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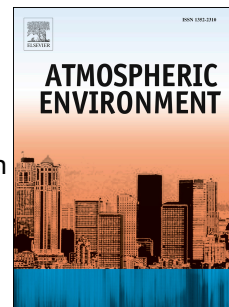
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3
4 **REVIEW OF THE EFFICACY OF LOW EMISSION**
5 **ZONES TO IMPROVE URBAN AIR QUALITY IN**
6 **EUROPEAN CITIES**

7
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34 Many cities still exceed the European Union (EU) air quality limit values for particulate matter (PM₁₀,
35 particles with an aerodynamic diameter less than 10 µm) and/or nitrogen dioxide (NO₂). In an attempt
36 to reduce emissions approximately 200 low emission zones (LEZs) have been established in 12 EU
37 countries. These restrict the entry of vehicles based on the emission standard the vehicles were
38 originally constructed to meet, but the restrictions vary considerably. This paper reviews the evidence
39 on the efficacy of LEZs to improve urban air quality in five EU countries (Denmark, Germany,
40 Netherlands, Italy and UK), and concludes that there have been mixed results. There is some
41 evidence from ambient measurements that LEZs in Germany, which restrict passenger cars as well as
42 heavy duty vehicles (HDVs), have reduced long term average PM₁₀ and NO₂ concentrations by a few
43 percent. Elsewhere, where restrictions are limited to HDVs, the picture is much less clear. This may
44 be due to the large number of confounding factors. On the other hand there is some, albeit limited,
45 evidence that LEZs may result in larger reductions in concentrations of carbonaceous particles, due to
46 traffic making a larger contribution to ambient concentrations of these particles than to PM₁₀ and
47 PM_{2.5}. The effects of day to day variations in meteorology on concentrations often mask more subtle
48 effects of a LEZ. In addition, separating the direct effects of a LEZ from the effects of other policy
49 measures, the economy and the normal renewal of the vehicle fleet is not easy, and may give rise to
50 false results.

51

52 **Key Words:** Low Emissions Zone; LEZs; NO₂; PM₁₀; vehicle emissions; air quality

54 A large proportion of the European population continues to be exposed to poor air quality despite the
55 significant reduction in emissions over the last few decades. The last evaluation by the European
56 Environmental Agency (2014) has estimated that, during 2012, 21-33% of the urban population live in
57 areas where the PM₁₀ limit value is exceeded, and 64-83 and 91-93% where the WHO PM₁₀ and
58 PM_{2.5} guidelines are exceeded. Whilst the adverse health effects of particulate matter (PM) are well
59 documented (WHO, 2005, and WHO, 2013) there is increasing evidence of the health effects of long
60 term exposure to NO₂ (WHO, 2013).

61
62 The European Union (EU) air quality Directive (2008/50/EC) requires the limit values for PM₁₀ and
63 NO₂ to be achieved by 2005 and 2010 respectively, but also allows the compliance to be delayed until
64 2010 and 2015 respectively subject to the Member State submitting an acceptable air quality action
65 plan for non-compliant agglomerations and zones. Most EU member states have sought time
66 extensions for one or both these pollutants.

67
68 In an effort to comply with the air quality limit values, and to protect human health, a number of
69 European cities have introduced low emission zones (LEZs). In the nearly two decades since the first
70 one was established LEZs have become regarded as an important measure to improve urban air
71 quality, and there are thought to be approximately 200¹ currently in existence in Europe (Sadler
72 Consultants Ltd, 2014a).

73
74 Whilst there are a large number of LEZs there have been few good quality studies quantifying their
75 impact on air quality using monitored data. As the ultimate aim for many LEZs is to contribute towards
76 compliance with the EU limit values, which are largely assessed thorough monitoring ambient
77 concentrations, this is perhaps surprising. Many cities have assessed the cost-effectiveness of
78 introducing a LEZ pre-implementation using emissions modelling and, in some cases, dispersion
79 modelling to assess their potential impact, but there have been few post-implementation studies
80 published.

¹ This assumes that the approximately 1550 mainly small LEZs in the Lombardi region of Italy count as one LEZ.

81 The aim of this review is to describe the types of LEZ in the EU and to assess the evidence of their
82 efficacy, focusing largely, but not exclusively, on ambient air quality measurements. It reviews studies
83 undertaken in five EU countries (Denmark, Germany, Netherlands, Italy and the UK), and is based on
84 a literature search of peer reviewed papers using a range of relevant terms and databases. To
85 identify reports commissioned by city and Government agencies a Google search was also
86 undertaken. As the searches were undertaken mainly in the English language and it is probable that
87 some relevant studies were missed. In addition not all relevant studies may be available on the
88 internet.

89
90 It discusses the evidence from the London LEZ in more detail than other LEZs as it is probably the
91 most extensively studied and certainly Europe's largest LEZ. Both modelled and measured data has
92 been discussed, to provide an insight into the often optimistic results of modelling studies. For other
93 LEZs the evidence is limited to ambient monitoring data.

94
95 A number of other urban scale traffic measures have been introduced into European cities, such as
96 parking restrictions, road and bridge charges, and bus lanes that discriminate in favour of low
97 emission vehicles. Another measure that is favoured in some European countries is the use of short
98 term vehicle restrictions to reduce emissions during pollution events. These measures, whilst
99 mentioned in passing, have not been included in the main part of this review, as these are not strictly
100 LEZs, although there are similar or greater difficulties in assessing the success or otherwise of these
101 measures.

102

103 **2. LOW EMISSION ZONES**

104 In broad terms LEZs are areas where access is restricted due to the emissions of certain road
105 vehicles. The restriction is generally based on the emissions standard the vehicle was constructed to
106 and may be a complete ban or there may be a charge to enter the LEZ. It may cover a few roads or a
107 large inner city area.

108

109 European emission standards apply to passenger cars and vans (i.e. light duty vehicles; LDVs),
110 two/three wheeled vehicles and the engines used in heavy duty vehicles (HDVs). Each type of

111 vehicle has different emission limits and test procedures. For LDVs there are separate requirements
112 for gasoline and diesel vehicles. For LDVs Arabic numbers (Euro 1, Euro 2, etc.) and HDVs Roman
113 numbers (Euro I, Euro II, etc.) are used to identify the emission standards. This convention has been
114 used in this paper.

