LOW EMISSIONS ZONES IN NORTHERN AND CENTRAL EUROPE
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1. INTRODUCTION

Low Emission Zones (LEZs) are areas where access to certain vehicles is restricted due to their emissions. The restriction may be a complete ban or there may be a charge to enter the LEZ if the entry criteria are not met. As new road vehicles in the European Union (EU) must meet emission limits that have become increasing stringent over the past few decades the vast majority of LEZs use these standards to categorise vehicles, sometimes in combination with a vehicle age restriction.

European emission standards apply to passenger cars, vans, two/three wheeled vehicles and the engines used in heavy duty vehicles (HDVs, defined as vehicles with a gross weight greater than 3.5 tonnes). Each type of vehicle has different emission limits and test procedures. For passenger cars and small vans there are separate requirements for gasoline and diesel vehicles. Since the early 1990s these emission limits have been become known as the Euro Standards. For the light duty vehicle emission standards it is the convention to use Arabic numbers (Euro 1, Euro 2, Euro 3, etc.), while the heavy duty engine emission standards use Roman numbers (Euro I, Euro II, Euro III, etc.) to describe the standards, and this convention has been used in this report.

The standards are complex. For example, there are separate implementation dates for new types of vehicle/engine and all new vehicles. The latter is typically one year later. For passenger cars the Euro 1 standard came into force from 1992, Euro 2 from 1996, Euro 3 from 2000, Euro 4 from 2005, Euro 5 from 2009 and Euro 6 from 2014 for new types. The heavy duty emissions standards were introduced over a similar, but not exactly the same, timescale. However, manufacturers have often introduced vehicles/engines meeting new standards before they are mandated, particularly in markets where the government has provided fiscal incentives to encourage the early purchase of lower emitting vehicles.

The principle aim of LEZs is to increase the number of lower emission vehicles in the vehicle fleet, to improve air quality faster than would otherwise happen.

The European LEZs are mainly aimed at reducing emissions of particulate matter (PM), although some also aim to reduce nitrogen oxides (NOx), as the EU ambient air quality limit values for PM with an aerodynamic diameter less than 10 microns (PM$_{10}$) and nitrogen dioxide (NO$_2$) have proved to be difficult to achieve in many cities. Emissions of PM$_{10}$ and nitrogen oxides (NOx) are greater from diesel vehicles than gasoline vehicles (with a three way catalytic converter), with heavy duty diesel vehicles generally having the greatest emissions per vehicle kilometre. Therefore LEZs in most countries have restricted these vehicles. The ultimate aim is to improve public health, although more of the focus has been on achieving the EU limit values.

The first LEZs in Europe were established in 1996 in the Swedish Cities of Stockholm, Göteborg and Malmo, where they are known as Environmental Zones (Miljözon). HDVs 8 to 15 years old were banned from the zones, unless they were fitted with a certified emission control device or a new engine (Göteborg Stad, 2006). All HDVs more than 15 years old were banned altogether. From January 2002 the LEZ entry criteria were modified to include
restrictions on NOx emissions, and some cities also introduced requirements for non-road mobile machinery operating within their Environmental Zone. In 2006 the Swedish Government established a national LEZ scheme using the EU emission standards as the entry criteria. The new regulation harmonised the requirements of different municipalities, with the aim of making it easier for transport companies working on a national scale to comply. HDVs could be used in LEZs for at least 6 years after first registration. Euro II and III HDVs could be driven in a LEZ for eight years from first registration Euro IV HDVs can be driven in a LEZ until 2016 and Euro V can be driven until 2020 regardless of year of first registration (Göteborg Stad et al., 2009).

The first LEZ outside Sweden was in the Mont Blanc Tunnel between France and Italy. It became a LEZ in 2002 and HDVs are banned from entering the tunnel unless they meet at least the Euro III standard.

Since these early LEZs were established cities in some countries, particularly Italy and Germany have widely adopted LEZs. According to the LEZ website (http://urbanaccessregulations.eu; previously www.lowemissionzones.eu), funded by the European Commission, there were approximately 216 LEZs\(^1\) operational in Europe at the end of 2015 with a further 5 planned (See Table 1). The requirements of these LEZs are very diverse, some restricting just one type of vehicle and others virtually all types. The emission criteria used also varies widely with some using Euro 1 for passenger cars, which was implemented (with a few exceptions) for new cars from the end of 1992. There are likely to be few pre Euro 1 vehicles in regular use today.

Other countries have been less enthusiastic. France, for example, has on one LEZ, in Paris, as well as the Mont Blanc Tunnel LEZ; there are no LEZs in Spain and only five operational in the UK at the end of 2015, four of which apply only to buses.

In France many areas exceed the EU PM\(_{10}\) and NO\(_2\) limit values as well as the PM\(_{2.5}\) target value. One of the highest annual mean concentrations of NO\(_2\) was measured in 2013 in Europe occurred in France (EEA, 2015). According to Charleux (2013) national legislation was passed in 2010 to allow towns with more than 100,000 inhabitants to restrict polluting vehicles for three years. ADEME, the French Environment and Energy Management Agency, offered financial assistance for trials in 2012. Although eight cities registered interest none applied before the deadline. Following a change in government the new Environment Minister issued a press release saying that targeting only the oldest vehicles would not reduce pollution on peak days sufficiently to comply with the European limits and that they would be socially unfair. Instead the Ministry chose to work with 38 local communities to strengthen their air quality management plans (Plans de Protection de l’Atmosphère). One measure promoted was for temporary restrictions during days of high pollution when only lower emitting vehicles would be permitted. Paris has introduced temporary bans on vehicles several times since the scheme was introduced. Free public transport is provided and vehicles with the wrong number plate are fined €18 (BBC, 2014).

Table 1 summarises the number of LEZ and the type of vehicles restricted by EU country. It shows that in most countries LEZs only restrict buses, trucks or both. In Germany, and

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\(^1\) This assumes that the large number of very small LEZs in the Lombardi region of Italy are counted as one LEZ.
increasingly other countries as LEZ are upgraded, restrictions apply to all types of vehicle except motorcycles.

Table 1 Summary of European Low Emission Zones (December 2015)

<table>
<thead>
<tr>
<th>Country</th>
<th>Number of LEZs</th>
<th>Applicable vehicles</th>
<th>National Framework/legislation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Implemented Schemes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Austria</td>
<td>7</td>
<td>HGVs</td>
<td>Yes</td>
</tr>
<tr>
<td>Denmark</td>
<td>4</td>
<td>HDVs</td>
<td>Yes</td>
</tr>
<tr>
<td>Finland</td>
<td>1</td>
<td>Buses and refuse trucks</td>
<td>No</td>
</tr>
<tr>
<td>France*</td>
<td>1</td>
<td>HGVs***</td>
<td>No</td>
</tr>
<tr>
<td>Germany</td>
<td>73</td>
<td>All vehicles with 4 or more wheels</td>
<td>Yes</td>
</tr>
<tr>
<td>Greece</td>
<td>1</td>
<td>All vehicles with 4 or more wheels</td>
<td>Yes</td>
</tr>
<tr>
<td>Italy</td>
<td>102**</td>
<td>Various</td>
<td>No</td>
</tr>
<tr>
<td>Netherlands</td>
<td>3</td>
<td>All vehicles with 4 or more wheels</td>
<td>Yes</td>
</tr>
<tr>
<td>Portugal</td>
<td>1</td>
<td>All vehicles with 4 or more wheels</td>
<td>No</td>
</tr>
<tr>
<td>Sweden</td>
<td>8</td>
<td>HDVs</td>
<td>Yes</td>
</tr>
<tr>
<td>UK</td>
<td>5</td>
<td>Various</td>
<td>No</td>
</tr>
<tr>
<td>EU</td>
<td>216</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Planned Schemes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belgium</td>
<td>1</td>
<td>All vehicles with 4 or more wheels</td>
<td>2016</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>1</td>
<td>HGVs</td>
<td>2017</td>
</tr>
<tr>
<td>Norway</td>
<td>3</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Notes:
* The Mont Blanc Tunnel LEZ is between France and Italy (it is included in Italy’s LEZs). There is an odd-even number plate scheme that restricts vehicles during high pollution events
** The large number of LEZs in the Lombardia Region, outside cities, have been counted as 1 LEZ
*** All vehicles from 1 July 2016 HGVs = heavy goods vehicles, i.e. goods vehicles with a gross vehicle weight (GVW) > 3.5 tonnes; Where the restriction includes all vehicles > 3.5 t it includes buses and coaches
Source: Sadler Consultants Ltd, 2015

Most LEZs are permanent and apply 24 hours a day, seven days a week. Some, however, only apply at peak times of the day or during defined periods of the year. For example, the Athens LEZs only apply from September to July, Monday to Thursday from 07.00 to 20.00 hours and on Fridays from 07.00 to 15.00 hours. It does not apply during 24-hour public transport strikes. The Lisbon and Prague LEZs applies only during the daytime on Monday to Friday (Sadler Consultants Ltd., 2015).

