A Critical Review Of The Effectiveness Of Low Emission Zones (LEZ) As A Strategy For The Management Of Air Quality In Major European Cities

Chukwunonye Ezeah, Keiron Finney, Chukwunonso Nnajide
[1]Faculty of Sciences and Engineering, University of Wolverhampton,
City Campus-South, Wulfruna Street, Wolverhampton, UK, WV1 1LY
Email: C.Ezeah2@wlv.ac.uk

***Abstract*— Implementation of Low Emission Zones (LEZ) in European cities is traceable to Sweden, where pilot schemes termed 'Environmental Zones' were first trialled in 1996. Although there was never a study to evaluate the effectiveness of the 'Environmental Zones', many other European cities have since introduced LEZ as a strategy for managing air pollution from vehicular emissions. Currently, LEZ is being implemented in 11 countries including Norway, Denmark, Sweden, Portugal, United Kingdom, Netherlands, Germany and Italy. This paper critically reviews the implementation of LEZ in three European cities: London, Berlin and Munich. Findings indicate that the impact of LEZ in the reduction of Particulate Matter (PM) concentration in London has been rather minimal, despite the high rate of compliance by vehicle users. Significantly higher reductions in PM and Nitrogen Oxides concentrations have been reported in Munich and Berlin. The paper argues that reported differences are likely as a result of differences in implementation.**

Keywords*— *Air Pollution, Particulate Matter, Low Emission Zones, European Cities.

I. INTRODUCTION

The Industrial Revolution saw an increase in industrial emissions in Europe's main industrial cities leading to pollution-related health problems and damage to the ecosystem [1]. Decline in industrial and domestic emissions have been replaced with increased traffic emissions from 1950s onwards [2]. Expectedly, this form of pollution is more evident in areas with large human concentrations, such as the urban areas, with large numbers of cars [3][4]. In cities across Europe, the emission of a range of air pollutants (gases and particulates) as a result of anthropogenic activities has become a cause for real concern, leading to legislative/regulatory actions and setting up of emission and air quality standards by the European Union (EU) as well as by the individual countries and local councils in efforts to limit the discharge and the concentration of these pollutants in the atmosphere [5]. A key strategy being adopted by significant numbers of European Municipalities for the management of air pollution is the Low Emission Zones (LEZ).

Low Emission Zones specifically target pollution emissions linked to road traffic. A Low Emission Zone by definition is a geographic area which, by law, can only be entered by specified vehicles that emit low levels of certain air pollutants, i.e., an area that can only be assessed by vehicles that meet certain emission criteria and standards, for example the standards set by the European Union (EU) [6][7]. The main aim of this paper is to evaluate the effectiveness of LEZ as an emission control strategy from a pan EU perspective. The paper is structured under the following sections: characteristics of PM from vehicular emissions, Implementation of LEZ in Europe, 'Euro' Emissions standards and a critical review of the effectiveness of LEZ as an Emissions Management Strategy in European cities.

II. LITERATURE REVIEW

A. *Air Pollutants and Vehicle Emmissions*

The principal air pollutants emitted by vehicles include:

- The oxides of nitrogen, commonly known as NOx (nitrogen monoxide/nitric oxide and nitrogen dioxide)
- The oxides of sulphur, commonly known as SOx (sulphur monoxide and sulphur dioxide)
- Carbon monoxide
- and Particulate Matter, commonly known as PM [8][9].

Also present in vehicle emissions are volatile organic compounds (VOCs) such as benzene, and polycyclic aromatic hydrocarbons such as benzo (a)pyrene [10][11].

These emissions are produced in vehicles by the incomplete combustion of fossil fuels (petrol or diesel) in car engines. There are, of course, industrial and agricultural sources of these gases and particulates, but road traffic emissions are a very significant source, particularly in urban areas. In 2011, for example, road traffic emissions contributed 47% of total NOx emissions in Europe [10]. In humans, the emissions exert harmful effects on the respiratory and the cardiovascular systems [12][13]. PM10-2.5 are also noted for carcinogenicity. [14][15]. Besides the negative impacts of air pollutants on human health there are other significant environmental consideration. Carbon monoxide (CO), for instance, oxidizes into carbon dioxide (CO2), also yielding ozone (O3) in the process [10]. Increased levels of both gases (CO2 and O3) are implicated in global warming and climate change. The oxides of nitrogen and sulphur also have acidifying effects on aquatic life, vegetation and soils [12].

B. Particulate Matter (PM)

Particulate Matter, the most lethal of all vehicular emissions, is a composite mix of minute fragments of metal, soot, nitrates, chlorides, sulphates, dust, soil, and other solid or liquid particles suspended in a gas [13][12][7][16]. Based on the size of the particulates, Particulate Matter is classified into different forms. The two most important, and thus best regulated, forms of Particulate Matter in Europe are PM10 (i.e., Particulate Matter less than ten microns in diameter) and PM2.5 (i.e., Particulate Matter less than 2.5 microns in diameter) [17][18].