115
116 A LEZ essentially introduces a step change in the normal fleet turnover, resulting in lower emissions
117 than would have occurred without the LEZ. Over time the fleet emissions will become similar to those
118 that would have occurred without the LEZ. For further benefits it is necessary to periodically tighten
119 the scheme's criteria.

120
121 The LEZs are mainly aimed at reducing exhaust emissions of PM, although some also aim to reduce
122 nitrogen oxides (NO_x). These emissions are greater from diesel vehicles than from conventional
123 gasoline vehicles (assuming, for NO_x, a three-way catalyst is fitted). HDVs, which are almost all diesel
124 fuelled in Europe, have the greatest emissions per vehicle kilometre. For example, Wang et al. (2010)
125 suggests that in an urban area in Copenhagen HDVs emit about 30 times more PM_{2.5} and 26 times
126 more NO_x than LDVs. Therefore many LEZs restrict these vehicles.

127

128 **2.1. Brief History of LEZs**

129 The first LEZs in Europe were established in 1996 in Stockholm, Göteborg and Malmo in Sweden,
130 where they are known as Environmental Zones (Miljözon). The oldest HDVs were banned, and
131 middle aged HDVs had to be fitted with a certified emission control device or new engine (Göteborgs
132 Stad, 2006). In 2002 the entry criteria were modified to include restrictions on NO_x emissions. In 2006
133 the Swedish Government established a national LEZ scheme. The current requirements are that Euro
134 II and III HDVs can be driven in a LEZ for eight years from first registration, Euro IV until 2016 and
135 Euro V until 2020 (Göteborgs Stad et al., 2009).

136
137 The first LEZ outside Sweden, established in 2002, was in the Mont Blanc Tunnel between France
138 and Italy. HDVs are banned from entering unless they meet at least the Euro III standard.

139

140

2.2. Summary of European LEZs Requirements

Table 1 summarises the LEZ requirements. Only HDVs are restricted in most countries, but in Germany LDVS are included as are cars in Athens (Greece) and Lisbon (Portugal). The Italian LEZs also restrict 2-wheeled vehicles

There are a large number of LEZs in Italy and Germany, but other countries have been less enthusiastic. In France, according to Charleux (2013), legislation was passed in 2010 to allow large urban communities to introduce LEZs, but following a change in government, the policy was abandoned. However, the Mayor of Paris (2015) has announced the establishment of a LEZ in the capital from the summer 2015.

According to Sadler Consultants Ltd. (2014a) most LEZs are permanent and apply 24 hours a day, seven days a week. Some, however, only apply on weekdays (Athens and Budapest LEZs) and the Lisbon LEZ only applies for 12 daytime hours on Monday to Saturday. Some Italian LEZs only restrict passenger cars in the winter, but restrict 2-stroke motorcycles and mopeds, and diesel public transport buses all year. Athens LEZ applies from September to July each year, with different requirements within the city centre and the rest of Athens. Vehicles up to 2.2 t are allowed to enter the city centre on alternative days depending on the last digit of the license plate. In the whole of Athens vehicles over 2.2 t and first registered before 1 January 1991 are banned. The date increases by one year, every year. LEZ restrictions are enforced by manual techniques or the use of automatic number plate recognition technology. Most LEZs require a sticker indicating compliance to be displayed.

2.3. National Frameworks

Some countries, (e.g. Germany, the Netherlands and Sweden) have national LEZ frameworks to provide a consistent approach and to increase the ease of driving across a country. However, each municipality has the option to declare a LEZ and to determine the exempt vehicles. In other countries, most notably Italy, there is no national framework and each municipality determines their own criteria. This approach has the potential advantage of tailoring the LEZ to the local air quality issues, but can make driving thorough several cities on a single journey problematic without researching the

169 requirements prior to starting the trip. It can also increase costs for national transport companies, as
170 the most stringent requirement(s) would need to be met to provide a national service.

171

172 **2.4 Evaluating the Effectiveness of an LEZ**

173 During the planning stage potential impacts can be quantified by emissions modelling, often combined
174 with an estimate of the impact on air quality using dispersion or empirical models. There have been
175 relatively few studies which have attempted to evaluate the impact of a LEZ using measured
176 concentrations, possibly because of the difficulty in identifying small changes in concentrations
177 following policy interventions.

178

179 To predict the potential LEZ impact a large amount of detailed local data is required, from the fleet
180 structure to traffic speeds. In recent years there has been considerable uncertainty regarding the
181 emission factors commonly used, such as those in the EU's COPERT 4 emission model (EMISIA,
182 2011), particularly for nitrogen oxides (NO_x). As a consequence many of the emission inventories and
183 forecasts have been shown to be optimistic (Beevers et al., 2012).

184

185 Carslaw and Rhys-Tyler (2013) show that under real world driving conditions diesel car NO_x emissions
186 have not changed over the last 20 years, and that this has not been reflected in the emission factors.
187 At the same time the proportion of NO₂ in vehicle NO_x emissions has increased. For heavy goods
188 vehicles (HGVs) NO_x emissions were fairly constant until Euro IV when they declined by about 30%
189 while there has been little change in urban buses emissions from Euro 1 to Euro IV, and there is some
190 evidence that some Euro VI buses continue to be high emitters.

191

192 Given the relatively high NO_x emissions from diesel vehicles and the lack of improvement over time,
193 any LEZ targeting NO₂ concentrations is unlikely to be successful until NO_x emissions are significantly
194 reduced under real world driving conditions.

195

196 Another factor that needs to be considered when assessing the impact of a LEZ is the contribution of
197 exhaust emissions from local traffic to ambient concentrations. In Berlin, for example, Lutz (2013)
198 estimated that just 4.1% of PM₁₀ at kerbside sites in 2009 was due to traffic exhaust emissions, with a

199 larger contribution (14.9%) from non-exhaust traffic emissions. However, the regional background
200 dominated, contributing almost two thirds of the PM₁₀. In situations such as this, reducing local
201 vehicle exhaust emissions can only have a very limited impact on PM₁₀ concentrations and
202 compliance with the EU limit values.