Some LEZs only operate in the winter, for example in the large LEZ that covers Milan, Varese, Como and Lecco in northern Italy passenger cars are restricted from 15 October to 15 April each year (for 12 hours on weekdays). However, 2-stroke motorcycles and mopeds, and diesel public transport buses are restricted all the year round.

Athens does not have an LEZ solely based on the Euro standards; the criteria include the vehicle license number. There are different requirements within the city centre and the rest of Athens. Vehicles up to 2.2 tonnes are allowed to enter the city centre on alternative days depending on the last digit of the license plate. There are a number of exceptions including
electric vehicles, Euro 5 vehicles with emissions of CO₂ less than 140 g km⁻¹ and Euro 4 gas vehicles. In the whole of Athens vehicles over 2.2 tonnes and first registered before 1 January 1992 were banned in 2015. The date increases by one year, every year (Sadler Consultants Ltd, 2015).

In some countries, such as Germany, the Netherlands and Sweden, national LEZ frameworks have been developed 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 or not. In other countries, most notably Italy, there is no national framework and each municipality determines their own criteria for restricting vehicles. This approach has the potential advantage of addressing local air quality issues, but can make driving thorough several cities on a single journey problematic without researching the requirements prior to starting the trip. It can also increase costs for national transport companies, as the most stringent requirement(s) would need to be met to provide a national service.

The LEZ restrictions are enforced manually, using automatic number plate recognition (ANPR) technology or transponders which automatically transits payment to toll booths. LEZs in Germany, Sweden and Austria require a sticker indicating compliance to be displayed. In Germany vehicles without the correct sticker are banned from the LEZ, and drivers face a fine of €40 and a penalty point on their driving license, even if the vehicle would be allowed to pass through the zone based on its emissions. This also applies to all vehicles registered in foreign countries. The Dutch, London and Milan-Ecopass LEZs use ANPR. The Italian LEZs are typically enforced manually but some use ANPR or electronic enforcement (Sadler Consultants Ltd, 2015).

The aim of this report is to summarise the available evidence of the effectiveness of LEZs. Exempting certain vehicles from parking restrictions, road and bridge tolls, and bus lanes have also been used to encourage the use of low emission vehicles. In addition, short term vehicle restrictions have been used to reduce emissions during pollution events such as in Paris. These measures have not been included as these are not strictly LEZs.

This report focuses on studies that have been undertaken to assess the impact of LEZs on air quality. Determining the impact on air quality is a direct measure of the effectiveness of the implementation of a LEZ, but can be difficult due to the small impact of most LEZs compared to the changes in air quality in response to meteorological conditions. The difficulty in quantifying an impact on local air quality is compounded by the fact that the local vehicle exhaust contribution, particularly to PM₁₀ concentrations, is often small compared to regional, and urban background concentrations, even at kerbside monitoring sites.

The following sections of this report discuss the available evidence, focusing on the scientific literature, but also drawing of the work undertaken by selected municipalities where it is readily available. There is an emphasis on the London LEZ because more analysis of its effects, both before and after implementation, have been undertaken than for many other LEZs, and this includes a review of the predicted emissions and air quality benefit as well as analysis of air quality monitoring data.

The University of Birmingham electronic library and Google were searched for low emissions zones, environmental zones, and LEZs. Further Google searches were undertaken using the terms used to describe a LEZ in Swedish and German.
2. EVALUATING THE EFFECTIVENESS OF AN LEZ

During the planning stage the impact of a LEZ cannot be measured. To quantify the potential impact emissions modelling is required, often combined with an estimate of the impact on air quality using dispersion or empirical models. There have been relatively few studies which have attempted to evaluate the impact of a LEZ using measured concentrations. The literature search identified less than 20 reported studies, many of which have not been peer reviewed. For some little or no information is available on the assessment methodology.

To predict the potential LEZ impact a large amount of detailed local data is required, from the fleet structure to traffic speeds. Estimating emissions from road transport within a city is not trivial. In recent years there has been considerable uncertainty regarding the emission factors commonly used, such as the EU’s COPERT 4 emission factors (EMISIA, 2015), particularly for nitrogen oxides (NOx), and the proportion that is emitted as NO2. As a consequence many of the emission inventories and forecasts have been shown to be optimistic (Beevers et al., 2012).

There is evidence that under real world driving conditions NOx emissions from diesel light duty vehicles have not changed over the last 20 years, and that this has not been reflected in the emission factors. At the same time the proportion of NO2 in the NOx emission has increased (Carslaw & Rhys-Tyler, 2013). Data from portable emission measurements of NOx from Euro 4 to Euro 6 diesel cars have also shown that the emissions are much higher when driven on the road than during the official type approval test. A meta-analysis undertaken by the International Council on Clean Technology (2014) suggests that early Euro 6 diesel cars emit on average 7 times the limit value under normal driving conditions. More recent work suggests that real world emissions from diesel cars are reducing but emissions remain many times the limit value. On the other hand, gasoline cars driven on the road have average emissions below the limit value (Molden, 2015).

For heavy goods vehicles (HGVs) NOx emissions were fairly constant until Euro IV when they declined significantly. For urban buses there has been little change from Euro 2 to Euro V. (Carslaw et al., 2011). The emissions were higher than the applicable emission limit when measured on-road, even though they tended to meet the emission limits in the laboratory.

The lack of improvement in NOx emissions and the significantly greater PM emissions from diesel light duty vehicles not fitted with a diesel particle filter compared to gasoline vehicles are particularly important because of the increase in popularity of diesel cars in recent decades. In 1992 about 15% of new cars in the EU were diesel compared to about 53% in 2014. The southern European countries, except Italy, have some of the highest shares of diesel cars in Europe (International Council of Clean Transportation, 2015). This data suggests that any LEZ targeting NOx emissions is unlikely to be effective at reducing NO2 concentrations until NOx emissions are significantly reduced under real world driving conditions.

Another factor that needs to be considered when assessing the impact of a LEZ is the contribution of exhaust emissions from local traffic to ambient concentrations. In Berlin, for example, Lutz (2013) estimated that just 4.1% of PM10 at kerbside sites in 2009 was due to exhaust emissions from local traffic, with a larger contribution (14.9%) from non-exhaust traffic emissions. The regional background dominated, contributing almost two thirds of the
PM$_{10}$. In situations such as this, reducing local vehicle exhaust emissions can only have a very limited impact on PM$_{10}$ concentrations and hence compliance with the EU limit values.

It has been argued, for example by Cyrys et al. (2014), that it may be more appropriate to assess the impact of LEZs in terms of the reduction in elemental carbon (EC) rather than PM$_{10}$, PM$_{2.5}$ or even PM$_{1}$. EC is considered by some to be more toxic than some of the other components of ambient particulate matter (PM) and hence a reduction in their ambient concentrations may have a greater benefit for human health than a small change in PM$_{10}$ concentrations may suggest. Janssen et al. (2011) evaluated the risk of black carbon particles (BCP) and concluded that BCP is a valuable indicator of the health risks of poor air quality where there are significant combustion particles, but should be an additional indicator to PM$_{10}$ and PM$_{2.5}$ due to other components also having health effects. Cyrys et al. (2014) suggest that black smoke (BS), black carbon (BC), absorption coefficient, and elemental carbon (EC) are all examples of BCP. The traffic contribution to urban concentrations of these indicators is generally high, making it easier to detect the impact of policy interventions (Keuken et al., 2012).

Assessments of the impact of LEZs also need to take account of other policy measures implemented at a similar time. For example, the EU requirement for ultra-low (<10ppm by mass) sulphur diesel (Jones et al., 2012) and the German scrappage scheme for vehicles more than nine years old (Cyrys et al., 2014). In some locations there may also be a large change in traffic due to planned transport management schemes or long term, albeit temporary, traffic diversions. The deep recession in Europe from 2008 onwards may also have affected the rate of replacement of vehicles, and traffic volumes. Certainly the average age of a passenger car has increased from 8.5 to 9.7 years old of the period 2008 to 2014 (ACEA, 2015).

Cyrys et al. (2014) noted that it is difficult to show a reduction in PM$_{10}$ annual mean concentrations around 1 µg m$^{-3}$, as meteorology has a large impact on the year to year variation of PM mass concentrations. In general, studies have compared monitoring data from several months (in some cases years) before and after establishing a LEZ. Adequate adjustment for the meteorological conditions can only be made over longer periods, preferably one year or more, to remove seasonal biases, and even with annual mean data there can be significant year-to-year differences due to meteorology.