PM10 and PM2.5 are capable of diffusing through the lungs and into the bloodstream, and have been cited as the most lethal air pollutants [19]. Particulate Matter has been connected to cases of cardiopulmonary disease, acute respiratory infection and cancer of the trachea, bronchi and lungs [6][12][14]. In a 2004 study, it was estimated that within the EU alone, PM10 was responsible for 348,000 premature deaths every year [6]. A more recent study puts the figure even higher at about 400,000 adult deaths annually [13]. To put these figures in perspective, ozone, which is EU's second most noxious air pollutant, was responsible for 21,000 deaths within the same period [6].

In most European cities, vehicle emissions and road transport-related sources have been identified as the prime sources of PM10 in the atmosphere [19]. Vehicle emissions refer to emissions from vehicle exhausts, worn tyres and brakes; while road transport sources refer to a broader group of sources which, in addition to vehicle emissions, include such sources as worn road surfaces and suspension of dust on road surfaces by vehicle traffic [20]. (Other gaseous emissions characteristic of Europe's large cities such as nitrogen oxides (NOx) and carbon monoxide (CO) are also largely connected to road transport [19]. Of particular significance are PM emissions from diesel engines [15][17][21].

Both diesel-run and petrol-run internal combustion engines are capable of contributing to PM emissions. However, diesel engines contribute a far larger share of total PM emissions [22][17]. This is largely due to the difficulty in controlling PM generation and emission in diesel engines (where the combustion process is far more complicated than in a petrol-run engine) [12].

Heavy-duty vehicles, such as trucks, are also known to contribute a significantly high proportion of PM as well as NOx emissions; it has been estimated that about 25% of PM10 and 57% of NOx emissions from road traffic in London come from heavy-duty vehicles [23]. As a result of the close relation between these vehicle and engine types and the emissions, the early regulations associated with improving the air quality in Europe, were often mainly directed towards heavy-duty vehicles and diesel engines [24]. Newer regulations, however, also target light commercial vehicles (such as taxis) and passenger cars [25].

III. IMPLEMENTATION OF LEZ IN EUROPE

Implementation of LEZ as a strategy for management of air pollution in Europe goes back to Sweden, where pilot schemes termed 'Environmental Zones' began in three of its largest cities – Stockholm, Gothenburg and Malmö in 1996 [26]. It specifically targeted trucks that ran on diesel and buses that weighed over 3.5 tonnes [26]. Although there was never a scheme to evaluate the effectiveness of the 'Environmental Zone' in Sweden, many other cities across Europe have since introduced LEZ [26][27]. Currently, LEZs are being implemented in over 200 cities spread across 11 countries – including Norway, Denmark, Sweden, Portugal, the United Kingdom, Netherlands, Germany and Italy [10].

A. Overview of the 'Euro' Emmissions Standards:

EU regulation on emissions dictates acceptable limits for vehicle exhaust emissions for new vehicles sold or brought into the EU. These limits are generally referred to as 'Euro emission standards' [28]. Table 1 below illustrates Euro emission standards for passenger cars, petroleum-related NOx, diesel-related NOx and diesel-related PM.

Table 1: History and levels of Euro standards for passenger cars [28]

Euro Standards	Entry into Force		Emission Limits		
	New Approvals	All New Registrations	Petrol NO_x (mg/km)	Diesel NO_x (mg/km)	Diesel PM (mg/km)
Euro 0	1 Oct 1991	1 Oct 1993	1,000	1,600	(no limit)
Euro 1	1 July 1992	31 Dec 1992	490	780	140
Euro 2	1 Jan 1996	1 Jan 1997	250	730	100
Euro 3	1 Jan 2000	1 Jan 2001	150	500	50
Euro 4	1 Jan 2005	1 Jan 2006	80	250	25
Euro 5	1 Sep 2009	1 Jan 2011	60	180	5
Euro 6	1 Sep 2014	1 Sep 2015	60	80	5

In addition to the EU emission standards, the EU has also introduced a set of air quality standards. These standards set a limit to the concentration of the various pollutants permissible in the atmosphere in a further attempt to limit their harmful effects on public health [5][6][29]. Table 2 below shows the EU air quality standards for the principal vehicle emissions.

Table 2: EU Air Quality Standards for the Chief Internal Combustion Engine Emissions Indicating the Averaging Period for their Highest Permissible Concentrations [28]

Pollutant	Highest Permissible Concentration	Averaging Period
Fine particles ($PM_{2.5}$)	25µg/m^3	1 year
Sulphur dioxide (SO_2)	350µg/m^3	1 hour
	125µg/m^3	24 hours
Nitrogen dioxide (NO_2)	200µg/m^3	1 hour
	40µg/m^3	1 year
PM_{10}	50µg/m^3	24 hours
	40µg/m^3	1 year
Carbon monoxide (CO)	10mg/m^3	Maximum daily 8 hour mean
Benzene	5µg/m^3	1 year
Polycyclic Aromatic Hydrocarbons	1ng/m^3 (expressed as concentration of Benzo(a)pyrene)	1 year

IV. LEZ Implementation in European Cities

A. Greater London LEZ

London's LEZ is by far the largest in Europe covering all local roads in Greater London, Heathrow Airport and sections of the M1 and M4 motorways, a total land area of 1600km2, with a population of about 7.5 million people [9]. Air quality within Greater London was judged to be among the worst of any European city at the beginning of the 21st Century [5][6]. This situation necessitated implementation of LEZ in 2008.

