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Decomposition of Low emission zone strategies into mechanisms and methodology for assessing their impacts on air pollution

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Abstract

The Low emission zone is one of the policies used in urban areas to improve air quality by restricting the entry into a zone to the most polluting vehicles. The first aim of this paper is to review several studies led in Europe to assess LEZ impacts on emissions, concentrations *etc*. The review enabled the identification of the main positive approaches, and the gaps that led to unexpected results or that showed the LEZ was less effective than expected. Then, with a view of improving the overall frame of assessment of actions, we propose the decomposition of the LEZ on mechanisms (restriction to the most polluting vehicles, car fleet turnover, the traffic shifting, modal shifting *etc.*) and impacts. The review about the LEZ and the mechanisms give useful insights to improve the methodology for assessing LEZ impacts.

Keywords: Low emission zone, air quality assessment, impacts, mechanisms, methodology

1 Introduction

Air pollution is a complex phenomenon, where concentrations are depending on direct emissions but also on many factors influencing pollutants transport and dispersion and secondary air pollutants formation. Besides, dispersion and transport of air pollutant from many sources or regions are occurring. Moreover, a

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large part of the European population is exposed to high concentrations of pollutants and in particular, urban populations are exposed to level of particulate matter with an aerodynamic diameter <10µm (PM_{10}) and nitrogen dioxide (NO_2) higher than World Health Organization (WHO) guidelines or the European Union (EU) limit values. The EU annual mean limit values are 40 µg/m^3 for PM_{10} and also 40 µg/m^3 for NO_2. The daily mean limit values are 50 µg/m^3 with 35 days of exceedances permitted per year for PM_{10} and 200 µg/m^3 with 18 permitted exceedances per year for NO_2 **[1]**.

As road transport in urban areas is identified as a major source of air pollution, countries and cities try to decrease their impacts, by setting up strategies to reduce their contribution to air pollution.. Among them, the Low Emission Zones (LEZ) have been implemented within many cities to reduce emissions from road traffic. Low emission zones are areas restricted to some categories of vehicles that do not meet emissions limits. Thus, for each LEZ, the categories of vehicles concerned are defined according to the type (Heavy goods Vehicles, Light commercial vehicles, passenger cars, buses, coaches *etc.*) and emission criteria which are the European emission standards. They also are defined depending on the area they cover, the date of enforcement, the time period when they are applied (week days, week-ends, hours *etc.*), exemptions *etc.*

Low emission zones are implemented to improve air quality in urban areas (**[2]**, **[3]**) by reducing the impact of traffic (**[4], [5]**) on air pollution and reducing emissions of air pollutants, Green House Gazes and noise **[6]**, and reducing PM concentrations **[7]**. They aim to achieve air quality target values **[4], [7], [8]** of PM_{10} and NO_2 concentrations (**[9], [10]**), and *in fine* to protect human health according to Holman et al. **[8]**, and Qadir et al. **[11]** or improve human health (**[3], [6]**). Finally, as reported by Cesaroni et al. **[12]**, the LEZ of Rome is acting on behaviors and may reduce the number of private vehicles in the city center, and encourage the use of public transport and the replacement of old polluting vehicles accelerating the natural fleet turnover. Thus, it is necessary to assess if LEZ enable some answers to those issues. In this paper, we analyze current assessment of LEZ on air quality, and we focused on European LEZ. We rely on impact studies conducted before and after the implementation of several LEZ in Europe to figure out the impacts measured or calculated, and to highlight the effective tracks of assessment, and also their limits. In the second part, we attempt to understand the LEZ and how they affect travels, emissions etc. by decomposing LEZ into mechanisms (traffic restriction, car fleet turnover *etc.*) and impacts (emissions, concentrations, health impacts). Those mechanisms are the links of the causal chain induced by the implementation of the LEZ. The identification of all the mechanisms is necessary to take into account every characteristics of a measure and their expected effects. On that basis, we propose some insights to improve the assessment of the LEZ.

2 Analysis of Usual Assessment of LEZ

As Tögel and Špička **[13]** mentioned it, Low Emission Zones are strategies implemented to achieve air quality objectives and reduction of air pollutant concentrations by reducing emissions from road traffic. However, their effectiveness must be assessed. We conducted a review of studies analyzing LEZ that have been introduced in many European countries since 1996. We exposed the principal findings of the *ex-ante* and *ex-post* studies, and when necessary, we described their principal characteristics. We analyzed the efficient approaches and tried to identify the limits that could be pushed in future assessment with recommendations provided in the last section.

2.1 The London Low Emission Zone, United Kingdom

The London Low Emission zone was part of the London Air Quality Strategy and was implemented in February 2008. The London LEZ was designed to reduce air pollutants emissions and in conjunction with other air quality initiatives to achieve UK and EU air quality objectives

The Feasibility study of the London Emission Zone in 2003 by Watkiss et al. **[14]** concluded that the LEZ should have encompassed the Greater London area. As a first step the LEZ should have target lorries, buses and coaches and vans as a second stage but they recommended to not include cars in the scheme. With several scenarios, they showed that the London LEZ would improve modestly the overall emissions and air pollutant concentrations in the Greater London, but would largely help to reduce the exceedances of air quality targets. They investigated each type of vehicles and how the enforcement should apply. One of the main issues they met was to assess the number of vehicles operating in London each year. However they were able to estimate that at least 14 % to about 36 % of the British lorry fleet came into London each year, about 50 % of British coaches operated in London each year, and finally 14 to 18 % of British vans travelled in London. Thus, it appeared that a London LEZ would have an impact on the British fleet. Another interesting point of the study is that the later implementation of the low emission zone would have led to greater benefits in 2010 (or later) than if an earlier scheme had been introduced in 2005. Indeed, in the framework of another action, they noticed that operators of buses anticipated by buying newer vehicles to comply with the policy. Thus, there was an increase of the most modern vehicles available which were Euro 3, while the EU was introducing the Euro 4 legislation, for which exhaust emission standards were lower. That meant there would have been a higher number of Euro 3 than Euro 4.