The difficulty in showing improvements to air quality as a result of traffic management interventions is illustrated by the London congestion charging scheme (CCS). It was introduced into central London in 2003 and resulted in a 15% reduction in traffic within the zone (Transport for London, 2007). However, in 2003 air pollution concentrations were higher than in 2002 because of unusual meteorological conditions making the impact difficult to assess using ambient monitoring data. Emissions modelling suggested between 2002 and 2003 total NOx emissions in the charging zone reduced by 12.0% and on the inner ring road increased by 1.5%, and PM$_{10}$ emissions reduced by 11.9% in the charging zone and 1.4% on the inner ring road (Beevers and Carslaw, 2005). However, when Atkinson et al. (2009) analysed measured concentrations from a single roadside monitor in the congestion charging zone, they could not identify any relative changes in concentrations associated with the introduction of the scheme. Kelly et al. (2011) undertook further modelling and estimated smaller changes in emissions than the earlier study and concluded that the congestion charging scheme would be associated with a 0.8 µg m$^{-3}$ decrease in mean concentrations of PM$_{10}$ and a 1.7 ppb (3.2 µg m$^{-3}$) decrease in mean NOx within the zone. Their analysis of the
air quality monitoring data showed small decreases in background PM$_{10}$ and larger decreases in NO$_x$, and small increases in background NO$_2$ concentrations. However, attributing the cause of these changes to the CCS alone was not possible. The authors suggested that the bus fleet being fitted with regenerative diesel particle filters (DPFs) as well as a general increase in diesel vehicles could explain the rise in NO$_2$, and the decrease in background NO could have been due to an increase in ozone concentrations.

3. UNITED KINGDOM

There are currently five LEZs in the UK. The London LEZ commenced operation in 2008 and is the world’s largest. The other British LEZs are in the centre of Brighton, Nottingham, Norwich and Oxford where buses are restricted. There is no national LEZ framework.

The London LEZ covers 1,580 km$^2$. All roads within Greater London, those at Heathrow and parts of the M1 and M4 motorways are included within the zone. However, the M25 motorway, which surrounds Greater London, is not included (even where it passes within the Greater London Authority boundary).

According to the Mayor’s Air Quality Strategy (Mayor of London, 2010) in 2008 approximately 60% of PM$_{10}$ emissions within London came from road transport, with about equal amounts emitted from vehicle exhausts and non-exhaust sources. Road transport also causes the re-suspension of particles deposited on road surfaces, although this is very difficult to quantify, and was not included in the London emission inventory. The other main source of PM$_{10}$ in the London emission inventory is industry. In central London, where PM$_{10}$ concentrations tend to be highest, cars contributed 23% and taxis 20% to total PM$_{10}$ emissions in 2008. This data, however, is for emissions from within London. It has been estimated that about 40% of the PM$_{10}$ in London originates from outside the capital.

Table 2 shows the evolution of the London LEZ from its introduction in 2008 to 2020 when an ultra-low emission zone in central London is planned. Originally large vans and minibuses were scheduled to be included in Phase 3 from October 2010 but the incoming Mayor of London postponed it until 2012.

The focus of the LEZ is on controlling emissions of particulate matter (PM) from diesel vehicles. It can be achieved by meeting the required European emissions standard or by retrofitting a diesel particle filter (DPF) to an older vehicle. Only retrofitted vehicles with a Reduced Pollution Certificate (RPC) are accepted as being compliant with the emission criteria. This is a national standard for retrofitted DPFs. NOx emissions were not included due to the lack of a national certification scheme for retrofitted NOx abatement equipment. Despite this, the London LEZ was expected to provide a small reduction in NOx emissions due to the accelerated replacement of older vehicles with those that meet more recent emission standards.
Table 2 Evolution of the Emissions Criteria for the London LEZ

<table>
<thead>
<tr>
<th>Phase</th>
<th>Date Introduced</th>
<th>Vehicles Restricted</th>
<th>Gross vehicle weight (GVW) (tonnes)</th>
<th>Minimum Emission standard*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 Feb 2008</td>
<td>Heavy goods vehicles</td>
<td>&gt; 12 t</td>
<td>Euro III for PM</td>
</tr>
<tr>
<td>2</td>
<td>7 July 2008</td>
<td>Heavy goods vehicles</td>
<td>&gt; 3.5 t</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3 Jan 2012</td>
<td>Large vans</td>
<td>1.205 (unladen) -3.5 t (GWV)</td>
<td>Euro III</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4x4 light utility vehicles</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motorised horseboxes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pickups</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ambulances</td>
<td>2.5 - 3.5 t</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor caravans</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minibuses (&gt;8 passengers)</td>
<td>≤5 t</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3 Jan 2012</td>
<td>Heavy goods vehicles</td>
<td>&gt; 3.5 t</td>
<td>Euro III</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Buses, coaches</td>
<td>&gt;5 t</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Dec 2015</td>
<td>Buses operated by Transport for London</td>
<td></td>
<td>Euro IV</td>
</tr>
<tr>
<td>6</td>
<td>2020</td>
<td>The proposed scheme will apply to the Congestion Charge Zone (a small area in the central London) is for all vehicles as follows:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-wheeled vehicle - Euro 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Car/small van Euro 4 - (gasoline) Euro 6 (diesel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large van/minibus - Euro 4 (petrol) Euro 6 (diesel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HDV - Euro VI</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

It was anticipated that the benefits of each phase of the LEZ would start to occur before implementation, reflecting vehicle operators upgrading or retrofitting their fleet ahead of the start date. At the time of implementation the majority of vehicles were expected to comply, although it was accepted that there would be a small residual ‘non-compliance’, primary due to the exemption of certain specialist vehicles.

A proportion of the new vehicles bought into the fleet conform to emissions standards higher than the minimum required for scheme compliance, and therefore the overall benefits of the scheme was anticipated to be higher than that implied by compliance with the minimum criteria. The LEZ essentially accelerates the normal fleet turnover, resulting in lower emissions than would have occurred without the LEZ for a few years. For benefits to continue it is necessary to periodically tighten the scheme’s criteria.
The London LEZ operates all the time and uses cameras with automatic number plate recognition (ANPR) technology linked to national vehicle registration data and the Transport for London (TfL) registration data to monitor compliance. Foreign vehicle operators need to register with TfL prior to entering the LEZ.

The operators of vehicles not meeting the emission criteria, or not registered, are charged a daily rate of £200 for HDVs and £100 for light goods vehicles (LGVs). The current penalties for non-compliance are £1,000 for HDVs and £500 for LGVs, subject to a 50% discount for paying within 14 days (http://www.tfl.gov.uk/modes/driving/low-emission-zone). The daily charge has been set at a rate considered sufficient to encourage operators to ensure that their vehicles meet the emission criteria, and to use non-compliant vehicles only on an occasional basis. Compliance with the emissions criteria was 99.26% for Phase 3 and 97.02% for Phase 4 (Transport for London, 2015).

The Mayor’s Air Quality Strategy (Mayor of London, 2010) includes a Euro IV NOx requirement in 2015 for larger diesel vehicles entering the LEZ (Phase 5). However, the poor performance of Euro IV and Euro V HDVs vehicles with respect to NOx emissions, especially in urban driving conditions, the fact that the UK government has not introduced a national verification scheme for retrofitted NOx emission control devices, and that most of the benefits of Phase 5 would be gained from upgrading buses, led the Mayor to decide that the most cost effective solution would be to revise Phase 5 such that it only applies to Transport for London (TfL) buses. TfL had an existing programme to upgrade the bus fleet to ensure that all TfL buses meet at least the Euro IV requirement for NOx by December 2015 (Transport for London, 2014).

Cars dominate the traffic in London. However, HDVs have much higher PM and NOx emissions per vehicle kilometre than light duty vehicles. Figure 1 illustrates the emissions from different types of Euro 2 / Euro II vehicles at the average London traffic speed. More recent data from Wang et al. (2010) suggests that in an urban area in Copenhagen heavy duty vehicles emit about 30 times more PM$_{2.5}$ and 26 times more NOx than light duty vehicles. Therefore the focus for the London LEZ, as well as many other LEZs in northern and central Europe, has been on reducing emissions from HDVs.

**Figure 1** NOx and PM$_{10}$ emissions from Euro 2 / Euro 2 Vehicles (Watkins et al., 2003)
One of the conclusions of the first feasibility study for the London LEZ (TRL, 2000) was that a LEZ covering all of Greater London would be more effective than one based on a smaller area for reducing NO$_2$ concentrations. This was because traffic emissions over a large area influence background NO$_2$ concentrations in central London. For PM$_{10}$ concentrations there would be little difference in the effectiveness of a large LEZ covering all of Greater London compared to a central London LEZ because traffic contributes only about a third of the background PM$_{10}$ concentration in central London. Therefore the scope to influence concentrations is less than for NO$_2$. Although the whole of London would benefit, emissions would reduce more in central and inner London than in outer London, corresponding to the severity of the air quality. There was also the concern that a smaller LEZ would result in vehicles driving around the LEZ, increasing emissions on the perimeter of the zone.