203

204 It has been argued, for example by Cyrus et al. (2014), that it may be more appropriate to assess the
205 impact of LEZs in terms of the reduction in elemental carbon (EC), black carbon (BC) or black smoke
206 (BS) rather than PM₁₀, PM_{2.5} or even PM₁. The former are considered by some to be more toxic than
207 some of the other components of ambient PM and hence a reduction in their ambient concentrations
208 may have a greater benefit for human health than a small change in PM₁₀ concentrations may
209 suggest. Janssen et al. (2011) evaluated the risk of BC and concluded that they are a valuable
210 indicator of the health risks of poor air quality where there are significant combustion particles, and
211 should be an additional indicator to PM₁₀ and PM_{2.5} due to other components also having health
212 effects. Black smoke (BS), BC, absorption coefficient (Abs.), and EC are different instrumentally
213 driven parameters reflecting the concentration of the graphitic component of the soot particles arising
214 from fuel combustion. The traffic contribution to urban concentrations of these indicators is generally
215 high, making it easier to detect the impact of policy interventions (Keuken et al., 2012).

216

217 Cyrus et al. (2014) noted that it is difficult to show a reduction in PM₁₀ annual mean concentrations
218 around 1 µg m⁻³ as meteorology has a large impact on the year to year variation of PM mass
219 concentrations. Some studies have compared monitoring data from several months before and after
220 establishing a LEZ. Adequate adjustment for the meteorological conditions can only be made over
221 long periods, preferably one year or more, to remove seasonal biases, and even with annual mean
222 data there can be significant year-to-year differences due to meteorology. This also means that
223 assessing the contribution of LEZs to compliance of short term air quality standards is even more
224 challenging.

225

226 **2.5 Effects of other Policy Measures**

227 Assessments of the impact of LEZs also need to take account of other policy measures implemented
228 at a similar time. For example, the EU requirement for zero (<10ppm by mass) sulphur diesel (Jones

229 et al., 2012), the effect of the implementation of the Euro standards and the German scrappage
230 scheme for vehicles more than nine years old (Cyrus et al., 2014). In some locations there may also
231 be a large change in traffic due to planned transport management schemes. The deep recession in
232 Europe from 2008 is also likely to have affected the rate of replacement of vehicles and traffic
233 volumes.

234
235 The difficulty in showing improvements to air quality as a result of traffic management interventions is
236 illustrated by the London congestion charging scheme (CCS). It was introduced in 2003 and resulted
237 in a 15% reduction in traffic within the zone (Transport for London, 2007). However, in 2003 air
238 pollution concentrations were higher than in 2002 because of unusual meteorological conditions.
239 Emissions modelling suggested total NO_x emissions in the charging zone reduced by 12.0% and on
240 the inner ring road increased by 1.5%, and PM₁₀ emissions reduced by 11.9% in the charging zone
241 and 1.4% on the inner ring road (Beevers and Carslaw, 2005). However, when Atkinson et al. (2009)
242 analysed measured concentrations from a roadside monitor in the CCS zone, they could not identify
243 any changes in concentrations associated with the scheme. Kelly et al. (2011) undertook further
244 analysis of monitoring data and showed small decreases in PM₁₀ and larger decreases in NO_x, and
245 small increases in NO₂ concentrations at background sites within the zone. However, attributing the
246 cause of these changes to the CCS alone was not possible. The authors suggested that the rise in
247 NO₂ could plausibly be explained by the bus fleet having been fitted with regenerative diesel particle
248 filters as well as the increase in diesel vehicles, and the decrease in background NO could have been
249 due to an increase in ozone concentrations.

250

251 **3. LONDON LEZ**

252 The London LEZ commenced operation in 2008 and is the world's largest. It covers an area of more
253 than 1,500 km². It operates 24 hours a day, seven days a week, and uses cameras with automatic
254 number plate recognition technology linked to vehicle registration data to monitor compliance.
255 Foreign vehicle operators need to register prior to entering the LEZ. It has been introduced in a series
256 of phases as shown in Table 2.

257

258 The operators of vehicles not meeting the emission criteria, or not registered, are charged a daily rate.

260 Barrett (2014) used automatic number plate recognition data to show that the compliance rate of
261 HGVs greater than 12 tonnes at the North Circular air quality monitoring site changed from less than
262 80% in the 12 months prior to implementation to 95% by the implementation date, and then stabilised
263 at about 98%. Transport for London (2008) found that 90% of the vehicle kilometres in Greater
264 London were driven in compliant vehicles at the start of Phase 1. Ellison et al. (2013) suggests that
265 the fleet turnover initially increased substantially but subsequently returned to the national average.
266 Although the LEZ also applied to buses the vast majority were already Euro III compliant at the start of
267 the study.

268

269 Transport for London (2014) found that compliance was 98.99% for Phase 3 and 95.81% for Phase 4
270 in the last quarter of 2013.

271

272 3.1. Modelling Studies

273 Transport Research Laboratory (TRL, 2000) concluded that a LEZ covering all of Greater London
274 would be more effective than one based on a smaller area for reducing NO₂ concentrations because
275 traffic emissions over a large area influence background concentrations in central London. For PM₁₀
276 concentrations the size of the LEZ would make little difference because traffic contributes only about a
277 third of the background PM₁₀ concentration in central London. Therefore the scope to influence
278 concentrations is less than for NO₂. Although the whole of London would benefit, emissions would
279 reduce more in central London than in outer London, corresponding to the severity of the air quality.
280 The most effective LEZ would exclude all pre-Euro 3 / III vehicles, but this was considered to be too
281 challenging as restrictions on cars would affect too many motorists, would require major expenditure
282 both to establish and enforce the LEZ, and would be disproportionate to the benefits. Therefore the
283 study recommended that the LEZ should be restricted to taxis and medium and heavy duty vehicles.

