(0.992 - 0.994)	(0.991 - 0.999)	(0.976 - 0.995)
$Post \times Treatment$		0.938***	1.010***	1.012***	1.013**
		(0.906 - 0.971)	(1.009 - 1.012)	(1.011 - 1.013)	(1.001 - 1.025)
$2012 \times Treatment$	1.117***				
	(1.062 - 1.176)				
$2013 \times Treatment$	1.119***				
	(1.065 - 1.177)				
$2014 \times Treatment$	1.121***				
	(1.067 - 1.179)				
$2015 \times Treatment$	1.102***				
	(1.051 - 1.157)				
$2016 \times Treatment$	1.067***				
	(1.018 - 1.118)				
$2017 \times Treatment$	1.043*				
	(0.997 - 1.092)				
Constant	0.002***	0.024***	3.607***	9.292***	6.160***
	(0.001 - 0.003)	(0.008 - 0.074)	(3.578 - 3.637)	(9.069 - 9.521)	(5.687 - 6.674)
Observations	179125	58660	179125	179125	179125
Number of LSOAs	32066	31548	32066	32066	32066
Control variables	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Wald Chi2	1.364e+06	230980	8.176e+06	1.757e+06	429176

Incidence risk ratio and 95% CI in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 5 The relationship between noise intervention and violent crimes

	(1)	(2)

	Poisson RE	Poisson RE
Dependent variable:	Ambient all-day $Lden$	Violent crimes
$Post$	0.926**	1.263***
	(0.873 - 0.982)	(1.226 - 1.302)
$Treatment$	2.649***	1.140***
	(2.383 - 2.944)	(1.068 - 1.217)
$Post \times Treatment$	1.081***	0.982
	(1.052 - 1.111)	(0.948 - 1.017)
Constant	0.018***	0.002***
	(0.005 - 0.060)	(0.001 - 0.002)
Observations	58660	179125
Number of LSOAs	31548	32066
Control variables	Yes	Yes
Local Authority District FE	Yes	Yes
Year FE	Yes	Yes
Wald Chi2	232817	1.365e+06

Incidence risk ratio and 95% CI in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6 The effect of the adoption of Noise Action Plans on alternative categories of crimes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Poisson RE	Poisson RE	Poisson RE	Poisson RE	Poisson RE	Poisson RE	Poisson RE	Poisson RE	Poisson RE
Dependent variable:	Burglary	Robbery	Shoplifting	Other thefts	Vehicle offences	Drug offences	Anti-social behaviour	Criminal damage and arson	Public order and weapon offences
$Post$	0.688***	0.601***	1.115***	0.707***	0.910***	0.771***	0.597***	0.875***	1.350***
	(0.670 - 0.706)	(0.566 - 0.638)	(1.027 - 1.211)	(0.664 - 0.752)	(0.885 - 0.935)	(0.725 - 0.819)	(0.581 - 0.613)	(0.854 - 0.897)	(1.261 - 1.445)
$Treatment$	1.070***	1.121***	1.562***	1.393***	1.135***	1.180***	1.076***	1.020	1.273***
	(1.043 - 1.097)	(1.062 - 1.183)	(1.349 - 1.808)	(1.290 - 1.504)	(1.097 - 1.173)	(1.107 - 1.258)	(1.028 - 1.126)	(0.985 - 1.055)	(1.176 - 1.379)
$Post \times Treatment$	1.003	1.035*	1.057**	0.968	1.011	1.007	1.012	1.005	0.931***
	(0.985 - 1.022)	(0.996 - 1.076)	(1.005 - 1.111)	(0.930 - 1.008)	(0.987 - 1.035)	(0.945 - 1.075)	(0.990 - 1.033)	(0.986 - 1.024)	(0.891 - 0.973)
Constant	0.006***	0.000***	0.002***	0.005***	0.007***	0.000***	0.072***	0.010***	0.000***
	(0.005 - 0.008)	(0.000 - 0.000)	(0.001 - 0.005)	(0.003 - 0.008)	(0.006 - 0.009)	(0.000 - 0.000)	(0.053 - 0.098)	(0.008 - 0.013)	(0.000 - 0.000)
Observations	179125	179125	179125	179125	179125	179125	179125	179125	179125
Number of LSOAs	32066	32066	32066	32066	32066	32066	32066	32066	32066
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local Authority District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wald Chi2	3.809e+06	1.652e+06	164450	1.207e+06	3.544e+06	1.550e+06	922427	2.050e+06	1.537e+06

Incidence risk ratio and 95% CI in parentheses
*** p<0.01, ** p<0.05, * p<0.1