Health effects of low emission and congestion charging zones: a systematic review

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Low emission zones (LEZs) and congestion charging zones (CCZs) have been implemented in several cities globally. We systematically reviewed the evidence on the effects of these air pollution and congestion reduction schemes on a range of physical health outcomes. We searched MEDLINE, Embase, Web of Science, IDEAS, Greenfile, and Transport Research International Documentation databases from database inception to Jan 4, 2023. We included studies that evaluated the effect of implementation of a LEZ or CCZ on air pollution-related health outcomes (cardiovascular and respiratory diseases, birth outcomes, dementia, lung cancer, diabetes, and all-cause) or road traffic injuries (RTIs) using longitudinal study designs and empirical health data. Two authors independently assessed papers for inclusion. Results were narratively synthesised and visualised using harvest plots. Risk of bias was assessed using the Graphic Appraisal Tool for Epidemiological studies. The protocol was registered with PROSPERO (CRD42022311453). Of 2279 studies screened, 16 were included, of which eight assessed LEZs and eight assessed CCZs. Several LEZ studies identified positive effects on air pollution-related outcomes, with reductions in some cardiovascular disease subcategories found in five of six studies investigating this outcome, although results for other health outcomes were less consistent. Six of seven studies on the London CCZ reported reductions in total or car RTIs, although one study reported an increase in cyclist and motorcyclist injuries and one reported an increase in serious or fatal injuries. Current evidence suggests LEZs can reduce air pollution-related health outcomes, with the most consistent effect on cardiovascular disease. Evidence on CCZs is mainly limited to London but suggests that they reduce overall RTIs. Ongoing evaluation of these interventions is necessary to understand longer term health effects.

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Introduction

Motorised transport poses risks for human and environmental health. Road transport is an important contributor to air pollution worldwide,[1] as well as being responsible for 1·3 million deaths per year through road traffic injuries (RTIs).[2] Increasing concern about these effects has spurred policy makers in some locations to implement schemes restricting private vehicle use in urban areas. Two main types of these schemes are low emission zones (LEZs) and congestion charging zones (CCZs). LEZs charge or ban vehicles that exceed specific exhaust emission standards and aim to reduce air pollution by encouraging use of lower emission vehicles or physically active forms of transport.[3] CCZs focus on reducing congestion through charging financial penalties for the majority of vehicles, with little or no differentiation by emission standards (appendix p 6). Although there are some differences between them, both LEZs and CCZs apply to defined geographical areas and have the potential to improve health through reducing car use and encouraging a shift towards lower emission motor vehicles or active travel. LEZs and CCZs can also both be implemented at a city level; this is important as cities are at the forefront of both effects and solutions to climate change issues.[4]

Although at least 320 LEZs had been implemented across Europe as of 2022,[5] the global evidence base regarding their health effects is relatively limited. A review of the effects of European LEZs on air quality concluded there was some evidence that German LEZs had reduced PM_{10} and nitrogen dioxide (NO_2) annual average concentrations, with a mixed picture across Europe overall.[3] By 2019, Bradley and colleagues[6] and Burns and colleagues[7] had both conducted reviews assessing the air pollution effects of a range of interventions, including LEZs, concluding that the evidence regarding the effect of LEZs on air quality was inconclusive. Both these reviews also highlighted that evidence on health effects was sparse, although Burns and colleagues[7] acknowledged that several studies had been published since their search. The evidence on the health effects of CCZs is also scarce; a 2021 scoping review[8] identified some evidence of RTI reductions, but did not consider air pollution-related health outcomes.

We therefore systematically reviewed the evidence for the effect of LEZs and CCZs on a range of physical health outcomes associated with air pollution or motorised traffic exposure.

Methods

See **Online** for appendix

We conducted our systematic Review in line with our pre-published protocol (PROSPERO CRD42022311453), with some minor changes (appendix p 31), and report results according to PRISMA guidelines.[9] We designed the search strategy (appendix p 3) in consultation with an information specialist and based on a previous review.[7] We searched six databases: Medline, Embase, Web of Science, IDEAS, Greenfile, and Transport Research International Documentation (TRID). Final searches were conducted on Jan 4, 2023, without date or language restrictions. Records were deduplicated using Covidence software, before two authors (RCC and AAL) independently screened in two stages, firstly using titles and abstracts and then full-text records. Non-consensus was resolved by a third reviewer. The reference lists of studies assessed during the full-text stage were reviewed to identify additional studies (backwards reference tracing).

We aimed to capture studies on the effects of LEZ or CCZ schemes on empirical health outcomes of resident populations compared with areas not affected by LEZ or CCZ schemes. Studies were eligible if they evaluated effects of a LEZ or CCZ on health conditions related to air pollution (birth outcomes, respiratory disease, cardiovascular disease, diabetes, dementia, lung cancer, or all-cause) or traffic exposure (RTIs; further details in the appendix [p 7]). We focused on these outcomes as there is existing evidence of their association with air pollution or traffic exposure. We did not include odd–even schemes that restrict vehicle access on specific days. Outcomes could be any measure of all-cause or cause-specific morbidity (ie, disease events or symptoms or health-care contacts such as hospital admissions) or mortality. Studies had to measure these outcomes using empirical data collected during the study period; studies that predicted outcomes using air quality or traffic changes and concentration–response or exposure–response functions were not eligible. We also excluded studies that only assessed intermediate factors such as air quality or congestion, without assessment of health outcomes.

Studies could use any longitudinal study design with at least one data point before and one data point after LEZ or CCZ implementation, such as pre-post designs, interrupted time series analyses, and difference-in-difference designs. We have focused on these studies to include only robust evaluations of LEZ or CCZ schemes with the capacity to show the temporal direction of the intervention–outcome relationship. The intervention group was the resident population of the intervention area. The comparison population could be from areas not exposed to the intervention, areas exposed to a different version of the intervention (such as less stringent LEZs), or the intervention area pre-intervention (such as in uncontrolled interrupted time series). Studies without primary data, including reviews, were excluded.

Study characteristics were extracted by RCC using a Covidence template, and effect estimates and statistical significance measures extracted into an excel spreadsheet (appendix p 8). We extracted results from the most fully adjusted model reported—ie, controlling for the most covariates. Meta-analysis was a priori considered inappropriate due to heterogeneity in study designs and outcomes. Instead, we used a synthesis without meta-analysis (SWiM) approach, involving tabulation, graphical summary using harvest plots, and narrative synthesis. Our approach was informed by guidance on SWiM[10] and narrative synthesis.[11] We used a vote counting method based on effect direction and statistical significance, with classification of each result into one of three categories: (1) reduction (effect direction is a reduction associated with the intervention, with p value <0·05, or the 95% CI not including the null); (2) no clear effect (95% CI includes the null, and is therefore compatible with no effect, or p value ≥0·05); or (3) increase (effect direction is an increase associated with the intervention, with p value <0·05, or the 95% CI not including the null).

We used harvest plots to graphically synthesise the results based on these effect directions and grouped by intervention type and outcome category (eg, cardiovascular or respiratory). When multiple results with different effect directions were reported for a single intervention–outcome pair (such as from different model specifications), the more conservative (ie, the highest number of the three categories above) is shown in the harvest plot. Subgroup analyses were tabulated but not included in the harvest plots. Where results were reported from multiple phases of an intervention (eg, of differing stringency) and from all phases combined, the combined phase results are shown in the harvest plots. As a secondary synthesis we also considered the effect direction of the point estimates for non-significant results (ie, those classified as no clear effect), as recommended by Cochrane.[12]

When results for intermediate factors (eg, air pollutants or traffic) were reported in addition to health outcomes, they were also synthesised to give context to the health results. However, this is not a systematic review of these intermediate factors. For each study, the most relevant intermediate factors to report were selected according to a hierarchy (appendix p 8). These results were tabulated and categorised in the same way as for the health outcomes. However, if a study reported multiple factors at the same level of the hierarchy (eg, several pollutant species), the result included in the harvest plot represents the factor showing the clearest effect. For example, the result for a factor with a reduction or increase is shown in preference to one with no clear effect; this is because the intention is to indicate when there is clearest evidence of change in any relevant intermediate factor.