The TRL study concluded that the most effective LEZ would exclude all pre-Euro 3 / III vehicles, but this was considered to be too challenging. Restrictions on cars would affect a large number of people and would require major expenditure both to establish and enforce the LEZ, but there would not be a proportionate benefit in terms of reduced emissions. In addition, the lowest income groups would be mainly affected as this group tends to have older vehicles, which was considered unacceptable. Therefore the study recommended that the LEZ should be restricted to taxis, and medium and heavy duty vehicles. Older vehicles that could demonstrate compliance with these standards for PM emissions (e.g. by fitting a DPF) should also be admitted.

Table 3 summarises the original estimates of the impact of the LEZ on emissions and air quality. To predict the change in air quality at background and urban centre sites TRL estimated the change in emissions, which were applied to estimates of the traffic contribution to concentrations in central, inner and outer London. An empirical relationship between NOx and NO$_2$ was used to estimate the change in NO$_2$ concentrations. It was anticipated that the UK 1997 air quality objectives$^2$ would be achieved at most locations where people would be exposed for most of the time but there would be some locations e.g. at busy roadside sites, where the objectives would continue to be exceeded. For PM$_{10}$ it was predicted that the 24-hour objective (50 µg m$^{-3}$ as a 99th percentile) would not be achieved at background locations in central London.

Table 3 Estimated Impact of London LEZ in 2005 (TRL, 2000)

<table>
<thead>
<tr>
<th>Location</th>
<th>Estimated change in emissions compared to a ‘do nothing’ scenario</th>
<th>Average Background Concentrations (µg m$^{-3}$)</th>
<th>Average Urban Centre Concentrations (µg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM$_{10}$</td>
<td>NO$_x$</td>
<td>PM$_{10}$</td>
</tr>
<tr>
<td>Central London</td>
<td>-55%</td>
<td>-20%</td>
<td>20.7</td>
</tr>
<tr>
<td>Inner London</td>
<td>-48%</td>
<td>-19%</td>
<td>19.5</td>
</tr>
<tr>
<td>Outer London</td>
<td>-46%</td>
<td>-18%</td>
<td>19.2</td>
</tr>
<tr>
<td>All London</td>
<td>-47%</td>
<td>-18%</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Notes:
Original paper used ppb for NO$_2$, the conversion to µg m$^{-3}$ used a factor of 1.88 to be consistent with other data in this report.

$^2$ These are national policy targets, set before the current EU air quality limit values were formally adopted.
The second London LEZ feasibility study (Watkins et al., 2003) also identified that it would be most cost-effective to target HDVs across the whole of Greater London. For these vehicles, due to their initial high costs, retrofitting is more cost effective than replacement. This is often not the case for light duty vehicles (LDVs). It was also suggested that a LEZ should progressively tighten the emission criteria in future years.

Table 4 shows the predicted reductions in emissions and the area of exceedence of the UK air quality objectives. The emission benefits are significantly less than those predicted to occur with a similar LEZ in 2005 (TRL, 2000). To some extent this is due to the emissions being estimated for 2007 and 2010, when the normal fleet turnover would have resulted in lower emissions, and therefore the benefits are predicted to be less. It is also due to a revision in the emission factors used. Watkiss et al. recognised the uncertainty of the predicted reductions in emissions.

Watkiss et al. concluded that the proposed LEZ would have relatively little impact on NOx emissions, but would be more effective at reducing the area of exceedance of the NO2 objective. For PM10 the annual mean objective / EU limit values were expected to be achieved at all locations in 2007 with the LEZ even at the busiest roads in London (e.g. Marylebone Road).

To test the uncertainty of the analysis Cambridge Environmental Research Consultants (CERC) was commissioned to repeat the assessment using their ADMS Urban model. The CERC model predicted smaller benefits of the LEZ than the King’s College model used in the main study. For example, the King’s College model predicted that the annum mean NO2 concentrations in 2007 would decrease on average by 0.6% with the LEZ in place while the CERC model predicted a decrease of 0.4%. Similarly the PM10 concentrations were predicted to decreases by 1.7% and 0.77% with the models respectively. This is important as the predictions were very close to the objective values and only small changes were required to significantly affect the areas of exceedance (Watkiss et al., 2003).

**Table 4 Predicted Air Quality Benefits of the Recommended London LEZ in 2007 and 2010 (Watkiss et al., 2003)**

<table>
<thead>
<tr>
<th>Scenario:</th>
<th>Year</th>
<th>NOx</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction in emissions (relative to baseline)</td>
<td>2007</td>
<td>1.5%</td>
<td>9.0%</td>
</tr>
<tr>
<td></td>
<td>2010 (A)</td>
<td>2.7%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>2010 (B)</td>
<td>3.8%</td>
<td>23%</td>
</tr>
<tr>
<td>Reduction in area exceeding air quality targets (relative to baseline)</td>
<td>2007</td>
<td>4.7%</td>
<td>0%*</td>
</tr>
<tr>
<td></td>
<td>2010 (A)</td>
<td>12.0%</td>
<td>32.6%**</td>
</tr>
<tr>
<td></td>
<td>2010 (B)</td>
<td>18.9%</td>
<td>42.9%**</td>
</tr>
</tbody>
</table>

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) includes HDVs plus vans and taxis
Carslaw and Beevers (2002) also modelled the effects of a central London LEZ at five locations in 2005. No adjustment was made for traffic growth. Restricting all HDVs to Euro III and banning all pre-Euro 1 light duty vehicles was predicted to reduce annual mean NO\textsubscript{2} concentrations by 3.6 to 11.1% or by up to 3.9 ppb (7.3 µg m\textsuperscript{-3}) at building façades close to busy roads. The introduction of the LEZ would not result in the annual mean concentrations being below the UK annual objective of 21 ppb (39.5 µg m\textsuperscript{-3}). Carslaw and Beevers noted that the scale of the LEZ is very important and will be limited in its effectiveness unless the background concentrations are reduced, thus agreeing with TRL (2000) and Watkiss et al. (2003) of the value of the LEZ covering the whole of London.

The limited response of NO\textsubscript{2} to changes in concentrations of NO\textsubscript{x} is due to the non-linear relationship between NO\textsubscript{x} and NO\textsubscript{2} concentrations. The authors commented that ambitious LEZ scenarios in central London would achieve the same emissions as a ‘do nothing’ scenario only five year later. Moreover, as the contribution made by road traffic to emissions of NO\textsubscript{x} reduces in future, it will become increasingly important to consider options to reduce emissions from non-road sources.

Since the implementation of the London LEZ several studies have been undertaken to assess its effectiveness of improving air quality. An analysis undertaken by Transport for London (TfL, 2008) suggests that by the start of Phase 1 90% of the vehicle kilometres in Greater London were driven in compliant vehicles compared to only 75% during 2007. The changes in the HGV vehicle fleet started from about September 2007, suggesting that there was a reduction in emissions before the start of the LEZ. A study by Ellison et al. (2013) which assessed the change in the age distribution of the vehicle fleet before and after the implementation of the LEZ suggests that the rate of fleet turnover in London increased substantially when the LEZ was first introduced, and subsequently returned to the national average rate. For example, at the end of 2006 London had a higher proportion of pre-Euro III rigid HGVs than elsewhere in the UK, but by the end of 2011 London had a lower proportion. According to the authors the greatest change in London occurred during 2008 when the LEZ was introduced. Preliminary evidence suggests that a similar phenomenon occurred for light goods vehicles in 2012 when the LEZ was extended to include these vehicles.

Ellison et al. also suggest that the proportion of both articulated HGVs and LGVs increased while the proportion of rigid HDVs decreased as a result of the LEZ. The emissions from articulated HDVs are greater than those from rigid HDVs (Watkiss et al., 2003), and therefore a trend towards more articulated HDVs would reduce the benefits of the LEZ. Ellison et al. (2013) also state that the total number of goods vehicles increased after the introduction of the LEZ. Ellison et al. used vehicle registration data to define the vehicle fleets in London and elsewhere, however some organisations register vehicles centrally and the fact a vehicle is registered in London does not mean that it is primarily used within the capital. Official statistics suggests that traffic in London has steadily declined over many years. For example, the 2008-2012 average vehicle kilometres driven in Greater London were 6% lower than the 2003-2007 average, and if cars are removed, the 2008-2012 average was 5% lower than in 2003-2007 (Department of Transport, 2014). This suggests that many of the goods vehicles registered in London are not driven in the capital.