The implementation process has been graduated and is still-ongoing. With each phase of the process come stricter measures and minimum emission requirements. Table 3 below is an outline of London's four-stage LEZ implementation plan.

Table 3: Stages of LEZ implementation in Greater London [23][5]

Implementation stage	Start date	Vehicles targeted	Minimum Euro emission standards
First stage	February, 2008	Heavy Goods Vehicles (HGVs) and other specialist vehicles.	Euro III standard (for PM emissions)
		Vehicles with Gross Vehicular Weight (GVW) more than 12 tonnes.	
Second stage	July, 2008	HGVs (and other vehicles over 3.5 tonnes GVW). Buses and coaches over 5 tonnes, with more than 8 passenger seats.	Euro III standard (for PM emissions)
Third stage	January, 2012	HGVs, buses and coaches. Large Goods Vehicles (LGVs) the over 1.205 tonnes and minibuses under 5 tonnes with more than 8 passenger seats.	Euro IV standard (for PM emissions). Euro III standard (for PM emissions).
Fourth stage	2015	HGVs, buses and coaches.	Euro IV standard (for NO_x emissions).

From Table 3, it can be seen that all vehicles entering London's LEZ since 2008 have been required to at least meet the Euro III standards. It is important to note here that new heavy vehicles in all EU member states have been required since 2000 (before LEZ became effective) to meet Euro III standards [30][27]. However the old, pre-Euro III vehicles had continued to be in use. Thus, one of the most important roles expected to be played by LEZ was to serve as an extra incentive for vehicle users to replace the existing, old non-compliant vehicles with newer, that are less-polluting [31].

Users of vehicles which do not meet the minimum Euro standards, but who wish to access the LEZ pay a fee for each day they are in the LEZ. For example, large vans pay £100 and heavy vehicles pay £200 each day; high penalty fines are incurred if the fee is not paid by midnight of the day the vehicle was in the LEZ [5]. Compliance to the LEZ regulations are monitored electronically, using cameras equipped with automatic number plate recognition (ANPR) technology [23].

B. *Berlin and Munich LEZ*

Forty-one cities in Germany have implemented LEZs, including Munich and Berlin. Berlin's LEZ covers an area of 88km2 in Inner Berlin, and is home to about a million people (i.e., 18 times less than the area of London's LEZ and about one-seventh the population) [32]. Beginning in January 2008, diesel-run commercial vehicles and passenger cars were mandated to meet at least Euro 2 or Euro 1 standards, or to have particulate filters fitted to their exhaust in order to adjust their PM emissions to conform to the standards [33]. In January 2010, the minimum standards for diesel-run commercial vehicles and passenger cars were raised to Euro 4 and 3 respectively, while petrol-run passenger cars with emission standards less than Euro 1 were also banned within Berlin LEZ.

Unlike Greater London which monitors compliance to LEZ statutes electronically, Munich and Berlin monitor compliance manually. Vehicles in the cities are categorized into four groups based on their levels of PM10 emissions [30][34][33][7]. Vehicles in all but one of the four groups are expected to display one of three colour-coded stickers on their windscreens, indicating their PM emission levels [34][33]. A red sticker indicates that the vehicle meets the Euro 2 emission standards; a yellow sticker indicates the vehicle meets the Euro 3 standard; and a green sticker indicates the vehicle meets the Euro 4 standards. Petrol-run vehicles fitted with catalytic converters were assigned Euro 4 status and given green stickers. Particulate filters could also be used to adjust emission levels of some non-compliant vehicles to conform to the required standard. All pre-Euro 1 and Euro 1 vehicles are banned from entering the Low Emissions Zones from the first stage of the strategy's implementation, in October 2008 [34]. In the second stage of the LEZ, which came into effect in October, 2010, Euro 2 vehicles (i.e., vehicles with red stickers) were banned from the LEZs; and in the third stage, starting in October, 2012, only Euro 4 vehicles or vehicles with green stickers are allowed within the LEZs.

V. Effectivenes of LEZ as an Emmissions Management Strategy: the example of Greater London

Based on a survey carried out in 2005 by Browne et al., LEZ implementation in Greater London was expected to have the following proposed effects:

1. The purchase of new vehicles by vehicle users to meet the minimum required standard, and (apparently) the discarding of old vehicles.

2. The redistribution (by large companies) of the non-compliant vehicles in their fleet to areas outside the boundaries of the LEZ.

3. A small proportion of the people who took part in the survey said they would enter the LEZ anyway and pay the required charge.

4. A similar proportion also indicated that they would switch to smaller cars which are not subject to LEZ regulations [35].

Transport for London, the local government body that oversees transport-related matters in Greater London, also predicted a 2% reduction in PM10 emissions and 4% reduction in NOx emissions within London's LEZ in the policy's first year of operation (i.e., 2008) [36].