Risk of bias assessment of the health outcome results used the Graphic Appraisal Tool for Epidemiological studies for correlation studies (GATE). This tool includes assessments of external validity, selection of exposure and comparison groups, measurement of outcomes, and rigour of analysis methods. There is also an overall assessment of internal validity. Full details are in the appendix (p 16). Two authors conducted the risk of bias assessment independently.

Role of the funding source

The study funders had no involvement in the study design, the collection, analysis, or interpretation of data, or writing the report.

Results

Searches identified 3588 studies, of which 2279 remained after de-duplication, and 14 after assessment against

	Intervention start date	Location	Main health outcomes assessed (ICD-10 codes included when available)	Data source (health outcomes)	Analysis period	Study population size	Study design	Temporal resolution	Intervention area or population	Control area or population
Gehrsitz (2017)[15]										
LEZ: applies to all vehicle types except motorcycles, implemented in 3 increasingly strict phases, with stricter limits for diesel than petrol	First cities: January, 2008	Germany	Birth outcomes (birthweight [continuous], LBW [binary, <2500 g], stillbirth)	Birth registrations	2005–12	1·85 million births	DiD	NA (individual level data)	Cities ≥100 000 population, with LEZ active in city during gestation period	Cities ≥100 000 population, without LEZ active in city in gestation period
Margaryan (2021)[16]										
LEZ: applies to all vehicle types except motorcycles, implemented in 3 increasingly strict phases, with stricter limits for diesel than petrol	First cities: January, 2008	Germany	Outpatient data: cardiovascular diseases (total [I00–I99], heart disease [I20–I49], cerebrovascular disease [I60–I66]); respiratory disease (J00–J06, J20–J22, J30–J47, J95–J99); diabetes (E10-E14); hospital diagnosis statistics (inpatient admissions and ED admissions without overnight stay): cardiovascular diseases (total), heart disease, cerebrovascular disease	Outpatient care records, from health insurance records (ambulatory care); hospital diagnosis statistics data	Outpatient data: 2009–17; hospital data: 2004–14	Outpatient data: 954 area-year observations; hospital data: 726 city-year observations	DiD	Annual	Cities or areas of cities >100 000 population with LEZ in place (at the time of measurement)	Cities >100 000 population with no LEZ in place by the end of the study
Pestel and Wozny (2021)[17]										
LEZ: applies to all vehicle types except motorcycles, implemented in 3 increasingly strict phases, with stricter limits for diesel than petrol	First cities: January, 2008	Germany	All disease (A00–N99); cardiovascular diseases (total [I00–I99], IHD [I20–I25], cerebrovascular disease [I60–I69], hypertension [I10–I15]); respiratory diseases (total [J00–J99], acute lower respiratory diseases [J20–J22], chronic lower respiratory diseases [J40–J47]); LBW (P07); diabetes (E10–E14); dementia (F00–F03)	Inpatient admission records from hospital quality report data	2006–16	2736 hospital-year observations (342 hospitals per year)	DiD	Annual	Hospitals in cities ≥100 000 population, where the hospital is located inside an active LEZ	Hospitals in cities ≥100 000, where the hospital is not located inside an active LEZ
Sarmiento et al 2021[18]										
LEZ: applies to all vehicle types except motorcycles, implemented in 3 increasingly strict phases, with stricter limits for diesel than petrol	First cities: January, 2008	Germany	Hypertension; doctor visits (all-cause)	National survey (German Socioeconomic Panel)	2009–18	9218 year-individual observations	DiD	Every 2 years	Participants living in a LEZ at time of measurement	Participants living in areas that never had a LEZ within the study period, and are not within 25 km of a LEZ
Beshir and Fichera 2022[19]										
LEZ: diesel heavy-duty commercial and passenger vehicles and minibuses and larger vans	Phased implementation 2008–12, phase 1–2 in 2008, phase 3 in 2012	London, UK	Specific health problems lasting ≥12 months: chest-related or breathing-related (including asthma, bronchitis); heart-related (including blood pressure, blood circulation problems)	Quarterly Labour Force Survey	2003–15	1·2 million individual-quarter observations	DiD	Quarterly	Participants living in Greater London	Participants living in other major towns or cities in England
Percoco (2016)[13]										
LEZ: applies to most vehicle types excluding motorbikes	January, 2008	Milan, Italy	Total incidents (all vehicles); injuries from road traffic incidents (all vehicles); deaths from road traffic incidents (all vehicles)	Incident reports, from police records	2001–11	120 months	uITS	Monthly	Eco-Pass area (central Milan)	Milan, outside the Eco-Pass area

(Table 1 continues on next page)

	Intervention start date	Location	Main health outcomes assessed (ICD-10 codes included when available)	Data source (health outcomes)	Analysis period	Study population size	Study design	Temporal resolution	Intervention area or population	Control area or population
(Continued from previous page)										
Yorifuji et al (2011)[20]										
LEZ: diesel heavy-duty vehicles, PM standards	October, 2003, with further tightening in April, 2006	Tokyo, Japan	All-cause mortality; cardiovascular-cause mortality (total [I10–I70], IHD [I20–I25], cerebrovascular disease [I60–I69]); respiratory-cause mortality (total [J00–J99]); mortality due to other causes	Death registrations	April 2003–December 2008	Intervention area population: 8 310 572; deaths in intervention area: 2003–08: 371 921	cITS	Daily	23 urban wards of Tokyo Metropolitan Government area	Rest of Japan
Yorifuji et al (2016)[21]										
LEZ: diesel heavy-duty vehicles, PM standards	October, 2003, with further tightening in April, 2006	Tokyo, Japan	All-cause mortality, non-trauma (A00–R99); cardiovascular-cause mortality (total [I00–I70], IHD [I20–I25], cerebrovascular disease [I60–I69]); respiratory-cause mortality (J00–J99); lung cancer mortality (C33–C34); non-trauma mortality due to other causes	Death registrations	October 2000–September 2012	Intervention area population: 8 489 653; deaths in intervention area: 2000–12: 702 845; control area population: 2 628 811; deaths in control area 2000–12: 287 022	cITS	Daily	23 urban wards of Tokyo Metropolitan Government area	Osaka, Japan

cITS=interrupted time series with control. DiD=difference-in-difference. ICD-10=International Classification of Diseases, 10th Revision. IHD=ischaemic heart disease. KSI=killed or serious injury. LBW=low birthweight. LEZ=low emission zone. NA=not applicable. PM=particulate matter. uITS=interrupted time series analysis without control.

Table 1: **Study characteristics of low emission zone studies**

eligibility criteria (appendix p 13). Backwards reference tracing identified one additional eligible study[13] and five annual reports from Transport for London (TfL) on the London CCZs at different times post-implementation. Of these five reports, we included only the one[14] with the most detailed analysis pre-intervention and post-intervention. Therefore, 16 studies were included in the final synthesis.

Study characteristics are summarised in tables 1 (LEZs) and 2 (CCZs). Eight studies assessed LEZs[13,15–21] and eight assessed CCZs.[14,22–28] Eight studies assessed RTIs,[13,14,22–27] six assessed respiratory outcomes,[16,17,19–21,28] six assessed cardiovascular outcomes,[16–21] two assessed birth outcomes,[15,17] two assessed diabetes,[16,17] and single studies assessed dementia[17] and lung cancer.[21] Four studies assessed all-cause outcomes (mortality,[20,21] hospital admissions,[17] or doctor visits[18]).