Jones at al (2012) identified a large reduction in particle numbers measured from late 2007 onwards, when the HGV fleet was changing in preparation for the introduction of the LEZ in February 2008. An investigation into the cause suggested that it was more likely to be due to
the introduction of ultra-low sulphur diesel (less than 10 ppm by mass) than the introduction of the LEZ. Both measures occurred over a similar time period. At Marylebone Road, a kerbside monitoring site in central London, there was a 55% reduction in average particle number concentrations between the two years from October 2005 and the year from February 2008; while at two urban background sites, Birmingham Centre and North Kensington (in central London), the measured reductions in particle number concentrations were 30% and 33% respectively. These reductions in particle number concentrations were associated with smaller reductions in NOx, PM$_{10}$ and black smoke concentrations. Given that the large reduction in particle number concentrations occurred in Birmingham as well as London it was considered more likely that the effect was due to the change in the EU diesel fuel specification than the LEZ, however, the authors did not preclude a small effect due to the introduction of the LEZ.

Ellison et al. (2013) also report the results of their preliminary analysis of the impact of the London LEZ on air quality. They compared roadside PM$_{10}$ concentrations within the LEZ (in Enfield, Hackney, and Sutton) and outside the LEZ (in Sawbridge, north of London). They concluded that the LEZ may have reduced PM$_{10}$ emissions by 2.47 to 3.07% within the zone compared to just 1% outside. No discernible differences were found in NOx concentrations, unlike the ex-ante modelling reported by Carslaw and Beevers (2002). It should be noted, however, that there were some differences between the LEZ modelling assumptions and what happened in reality.

A study undertaken by the Kings College London provides a different conclusion; that is that NOx emissions and components of PM$_{10}$, but not PM$_{10}$ itself, declined as a result of the LEZ (Barrett et al., 2011). A detailed baseline study prior to the introduction of the LEZ was undertaken including the establishment of a long term air quality and traffic monitoring network specifically to identify the effects of the LEZ (Kelly et al., 2011). The potential impact (essentially Phase 2, see Table 2) was modelled on a 20m x 20m grid across London to identify those areas most likely to be affected. The roadside air quality monitoring sites in these areas were assessed and upgraded where necessary to provide high quality data in areas likely to experience the greatest change in concentrations. Traffic data was also collected from the same sites. The modelling predicted little impact on PM$_{10}$ concentrations but it was considered that there might be a more significant impact on smaller size fractions, and therefore the air quality monitoring network also included black carbon, PM$_{2.5}$ and particle number (Kelly et al., 2011).

To identify any impact of the LEZ the air quality data from the roadside monitoring stations was compared for four 12 month periods; two years before and two years after the implementation of Phase 1 (Barrett, 2014). To isolate the impact of the LEZ on air quality from confounding factors a series of filters were used to remove the influence of non-local traffic pollution sources. In addition the weekends were excluded from the dataset, as the proportion of HGVs was lower, to increase the signal and to make any impact easier to detect.

The automatic number plate recognition (ANPR) data showed no statistically significant changes in vehicle numbers in each class following the start of the LEZ, except in central London where the number of buses increased by 12.5%. However, it showed that the compliance rate of HGVs greater than 12 tonnes at the North Circular monitoring site changed from less than 80% in the 12 months prior to implementation to 95% by the implementation date, and then stabilised at about 98%. The HGVs less than 12 tonnes...
changed from 60% to 95% and then also stabilised at around 98%. The data also showed that the percentage of HGVs in outer London is higher than in central London, suggesting that the potential impact of a change in HDV emissions is also higher in these areas. Although the LEZ also applied to buses the vast majority were already Euro III compliant at the start of the study due to the emissions controls implemented by Transport for London under a separate policy (Barrett, 2014).

None of the sites showed any clear trend in the local traffic contribution to ambient PM$_{10}$ and NO$_2$ concentrations. For PM$_{2.5}$, black carbon and NO$_x$, the two outer London sites showed year on year downward trends in the local traffic contributions (i.e. the filtered data) but not at the Central London sites. The local traffic contribution to PM$_{2.5}$ concentrations decreased by 0.5 µg m$^{-3}$ (11%) per year at the Blackwell site and 1 µg m$^{-3}$ (7%) per year at the North Circular Site. The corresponding decreases in local road NO$_x$ concentrations were 8 µg m$^{-3}$ (3%) and 11 µg m$^{-3}$ (7%) per year. Decreases in the local road black carbon (BC) contributions were 2.3 µg m$^{-3}$ (15%) and 1.6 µg m$^{-3}$ (17%) per year. The filtered BC concentrations were higher than the filtered PM$_{2.5}$ concentrations, and in the two years prior to the implementation of the LEZ were higher than the filtered PM$_{10}$ concentrations at the North Circular site (Barrett, 2014).

The study found that the introduction of the LEZ is likely to have led to an identifiable reduction in NO$_x$, PM$_{2.5}$ and black carbon concentrations at roadside locations within Greater London where emissions are dominated by HGVs. The London LEZ was specifically introduced to help achieve compliance with the EU limit values for PM$_{10}$, and it was hoped that it would also have a beneficial impact on NO$_2$ concentrations. This study found no clear evidence of a reduction in either pollutant that could be attributed to the LEZ. However the reduction in PM$_{2.5}$ and particularly black carbon concentrations in outer London suggest that there may have been health benefits.

4. **GERMANY**

Germany also has a national LEZ framework which came into force in March 2007. To enter a LEZ (Umweltzone) a vehicle must have an appropriate sticker displayed on the windscreen. Currently there are three emission stickers: green, red and yellow. The green sticker indicates the vehicle is either diesel fuelled and meets at least Euro 4 or IV standards, is Euro 3 or III with a DPF, or is a gasoline vehicle meeting Euro 1 standards. All diesel vehicles constructed prior to 2000 are banned. A yellow sticker is for diesel 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 one is for diesel vehicles meeting at least Euro 2 or II or Euro 1 plus DPF and built in 1992 or later. Vehicles not meeting any of these requirements are in pollution class 1. The yellow and red stickers are only temporary and are being phased out. From 2011 cities started restricting access to vehicles with a green sticker; and now most cities required it (Cyrys et al., 2014). A sign indicates which colour sticker a vehicle must have in order to enter the LEZ. The relevant sticker must be displayed to avoid the fine. Two-wheeled vehicles, vintage cars, and off-road, police, fire brigade and emergency vehicles are exempt from the scheme. There is manual enforcement of the LEZ by the police. Failure to comply results in a penalty point on the drivers’ licence.
Cyrys et al. (2014) reviewed the available German LEZ impact assessments, most of which are only available in German. Many municipalities estimated the expected reduction in PM\textsubscript{10} concentrations using dispersion models, the latest traffic emission data and the LEZ adjusted vehicle fleet. It was noted that between 2009 and 2010 the German Government provided a subsidy of €2,500 to car owners replacing cars older than 9 years with a new model. The car scrappage scheme led a much faster update of the car fleet across Germany than would otherwise have occurred. Despite this the authors concluded that the LEZ motivated people to replace their old cars by modern vehicles earlier than they had in the past.

Morfeld et al. (2014a, 2014b) have investigated the effects of the introduction on the Stage 1 LEZs in 17 cities for NO\textsubscript{2} and NOx, and 19 cities for PM\textsubscript{10}. These studies have used matches pairs of data from inside and outside the LEZs from before and during the operation of the LEZs. The data was analysed using multiple linear and log-linear fixed-effects regression modelling taking into account a range of co-variables including wind velocity, precipitation, mixing depth, school holidays, and truck-free periods. Mean LEZ reductions in NO\textsubscript{2}, NO, and NOx concentrations were estimated to be, at most, 2 µg m\textsuperscript{-3} (4%). For PM\textsubscript{10} the LEZs were estimated reduce concentrations at monitoring stations influenced by traffic emissions by less than were below 1 µg m\textsuperscript{-3} (5%). For EC the estimated reduction was less than 0.5 µg m\textsuperscript{-3}, (9%), for organic carbon less than 0.3 µg m\textsuperscript{-3} (3%). They found no effect on PM\textsubscript{2.5} concentrations (Morfeld et al., 2015).

Wolff (2014) studied the effects of German LEZs by comparing air quality in LEZ cities to a set of control cities. Data from April to October 2007 and 2008 were compared and the difference between how much PM\textsubscript{10} changes after adoption of LEZs in LEZ cities and how much PM\textsubscript{10} changes over the same period in control cities were estimated. This controlled for underlying differences between LEZ and control cities and temporal changes in PM\textsubscript{10} levels common across all cities. They did not find any statistically significant increase in PM\textsubscript{10} levels around LEZs due to increased driving by dirty vehicles that could not enter the LEZs, nor any change in concentrations at background stations. However at traffic stations PM\textsubscript{10} concentrations reduced by an average of 9% in the LEZs.

Several other studies have investigated the effect of German LEZs using monitoring data. Three studies reported no observable effect on annual average PM\textsubscript{10} concentrations, although one other study did report a reduction on PM\textsubscript{10} concentrations during the summer months. Other studies reported a reduction in PM\textsubscript{10} concentrations in the range 5 to 15%, but these studies tend to have been undertaken over short periods or used simple statistical approaches. However, studies of the impact of LEZs on black smoke or elemental carbon concentrations have tended to show a larger effect, up to 29% reduction (Cyrys et al., 2014).