C. *Actual Impact of LEZ in Greater London*

Reports published since the introduction of the first stage of the LEZ in 2008 indicate a large drop in the percentage of the non-compliant pre-Euro III vehicles entering London's LEZ. According to a study released in July, 2008 – five months after the beginning of the first phase of the LEZ and just before the inception of the second – approximately 90% of all heavy vehicles and buses entering the LEZ conformed to the minimum emission standards [23]. Another study by Ellison et al. [5], found that by the end of 2011, London had the lowest percentage of pre-Euro III vehicles registered in the United Kingdom at 19.4%, compared to the national average of 29.8%. Before 2008, the percentage of pre-Euro III vehicles in London had stood at 56.3%, and the national average had been 57.1% [5].

Without doubt natural replacement of old pre-Euro III vehicles with new compliant ones partly accounted for the drop in the percentage of old vehicles within this period (2008 – 2011). However, LEZ alone accounted for an additional 2% of the pre-Euro II vehicles being replaced over and above the normal replacement rate in 2008 when the proportion of the old non-compliant vehicles in London dropped from 47.4% to 31.9% [23].

Figure 1 illustrates the decline in the percentage of pre-Euro III vehicles in London's LEZ over the three stages of LEZ implementation (ie LEZ Phases 1-3), and make comparisons with the decline in the same types of vehicles in neighbouring non-LEZ areas and the country as a whole. Table 4 below equally indicates a gradual fall in the percentages of pre-Euro III heavy articulated vehicles (i.e., vehicles with pivoting joints in its construction which allow the vehicles to turn more sharply) and heavy rigid vehicles. Just before 2008 when LEZ became effective, a more significant drop in the proportion of non-compliant rigid and articulated vehicles was recorded for London's LEZ zone, while for other areas of the country the rate of drop remained fairly constant. This significant drop is attributable to the LEZ policy as vehicle owners/users responded to meeting the minimum standards before the set date.

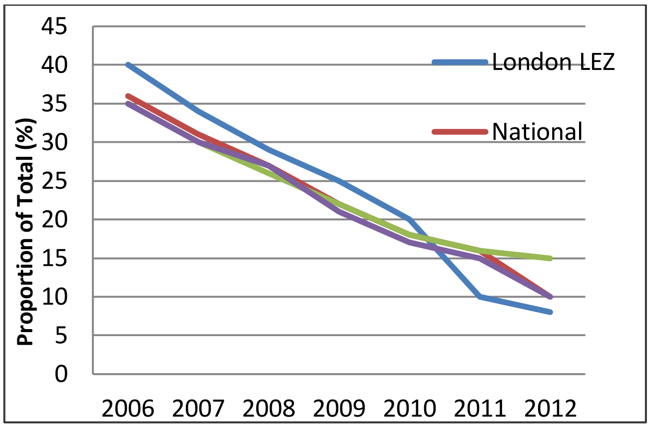

Fig 1: Proportion of LCVs (Light Commercial Vehicles) not meeting the LEZ requirements [5].

The chart in Figure 1 illustrates the progressive decline in the percentage of Light Commercial Vehicles (LCVs) across the UK since 2006. A slightly sharp decline was observed in 2010, and an even sharper decline in 2011. The sharper decline of 2011 came just before the set date for the third phase of Greater London's LEZ.

Table 4: Proportion of registered pre-Euro III rigid and articulated vehicles [5]

	2006		2007		2008		2009		2010		2011		2012	
Proportion %	R	A	R	A	R	A	R	A	R	A	R	A	R	A
London LEZ	58	42	50	34	30	25	29	20	27	18	24	15	23	10
National	52	35	46	28	42	22	40	18	38	17	37	15	36	11
Neighbouring Counties	58	34	52	37	50	22	48	17	44	18	42	15	41	10
Others	51	35	45	28	42	22	40	17	38	16	37	15	36	11

R = Rigid vehicles A = Articulated vehicles

While the drop in the proportion of non-compliant high-polluting vehicles within the LEZ could serve as an indirect measure of the effectiveness of the LEZ, measurements of the ambient air quality presents a more direct quantification. Ambient air quality measurements indicate that the percentage of PM10 emissions within the LEZ have reduced by between 2.46 – 3.07% by the end of 2012 [5]. To put those figures in context, PM emissions outside the LEZs dropped by a little over 1% (Ellison et al., 2013). These figures would appear to indicate that the effect of LEZ in the reduction of PM concentration in the air have been rather minimal, despite the high rate of compliance by vehicle users. The study by Ellison et al. indicates further that LEZ has had no detectable effect on the reduction of NOx concentration, as the respective concentrations within and outside the LEZ had remained almost the same [5].

D. The Impact of LEZ in Berlin and Munich

As with London's LEZ, there was very high compliance by vehicle operators within Berlin's LEZ – 99% compliance for cars and 88% compliance for commercial vehicles [32]. According to a 2010 study, PM emissions from vehicle exhausts reduced by 35% or 100 tonnes as a result of the Berlin LEZ in 2009, and NOx emissions from vehicles dropped by 19% or 1,500 tonnes in the same year [7].

Table 5 below presents a summary of a number of studies that have evaluated the effects of LEZ on German cities including Berlin and Milan, particularly the effects on the reduction of Particulate Matter (PM), elemental carbon (EC), and 'black smoke' (BS). A few of the studies showed no observable reduction in emissions; many showed a significantly higher reduction than in London's LEZ. This may be due to difference in LEZ implementation strategies between London and Germany's LEZs.