Low emission zones

The eight LEZ studies were published between 2011 and 2022. Four studies assessed schemes in several German cities,[15–18] two in Tokyo, Japan,[20,21] one in Milan, Italy,[13] and one in London, UK.[19] There were five difference-in-difference (DiD) designs,[15–19] one interrupted time series without a control group (uITS),[13] and two interrupted time series with a control group (cITS).[20,21] In risk of bias assessment (appendix p 13), three studies received a strong internal validity rating[15,16,19] and five received a medium rating (ie, some limitations).[13,17,18,20,21] Absence of a control group and insufficient control for possible confounding factors were key limitations for studies receiving medium ratings. The findings from the primary synthesis of LEZ studies are summarised in table 3 and the figure. The secondary synthesis results are in the appendix (p 14). Seven studies[15–21] reported results for at least one intermediate factor, with this being a measure of air quality in all cases. These results are summarised in the appendix (p 9) and the figure.

Cardiovascular outcomes

Of the six LEZ studies considering cardiovascular outcomes, three were from Germany,[16–18] two from Tokyo, Japan,[20,21] and one from London, UK.[19] Five of the six studies found reductions in at least one cardiovascular disease subcategory. No studies found an increase. Of the four studies with a no clear effect finding in any subcategory, in two the effect direction was towards a reduction, and in two the direction varied between subcategories.

In a DiD study from Germany, Pestel and Wozny[17] used hospital records from 2006 to 2016 to assess changes in annual cause-specific diagnoses as a proportion of total inpatient diagnoses, associated with a hospital being inside an active LEZ. Pestel and Wozny found a 1·3 percentage point LEZ-associated reduction (9% from baseline, $p<0 \cdot 01$) in cardiovascular disease inpatient diagnosis share. In addition, there was a reduction for

	Intervention start date	Location	Main health outcomes assessed (ICD-10 codes included when available)	Data source (health outcomes)	Analysis period	Study population size	Study design	Temporal resolution	Intervention area or population	Control area or population
Green et al (2016)[22]										
CCZ	Original area: February 2003; western extension: February 2007 to January 2011	London, UK	Total incidents (all vehicles, and bike only); incident causing serious injury, including fatality (all vehicles, and bike only; incident causing fatality (all vehicles)	Government data on road incidents, from police reports (STATS 19 database)	2000–09	21 areas (CCZ and 20 cities); 2520 area-month observations (or 240 for synthetic control method)	DiD	Monthly	London CCZ	20 largest cities in Britain, by population (excluding London)
Li et al (2012)[23]										
CCZ	Original area: February 2003; western extension: February 2007 to January 2011	London, UK	Total car incidents; car incident with ≥1 person slightly injured; car incident with ≥1 person killed or seriously injured; total incidents involving a bicycle; bicycle incident with ≥1 person slightly injured; bicycle incident with ≥1 person killed or seriously injured; total incidents involving a motorcycle; motorcycle incident with ≥1 person slightly injured; motorcycle incident with ≥1 person killed or seriously injured	Government data on road incidents, from police reports (STATS 19 database)	2001–04	Car and bike casualty analysis: 244 ward-year observations; motorcycle casualty analysis: 268 ward-year observations	DiD	Annual	London CCZ wards	Wards in central areas of English cities excluding London; the city used depends on the outcome; Leeds was used as for the analysis of car casualties, Manchester for bike casualties and Birmingham for motorcycles
Li and Gao (2019)[24]										
CCZ	Original area: February 2003; western extension: February 2007 to January 2011	London, UK	Total car incidents; car incident with slight injury; car incident with fatality or serious injury	Government data on road incidents, from police reports (STATS 19 database)	1998–2007	Number of wards in the intervention area is unclear; synthetic control for each outcome is a weighted average of 4–6 wards	DiD with synthetic control	Annual	London CCZ wards	Synthetic control, using 33 wards of Manchester as donor pool; different weighted combination of (a subset of) these wards are used as the synthetic control for each outcome
Noland et al (2008)[25]										
CCZ	Original area: February 2003; western extension: February 2007 to January 2011	London, UK	Slight injury (casualties; all vehicles, car, cyclist, motorcyclist); KSI (casualties; all vehicles, car, cyclist, motorcyclist)	Government data on road incidents, from police reports (STATS 19 database)	January 1991–November 2004	145 preintervention observations	uITS	Monthly	London CCZ including inner ring road (non-charged boundary road)	NA
Quddus (2008)[26]										
CCZ	Original area: February 2003; western extension: February 2007 to January 2011	London, UK	RTA car casualties	Government data on road incidents, from police reports (STATS 19 database)	January 1991–October 2005	178 observations	uITS	Monthly	London CCZ	NA
Tang and van Ommeren (2022)[27]										
CCZ	Original area: February 2003; western extension: February 2007 to January 2011	London, UK	Total incidents (with at least one injury/fatality); slight injury from RTA; KSI from RTA; incidents involving 2-wheel vehicle; incidents involving buses; pedestrian injuries from RTA	Government data on road incidents, from police reports (STATS 19 database)	2000–14	Main analysis: 1661 LSOAs (68 within CCZ); 20 858 year-LSOA observations (for total incidents); sub-analysis using LSOAs within 2·5 km of CCZ boundary: 3158 LSOA-year observations	DiD	Annual	LSOAs within the CCZ, with traffic count points	London LSOAs outside the CCZ, with traffic count points

(Table 2 continues on next page)

	Intervention start date	Location	Main health outcomes assessed (ICD-10 codes included when available)	Data source (health outcomes)	Analysis period	Study population size	Study design	Temporal resolution	Intervention area or population	Control area or population
(Continued from previous page)										
Transport for London (2005)[14]										
CCZ	Original area: February 2003; western extension: February 2007 to January 2011	London, UK	Incidents with injury (all vehicles, all severities)	Police incident statistics	February 2002–February 2004	2 time points; population of intervention area is not reported	DiD	Annual	CCZ and non-charged boundary roads	London excluding intervention area
Simeonova et al (2021)[28]										
CCZ	Trial period Jan–July 2006, permanent from August 2007	Stockholm, Sweden	Asthma (children, age 0–5 years)	Inpatient and outpatient registries (hospital admissions and acute (unplanned) outpatient visits (including primary care and EDs)	2004–10	103 municipalities (7416 month-municipality observations)	DiD	Monthly	Congestion payment zone (Stockholm city centre)	Swedish city centres without congestion charging zones, but with ambient air monitoring

CCZ=congestion charging zone. DiD=difference-in-difference. ED=emergency department. ICD-10=International Classification of Diseases, 10th Revision. KSI=killed or serious injury. LSOA=Lower Layer Super Output Areas. NA=not applicable. RTA=road traffic accident. uITS=interrupted time series analysis without control group.

Table 2: **Study characteristics of congestion charging zone studies**

the ischaemic heart disease (IHD) subcategory, but no clear effect for cerebrovascular disease or hypertension. Pestel and Wozny also found reductions in annual mean PM_{10} (1·3 μg/m³, 6% from baseline, $p<0·01$) and NO_2 (1·6 μg/m³, 5% from baseline, $p<0·01$). The study was judged as having moderate internal validity.

In a DiD study with strong internal validity from Germany, Margaryan[16] assessed annual outpatient attendances using ambulatory care health insurance data from 2009 to 2017. They found a LEZ-associated reduction (2·2%, $p<0·05$) in cardiovascular disease attendances in a model excluding cities with a LEZ introduced before 2009 (ie, before available health data). A model without this restriction found no clear effect. Of cardiovascular subcategories, there was a reduction for cerebrovascular disease, and a reduction in heart disease attendances in those older than 65 years. The study reported a reduction in monthly average PM_{10} (0·9 μg/m³, 3·1% from baseline, $p<0·05$), but no clear effect for particulate matter ≤2·5 μm diameter ($PM_{2·5}$) or NO_2.