4.1. Berlin

The Berlin LEZ covers 88 km\textsuperscript{2}, which is approximately 10% of the total area of Berlin, where there are about 1 million inhabitants. The Stage 1 of the Berlin LEZ was introduced on 1 January 2008 (red, yellow or green sticker required), and Stage 2 was introduced two years on 1 January 2010 (green sticker required).

During the planning phase it was anticipated that Stage 1 would result in exhaust PM emissions decreasing by 15%, which would be reflected in a 3% decrease in annual mean PM\textsubscript{10} concentrations and five fewer days with concentrations greater than 50 µg m\textsuperscript{-3}. Stage 2
would reduce PM exhaust emissions by 50%, with 5 to 10% decrease in annual mean PM$_{10}$ concentrations, and about 4% reduction in annual mean NO$_2$ concentrations. There would be 10 to 15 fewer days with PM$_{10}$ concentrations above 50 µg m$^{-3}$ and approximately 10,000 fewer residents living along main roads in the LEZ in non-compliance with the PM$_{10}$ standards (20 to 25% reduction) (Lutz, 2009).

After one year the impacts were assessed and it was concluded that the LEZ had no measureable impact on traffic flows. Initial concerns that traffic would be pushed into residential areas around the zone did not materialise. There was an observed decrease in traffic both inside and outside the LEZ which was attributed to a rise in fuel prices in 2008 and Berlin’s policy to promote cleaner modes of transport. However the number of vehicles in pollution class 1 dropped significantly after the LEZ came into force. For example, 70% of class 1 passenger cars and more than 50% of class 1 commercial vehicles were removed from the fleet. The accelerated fleet renewal was observed in Berlin both inside and outside the LEZ. As a result, exhaust PM and NOx emissions in the LEZ were estimated to have reduced by 24% and 14% respectively. Attempts to determine the direct effects of the LEZ on ambient air quality, however, failed as there was too much variation in the concentrations due to the weather conditions and other unknown factors. As a consequence black carbon (BC) data was analysed. In the first year of operation of the LEZ the BC concentrations, after accounting for the lower traffic volumes, decreased by 14 to 16%. Traffic adjusted NO$_2$ concentrations also decreased by 8% (Lutz, 2009).

4.2. Munich

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

Cyrys et al. (2009) (cited in Cyrys et al., 2014) compared PM$_{10}$ concentrations measured in the LEZ with those at a regional background site close to the city. PM$_{10}$ concentrations in the LEZ reduced by 5-12% at almost all the monitoring sites. However, Morfeld et al. (2013) (in German, cited in Cyrys et al., 2014) analysed the same dataset using regression analyses of matched pairs of concentration data and found no significant effect.

Fensterer et al. (2014) used a sophisticated semi-parametric regression model over four years and showed statistically significant reductions in PM$_{10}$ concentrations at a traffic monitoring site (13% average reduction, p-value <0.001) as a result of the Stage 1 (red, yellow and green sticker) LEZ. The PM$_{10}$ concentrations were adjusted using concentrations at a reference station, wind direction, season, time of day, and public holidays. When the same statistical analysis was applied to the shorter period of data used by the earlier work of Cyrys et al. (2009), the authors found only negligible and statistically insignificant changes in PM$_{10}$ concentrations. This study and Morfield et al. (2013) illustrates the influence of the monitoring period and the statistical methods used on the results.

Qadir et al., 2013 analysed PM$_{2.5}$ samples collected before and after the implementation of the Munich LEZ. Heavy goods vehicles were banned from the city centre in February 2008 and in October 2008 a stage 1 LEZ was established in the inner city. The PM$_{2.5}$ samples were collected in 2006/2007 (before the LEZ) and 2009/2010 (after the Stage 1 LEZ). The samples
were analysed for elemental and organic carbon and particulate organic compounds (POC). Positive matrix factorisation (PMF) was used to identify the main sources of POC. There were significantly lower concentrations of elemental carbon and some of the particulate organic compounds after the introduction of the LEZ. The contribution of traffic POC decreased by about 60% after implementation of the LEZ and the average concentration of EC from traffic decreased by a similar proportion (from 1.1 to 0.5 µg m\(^{-3}\)) after implementation of the LEZ.

5. **ITALY**

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

5.1. **Milan**

In January 2008 the Municipality of Milan restricted certain vehicles entering an 8.2 km\(^2\) area in the historic city centre, known as the Ecopass zone. Drivers of pre-Euro 4 / IV diesel vehicles had to pay a charge to enter the restricted zone between 08:00 and 20:00. At the end of 2011 the scheme was replaced by a combined LEZ and urban road charging scheme known as Area C. There is also a LEZ covering the whole of the Lombardi region and another covering the Greater Milan area. The Lombardi LEZ is a permanent restriction on pre Euro 1 2-stroke motorcycles and mopeds and pre- Euro III diesel fuelled public buses from Monday to Sunday. This LEZ was introduced on 15 October 2011. In addition, from 15 October to 15 April every year the Greater Milan LEZ restricts pre Euro 1 gasoline, and pre Euro 3 and III diesel vehicles from 7:30 to 19:30 on weekdays. Diesel vehicles fitted with a DPF to meet Euro 3 / III standards are allowed in the LEZ.

The municipality to reduce traffic by 19% and PM10 concentrations by 30% originally predicted the Ecopass zone. A study undertaken in 2009, however, failed to demonstrate any difference in PM\(_{10}\), PM\(_{2.5}\) or PM\(_1\) concentrations between the Ecopass area and those outside, despite a reduction in the number of vehicles entering the zone. It was considered that the failure to find air quality improvements may be due to the small area of the Ecopass, or due to that fact that PM\(_{10}\) concentrations are relatively homogeneous across Milan, due to the large regional component. The authors suggested that black carbon, from combustion of carbonaceous fuels, may be a more suitable indicator (Invernizzi et al., 2011).

A further, short term study of black carbon, PM\(_{10}\), PM\(_{2.5}\) and PM\(_1\) concentrations in a pedestrian zone, the Ecopass zone and outside the Ecopass zone was undertaken. The three
day mean concentrations of PM\textsubscript{10}, PM\textsubscript{2.5}, and PM\textsubscript{1} were not significantly different at the three locations. However, the ratio of black carbon to PM\textsubscript{10} for each of three monitoring locations showed a decrease from outside the Ecopass zone > Ecopass Zone > pedestrian zone. The mean ratios were 22.6%, 11.8% and 8.5% respectively. On average the black carbon concentration was 47% and 62% in the Ecopass Zone and the pedestrian zone respectively of that measured outside the Ecopass zone (Invernizzi et al., 2011).

6. **THE NETHERLANDS**

In the Netherlands there is a national LEZ agreement between the Government, municipalities and other stakeholders to apply the same LEZ standards across the country. The original agreement covered HGVs but was extended from 2011 to include LDVs. Entry to the Dutch LEZs was first restricted for pre-Euro III HDVs, and then, from 2013, tightened to pre Euro IV vehicles. The criterion for LDVs is that they should be first registered after 1 January 2001. The first LDV LEZ is planned to be introduced from the beginning of 2015 in Utrecht.

The first Dutch LEZ (*Milieuzones*) was established in Eindhoven in July 2007, and by the end of the year there were five LEZs. This has gradually increased to 13 LEZs operating in the Netherlands by April 2014 (Sadler Consultants Ltd, 2014).

The national agreement defines a number of exempt vehicles, and allows the municipalities to have additional local exemptions. The national exemptions include special vehicles (e.g. street cleaners, and cranes) and Euro III vehicles that cannot be retrofitted with a DPF for technical reasons. Up to 12 entries into the LEZ per year are permitted for non-compliant vehicles. Municipalities are permitted to charge these vehicles for entry. There is no enforcement of foreign registered vehicles (Sadler Consultants Ltd, 2015).

Boogaard et al. (2012) studied the impact of LEZs on ambient air quality in five Dutch cities (Amsterdam, The Hague, Den Bosch, Tilburg and Utrecht). They concluded that the LEZs did not substantially change concentrations of traffic-related pollutants at street monitoring sites more than at suburban background sites outside the LEZs, even though concentrations were lower in 2010 (post-implementation year) than in 2008 (pre-implementation year). They suggested several explanations: (1) the impact of the LEZ may have been too small to measure; (2) the differences in emissions between the Euro standards are much smaller than anticipated when the policy was formulated; (3) some LEZs effects may have occurred during the baseline measurement period since the LEZs were gradually implemented; (4) the effect of the LEZs may counteract or coincide with other policy changes, for example the encouragement of retrofitting DPFs which can increase primary NO\textsubscript{2} emissions; (5) the economic recession from 2008 may have affected emissions everywhere making the detection of an impact more difficult; (6) the sampling periods may have been too short; and (7) possibly different weather conditions may have masked the effect.