284

285 Table 3 summarises the original estimates of the impact of the LEZ on annual average
286 concentrations.

287

288 Watkiss et al. (2003) identified that it would be most cost-effective to target HDVs across the whole of
289 Greater London. For these vehicles, due to their initial high costs, retrofitting is more cost effective
290 than replacement. This is often not the case for LDVs. It was also recommended that the emission
291 criteria should be progressively tightened in future years.

292

293 Table 4 shows the predicted reductions in emissions and the area of exceedence of the UK air quality
294 objectives. The emission benefits are significantly less than those predicted for 2005. To some extent
295 this is due to the emissions being estimated for 2007 and 2010, when the normal fleet turnover would
296 have resulted in lower emissions, and therefore the benefits are predicted to be less, but is also due to
297 a revision in the emission factors used. Watkiss et al. (2003) concluded that the proposed LEZ would
298 have relatively little impact on NO_x emissions, but would be more effective at reducing the area of
299 exceedance of the NO_2 objective. For PM_{10} the annual mean objective / EU limit values were
300 expected to be achieved at all locations in 2007 with the LEZ even at the busiest roads in London.

301

302 Carslaw and Beevers (2002) modelled the effects of a central London LEZ at five locations in 2005.
303 No adjustment was made for traffic growth. Restricting all HDVs to Euro III and banning all pre-Euro 1
304 light duty vehicles was predicted to reduce annual mean NO_2 concentrations by 3.6 to 11.1% or by up
305 to 3.9 ppb ($7.3 \mu\text{g m}^{-3}$) at building façades close to busy roads. The introduction of the LEZ would not
306 result in the annual mean concentrations being below the UK annual objective of $40 \mu\text{g m}^{-3}$ (21ppb).

307

308 **3.2 Monitoring Studies**

309 Jones et al. (2012) identified a large reduction in particle numbers from late 2007 when the HGV fleet
310 was beginning to change in preparation for the implementation of LEZ in early 2008. The authors
311 concluded, however, that it was more likely to be due to the introduction of zero sulphur diesel (less
312 than 10 ppm by mass) which occurred over a similar time period than the introduction of the LEZ.
313 However the authors did not preclude a small effect due to the introduction of the LEZ.

314

315 Ellison et al. (2013) compared roadside PM_{10} concentrations within the LEZ (in Enfield, Hackney, and
316 Sutton) and outside the LEZ (in Sawbridge, north of London). They concluded that the Phase 1 LEZ

317 may have reduced PM₁₀ emissions by 2.47 to 3.07% within the zone compared to just 1% outside. No
318 discernible differences were found in NO_x concentrations.

319

320 Barratt (2014) also compared roadside air quality data before and after the implementation of Phase
321 1. To isolate the impact of the LEZ on air quality from confounding factors a series of filters were used
322 to remove the influence of non-local traffic pollution sources. In addition, the weekends were
323 excluded from the dataset, as the proportion of HGVs was lower, to make any impact easier to detect.
324 None of the sites showed any clear trend in the local traffic contribution (i.e. the filtered data) to
325 ambient PM₁₀ and NO₂ concentrations. At two outer London sites where HGVs dominate the traffic
326 emissions the local traffic contribution of PM_{2.5}, black carbon and NO_x reduced with the LEZ, but not at
327 the central London sites. The reduction in PM_{2.5} concentrations with no observed reduction in PM₁₀
328 concentrations suggests that coarse PM concentrations increased over the same period. This is may
329 be due to the effect of increasing vehicle weight on non-exhaust emissions. The London LEZ was
330 specifically introduced to help achieve compliance with the EU limit values for PM₁₀, and it was hoped
331 that it would also have a beneficial impact on NO₂ concentrations. This study found no clear evidence
332 of a reduction in either pollutant that could be attributed to the LEZ. However the reduction in PM_{2.5}
333 and particularly black carbon concentrations in outer London suggest that there may have been health
334 benefits.

335

336 In summary, the modelling studies undertaken during the decision making phase suggest much larger
337 benefits than have been observed. This is likely to be due to a number of factors including optimistic
338 assumptions regarding the NO_x emissions from diesel vehicles, their higher proportion of direct NO₂
339 emissions and the increase in the proportion of diesel LDVs. In addition, the large contribution from
340 outside London to measured concentrations, particularly for PM₁₀, means that there is a limit to the
341 emission reduction potential of any traffic related measure.

342

343 Because of the limitations of using modelled data, particularly the failure of the emissions modelling to
344 reflect real world emissions, the rest of this paper has focused upon evidence of an impact from
345 ambient air quality monitoring data.

346

348 Germany has a national LEZ framework which came into force in March 2007. To enter a LEZ
349 (Umweltzone) a vehicle must have an appropriate sticker displayed on the windscreen or face a fine.
350 There is manual enforcement of the LEZ by the police. There are three emission stickers: green, red
351 and yellow. The green sticker indicates the vehicle is either diesel fuelled and meets at least Euro 4
352 or IV standards, is Euro 3 or III with a diesel particle filter (DPF), or is a gasoline vehicle meeting Euro
353 1 standards. All diesel vehicles constructed prior to 2000 are banned. A yellow sticker is for diesel
354 vehicles meeting at least Euro 3 or III, or Euro 2 or II with a DPF, and built in 1996 or later, and a red
355 one is for diesel vehicles meeting at least Euro 2 or II or Euro 1 plus DPF and built in 1992 or later.
356 Vehicles not meeting any of these requirements are in pollution class 1.

357

358 Cyrus et al. (2014) noted that in 2009 and 2010 the German Government provided a subsidy of
359 €2,500 to car owners replacing cars older than 9 years with a new model. The scrappage scheme led
360 a more rapid update of the car fleet across Germany than would otherwise have occurred, and this
361 may have interfered with LEZ impact studies.

362

363 According to Morfeld et al. (2014) German cities started requiring the green sticker from 2011; and
364 Cyrus et al. (2014) states that most cities now require it. Two-wheeled vehicles, vintage cars, and off-
365 road, police, fire brigade and emergency vehicles are exempt from the scheme.