In another German DiD study, Sarmiento and colleagues[18] used biennial surveys to follow up individuals from 2009 to 2018 and found a reduction in self-reported hypertension of 4·6% ($p<0·05$) from baseline associated with living inside a LEZ. This study was rated as having moderate internal validity. Sarmiento and colleagues also reported a reduction in annual mean PM_{10} of 1·9 μg/m³ and NO_2 of 3·5 μg/m³ (both $p<0·01$).

In a 2016 cITS study, Yorifuji and colleagues[21] considered changes in daily mortality rates between 2000–03 and 2009–12 periods in the Tokyo Metropolitan Government area, adjusted for the rate in Osaka, Japan, and found an 11·0% (95% CI 10·0–13·0) LEZ-associated reduction in total cardiovascular disease mortality, including reductions for IHD and cerebrovascular disease. The study was rated as moderate internal validity due to possible uncontrolled confounding from differential changes in tobacco smoking rates. This study reported a greater reduction in mean daily $PM_{2·5}$ concentrations in the intervention areas than control (8·3 *vs* 3·8 μg/m³), but similar NO_2 reductions in the two areas (8·9 *vs* 7·7 parts per billion), although without reporting statistical significance.

An earlier cITS study in 2011 by the same authors[20] compared Tokyo with the rest of Japan for 2003–05 and 2006–08 and found a LEZ-associated reduction (8·5%, 95% CI 5·9–11·0, $p<0·001$) for cerebrovascular disease mortality, but no clear effect for total cardiovascular disease or IHD. The study had moderate internal validity due to limitations in control area suitability, and the fact that the baseline period started concurrently with, rather than before, the intervention. This study reported a reduction in NO_2 and $PM_{2·5}$ (both $p<0·001$) in the Tokyo Metropolitan Government area, without comparing with the control.

A 2022 DiD study by Beshir and Fichera[19] compared the London LEZ area with other major towns and cities in England, using quarterly survey data from 2003 to

	Location	Effect estimate	Measure of variability or statistical significance	Narrative description*
Gehrsitz (2017)[15]				
Birthweight (continuous)				
Main analysis	Germany	DiD estimator=0·2575	SE=1·8943, p>0·1	No clear effect
Controls restricted to LEZ ever-adopters	Germany	DiD estimator=3·3998	SE=2·5385, p>0·1	No clear effect
LBW (binary)				
Main analysis	Germany	DiD estimator=0·0003	SE=0·0008, p>0·1	No clear effect
Controls restricted to LEZ ever-adopters	Germany	DiD estimator=–0·0007	SE=0·0008, p>0·1	No clear effect
Stillbirth				
Main analysis	Germany	DiD estimator=0·0000	SE=0·0002, p>0·1	No clear effect
Controls restricted to LEZ ever-adopters	Germany	DiD estimator=–0·0006	SE=0·0002, p<0·01	Reduction equivalent to ~16% reduction in incidence from 2005 baseline
Margaryan (2021)[16]				
Cardiovascular diseases (total), outpatient data				
Main analysis, all ages	Germany	DiD estimator†=–0·012	SE=0·010, p>0·1	No clear effect
Main analysis, age >65 years	Germany	DiD estimator†=–0·021	SE=0·009, p<0·05	Reduction of 2·1%
Exclude LEZ introduced pre-2009, all ages	Germany	DiD estimator†=–0·022	SE=0·009, p<0·05	Reduction of 2·2%
Exclude LEZ introduced pre-2009, age >65 years	Germany	DiD estimator†=–0·031	SE=0·009, p<0·01	Reduction of 3·1%
Heart disease, outpatient data				
Main analysis, all ages	Germany	DiD estimator†=–0·006	SE=0·010, p>0·1	No clear effect
Main analysis, age >65 years	Germany	DiD estimator†=–0·016	SE=0·011, p>0·1	No clear effect
Exclude LEZ introduced pre-2009, all ages	Germany	DiD estimator†=–0·012	SE=0·009, p>0·1	No clear effect
Exclude LEZ introduced pre-2009, age >65 years	Germany	DiD estimator†=–0·021	SE=0·009, p<0·05	Reduction of 2·1%
Cerebrovascular disease, outpatient data				
Main analysis, all ages	Germany	DiD estimator†=–0·072	SE=0·036, p<0·05	Reduction of 6·9%
Main analysis, age >65 years	Germany	DiD estimator†=–0·071	SE=0·036, p<0·1	No clear effect
Exclude LEZ introduced pre-2009, all ages	Germany	DiD estimator†=–0·126	SE=0·059, p<0·05	Reduction of 11·8%
Exclude LEZ introduced pre-2009, age >65 years	Germany	DiD estimator†=–0·126	SE=0·059, p<0·05	Reduction of 11·8%
Respiratory disease, outpatient data				
Exclude LEZ introduced pre-2009, all ages	Germany	DiD estimator†=0·004	SE=0·006, p>0·1	No clear effect
Exclude LEZ introduced pre-2009, age >65 years	Germany	DiD estimator†=–0·065	SE=0·060, p>0·1	No clear effect
Diabetes, outpatient data				
Exclude LEZ introduced pre-2009, all ages	Germany	DiD estimator†=–0·004	SE=0·007, p>0·1	No clear effect
Exclude LEZ introduced pre-2009, age >65 years	Germany	DiD estimator†=–0·011	SE=0·010, p>0·1	No clear effect
Cardiovascular disease, hospital admissions				
Main analysis, all ages	Germany	DiD estimator†=–0·037	SE=0·031, p<0·1	No clear effect
Main analysis, age >65 years	Germany	DiD estimator†=–0·030	SE=0·034, p<0·1	No clear effect
Heart disease, hospital admissions				
Main analysis, all ages	Germany	DiD estimator†=–0·048	SE=0·035, p<0·1	No clear effect
Main analysis, age >65 years	Germany	DiD estimator†=–0·046	SE=0·036, p<0·1	No clear effect
Cerebrovascular disease, hospital admissions				
Main analysis, all ages	Germany	DiD estimator†=–0·050	SE=0·052, p<0·1	No clear effect
Main analysis, age >65 years	Germany	DiD estimator†=–0·042	SE=0·058, p<0·1	No clear effect

(Table 3 continues on next page)