6.1. **Amsterdam**

Amsterdam introduced a low emissions zone on 9 October 2008 covering an area of approximately 20 km\textsuperscript{2}. Initially it was a trial with no penalties or enforcement, but from
9 January 2009 pre Euro III HDVs were prohibited from entering the LEZ. From 1 January 2010 the criteria was tightened to also prohibit Euro III vehicles without a DPF. Automatic number plate recognition is used to identify vehicles and penalties are issued automatically. The restrictions apply 24 hours a day, 365 days a year, and the fine for non-compliance is €230 (Milieuzones, 2014).

Keuken et al. (2012) modelled the impact of the Amsterdam LEZ on elemental carbon (EC) concentrations, using specially developed emission factors for the HDV fleet in the LEZ. A street canyon model was used to predict the impact of the LEZ along roads with more than 7,500 vehicles per day. The traffic contribution was estimated to be in the range 50 to 1450 ng m$^{-3}$. The introduction of the LEZ led to a reduction in the average population-weighted EC concentration of 25 ng m$^{-3}$. For the population living alongside major inner city roads this was estimated to result in a population-weighted average increase in life expectancy of 2.9 months. For the whole population within the LEZ the average gain in life expectancy was estimated to be 0.2 months. Keuken et al. concluded that EC is a better indicator of the health impacts of traffic than either PM$_{10}$ or PM$_{2.5}$. The residual mass in exhaust emissions is represented by organic carbon (OC) which is a less appropriate indicator than EC due to its relatively high background concentrations.

Panteliadis et al. (2014) found a statistically significant decrease in concentrations of NO$_2$, NO$_x$, PM$_{10}$, EC and absorbance measured at a roadside monitoring station in the Amsterdam LEZ. The greatest effects were observed for EC and absorbance. However, when the data was corrected for type of day, and wind direction and speed, greater reductions in concentrations were observed for all pollutants except absorbance. After the introduction of the LEZ the average concentrations reduced by 4.9% for NO$_2$, 6.4% for NOx, 5.8% for PM$_{10}$, 12.9% for EC and 7.7% for absorbance. When the rural background concentrations were subtracted from the roadside concentrations the impact of the LEZ was increased. However data for EC and absorbance were not collected every day. When the limited data was compared to the full NO$_2$, NOx and PM$_{10}$ dataset, there was no noticeable difference in concentrations in the post LEZ implementation period. The authors suggested that the limited dataset may have biased the result, and over-estimated the impact on the LEZ by chance due to the selection of the sampling days for EC and absorbance.

7. DANISH LEZS

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

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

Over 200 LEZs\(^3\) have been declared in the EU, but there have been few studies reported in the scientific literature demonstrating the impact on air quality using ambient measurements.

There are no EU standards for LEZs, although there are national standards in some countries. Most of the early LEZs in northern and central Europe restricted heavy duty diesel vehicles, but over time have excluded a wider range of vehicles. In Germany all vehicles except two-wheelers have been restricted since the first LEZ was established. However, for gasoline passenger cars the Germany LEZ standard is not very demanding, as they only have to meet the Euro 1 standards which were introduced over 20 years ago.

The primary aim of many LEZs is to meet the EU ambient air quality limit value for PM\(_{10}\), and to a lesser extent the limit value for NO\(_2\). The focus is on diesel vehicles because the emissions of both PM and NOx from diesel vehicles are greater than from gasoline vehicles fitted with a catalytic convertor (i.e. Euro 1 vehicles). Most LEZs allow the retrofitting of DPFs to meet the emission criteria.

Table 5 summarises the results of studies that have analysed air quality monitoring data to evaluate the impact of one or more LEZs. Modelling data has not been considered due to the uncertainty over emission factors. The table provides a wide range of results which is not surprising as the impacts will depend on many factors including the analytical method used, the composition of traffic close to the monitoring station, the emissions criteria of the LEZ studied, the length of the study, and the contribution traffic makes to the ambient concentrations at the monitoring station(s). Some studies use very simple statistics while other used detailed filtering of the data to identify the impact. Where comparisons are made between sites within and outside a LEZ over time it is important that traffic flow data is available as any improvement in air quality may be due to changes in traffic flows rather than the influence of the LEZ.

The table presents a mixed picture. Annual mean PM\(_{10}\) concentrations were reduced by 0 to 7%, with no effects observed in most LEZs. In Munich the LEZ and a ban on HGVs in the city centre reduced annual mean PM\(_{10}\) concentrations by up to 12%. It appears that the impact is greater in summer than in winter, possibly due to traffic contribution being lower due to other sources (e.g. for heating and electricity generation) increasing PM\(_{10}\) emissions in winter.

In many cities there is a large regional component and significant contributions from other sources resulting in only a small portion from vehicle exhaust emissions, and therefore available for the LEZ to influence. In these cases it is not surprising that it is difficult to detect an impact.

The impact of LEZs on the following PM metrics has also been evaluated: PM\(_{2.5}\), PM\(_1\), black carbon (BC), elemental carbon (EC), and absorption (Abs.). LEZs have been found to reduce PM\(_{2.5}\) concentrations in London and Munich, but not in Amsterdam. The only study

\(^3\) This assumes that the Lombardi Regional LEZ is one LEZ,
investigating the impact on PM$_1$ concentrations found no effect. However, the studies that have investigated the impact of LEZs on a measure of carbonaceous particles (BC, EC and Abs.) have in general found a larger impact. BC has been reduced by 15 to 17% in London and 14 to 16% in Berlin, EC by 6 to 16% in Amsterdam, Berlin and Leipzig, with the traffic contribution reduced by 55% in Munich. In addition, the results of a very short term study in Milan suggested that the LEZ has had a beneficial impact on black carbon concentrations. On the other hand, one study found no impact on Abs. in Amsterdam, while another, in the same city, found a 7.7% reduction, although the selection of sampling days may have biased the results.

No impact of LEZs in 11 Dutch cities and London on NO$_2$ concentrations were found, although one study showed a 7 to 10% reduction in the Berlin LEZ and another up to a 4% reduction in concentrations from 17 German cities with LEZs. In Amsterdam, no impact on NOx has been detected, but in one study in London identified a 3 to 7% reduction in NOx.
Table 5: Summary of the Air Quality Benefits of LEZs Identified From Monitoring Data

<table>
<thead>
<tr>
<th>City</th>
<th>Reduction in Concentrations due to LEZ (%)</th>
<th>Notes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berlin, Manheim, Stuttgart, Tubingen, Ludwigsburg</td>
<td>No effect</td>
<td>Comparison of cities with and without LEZs</td>
<td>Nierdermaier, 2009, cited in Cyrys et al., 2014</td>
</tr>
<tr>
<td>17 German cities with LEZs</td>
<td>Up to 4%</td>
<td>Comparison of concentrations from inside and outside the LEZs, before and during the LEZ operation.</td>
<td>Morfeld et al., 2014a</td>
</tr>
<tr>
<td>19 German cities with LEZs</td>
<td>&lt;1%</td>
<td></td>
<td>Morfeld et al., 2014b</td>
</tr>
<tr>
<td>German cities with LEZ in 2008 (during 6 months including summer)</td>
<td>9%</td>
<td>Comparison of concentrations from April-October in 2007 and 2008 in cities with and without a LEZ</td>
<td>Wolff, 2014</td>
</tr>
<tr>
<td>Berlin, Cologne</td>
<td>5-7%</td>
<td>Comparison of annual average concentrations</td>
<td>Bruckmann and Lutz, 2010, cited in Cyrys et al., 2014</td>
</tr>
<tr>
<td>Berlin</td>
<td>3%</td>
<td>14-16%</td>
<td>Comparison of BC concentrations within and outside LEZ. Adjusted for the changes in traffic intensity. 2008 (with LEZ) compared to 2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42% (traffic contribution)</td>
<td>7-10%</td>
</tr>
<tr>
<td>Bremen</td>
<td>6%</td>
<td>6%</td>
<td>No details provided</td>
</tr>
</tbody>
</table>
# Reduction in Concentrations due to LEZ (%)