366

367 Cyrus et al. (2014) reviewed German studies on the impact of LEZs on PM_{10} and diesel soot
368 concentrations. Three studies showed no effect on monitored annual average PM_{10} concentrations,
369 although one did show a reduction during the summer months. Other studies reported a reduction in
370 PM_{10} concentrations in the range 5 to 15%, but these studies generally were undertaken over short
371 periods or used simple statistical approaches. Studies of annual mean BS or EC concentrations
372 tended to show a larger effect, up to 16%, reduction. This is thought to be due to vehicle exhaust
373 emissions contributing a larger proportion to the total ambient concentration, and therefore there is
374 greater potential for traffic measures to reduce concentrations.

375

376 Morfeld et al. (2014) investigated the effect of German LEZs on NO_x and NO_2 concentrations using
377 matched quadruplets i.e. two pairs of 15 minute average concentrations from a street and reference
378 station, before and after the introduction of 17 LEZs in Germany. They also used monthly passive
379 diffusion tube data. The study showed a statistically significant but small impact of LEZs on NO_2
380 concentrations of less than $2 \mu\text{g m}^{-3}$.

381

382 4.1. Berlin

383 The first German LEZ was established in Berlin. It covers 88 km^2 of the central area of the city and
384 approximately 10% of the total area of Berlin. About 1 million people live within the LEZ. Stage 1 (red,
385 yellow or green sticker required) was introduced in January 2008 and Stage 2 (green sticker required),
386 two years later on 1 January 2010.

387

388 According to Lutz (2009) during the planning phase it was anticipated that Stage 1 would result in a
389 3% decrease in annual mean PM_{10} concentrations and five fewer days with concentrations greater
390 than $50 \mu\text{g m}^{-3}$, and Stage 2 would reduce PM_{10} concentrations by 5 to 10% and NO_2 concentrations
391 by about 4%. There would also be 10 to 15 fewer days with PM_{10} concentrations above $50 \mu\text{g m}^{-3}$ and
392 approximately 10,000 fewer residents living along main roads in the LEZ in non-compliance with the
393 PM_{10} standards. However, attempts to identify the direct effects of the LEZ on ambient PM_{10}
394 concentrations failed as there was too much variation due to the weather and other unknown factors.
395 In the first year of operation of the LEZ (red, yellow or green sticker) the EC concentrations, after
396 accounting for the lower traffic volumes, decreased by 14 to 16% and NO_2 concentrations decreased
397 by 8%.

398

399 4.2. Munich

400 The City of Munich established a LEZ (red, yellow and green sticker) covering 44 km^2 , 14% of the city
401 area, in 2008, eight months after a ban on HDVs driving through the city. Almost one third of the city
402 population live within the LEZ. In 2010 Stage 2 (yellow and green sticker) was implemented, and in
403 2012 the final stage (green sticker) was implemented.

404

405 Cyrus et al. (2009) (cited in Cyrus et al., 2014) compared PM₁₀ concentrations measured in the LEZ
406 with those at a regional background site close to the city. PM₁₀ concentrations in the LEZ reduced by
407 5 to 12% at almost all the monitoring sites. However, Morfeld et al. (2013) (in German, cited in Cyrus
408 et al., 2014) analysed the same data set using regression analyses of matched pairs of concentration
409 data and found no significant effect.

410
411 Fensterer et al. (2014) used a sophisticated semi-parametric regression model over four years and
412 showed statistically significant reductions in PM₁₀ concentrations at a traffic monitoring site (13%
413 average reduction, p-value <0.001) as a result of the Stage 1 (red, yellow and green sticker) LEZ. The
414 PM₁₀ concentrations were adjusted using concentrations at a reference station, wind direction,
415 season, time of day, and public holidays. When the same statistical analysis was applied to the
416 shorter period of data used by the earlier work of Cyrus et al. (2009), the authors found only negligible
417 and statistically insignificant changes in PM₁₀ concentrations. This study and Morfeld et al (2013)
418 illustrates the influence of the monitoring period and the statistical methods used on the results.

419 Qadir et al. (2013) analysed PM_{2.5} samples collected before and after the implementation of the stage
420 1 (red, yellow and green sticker) LEZ. The contribution of traffic particulate organic compounds was
421 found to decrease by about 60% with the LEZ and the average concentration of EC from traffic also
422 decreased by a similar proportion.

423

424 **5. ITALIAN LEZs**

425 Italy has a very large number of LEZs (Zona a Traffico Limitato), mainly in the north of the country.
426 There is no national scheme, and many Italian LEZs have complex requirements. Many are
427 operational only during the winter and some only in the rush hour. There are regional LEZs which
428 may have different entry criteria to the local LEZs within them. There are also extensive exemptions
429 and the restrictions often apply only to very old vehicles. A vehicle's emission category is not
430 indicated by use of a windscreen sticker as in many other countries, and according to Sadler, (2010)
431 little is known regarding enforcement. There is little published data on their efficacy in the English
432 language, except for the Milan LEZ, which is described below.

433

434 **5.1 Milan**

435 In 2008 the Municipality of Milan restricted certain vehicles entering an 8.2 km² area in the historic city
436 centre, known as the Ecopass zone. Drivers of pre-Euro 4 / IV diesel vehicles had to pay a charge to
437 enter the zone between 08:00 and 20:00. At the end of 2011 the scheme was replaced by a
438 combined LEZ and urban road charging scheme known as Area C. There is also a LEZ covering the
439 whole of the Lombardi region and another covering the Greater Milan area. The Lombardi LEZ is a
440 permanent restriction on pre Euro 1 2-stroke motorcycles and mopeds and pre- Euro III diesel fuelled
441 public buses. In addition, from October to April the Greater Milan LEZ restricts pre Euro 1 gasoline,
442 and pre Euro 3 / III diesel vehicles from 7:30 to 19:30 on weekdays. Diesel vehicles fitted with a DPF
443 to meet Euro 3 / III standards are allowed in the LEZ.