	Location	Effect estimate	Measure of variability or statistical significance	Narrative description*
(Continued from previous page)				
Pestel and Wozny (2021)[17]				
All disease				
Main analysis	Germany	DiD estimator=–1·412	SE=1·460, p>0·1	No clear effect
Cardiovascular diseases (total)				
Main analysis	Germany	DiD estimator=–1·262	SE=0·484, p<0·01	Reduction in percentage share of diagnoses of 1·3 percentage points, from baseline of 14% (9% reduction)
IHD				
Main analysis	Germany	DiD estimator=–0·545	SE=0·214, p<0·05	Reduction in percentage share of diagnoses of 0·5 percentage points, from baseline of 4% (12% reduction)
Cerebrovascular disease				
Main analysis	Germany	DiD estimator=0·018	SE=0·081, p>0·1	No clear effect
Hypertension				
Main analysis	Germany	DiD estimator=–0·232	SE=0·148, p>0·1	No clear effect
Respiratory diseases (total)				
Main analysis	Germany	DiD estimator=–0·100	SE=0·233, p>0·1	No clear effect
Acute lower respiratory diseases				
Main analysis	Germany	DiD estimator=–0·053	SE=0·030, p<0·1	No clear effect
Chronic lower respiratory diseases				
Main analysis	Germany	DiD estimator=–0·160	SE=0·075, p<0·05	Reduction in percentage share of diagnoses of 0·16 percentage points, from baseline of 1% (16% reduction)
LBW				
Main analysis	Germany	DiD estimator=–0·022	SE=0·016, p>0·1	No clear effect
Diabetes				
Main analysis	Germany	DiD estimator=–0·085	SE=0·087, p>0·1	No clear effect
Dementia				
Main analysis	Germany	DiD estimator=0·002	SE=0·015, p>0·1	No clear effect
Sarmiento et al (2021)[18]				
Doctor visits				
Main analysis	Germany	DiD estimator=–1·292	SE=0·938, p>0·1	No clear effect
Hypertension				
Main analysis	Germany	DiD estimator=–0·046	SE=0·022, p<0·05	4·6% reduction (1·4 percentage points from 31% baseline)
Beshir and Fichera (2022)[19]				
Chest or breathing related				
All LEZ phases combined	London, UK	DiD estimator=–0·006	SE=0·002, p<0·01 (Ferman-Pinto p value=0·137)	Reduction in probability (0·6 percentages points) equivalent to 11% from baseline (though no clear effect in alternative specification with Ferman-Pinto p values)
Phase 1	London, UK	DiD estimator=–0·002	SE=0·002, p>0·1 (Ferman-Pinto p value=0·619)	No clear effect
Phase 2	London, UK	DiD estimator=–0·008	SE=0·002, p<0·01 (Ferman-Pinto p value=0·002)	Reduction (including using Ferman-Pinto p values) of 0·8 percentage points (15% from baseline)
Phase 3	London, UK	DiD estimator=–0·009	SE=0·003, p<0·01 (Ferman-Pinto p value=0·003)	Reductions (including using Ferman-Pinto p values) of 0·9 percentage points (16% from baseline)
Heart-related				
All LEZ phases combined	London, UK	DiD estimator=–0·000	SE=0·002, p>0·1 (Ferman-Pinto p value=0·932)	No clear effect
Phase 1	London, UK	DiD estimator=–0·000	SE=0·003, p>0·1 (Ferman-Pinto p value=0·951)	No clear effect
Phase 2	London, UK	DiD estimator=–0·005	SE=0·003, p<0·05 (Ferman-Pinto p value=0·065)	Reduction using main p values (no clear effect using Ferman-Pinto p values)
Phase 3	London, UK	DiD estimator=–0·012	SE=0·004, p<0·01 (Ferman-Pinto p value= 0·000)	Reduction (including using Ferman-Pinto p values) of 1·2 percentage points, equivalent to 13% from baseline

(Table 3 continues on next page)

	Location	Effect estimate	Measure of variability or statistical significance	Narrative description*
(Continued from previous page)				
Percoco (2016)[13]				
Total incidents (all vehicles)				
Main analysis	Milan, Italy	uITS estimator†=–0·188	SE=0·0315, p<0·01	Reduction of 17·1%
Injuries (all vehicles)				
Main analysis	Milan, Italy	uITS estimator†=–0·167	SE=0·0340, p<0·01	Reduction of 15·4%
Fatalities (all vehicles)				
Main analysis	Milan, Italy	uITS estimator†=–0·842	SE=0·729, p>0·1	No clear effect
Yorifuji et al (2011)[20]				
All-cause mortality				
Main analysis	Tokyo, Japan	cITS % change=–0·13	95% CI –1·99 to 1·77, p=0·893	No clear effect
Cardiovascular-cause mortality (total)				
Main analysis	Tokyo, Japan	cITS % change=1·27	95% CI –2·11 to 4·78, p=0·466	No clear effect
IHD				
Main analysis	Tokyo, Japan	cITS % change=–0·61	95% CI –3·67 to 2·56, p=0·703	No clear effect
Cerebrovascular disease				
Main analysis	Tokyo, Japan	cITS % change=–8·50	95% CI –11·0 to –5·93, p<0·001	Reduction of 8·5%
Respiratory-cause mortality				
Main analysis	Tokyo, Japan	cITS % change=3·02	95% CI –0·16 to 6·29, p=0·063	No clear effect
Mortality due to other causes				
Main analysis	Tokyo, Japan	cITS % change=1·30	95% CI –1·92 to 4·63, p=0·432	No clear effect
Yorifuji et al (2016)[21]				
All-cause mortality, non-trauma				
Main analysis	Tokyo, Japan	cITS % change=–6·0	95% CI –6·7 to –5·3	Reduction of 6·0%
Cardiovascular-cause mortality (total)				
Main analysis	Tokyo, Japan	cITS % change=–11	95% CI –13 to –10	Reduction of 11·0%
IHD-cause mortality				
Main analysis	Tokyo, Japan	cITS % change=–10	95% CI –13 to –7·9	Reduction of 10·0%
Cerebrovascular-cause mortality				
Main analysis	Tokyo, Japan	cITS % change=–6·2	95% CI –7·6 to –4·7	Reduction of 6·2%
Respiratory-cause mortality				
Main analysis	Tokyo, Japan	cITS % change=–22	95% CI –23 to –20	Reduction of 22·0%
Lung cancer mortality				
Main analysis	Tokyo, Japan	cITS % change=–4·9	95% CI –6·7 to –3·0	Reduction of 4·9%
Non-trauma mortality of other causes				
Main analysis	Tokyo, Japan	cITS % change=–0·20	95% CI –1·0 to 0·63	No clear effect

In all cases, the results discussed are those from the most fully adjusted model reported. The structure of this table is adapted from Burns and colleagues (2019).[7] Subgroup analysis is reported if statistically significant effect is seen for any outcome in the subgroup analysis. CCZ=congestion charging zone. cITS=interrupted time series analysis with control. DiD=difference-in-difference. KSI=killed or serious injury. LEZ=low emission zone. LSOA=Lower Layer Super Output Areas. NR=not reported. SE=standard error. uITS=interrupted time series analysis without control. *No clear effect indicates a non-statistically significant effect at a 0·05 threshold. †Dependent variable is in logs.

***Table 3*: Study results (health outcomes in low emission zone studies)**

2015. This time period covered three increasingly stringent phases of the LEZ. They found no clear LEZ-associated reduction in probability of survey participants reporting heart problems lasting more than 12 months when the three phases were analysed in combination. When analysed separately, there was a reduction (1·2 percentage points, 13% from baseline, p<0·01) for the most stringent phase. The study was assessed as having strong internal validity. There was also a reduction in PM_{10} concentrations (3·5 μg/m³, 12% from baseline, p<0·01), but no clear effect for NO_2, for the combined phases.

Respiratory outcomes

Of the five LEZ studies considering respiratory outcomes, two were from Germany,[16,17] two were from Tokyo, Japan,[20,21] and one was from London, UK.[19] Two studies found reductions[17,21] in at least one respiratory disease subcategory. No studies found an increase. Of the four studies with a no clear effect finding in any subcategory,