Table 5: Overview of studies evaluating the effects of German LEZs on reduction of PM, EC and BS [32]

Reference	*Study area and analysis in method*	*Results*
Niedermaier, 2009	Berlin, Mannheim, Stuttgart, Tübingen, Ludwigsburg Directly comparison of PM_{10} concentrations in cities with LEZ with cities without LEZ.	No effects were observed
Crysys *et al.*, 2009	Munich Comparison of PM_{10} concentrations before and after establishing the LEZ (4 months). Multiplicative adjustment to reference station.	5–12% relative reduction of PM_{10}
Lutz *et al.*, 2009	Berlin Comparison of annual averages of PM_{10} and EC Concentrations Additive adjustment to reference station	5% reduction of PM_{10} 14–16% reduction of EC
Bruckmann and Lutz, 2010	Berlin and Cologne Comparison of annual averages of PM_{10} and EC. Additive adjustment to reference station levels	5–7% reduction of annual PM_{10}
LRP, 2010	Munich Estimation by dispersion modelling	2–10% reduction of PM_{10}, stage 3 of LEZ
Rauterberg-Wulff und Lutz, 2011	Berlin Comparison of BS concentrations before and after establishing the LEZ. Adjusted for the changes in traffic intensity. Reference year: 2007.	21–24% decrease of BS in 2008 52% decrease of BS in 2010
Qadir *et al.*, 2013	Munich PMF analysis of data on particulate organic	50% decrease EC concentration in the traffic factor 60%

	compounds (POC) and EC on $PM_{2.5}$ before and after establishing the LEZ	reduction of traffic factor contribution to $PM_{2.5}$
Morfeld *et al.*, 2013	Munich Comparison of PM_{10} concentrations before and after establishing the LEZ (4 months). Additive adjustment for reference station.	No effects were observed
Lutz, 2013	Berlin Estimation of changes in soot emissions for 2012 by comparison to a business-as-usual scenario.	An additional reduction of diesel particle emissions by 63% in 2012.

Wolff and Perry [7] also demonstrated in their study a clear correlation between mortality and PM emission levels. Table 6 below show that mortality due to air-pollution causes in German cities actually decreased as PM levels decreased, and rose as PM levels increased.

Table 6: Value of mortality benefits from decreased PM_{10} [7]

City	Average 2007 Traffic Station PM	Amount PM decreases in 2008	Number of inhabitants of LEZ	Number of lives saved
Berlin	28.86	4.33	1,300,000	191.33
Ludwigsburg	34.65	-1.69	55,000	-3.17
Tubingen	31.26	0.98	783,000	2.46
Reutlingen	38.12	2.22	78,523.2	5.92
Stuttgart	33.01	0.95	590,000	19.07
Hannover	26.02	2.44	218,000	18.11
Leonberg	33.42	-2.30	40,000	-3.12
Koln	32.98	2.45	130,000	10.82
Mannheim	28.43	2.82	93,9000	9.00

E. Non- Exhaust Traffic PM Emissions and the Effectiveness of LEZ

In considering LEZ and its relatively modest success in Europe, it is useful to consider also the impact of non-exhaust, but traffic-related sources of PM emissions on general atmospheric PM levels. Non-exhaust sources of traffic-related PM are becoming ever more significant, although so far research in that area has been relatively insufficient [37][38].

Non-exhaust PM refers to the additional PM emissions which are not discharged from the exhaust pipes of vehicles, but are nonetheless connected to traffic and road transport [37]. Sources of non-exhaust PM include:

i. Resuspension of dusts on road surfaces (due to road traffic)

ii. Wear and tear or corrosion of old vehicle parts, e.g., the clutch, brakes and tyres.

iii. Road surface abrasion (caused by tyres).

[20][37].

It has been shown by studies that non-exhaust PM emissions contribute approximately 50% of the PM concentration of roadside air samples [39]. There are known cases where the contribution from non-exhaust sources is significantly higher than that. For example, in very cold countries, such as those of Scandinavia, resuspended dust due to road traffic accounts for 90% of PM in roadside air [40][41]. This is thought to result from the practice of road-sanding and use of studded tyres to increase friction on ice-covered roads and reduce slips [40][41][42].

In the case of London, Harrison et al. [39] found out that non-exhaust sources were almost an equal contributor of atmospheric PM as vehicle exhaust on a busy London road; while in Berlin, Lenschow et al. [43] showed that about 50% of the discernible increase in PM levels on the roadside against urban background levels was due to dust particle re-suspension alone.

It is clear from available statistics in the various studies that even if exhaust emissions were to be totally eliminated, the contribution of traffic to total particulate matter in suspension will remain significantly high. It has been projected that by the end of the decade, non-exhaust emission contribution to total PM emissions will be 90% [37]. Non-exhaust PM are also a cause for additional concern because of their typical toxicity and carcinogenicity, more so than exhaust PM [37]. They typically have significant amounts of certain metals (copper, zinc, barium, antimony, manganese, etc.), some of which are derived from worn vehicle parts and are toxic, and carcinogenic polycyclic aromatic hydrocarbons [20].