444

445 According to Invernizzi et al. (2011) the Ecopass zone was originally predicted by the municipality to
446 reduce PM₁₀ concentrations by 30%, but a study undertaken in 2009 failed to demonstrate any
447 difference in PM₁₀, PM_{2.5} or PM₁ concentrations inside and outside of the Ecopass area, despite a
448 reduction in the number of vehicles entering the zone. The failure to find air quality improvements
449 may be due to the small area of the Ecopass zone or due to that fact that PM₁₀ concentrations are
450 relatively homogeneous across Milan, due to the large regional component. The authors suggested
451 that black carbon, from combustion of carbonaceous fuels, may be a more suitable indicator of the
452 beneficial impact of LEZs and undertook a short term study of BC, PM₁₀, PM_{2.5} and PM₁
453 concentrations in a pedestrian zone, the Ecopass zone and outside the Ecopass zone. The three day
454 mean concentrations of PM₁₀, PM_{2.5}, and PM₁ were not significantly different at the three locations.
455 However, the ratio of black carbon to PM₁₀ in the three locations showed a decrease from outside the
456 Ecopass zone > Ecopass Zone > pedestrian zone. The mean ratios were 22.6%, 11.8% and 8.5%
457 respectively. On average the BC concentration was 47% and 62% in the Ecopass Zone and the
458 pedestrian zone respectively of that measured outside the Ecopass zone.

459

460 **6. DUTCH LEZs**

461 According to Sadler Consultants Ltd (2014a) the Netherlands has a national LEZ framework which
462 originally covered HGVs but was extended from 2011 to include LDVs. Entry was first restricted for
463 pre-Euro III HDVs, and then, from 2013, tightened to pre-Euro IV vehicles. LDVs should be first
464 registered after 1 January 2001. The national agreement defines a number of exempt vehicles, and

465 allows for additional local exemptions. Up to 12 entries into the LEZ per year are permitted for non-
466 compliant vehicles. Six Dutch LEZs (*Milieuzone*) were established in 2007 and by April 2014 there
467 were 13 LEZs.

468 Boogaard et al. (2012), in a study in five Dutch cities (Amsterdam, The Hague, Den Bosch, Tilburg
469 and Utrecht), concluded that the LEZs did not substantially change concentrations of traffic-related
470 pollutants at street monitoring sites more than at suburban background sites outside the LEZs, even
471 though concentrations were lower in 2010 (post-implementation year) than in 2008 (pre-
472 implementation year).

473

474 **6.1 Amsterdam**

475 Amsterdam introduced a LEZ in October 2008 covering an area of approximately 20 km². Initially it
476 was a trial with no penalties or enforcement, but from January 2009 pre Euro III HDVs were prohibited
477 from entering the LEZ. From 1 January 2010 the criteria was tightened to also prohibit Euro III
478 vehicles without a DPF. Automatic number plate recognition is used to identify vehicles and penalties
479 are issued automatically. The restrictions apply all the time and there is a fine for non-compliance
480 (*Milieuzones*, 2014).

481

482 Panteliadis et al. (2014) found a statistically significant decrease in concentrations of NO₂, NO_x, PM₁₀,
483 EC and Abs. measured at a roadside location in the Amsterdam LEZ. However data for EC and Abs.
484 were not collected every day. When the limited data was compared to the full NO₂, NO_x and PM₁₀
485 dataset, there was no noticeable difference in concentrations in the post LEZ implementation period.
486 The authors suggested that the limited dataset may have biased the result, and over-estimated the
487 impact on the LEZ by chance due to the selection of the sampling days for EC and Abs.

488

489 **7. DANISH LEZs**

490 Denmark also has national legislation defining LEZs. From 2008 HDVs in a LEZ had to meet the Euro
491 II emission standards and from July 2010 the Euro III standards.

492

493 Jensen et al. (2011) investigated the effects of the Copenhagen LEZ using long term monitoring data
494 from H.C. Andersens Boulevard, one of the busiest streets in the city. The authors concluded that the
495 LEZ reduced average PM_{2.5} concentrations by about 5%, equivalent to 0.7 µg m⁻³. This was 12% of
496 the traffic contribution. However, the authors noted the difficulty of identifying small changes in
497 concentrations when there is a continuous renewal of the car fleet and associated reduction in
498 emissions.

499

500 **8. DISCUSSION**

501 Approximately 200 LEZs have been declared in the EU, but there have been relatively few peer
502 reviewed studies reported in the scientific literature demonstrating their impact using monitoring data.
503 Table S1 in the supplementary information summarises the results of the available studies including
504 those undertaken by municipalities. Modelling data has not been considered due to the uncertainty
505 over the emission factors used, particularly for NO_x.

506

507 LEZs can only impact on the traffic component, which for PM₁₀ and PM_{2.5} is relatively small as the
508 regional background often dominates. Also they do not impact on non-exhaust PM emissions from
509 traffic which may be an equally or more important emission source, but is currently uncontrolled
510 (Harrison et al., 2012).

511

512 Determining the impact on air quality is difficult due to a range of confounding factors, particularly
513 meteorological influences, but also the traffic contribution, the changing nature of vehicle fleets,
514 policies such as the introduction of vehicle scrappage schemes, the composition of traffic close to the
515 monitoring stations and changes in vehicle flows. Economic factors such as recession and oil prices
516 can also play an important role in determining the rate of new car purchase and use of vehicles.

517

518 The statistical method and period of data used to isolate the LEZ effect are also important. Some
519 studies have used very simple statistics while other used detailed pairing or filtering of the data to
520 identify an impact. Where comparisons are made between sites within and outside a LEZ over time it
521 is important that traffic flow data is available as any improvement in air quality may be due to changes
522 in traffic flows rather than the influence of the LEZ.

524 The data presents a mixed picture. This is not surprising as LEZs differ hugely in terms of the area
525 covered and the vehicles restricted. Many of the studies of the efficacy of LEZs have been
526 undertaken on early phases due to the need for long term monitoring data, and it may be that later
527 phases are more effective.

528

529 Reductions in annual mean PM_{10} concentrations up to 7% have been reported in German LEZs, but in
530 many LEZs no effect has been observed. In Munich the combination of a LEZ and a ban on HGVs
531 travelling through the city centre has been shown to reduce PM_{10} concentrations by up to 13%. There
532 seems to be a greater effect in the summer months, presumably because the traffic contribution is
533 relatively large compared to the winter when other sources become more important. The German
534 LEZs restrict diesel cars as well as pre-Euro 1 gasoline cars, and therefore a greater impact may be
535 expected in these LEZ than in other countries where the LEZs typically only restrict heavy duty
536 vehicles.