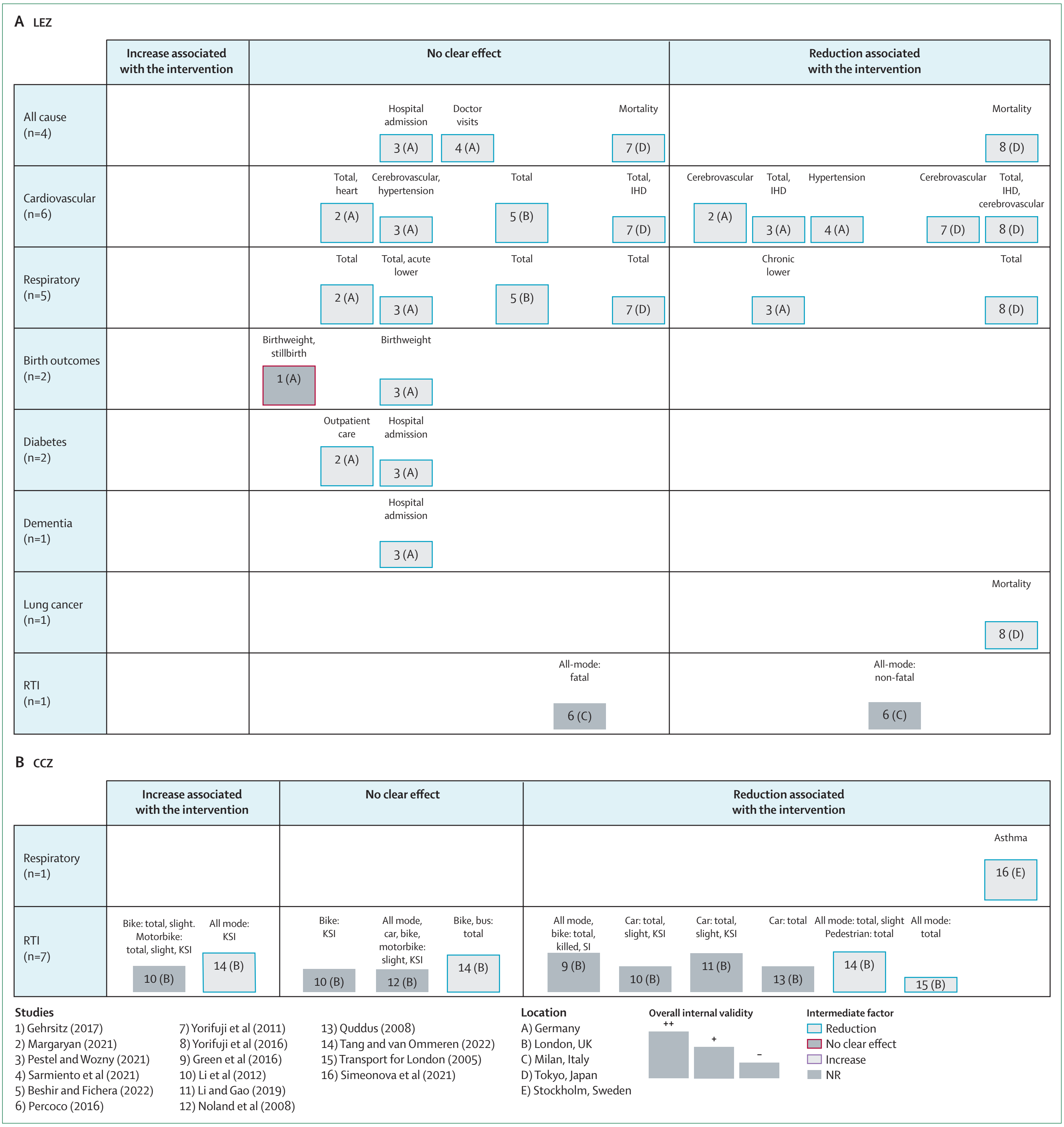

***Figure:* Harvest plots showing results for studies assessing (A) LEZs (B) CCZs (primary synthesis)**
The intermediate factor key is reduction or increase if the study finds evidence of a reduction or increase in any intermediate factor (eg, any air pollutant or traffic volume), no clear effect if the study finds no significant reduction or increase in any intermediate factor, and NR if the study does not consider intermediate factors. CCZ=congestion charging zone. IHD=ischaemic heart disease. KSI=killed or serious injury. LEZ=low emission zone. NR=not reported. RTI=road traffic injury. SI=serious injury.

in two the effect direction was towards a reduction, and in two it was towards an increase.

The Pestel and Wozny study[17] identified a 0·16 percentage point reduction (16% from baseline, $p<0·05$) in chronic lower respiratory disease diagnosis share associated with a hospital being in an active LEZ, but no clear effect for acute lower respiratory or total respiratory diagnoses. The DiD study by Margaryan[16] also found no LEZ-associated respiratory-cause outpatient attendances. The 2016 cITS study by Yorifuji and colleagues[21] from Tokyo reported a 22·0% (95% CI 20·0–23·0) LEZ-associated reduction in respiratory disease mortality, but the 2011 cITS study by Yorifuji and colleagues[20] found no clear effect for this outcome.

Beshir and Fichera[19] also considered respiratory outcomes. When analysing the three London LEZ phases in combination they found no clear LEZ-associated reduction in self-reported chest-related or breathing-related problems, but reductions of 0·8 percentage points (15% from baseline, $p<0·01$) for the second phase and 0·9 percentage points (16% from baseline, $p<0·01$) for the third phase.

Birth outcomes

Two studies considered birth outcomes, both in Germany.[15,17] Neither study found a clear effect for any outcome; in one study the effect direction was towards a reduction, and in the other the direction varied between specific outcomes.

Gehrsitz[15] assessed outcomes from 1·85 million births from 2005 to 2012 and found no clear LEZ-associated effect on stillbirth incidence in their main model, but a 16% reduction from baseline ($p<0·01$) when the control group was restricted to cities that later adopted a LEZ. There was no clear effect on birthweight. There were reductions in mean daily PM_{10} (0·6 μg/m³, 2·1% from the 2005 baseline, $p<0·05$), in the main model, but no clear effect in the restricted model. The study by Pestel and Wozny[17] also found no reduction in low birthweight diagnosis share associated with a hospital being in an active LEZ.

All-cause outcomes

Four studies considered all-cause outcomes,[17,18,20,21] with one finding a clear reduction.[21] No studies found an increase. In all three of the studies with a no clear effect finding, the effect direction was towards a reduction.

The 2016 study from Tokyo[21] reported a 6·0% (95% CI 5·3–6·7) LEZ-associated reduction in all-cause mortality, but the 2011 study[20] found no clear effect. In Germany, Sarmiento and colleagues[18] found no clear effect on self-reported all-cause doctor visits, and Pestel and Wozny[17] found no clear effect on all-cause inpatient diagnoses.

Diabetes

Two studies from Germany considered diabetes (type 1 and 2), with no clear LEZ-associated effects on inpatient diagnosis share[17] or outpatient attendances.[16] In both cases, the direction of the effect was towards a reduction.

Other outcomes

Dementia, lung cancer, and RTIs were each considered by single LEZ studies. The Pestel and Wozny study from Germany[17] found no clear LEZ-associated effect on inpatient dementia diagnosis share, whereas the 2016 study[21] from Tokyo found a 4·9% (95% CI 3·0–6·7) LEZ-associated reduction in lung cancer mortality. Percoco[13] compared the LEZ in Milan, Italy with the rest of the city using a DiD approach, and identified a 15% reduction ($p<0·01$) in RTIs from all vehicle types combined, but no clear effect on fatalities; it was rated as moderate internal validity.

Congestion charging zones

The CCZ studies were published between 2005 and 2021, with six using DiD[14,22–24,27,28] and two uITS.[25,26] Of the eight studies, seven assessed RTIs associated with the London CCZ,[14,22–27] and one assessed child hospital admissions for asthma associated with the Stockholm CCZ.[28] Four studies were rated as having strong internal validity,[22,24,27,28] three as medium,[23,25,26] and one as weak[14] (appendix p 14). Absence of a control group and insufficient control for possible confounding were key factors affecting risk of bias. Primary results are in table 4 and the figure, and secondary results are in the appendix (p 14). Three studies reported results for at least one intermediate factor, namely air quality,[28] traffic flow,[27] and vehicle-kilometres driven,[14] with these results summarised in the appendix (p 9) and the figure.

Road traffic injuries

All seven studies on RTIs in the London CCZ used data from the STATS19 database.[29] Six of seven studies reported reductions in total or car RTIs,[14,22–24,26,27] although one reported an increase in cyclist and motorcyclist injuries[23] and one reported an increase in serious or fatal injuries.[27] Of the three studies with a no clear effect finding in any subcategory, in one the effect direction was towards a reduction, in one the direction varied between subcategories, and in one the effect direction was towards an increase.