Yet for its significance, there are no action plans in place to reduce PM emissions from non-exhaust sources. It is thought that LEZ has yielded very little positive result on the average probably because almost half the sources of PM (non-exhaust sources) are not under any form of control.

VI. DISCUSSION

Figures 1 illustrate that, LEZ in Europe has had great positive effect in accelerating the switch from old, high-polluting vehicles to newer, cleaner, less-polluting ones. However it does seem that the effect of the switch to cleaner vehicles on the general air quality within the LEZs has so far been only modest at best. As has already been indicated, LEZ has led to a 2.46% to 3.07% reduction in PM emissions in Inner London, but has failed to make any significant impression on NOx emissions reduction despite an early prediction that LEZ would reduce NOx emission by 4% by the end of 2008 [5][23]. It is not very easy to account for the lack of any notable impact made on NOx emission by LEZ implementation. It is plausible that the origins, behaviour and chemistry of NOx in Inner London are not yet fully understood. In some of Germany's cities, LEZ has had a relatively greater success in reducing ambient emissions, sometimes achieving up to 10% reduction of PM, though in some other cases having no observable effects (see Table 4).

Currently, most of the cities (including LEZ cities) in Europe still regularly exceed the air quality standards for PM and NOx [10]. This has called into question the effectiveness of the Low Emissions Zones as an air pollution control measure, especially given the fact that its implementation has come at some cost to European governments and businesses. It was estimated, for instance, that it would cost nearly £10 million to set up Inner London's LEZ, and that it would cost nearly £7 million pounds annually to keep it running [44].

Private businesses, especially small enterprises have also been damaged by LEZ. For instance, small business owners who are unable, for financial reasons, to update their vehicles to comply with the standards may find themselves being driven to close. In Germany, business owners have complained that LEZ leads to decline in sales [10][30]. This is not too hard to imagine. Operators of vehicles that do not meet the emission requirement will naturally hesitate to drive into an LEZ to do business, hence diminished returns for owners of businesses within an LEZ. Seventy percent of the drivers in Berlin stated that they were reluctant to drive into an LEZ [30].

Another illustration of how LEZ could be affecting businesses comes from the German tourist city of Freiburg. Freiburg is a favourite haunt of tourists from neighbouring France and Switzerland. It is estimated that the LEZ has led to a drop in revenue of about 100 million Euros per year [7]. French and Swiss tourists may not own vehicles that comply with Freiburg's LEZ requirements.

Besides the cost to the government and businesses, there is also the possibility of increasing pollution elsewhere. For example, the preference by vehicle operators to stay in non-LEZ areas could result in higher PM levels outside of the LEZ, as the activity of non-compliant vehicles outside the LEZs rose in relation to their activity within the LEZ. Indeed figures from the area surrounding London's LEZ show that PM10 emissions have been increasing by an average of 1.9% per year [5]. Thus rather than solving the problem of these emissions, LEZ might be reducing their concentration in one area and increasing them in other areas.

It is probably too early in the process to conclude that LEZ is likely to have only little impact in the long run. Air pollution is a decades-old problem in Europe; only recently have governments began to make concerted efforts to control it, and it might take a lot longer before significant improvements in air quality is recorded. Some of the results coming out from Germany are already promising as can be seen in Table 5 with reduction in diesel particulate emission of 62% in 2012.

Noticeable impact has also been made in public health in some area where LEZ has been introduced. In this regard a number of studies have established a clear correlation between decreased PM emissions and decreased mortality in some of Germany's LEZs. With the introduction of stricter emission standards in 2015, the mortality is expected to decrease.

VII. CONCLUSION AND RECOMMENDATION

Despite its generally modest success, LEZ could still play a more significant role in achieving a cleaner and healthier environment. The rapid turnover from old vehicles to newer vehicles is an impressive achievement that has been accelerated by LEZ policies. While it costs millions of Euros to implement LEZ, it will in the long run probably also save millions in health care.

The negative effect on businesses will also in all likelihood be temporary, given the rate of compliance observed in London as well as in Berlin and Munich. A government scheme could be set up to offer subsidies or loans to small-business operators who use vehicles in their businesses to enable them to quickly make the change to compliant vehicles.

Efforts should be made to extend LEZs to areas outside of the bigger cities (especially in the United Kingdom) to avoid the risk of vehicle operators simply reassigning their old vehicles to non-LEZ zones; LEZ will probably work better if it is simultaneously and uniformly implemented by as many cities and towns within a wide geographic circle as possible.

As much as possible, LEZ regulations should aim at including all types of vehicles. This will prevent vehicle users from simply replacing their non-compliant vehicles with cheaper, but air-polluting vehicles not covered by LEZ regulations.

In addition, there is the need to develop a complementary strategy to mitigate non-exhaust emissions. For example, wear-resistant materials could be used in road construction, as well as in making vehicle components (tyres, brakes, etc.). Research in this area has barely begun, but already studies suggest that use of larger stones and certain material in pavement making, such as porous asphalt, could increase the road's resistance to wear, and thus reduce PM generation from road abrasion. Road cleaning, especially with water has also been found to be quite effective in reducing dust re-suspension, especially in dry climates. Alternatively, chemicals such as Calcium Magnesium Acetate and potassium formate could be used to bind and immobilize dust particles on roads. The use of these dust binders in North European countries like Sweden has been found to reduce PM concentrations by up to 35% of its daily mean. It has not however proven very successful in the United Kingdom and Continental Europe. The reason is not clearly understood, but this is a strategy that could be further researched.