537

538 The impact of LEZs on the following PM metrics has also been evaluated: $PM_{2.5}$, PM_{1} , and
539 carbonaceous particles. LEZs have been found to reduce $PM_{2.5}$ concentrations in London and
540 Copenhagen, but not in Dutch cities or Milan. The only study investigating the impact on PM_{1}
541 concentrations found no effect, but it was a very short term study. A larger impact has generally been
542 found on carbonaceous particles (BC, EC and Abs.). The traffic contribution to BC concentrations has
543 been reduced by 15 to 17% in London, while the total EC concentration has been reduced by 13-16%
544 in Amsterdam, Berlin and Leipzig, with the traffic contribution reduced by 56% in Berlin. However,
545 there may have been a bias in the Amsterdam study, acknowledged by the authors, due to the
546 sampling days. In addition, the results of the short term study in Milan suggested that the LEZ had a
547 beneficial impact on BC concentrations. On the other hand, no impact on Abs. was found in several
548 Dutch cities.

549

550 No impact of LEZs on NO_2 concentrations has been found, except in a multi-city study in Germany.
551 Given the evidence that has emerged in recent years that real world diesel NO_x emissions have
552 remained essentially unchanged per vehicle kilometre since the introduction of the Euro emission

553 standards, with the probable exception of late Euro V and Euro VI HDVs, it is perhaps surprising that
554 any benefit of LEZs on NO_x or NO₂ concentrations have been observed. It may be that other factors
555 have contributed to the observed changes in NO₂ concentrations.

556 None of the studies reviewed have explicitly stated whether LEZs have contributed to compliance with
557 the EU limit value for either PM₁₀ or NO₂. Given the many confounding factors identifying the
558 contribution would be challenging.

559

560 **9. CONCLUSIONS**

561 The original aim of many LEZs was to reduce ambient concentrations of PM₁₀, and to a lesser extent
562 NO₂, to help achieve compliance with the EU limit values. In German cities reductions in annual mean
563 PM₁₀ and NO₂ concentrations up to 7% and 4% respectively due to the implementation of an LEZ
564 have been reported.

565

566 These LEZs may have helped achieve compliance with the annual mean limits but no data is available
567 from air quality monitoring studies on whether LEZs have contributed towards the achievement of the
568 short term limit values. To demonstrate compliance with these limit values would be challenging due
569 to the large influence of meteorological conditions on the daily and hourly concentrations.

570

571 In other countries the picture is much more mixed with no effects generally being observed. This may
572 be explained by the German LEZs restricting passenger cars, particularly diesel cars as well as HDVs.
573 Many of the studies, however, have used simple statistical methods that have not taken sufficient
574 account of the confounding factors that affect urban air quality. Studies that have used more
575 sophisticated statistical analyses to remove the confounding factors, particularly the effects of
576 meteorology, suggest that the German LEZs may have resulted in a small, possibly a few percent,
577 reduction in long term average PM₁₀ and NO₂ concentrations.

578

579 On the other hand there is some, albeit limited, evidence that LEZs may result in larger reductions in
580 the concentration of carbonaceous particles, which may be beneficial for public health (WHO, 2012).
581 This must imply that PM₁₀ mass concentrations have also diminished by a small amount.

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TABLE LEGENDS

- Table 1:** Summary of European Low Emission Zones
- Table 2:** Evolution of the Emissions Criteria for the London LEZ
- Table 3:** Estimated Impact of London LEZ in 2005 (TRL, 2000)
- Table 4:** Predicted Air Quality Benefits of the Recommended London LEZ in 2007 and 2010 (Watkiss et al., 2003)

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Country	Number of LEZs	Applicable vehicles	National Framework/ legislation
Austria	3	Heavy goods vehicles (HGVs)	Yes
Czech Republic	1	HGVs	No
Denmark	6	HDVs	Yes
Finland	1	Buses and refuse trucks	No
France	1	HGVs	No
Germany	~70	All vehicles except motorcycles	Yes
Greece	1	All vehicles in inner LEZ, vehicles > 2.2 tonnes outer LEZ.	No
Italy	~92**	Various	No
Netherlands	13	HGVs	Yes
Portugal	1	Cars & HGVs	No
Sweden	8	All vehicles > 3.5 t	Yes
UK	3	HDVs and in London also large commercial LDVs.	No
EU	~200	-	No

Notes:

***The Lombardi Regional LEZ has been counted as one.

Table only includes those in existence in 2014. LEZs are planned for Belgium and Czech Republic.

Source: (<http://urbanaccessregulations.eu>) / Sadler Consultants Ltd, 2014b

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Phase	Date Introduced	Vehicles Restricted	Gross vehicle weight (GVW) (tonnes)	Minimum Emission standard*
1	4 Feb 2008	Heavy goods vehicles (HGVs)	> 12 t	Euro III for PM
2	7 July 2008	HGVs	> 3.5 t	
3	3 Jan 2012	Large vans 4x4 light utility vehicles Motorised horseboxes Pickups	1.205 (unladen) -3.5 t (GVW)	Euro III
		Ambulances Motor caravans	2.5 - 3.5 t	
		Minibuses (>8 passengers)	≤5 t	
4	3 Jan 2012	HGVs	> 3.5 t	Euro III
		Buses, coaches	>5 t	
5	Dec 2015	Buses operated by Transport for London		Euro IV
6	Planned for 2020	All vehicles. This ultra-low emissions zone is currently under development, and may apply just within the 22 km ² of the London Congestion Charging Zone in Central London, and for restricted hours.	All vehicles	Euro 6/VI (?)

Notes:

* Or fitted with a diesel particle filter with a Reduced Pollution Certificate. Euro III and Euro IV standards were mandated for all vehicles first registered after October 2001 and 2005 respectively.