The earliest study is a TfL DiD analysis,[14] which reported a 5% CCZ-associated reduction in total injury-causing road traffic incidents between the 12 months before and after CCZ implementation. It includes adjustment for concurrent changes in road traffic incidents in the rest of London, but was judged to have weak internal validity, mainly due to no further control for confounding factors. There is also no measure of precision or statistical significance reported. Two uITS studies published in 2008 analysed monthly data for 1991–2004[26] and 1991–2005.[25] Quddus[26] reported a CCZ-associated 26·5% ($p<0·05$) reduction in monthly car RTIs. In their main model, Noland and colleagues[25] reported no clear effect for RTIs involving cars or all vehicle types combined, although a secondary model specification identified reductions in severity subcategories for car RTIs. Neither study used a formal control area, contributing to moderate internal validity ratings.

Li and colleagues[23] used annual data from 2001 to 2004 to compare the London CCZ with central areas of other English cities in a DiD analysis, and reported a CCZ-associated 5·3% ($p<0·01$) reduction in total car incidents, including slight injuries and severe or fatal injuries. Li and colleagues also reported a 13·5% ($p<0·01$) increase in slight bicycle injuries, but no clear effect on serious or fatal bicycle injuries. Li and colleagues also reported a 1·9% ($p<0·01$) increase in slight motorcyclist injuries, and a 17·4% ($p<0·01$) increase in severe or fatal motorcyclist injuries. The study had a moderate internal

	Location	Effect estimate	Measure of variability or statistical significance	Narrative description*
Green et al (2016)[22]				
Total traffic incidents (all vehicles)				
Main analysis	London, UK	DiD estimator=–40·847	SE=1·193, p<0·01	Reduction of 40·8 per month, equivalent to ~37% from baseline
Total traffic incidents (bike only)				
Main analysis	London, UK	DiD estimator =–2·853	SE=0·263, p<0·01	Reduction of 2·9 per month, equivalent to ~9% from baseline
Incident causing KSI (all vehicles)				
Main analysis	London, UK	DiD estimator=–3·600	SE=0·241, p<0·01	Reduction of 3·6 per month, equivalent to ~25% from baseline
Incident causing KSI (bike only)				
Main analysis	London, UK	DiD estimator=–0·604	SE=0·083, p<0·01	Reduction of 0·6 per month, equivalent to ~15% from baseline
Incident causing fatality (all vehicles)				
Main analysis	London, UK	DiD estimator=–0·359	SE=0·073, p<0·01	Reduction of 0·36 per month, equivalent to ~35% from baseline
Li et al (2012)[23]				
Total car incidents				
Main analysis	London, UK	DiD estimator†=–0·054	SE=0·000125, p<0·01	Reduction of 5·3%
Car incidents with slight injury				
Main analysis	London, UK	DiD estimator†=–0·0467	SE=0·000173, p<0·01	Reduction of 4·6%
Car incidents with KSI				
Main analysis	London, UK	DiD estimator†=–0·153	SE=0·0495, p<0·01	Reduction of 14·2%
Total bike incidents				
Main analysis	London, UK	DiD estimator†=0·125	SE=0·00476, p<0·01	Increase of 13·3%
Bike incidents with slight injury				
Main analysis	London, UK	DiD estimator†=0·127	SE=0·0012, p<0·01	Increase of 13·5%
Bike incidents with KSI				
Main analysis	London, UK	DiD estimator†=0·0267	SE=0·0241, p>0·1	No clear effect
Total motorcycle incidents				
Main analysis	London, UK	DiD estimator†=0·0557	SE=0·0115, p<0·01	Increase of 5·7%
Motorcycle incidents with slight injury				
Main analysis	London, UK	DiD estimator†=0·0183	SE = 0·000459, p<0·01	Increase of 1·9%
Motorcycle incidents with KSI				
Main analysis	London, UK	DiD estimator†=0·160	SE=0·00709, p<0·01	Increase of 17·4%
Li and Gao (2019)[24]				
Total car incidents				
Main analysis	London, UK	Post-treatment difference (n, %) between intervention and synthetic control=–1·9 (–4·29%)	p (placebo control)=0·032	Reduction of 4·3%
Car incidents with slight injury				
Main analysis	London, UK	Post-treatment difference (n, %) between intervention and synthetic control=–2·0 (–5·05%)	p (placebo control)=0·028	Reduction of 5·1%
Car incidents with KSI				
Main analysis	London, UK	Post-treatment difference (n, %) between intervention and synthetic control=–0·64 (–12·12%)	p (placebo control)=0·041	Reduction of 12·1%

(Table 4 continues on next page)

	Location	Effect estimate	Measure of variability or statistical significance	Narrative description*
(Continued from previous page)				
Noland et al (2008)[25]				
Slight injury (all vehicles)				
Main analysis	London, UK	uITS estimator=–8·203	p>0·15	No clear effect
KSI (all vehicles)				
Main analysis	London, UK	uITS estimator=–1·046	p>0·15	No clear effect
Slight injury (car)				
Main analysis	London, UK	uITS estimator=–4·703	p<0·10	No clear effect
Alternative model	London, UK	uITS estimator†=–0·389	p<0·05	Reduction of 32%
KSI (car)				
Main analysis	London, UK	uITS estimator=–0·939	p<0·15	No clear effect
Alternative model	London, UK	uITS estimator†=–0·810	p<0·05	Reduction of 56%
Slight injury (cyclist)				
Main analysis	London, UK	uITS estimator=–0·748	p>0·15	No clear effect
Alternative model	London, UK	uITS estimator†=0·144	p<0·10	No clear effect
KSI (cyclist)				
Main analysis	London, UK	uITS estimator=–0·425	p>0·15	No clear effect
Alternative model	London, UK	uITS estimator†=0·127	p>0·15	No clear effect
Slight injury (motorcyclist)				
Main analysis	London, UK	uITS estimator=–0·815	p>0·15	No clear effect
KSI (motorcyclist)				
Main analysis	London, UK	uITS estimator=0·281	p>0·15	No clear effect
Quddus (2008)[26]				
RTA car casualties				
Main analysis	London, UK	uITS estimator†=–0·3076	p<0·05	Reduction of 26·5%
Tang and van Ommeren (2022)[27]				
Total incidents (with ≥1 injury or fatality)				
Main analysis	London, UK	DiD estimator†=–0·0716	SE=0·0248, p<0·01	Reduction of 6·9%
Slight injury from RTA				
Main analysis	London, UK	DiD estimator†=–0·1017	SE=0·0288, p<0·01	Reduction of 9·7%
KSI from RTA				
Main analysis	London, UK	DiD estimator†=0·1100	SE=0·0387, p<0·01	Reduction of 11·6%
Incidents involving 2-wheel vehicle				
LSOAs within 2·5 km of CCZ boundary	London, UK	DiD estimator†=–0·0615	SE=0·0427, p>0·1	No clear effect
Incidents involving buses				
LSOAs within 2·5 km of CCZ boundary	London, UK	DiD estimator†=–0·0060	SE=0·0732, p>0·1	No clear effect
Pedestrian injuries from RTA				
LSOAs within 2·5 km of CCZ boundary	London, UK	DiD estimator†=–0·0930	SE=0·0451, p<0·05	Reduction of 8·9%
Transport for London (2005)[14]				
RTAs resulting in injury				
Main analysis	London, UK	% change in intervention area relative to control area=–5%	NR	Reduction of 5%, statistical significance unknown
Simeonova et al (2021)[28]				
Asthma				
Main analysis	Stockholm, Sweden	DiD estimator=–9·597	SE=1·935, p<0·001	Reduction of 9·6 per 10 000, equivalent to 50%

In all cases, the results discussed are those from the most fully adjusted model reported. The structure of this table is adapted from Burns and colleagues (2019).[7] Subgroup analysis is reported if statistically significant effect is seen for any outcome in the subgroup analysis. CCZ=congestion charging zone. cITS=interrupted time series analysis with control group. DiD=difference-in-difference. KSI=killed or serious injury. LEZ=low emission zone. LSOA=Lower Layer Super Output Areas. NR=not reported. SE=standard error. uITS=interrupted time series analysis without control group. *No clear effect indicates a non-statistically significant effect at a 0·05 threshold. †Dependent variable is in logs.