REFERENCES

[1] Gurjar, B. R., Molina, L. T., & Ojha, C. S. P. (Eds.). (2010). Air pollution: health and environmental impacts. CRC Press.

[2] Viegi, G., & Enarson, D. A. (1998). Human health effects of air pollution from mobile sources in Europe State of the Art. The International Journal of Tuberculosis and Lung Disease, 2(11), pp. 947-967

[3] Salvida, P. H. N. (1998) Air pollution in urban areas: the role of automotive emissions as a public health problem. The International Journal of Tuberculosis and Lung Disease, 2 (11), pp. 868.

[4] Kan, H., & Chen, B. (2004). Particulate air pollution in urban areas of Shanghai, China: health-based economic assessment. Science of the Total Environment, 322(1), 71-79

[5] Ellison, R.B., Greaves, S.P. and Hensher, D.A. (2013) Five years of London's low emission zone: Effects on vehicle fleet composition and air quality. Transportation Research Part D 23, pp. 25–33

[6] Environmental Protection Agency (2004) Air quality criteria for particulate matter, volume II, EPA/600/P-99/002bF. Available from: http://cfpub2.epa.gov/ncea/cfm/recordisplay.cfm?deid=87903. Retrieved on May 2nd, 2014.

[7] Wolff, H., & Perry, L. (2010b). Fresh Air: Low Emission Zones and Adoption of Green Vehicles in Germany. Mimeo, University of Washington

[8] Boogaard, H., Janssen, N.A.H., Fischer, P.H., Kos, G.P.A., Weijers, E.P., Cassee, F.R., van der Zee, S.C., de Hartog, J.J., Meliefste, K., Wang, M., Brunekreef, B. and Hoek, G. (2012) Impact of low emission zones and local traffic policies on ambient air pollution concentrations. Science of the Total Environment 435–436, pp. 132–140

[9] Jones, A. M., Harrison, R. M., Barratt, B., & Fuller, G. (2012). A large reduction in airborne particle number concentrations at the time of the introduction of "sulphur free" diesel and the London Low Emission Zone. Atmospheric Environment, 50, pp. 129-138.

[10] European Environmental Agency (2013) Air implementation pilot: Lessons learnt from implementation of air quality legislations at urban level. EEA Report 7, ISSN 1725-9177.

[11] Viegi, G., & Enarson, D. A. (1998). Human health effects of air pollution from mobile sources in Europe State of the Art. The International Journal of Tuberculosis and Lung Disease, 2(11), pp. 947-967

[12] Ristovski, Z. D., Miljevic, B., Surawski, N. C., Morawska, L., Fong, K. M., Goh, F., & Yang, I. A. (2012). Respiratory health effects of diesel particulate matter. Respirology, 17(2), 201-212

[13] Harrison, R. M., & Yin, J. (2000). Particulate matter in the atmosphere: which particle properties are important for its effects on health? Science of the Total Environment, 249(1), pp. 85-101

[14] Hung-Lung, C., & Yao-Sheng, H. (2009). Particulate matter emissions from on-road vehicles in a freeway tunnel study. Atmospheric Environment, 43(26), 4014-4022.

[15] Neeft, J.P.A., Michiel Makkee, M. and Jacob A. Moulijn, J.A.(1996) Diesel particulate emission control. Fuel Processing Technology 47, pp. 1-69.

[16] Hueglin, C., Gehrig, R., Baltensperger, U., Gysel, M., Monn, C., & Vonmont, H. (2005). Chemical characterisation of PM2. 5, PM10 and coarse particles at urban, near-city and rural sites in Switzerland. Atmospheric Environment, 39(4), pp. 637-651.

[17] Matti Maricq, M. (2007). Chemical characterization of particulate emissions from diesel engines: a review. Journal of Aerosol Science, 38(11), pp. 1079-1118.

[18] Querol, X., Alastuey, A., Ruiz, C. R., Artiñano, B., Hansson, H. C., Harrison, R. M., ... & Schneider, J. (2004). Speciation and origin of PM10 and PM2. 5 in selected European cities. Atmospheric Environment, 38(38), 6547-6555.

[19] Krzyzanowski, M., Kuna-Dibbert, B., & Schneider, J. (Eds.). (2005). Health effects of transport-related air pollution. WHO Regional Office Europe.

[20] Keuken, M., Denier van der Gon, H., & van der Valk, K. (2010). Non-exhaust emissions of PM and the efficiency of emission reduction by road sweeping and washing in the Netherlands. Science of the total environment, 408(20), 4591-4599.

[21] Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., & Britter, R. (2014). Ultrafine particles in cities. Environment international, 66, 1-10.

[22] Mamakos, A., Bonnel, P., Perujo, A., & Carriero, M. (2013). Assessment of portable emission measurement systems (PEMS) for heavy-duty diesel engines with respect to particulate matter. Journal of Aerosol Science, 57, 54-70.