750

751

Location	Estimated change in emissions compared to a 'do nothing' scenario		Average Background Concentrations ($\mu\text{g m}^{-3}$)		Average Urban Centre Concentrations ($\mu\text{g m}^{-3}$)
	PM ₁₀	NO _x	PM ₁₀	NO ₂	NO ₂
Central London	-55%	-20%	20.7	34.2	35.7
Inner London	-48%	-19%	19.5	31.8	38.5
Outer London	-46%	-18%	19.2	27.3	30.3
All London	-47%	-18%	n/a	n/a	n/a

Notes:

The original paper used ppb for NO₂, the conversion to $\mu\text{g m}^{-3}$ used a factor of 1.88 to be consistent with other data in this report.

753

754

Scenario:			
Reduction in emissions (relative to baseline)	Year	NO_x	PM₁₀
	2007	1.5%	9.0%
	2010 (A)	2.7%	19%
	2010 (B)	3.8%	23%
Reduction in area exceeding air quality targets (relative to baseline)	Year	NO₂	PM₁₀
	2007	4.7%	0%*
	2010 (A)	12.0%	32.6%**
	2010 (B)	18.9%	42.9%**

Notes:

*London should meet the relevant air quality objectives for PM₁₀ in an average meteorological year.

** Exceedence of the provisional annual mean PM₁₀ objective of 23 µg m⁻³ (40 µg m⁻³ applicable in 2007). This objective was removed in the 2007 Air Quality Strategy.

2010 (A) HDVs

2010 (B) HDVs, vans and taxis

Highlights

- Most studies of LEZs have not taken confounding factors into account adequately
- German LEZs may have reduced PM₁₀ and NO₂ concentrations by a few percent
- Elsewhere no clear effects on PM₁₀ and NO₂ observed
- Carbonaceous particle concentrations may be reduced significantly

Supplementary Information

Table S1: Summary of the Air Quality Benefits of LEZs Identified From Monitoring Data

City	Reduction in Long Term Concentrations Due to LEZ (%)								Notes	Reference	
	PM ₁₀	PM _{2.5}	PM ₁	BC	EC	Abs.	NO _x	NO ₂			
Berlin, Manheim, Stuttgart, Tubingen, Ludwigsburg	No effect									Comparison of cities with and without LEZs	Nierderemaier, 2009, cited in Cyrys et al., 2014
17 German cities with LEZs								Up to 4%		Matched quadruplets for before and after LEZ and within LEZ and at reference stations. LEZ Stage1.	Morfeld et al., 2014
Berlin, Cologne	5-7%									Comparison of annual average concentrations	Bruckmann and Lutz, 2010, cited in Cyrys et al., 2014
Berlin	3%				14-16%					Comparison of BS concentrations within and outside LEZ. Adjusted for the changes in traffic intensity. 2008 (with LEZ) compared to 2007	Lutz, 2009
					42% (traffic contribution)				7-10%	Comparison between 2007 (no LEZ) and 2012	Lutz, 2013
Bremen	6%								6%	No details provided	Reported in Sadler, 2011

City	Reduction in Long Term Concentrations Due to LEZ (%)							Notes	Reference	
	PM ₁₀	PM _{2.5}	PM ₁	BC	EC	Abs.	NO _x			NO ₂
Cologne	7%							1.5%	Early estimate from monitoring data. PM ₁₀ affected by construction works	Reported in Sadler, 2011
Hanover	1-2%							5%	No details provided	Reported in Sadler, 2011
Leipzig	No effect (6-15% in summer)				6-14% (14-29% in summer)				Comparison of annual/summer average concentrations, adjusted wrt reference station	Löschau et al., 2013, cited in Cyrus et al., 2014
Ruhr Area	4%							1.2%	Comparison of average concentrations in and out of LEZ	Reported in Sadler, 2011
Munich	5-12%								Ban in through HDV traffic introduced 8 months before LEZ. Analysis based on 4 months monitoring data, adjusted wrt reference station	Cyrus et al., 2009, cited in Cyrus et al., 2014
	No effect								Comparison before and after LEZ, adjustment using reference station data	Morfeld et al., 2013, cited in Cyrus et al., 2014

City	Reduction in Long Term Concentrations Due to LEZ (%)								Notes	Reference	
	PM ₁₀	PM _{2.5}	PM ₁	BC	EC	Abs.	NO _x	NO ₂			
	13% (19.6% in summer; 6.8% in winter)									Data for traffic site; 4.5% reduction in annual mean at urban background. Analysis took account of multiple factors using semi-parametric regression model. HDV ban as well as LEZ	Fensterer et al., 2014
					55% (traffic contribution)					Positive matrix factorization of PM _{2.5} samples collected before and after LEZ.	Qadir et al., 2013
Milan	No effect	No effect	No effect							Very short term data. Ratio of BC to PM ₁₀ lower in LEZ than outside.	Invernizzi et al., 2011
Amsterdam, The Hague, Den Bosch, Tilburg, Utrecht	No effect	No effect				No effect	No effect	No effect		Comparison before and after LEZ (and in some cases other traffic measures), four suburban stations used as reference stations.	Boogaard et al., 2012
Amsterdam	No effect				12.9% (limited data)	7.7% (limited)	No effect	No effect		Linear regression. Traffic	Panteliadis et al., 2014

City	Reduction in Long Term Concentrations Due to LEZ (%)								Notes	Reference
	PM ₁₀	PM _{2.5}	PM ₁	BC	EC	Abs.	NO _x	NO ₂		
						data)			contribution estimated by subtracting data from urban background monitoring site in LEZ.	
Copenhagen		5%					No effect		Comparison of data from traffic site before and after LEZ.	Jensen et al., 2011
London	No effect	5-11% (per year) (traffic contribution)		15-17% (per year) (Traffic contribution)			3-7% (Traffic contribution)	No effect	Detailed filtering of data to remove confounding factors. Data from sites most likely to be affected by LEZ	Barrett, 2014
	1-2%						No effect		Simple comparison of data from sites in and outside LEZ.	Ellison et al., 2013

Notes: Sadler (2011) provides a review of the efficacy of LEZs, and is more optimistic than Cyrus et al (2014). Little detail of the methodology used to identify the LEZ effect is given. In this Table data from Sadler (2011) has only been included for those LEZs that there is no other source is readily available. Data is derived from measurements not modelling.

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