Table 4: **Study results (health outcomes in congestion charging zone studies)**

validity rating due to concerns over meeting the parallel trend assumption, and the appropriateness of control areas.

Green and colleagues[22] used monthly data from 2000 to 2009 in a DiD analysis, with the 20 next-most populous British cities as control areas, and a reported CCZ-associated reduction in total traffic incidents, equivalent to 37% from baseline (41 incidents per month, $p<0\cdot01$). This finding included reductions in serious and fatal injuries for all vehicles combined, and for bicycles. The study had strong internal validity.

Li and Gao[24] used annual data from 1998 to 2007 in a DiD analysis with a synthetic control constructed from neighbourhoods of Manchester, UK, and a reported CCZ-associated reduction of 4·3% ($p=0\cdot032$) for total car incidents. Analyses of all injury severity subcategories also showed reductions. The study had strong internal validity.

Tang and van Ommeren[27] used annual data from 2000 to 2014 to compare the CCZ with other London areas in a DiD analysis and reported a CCZ-associated reduction in total incidents equivalent to 6·9% ($p<0\cdot01$); this included a reduction in slight injuries, but an increase in serious injuries and fatalities. Tang and van Ommeren found no clear effect for incidents involving 2-wheel vehicles or buses, but a reduction in pedestrian injuries. The study had strong internal validity.

Few studies on the London CCZ considered intermediate factors. The TfL analysis[14] reported a 12% reduction in vehicle-kilometres driven in the intervention area, and Tang and van Ommeren[27] reported a 13·5% ($p<0\cdot01$) CCZ-associated traffic flow reduction.

Respiratory

Simeonova and colleagues[28] analysed 2004–10 monthly data on emergency health-care visits for asthma in children aged 5 years or younger, comparing those within the Stockholm CCZ with other Swedish city centres in a DiD analysis. The study had strong internal validity. Simeonova and colleagues reported a reduction of 9·6 acute asthma visits per 10 000 (50% from baseline, $p<0\cdot001$) associated with the CCZ introduction. The authors also reported reductions in monthly average PM_{10} (4·6 μg/m³, 13·7% from baseline, $p<0\cdot001$) and NO_2 (6·2 μg/m³, 18·7% from baseline, $p<0\cdot001$).

Discussion

This systematic Review of the health effects of LEZs and CCZs identified benefits associated with these interventions. Studies of LEZs found consistent evidence of reductions in cardiovascular disease outcomes, although results were less consistent for other outcomes. Studies of CCZs found consistent evidence of reductions in total injuries or car-related injuries. The current evidence therefore suggests that schemes to restrict private vehicle use in cities could reduce cardiovascular disease events and RTIs.

This Review advances previous work by adding greater certainty of cardiovascular disease effects of LEZ schemes and RTI effects of CCZ schemes. We followed a preregistered protocol and searched six databases as well as the references of included studies to ensure comprehensiveness. Of the seven LEZ studies considering health effects other than RTIs, five had been published since the 2019 review by Burns and colleagues.[7] We included only longitudinal studies with data from pre and post LEZ or CCZ implementation, because of the capacity of these study designs to show temporal direction of the intervention–outcome association, as required for causal inference. Longitudinal studies are also at lower risk of unobserved confounding than cross-sectional studies.[30] We focused on empirically measured health outcomes rather than predictions using exposure–response or concentration–response functions.

Health outcomes considered here are influenced by other factors, so we extracted information on intermediate factors when reported, including air pollution and traffic flow, to strengthen causal inference. In many cases, the observed reductions in health outcomes were accompanied by reductions in these intermediate factors, although this work is not a systematic review of the effect of CCZs and LEZs on these factors. However, the included studies did not include data on other possible contributory factors related to the intervention, such as physical activity and road noise; further research could usefully investigate the pathways underpinning the health effects identified here.

There are some potential limitations to our Review. Although we searched a range of databases without language restrictions, papers outside of health or economic disciplines could have been missed. Additionally, we could not perform meta-analyses due to the small number of studies using comparable designs and outcomes. We instead used harvest plots and narrative synthesis to summarise findings. Although appropriate and valuable in synthesising the heterogenous studies, our vote-counting synthesis approach based on effect direction and statistical significance does not take account of effect magnitude. We also conducted a secondary synthesis describing the effect directions of results indicating no clear effect, but this should not be overinterpreted, as the uncertainty in these estimates means they are compatible with a null effect. Finally, we took a conservative approach in selecting which estimates to include in harvest plots to minimise the risk of falsely positive conclusions, but this approach could have led to underestimation of effects.

Reviews are necessarily constrained by the available evidence. The included studies came from a range of quasi-experimental designs in a range of locations, and 15 of 16 had moderate-to-strong internal validity. There were some discrepant results; six of seven studies on RTIs in the London CCZ found overall reductions in total or car RTIs, whereas one study identified increases in cyclist and motorcyclist injuries, and one identified an increase in serious or fatal injuries. Although increased cycling injuries could be linked to increased cycling, this remains to be fully ascertained.[31] Available studies did not consider potential inequalities in effect by socio-demographic factors and gave little consideration to potential effects on bordering areas. Additionally, future evaluations of such schemes should adhere to best practice recommendations.[32] Key issues for the research base include an overall low number of rigorous evaluations of schemes in different contexts and minimal research using comparable outcomes. An expansion of evaluations of future schemes using routine data systems and standardised mechanisms for capturing outcomes would enhance the evidence base and make future reviews more comprehensive through approaches such as meta-analyses.[7]

Although both CCZs and LEZs restrict private vehicle use within cities, they are in practice different; CCZs ban or charge most vehicles and aim specifically to reduce congestion, whereas LEZs aim specifically to discourage the use of high-emission vehicles. This difference in focus is reflected in the fact that the majority of CCZ evidence focuses on RTIs, whereas the majority of LEZ evidence examines air pollution-related health effects. It should be noted that other schemes to reduce or restrict the use of private vehicles within cities do exist, such as odd–even restriction schemes, which restrict vehicle use to alternate days based on registration numbers and are in place in cities such as Jakarta, Indonesia, and have previously been used in New Delhi, India.[33,34] We considered such schemes as out of our scope, but they might have similar health effects to those seen here and this could be a fruitful avenue for future research.

We did not include other possible effects, including on congestion, residents' quality of life, or long-term disease development; these effects probably strengthen arguments for such schemes.[35] The observed heterogeneity in design and implementation highlights the fact that there is no standard for LEZs or CCZs; the design and implementation of any future schemes will be important in determining their effect. Nonetheless, both environmental and human health require comprehensive solutions to our reliance on private motorised transport, and the largest health benefits are likely to come from schemes that integrate approaches to support both a reduction in private motorised traffic and increases in active travel and public transport use.[36]

Conclusion

Available evidence suggests observable health benefits from schemes restricting private vehicles in cities. Evidence for LEZs is most consistent for cardiovascular disease, whereas evidence for CCZs is restricted to RTIs in London. Further research could usefully investigate how to optimise the design of such schemes to improve health.

Contributors

RCC and AAL designed the study, with input from DF and BD. RCC and AAL did the screening, data extraction, and synthesis. RCC and AAL wrote the first draft, with all authors commenting and contributing to revisions. RCC and AAL had access to all the underlying data. All authors have approved the final version of the manuscript for publication.

Declaration of interests

We declare no competing interests.

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