[23] Transport for London (2011). Stricter emissions standards for central or inner London: a provisional assessment of potential feasibility and effectiveness. Available at: http://www.london.gov.uk/sites/default/files/Central%20and%20Inner%20London%20LEZ%20Feasibility%20Study.pdf Retrieved on the 2nd of April, 2014.

[24] Poulikakos, L. D., Heutschi, K., & Soltic, P. (2013). Heavy duty vehicles: Impact on the environment and the path to green operation. Environmental Science & Policy, 33, pp. 154-161.

[25] Leihs, D. (2011). Effects and potentials of LEZ in Europe: Do they really work?. In ITS Telecommunications (ITST), 2011 11th International Conference on (pp. 213-216). IEEE.

[26] Rapaport, E. (2002). The Stockholm environmental zone, a method to curb air pollution

from bus and truck traffic. Transportation Research Part D: Transport and Environment, 7(3), pp.213-224.

[27] Panteliadis, P., Strak, M., Hoek, G., Weijers, E., van der Zee, S., Dijkema, M. (2014) Implementation of a low emission zone and evaluation of effects on air quality by long-term monitoring. Atmospheric Environment 86, pp. 113 – 119.

[28] ACEA (European Automobile Manufacturers Association) (2014). Euro standards. Available from: http://www.acea.be/news/article/euro-standards Retrieved on 2nd of May, 2014.

[29] Council Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air qualiy and clearer air for Europe. Official Journal of the European Union. L 152/1, 11.06.2008, pp.42-46.

[30] De Borger, B. and Proost, S. (2013) Traffic externalities in cities: The economics of speed bumps, low emission zones and city bypasses. Journal of Urban Economics 76, pp. 53–70.

[31] Qadir, R.M, Abbaszade , G., Schnelle-Kreis , J., Chow, J.C. and R. Zimmermann, R. (2013) Concentrations and source contributions of particulate organic matter before and after implementation of a low emission zone in Munich, Germany. Environmental Pollution, 175, pp. 158 – 167.

[32] Cyrys, J., Peters, A., Soentgen, L. & Wichmann, H. (2014) Low emission zones reduce PM10 mass concentrations and diesel soot in German cities, Journal of the Air & Waste Management Association, 64(4), pp. 481-487.

[33] Wolff, H., & Perry, L. (2010a). Policy Monitor Trends in Clean Air Legislation in Europe: Particulate Matter and Low Emission Zones1. Review of Environmental Economics and Policy, 4(2), 293-308.

[34] Fensterer, V., Küchenhoff, H., Maier, V., Wichmann, H. E., Breitner, S., Peters, A., ... & Cyrys, J. (2014). Evaluation of the Impact of Low Emission Zone and Heavy Traffic Ban in Munich (Germany) on the Reduction of PM10 in Ambient Air. International journal of environmental research and public health, 11(5), 5094-5112.

[35] Browne, M., Allen, J., & Anderson, S. (2005). Low emission zones: the likely effects on the freight transport sector. International Journal of Logistics: Research and Applications, 8(4), 269-281.

[36] Kelly, F. J., & Kelly, J. (2009). London air quality: a real world experiment in progress. Biomarkers, 14(S1), 5-11.

[37] Pant, P., & Harrison, R. M. (2013). Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: a review. Atmospheric Environment, 77, 78-97.

[38] Hendriks, C., Kranenburg, R., Kuenen, J., van Gijlswijk, R., Wichink Kruit, R., Segers, A., ... & Schaap, M. (2013). The origin of ambient particulate matter concentrations in the Netherlands. Atmospheric Environment, 69, 289-303.

[39] Harrison, R.M., Yin, J., Mark, D., Stedman, J., Appleby, R.S., Booker, J., Moorcroft, S., 2001. Studies of the coarse particle (2.5 -107 mm) component in UK urban atmospheres. Atmospheric Environment 35 (21), 3667 - 3679.

[40] Forsberg, B., Hansson, H. C., Johansson, C., Areskoug, H., Persson, K., & Järvholm, B. (2005). Comparative health impact assessment of local and regional particulate air pollutants in Scandinavia. AMBIO: A Journal of the Human Environment, 34(1), 11-19.

[41] Kupiainen, K. J., Tervahattu, H., Räisänen, M., Mäkelä, T., Aurela, M., & Hillamo, R. (2005). Size and composition of airborne particles from pavement wear, tires, and traction sanding. Environmental science & technology, 39(3), 699-706.

[42] [42] Thorpe, A., & Harrison, R. M. (2008). Sources and properties of non-exhaust particulate matter from road traffic: a review. Science of the total environment, 400(1), 270-282.

[43] Lenschow, P., Abraham, H. J., Kutzner, K., Lutz, M., Preuß, J. D., & Reichenbächer, W. (2001). Some ideas about the sources of PM10. Atmospheric Environment, 35, S23-S33.

[44] Watkiss, P., Allen, J., Anderson, S., Beevers, S., Browne, M., Carslaw, D. and Young, T. (2003). London low emission zone feasibility study phase II: final report to the London low emission zone steering group.