<table>
<thead>
<tr>
<th>City</th>
<th>PM(_{10})</th>
<th>PM(_{2.5})</th>
<th>PM(_1)</th>
<th>BC</th>
<th>EC</th>
<th>Abs.</th>
<th>NOx</th>
<th>NO(_2)</th>
<th>Notes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cologne</td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.5%</td>
<td>Early estimate from monitoring data. PM(_{10}) affected by construction works</td>
<td>Reported in Sadler, 2011</td>
</tr>
<tr>
<td>Hanover</td>
<td>1-2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td>No details provided</td>
<td>Reported in Sadler, 2011</td>
</tr>
<tr>
<td>Leipzig</td>
<td>No effect (6-15% in summer)</td>
<td>6-14% (14-29% in summer)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Comparison of annual/summer average concentrations, adjusted wrt reference station</td>
<td>Löschau et al., 2013, cited in Cyrys et al., 2014</td>
<td></td>
</tr>
<tr>
<td>Ruhr Area</td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Comparison of average concentrations in and out of LEZ</td>
<td>Reported in Sadler, 2011</td>
</tr>
<tr>
<td>Munich</td>
<td>5-12% (LEZ + HDV ban in city centre)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ban in through HDV traffic introduced 8 months before LEZ. Analysis based on 4 months monitoring data, adjusted wrt reference station.</td>
<td>Cyrys et al., 2009, cited in Cyrys et al., 2014</td>
<td></td>
</tr>
<tr>
<td>Milan</td>
<td>13% (19.6% in summer; 6.8% in winter)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>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</td>
<td>Fensterer et al., 2014</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>55% (traffic contribution)</td>
<td>Positive matrix factorization of PM(_{2.5})</td>
<td>Qadir et al., 2013</td>
</tr>
</tbody>
</table>
### Reduction in Concentrations due to LEZ (%)

<table>
<thead>
<tr>
<th>City</th>
<th>PM$_{10}$</th>
<th>PM$_{2.5}$</th>
<th>PM$_{1}$</th>
<th>BC</th>
<th>EC</th>
<th>Abs.</th>
<th>NOx</th>
<th>NO$_2$</th>
<th>Notes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsterdam, The Hague, Den Bosch, Tilburg, Utrecht</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
<td>samples collected before and after LEZ.</td>
<td>Invernizzi et al., 2011</td>
</tr>
<tr>
<td>Amsterdam</td>
<td>No effect</td>
<td>No effect</td>
<td>1.9% (limited data)</td>
<td>7.7% (limited data)</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
<td>Very short term data. Ratio of BC to PM$_{10}$ lower in LEZ than outside.</td>
<td>Boogaard et al., 2012</td>
</tr>
<tr>
<td>Copenhagen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No effect</td>
<td>No effect</td>
<td>Comparison before and after LEZ (and in some cases other traffic measures), four suburban stations used as reference stations.</td>
<td>Jensen et al., 2011</td>
</tr>
<tr>
<td>London</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15-17% (per year)</td>
<td>3-7% (per year)</td>
<td>No effect</td>
<td>No effect</td>
<td>Linear regression. Traffic contribution estimated by subtracting data from urban background monitoring site in LEZ.</td>
<td>Panteliadis et al., 2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No effect</td>
<td>No effect</td>
<td>Detailed filtering of data to remove confounding factors. Data from sites most likely to be affected by LEZ</td>
<td>Barrett, 2014</td>
</tr>
</tbody>
</table>

Notes:
- Ratio of BC to PM$_{10}$ lower in LEZ than outside.
- Comparison of data from traffic site before and after LEZ.
- Linear regression.
- Simple comparison of data from sites in and outside LEZ.
9. RECOMMENDATIONS

This section provides recommendations for cities contemplating establishing a LEZ. It lists factors that need to be considered when establishing emission criteria, and has been developed drawing on best practice identified in a report prepared for ADEME (Sadler, 2011).

1. National LEZ frameworks

National frameworks are recommended as they reduce cost, time and effort in setting up LEZs, make communicating the entry criteria easier and increase industry and public acceptance.

2. Aim of LEZ

The aim of the LEZ should be clear. Is it to achieve EU limit values or to improve the health of citizens? Reducing diesel PM emissions will have a direct health benefit but may not result in the PM$_{10}$ limit values being achieved.

3. Understand local air quality

It is important that the proportion of PM$_{10}$ and NO$_x$ from vehicle exhausts is understood before developing a LEZ. Source apportionment should be undertaken at several roadside locations. This will identify the potential contribution that the LEZ can influence. It may be very small as regional and/or urban background concentrations may dominate. Non-exhaust road traffic sources may contribute more to ambient concentrations than vehicle exhausts (e.g. Harrison et al., 2012). If vehicle exhaust emissions only contribute a very small portion of the ambient concentrations then a LEZ is unlikely to be effective. However, even small changes can have a significant impact on compliance with EU limit values where there are only small exceedances.

Also understand the composition of the local vehicle fleet (vehicle types/Euro classes), traffic flows, congestion and other factors that influence vehicle emissions to enable more accurate modelling of potential impacts of a LEZ. Use realistic emission factors, and undertake sensitivity analysis of model inputs and assumptions.

4. LEZ Area

Determine the area the potential LEZ should cover. This will depend on a number of factors including the magnitude of the contribution of traffic to the urban background, the city’s road network, and administrative boundaries.

5. Vehicles

Determine which vehicles will be targeted. Diesel vehicles make a significant contribution to traffic PM and NOx emissions, and their proportion in the vehicle fleet in most EU countries is growing. Consider the dominant vehicles in pollution hot spots; it may not be the same as the city average.

Decide whether passenger cars should be included. In most cities these are the dominant vehicles by number but not necessarily the greatest source of traffic emissions. There are social justice issues of penalising older cars which tend to be owned by poorer members of
the community. Older vehicles tend to be driven less than newer vehicles and therefore, despite the emissions per kilometre being higher, overall the emissions may be lower than from a newer vehicle built to a higher emission standard.

6. **Appropriate Assessment**

An assessment of the potential impact of the proposed LEZ should be undertaken to determine if there is likely to be an improvement in air quality. A pre-implementation assessment needs to be undertaken using models; post-implementation assessments should primarily use monitoring data. This is not straightforward and needs to be undertaken by professionals with experience of this type of work as there are many confounding factors that need to be taken into account. It may need to be supplemented by modelling.

It is important that permanent roadside monitoring stations are established some time (preferably more than a year) before the establishment of the LEZ and continue for some years after implementation. It should include traffic monitoring, preferably using automatic number plate recognition to enable the emission class of vehicles to be identified. The pollutants to be monitored need to be carefully considered and an indicator of combustion particles, such as black carbon or elemental carbon, may be useful.

The financial, socio-economic and political impacts of the LEZ also need to be considered at the planning stage. When estimating the cost of the scheme consider separately the costs to the authority of implementation, operation, enforcement and monitoring, the vehicle operator/owner of upgrading vehicle(s), and the societal benefits.

7. **Retrofitting**

If retrofitting pollution abatement (i.e. DPF or SCR) to meet the emission criteria would be permitted, determine how the equipment will be certified, its minimum efficiency, and how often recertification will be required. EU wide certification schemes are under development, but the timescale is unclear.

8. **Enforcement**

Determine how the LEZ would be enforced. A windscreen sticker with manual enforcement, automatic number plate recognition linked to a vehicle licensing database or electronic devices? For large LEZs affecting a large number of vehicles automatic enforcement is appropriate, however for small LEZs only affecting buses, manual enforcement would be appropriate. The less likely a vehicle will be detected the higher the penalty should be. An added incentive to comply would be for the vehicle driver to be given penalty points on their license, as happens in Germany.

In some countries the use of cameras may be politically unacceptable, and in these cases, manual enforcement will need to be used.

9. **Industrial and public acceptance**

Getting the freight transport industry, bus and coach operators and, if applicable motorists, to accept a LEZ requires a well thought out and consistent communication campaigns. A simple LEZ is easier to understand and will gain more public acceptance than a highly complex scheme. Using an existing boundary such as a ring road will help communicate the LEZ, and where there are several towns close together, adopting a single LEZ may be more beneficial and easier to communicate than individual LEZs. Using the same
emission criteria as existing LEZs would reduce the proliferation of different standards and make it easier for the freight transport industry to comply.

Publicise the LEZ restrictions widely to make it easier for vehicle operators/drivers to comply. Use simple and clear signs at the LEZ boundary. Communicate with a wide range of stakeholders before implementation.

10. **Exemptions**

In general, the fewer exemptions the more impact and credibility the LEZ would have, however, there are some exemptions that can increase credibility of the scheme. For example some countries have ‘hardship exemptions’ for companies that are having financial difficulties.

11. **Phased implementation**

Phased implementation with the emission criteria tightened over time allows the worst polluting vehicles to be removed in the first phase and the affected communities to get accustomed to the LEZ concept. The later phases of the LEZ should have tighter emissions standards to ensure that the emission criteria are ahead of the natural fleet characteristics.

12. **EU Requirements**

Finally, ensure compliance with the EU freedom of movement principle. The LEZ criteria should not be harder for a foreign vehicle to comply than a local one, and publicity needs to be EU-wide. The emission standards must be in line with the EU Euro standards. Currently the EU has no plans to introduce EU wide LEZ emission criteria, but may introduce a LEZ framework.
10. REFERENCES


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Carslaw, D.C., S. D. Beevers, J.E. Tate, E.J. Westmoreland and M.L. Williams, 2011. Recent evidence concerning higher NOx emissions from passenger cars and light duty vehicles. Atmospheric Environment. 45 (39), 7053-7063.