Concerning air quality, the feasibility study focused on PM_{10} and NO_2. The results showed that air quality benefits would be less important than expected. The emission factors improvements for some vehicles (Diesel for instance) were smaller with the recent EU standards. Moreover, an action targeting London buses before the LEZ had caused the fleet renewal with EURO 3 buses. Thus, with the LEZ implemented few years after that renewal, the expected change in London buses with the last EU standards was smaller. Expected reductions of emissions in 2010 were higher for PM_{10} (-20 to -23 %) than for NOx (-3 to 4 %). Finally, they concluded that a LEZ would have a greater impact in improving air quality concentrations than in reducing emissions. Indeed, they considered air quality targets. And as big areas were close to air quality target levels, small change would significantly affect area of exceedance. However, even the most ambitious scenario would not have enabled to achieve EU or national NO_2 objectives in London in 2005 and 2010. They showed that the recommended LEZ would have reduced the area exceeding NO_2 objective by 47 % in 2007 and 12 % in 2010 relative to the baseline. For PM_{10}, annual mean concentrations was expected to be met in 2007 in London without action, but in 2010, the annual mean concentration was tightened, and 2.7 % of the overall London zone would exceed the target and the presence of a LEZ would greatly reduce this area of exceedance for annual mean concentration of PM_{10} of 32 to 42 %. The study also noticed that the areas were mostly occupied by roads and then had less relevance considering population exposure. For the 24hour mean concentration objective, the Low Emission Zone would enable to meet this target in 2007, and in 2010 with a tightened objective. Concerning the health impacts, they concluded that the highest health benefits would be achieved with a LEZ primarily targeting PM_{10} concentrations. They also estimated that health benefits would be more important than expected in the study, because smaller particles largely emitted by transports have significant impacts on health and would be affected by the LEZ. Moreover, as there is no evidence for a threshold of health impacts for PM_{10}, decreasing their concentrations above the target would induce health benefits.

Transport for London (TfL) also published in 2008 a report **[15]** which was a baseline for future assessment of impacts of the LEZ. The report set out the conditions before the implementation. The Table 1 shows the several phases of the LEZ that have been implemented, and which EU standards the affected vehicles have to meet to enter the LEZ. LEZ are generally enforced by phases. In London, the first phase applied to heavy goods vehicles (HGV) of over 12 tonnes gross vehicle weight in 2008. Then, buses coaches and lighter HGV were affected. The operators of non-exempt vehicles that do not comply with the requirements have to pay a daily charge. The LEZ applies 365 days per year and 24h per day. An Ultra-Low Emission Zone will be set up in 2020.

Table 1: Summary of the vehicles affected, the EU standards required and date of implementation of London LEZ

Date	Vehicle type affected	EU standards required
February 2008	HGV with gross vehicle weight (GVW) of more than 12 tonnes	Euro III
July 2008	HGV with GVW of more than 3.5 tonnes	Euro III
	Buses and coaches with GVW of more than 5 tonnes	Euro III
January 2012	HGV with GVW more than 3.5 tonnes	Euro IV
	Buses and coaches with GVW of more than 5 tonnes	Euro IV
	Large vans	Euro III
	Minibuses	Euro III
December 2015	Transport for London Buses	Euro IV

TfL projected that the scheme would reduce total PM_{10} emissions related to road traffic in Greater London by 2.6 % in 2008, and 6.6 % in 2012. The reductions of NOx emissions expected were 4 % in 2008 and 10 % in 2012. They expected the scheme to reduce the area of Greater London that exceeds the annual mean air quality objective for PM_{10} of 23 $\mu g.m^{-3}$ by about 5.8 % in 2008, assuming the implementation of the first two phases of the scheme. However, we note that it is related to PM_{10} from road traffic only, changes of other sources, secondary pollutants or regional contribution are not included and one third come from non-exhaust emissions (as resuspension, brake wear *etc.*), that are unchanged with a LEZ. The reduction of Greater London area that exceeds the annual mean NO_2 objective is 5 % in 2008, and 16 % in 2012.

Ellison et al. **[16]** studied the effects of the LEZ on car fleet turnover after the implementation of the LEZ. They found that the fleet change started in the months preceding the enforcement, and continued one year after. This was repeated for each phase of the LEZ observed. By comparing the rate of pre-Euro III rigid vehicles in London with national average, they noticed that the introduction of the LEZ permitted the replacement of 20% of pre-Euro III vehicles in addition to the natural replacement rate. Then, the replacement rate returns to its natural trend, which means that operators continued to replace their vehicles as they would have done without the LEZ. Moreover, the LEZ affected the vehicle use, since until January 2012 it did not include Light Commercial Vehicles (LCV), it appeared to be a switch away from rigid vehicles towards LCV and articulated vehicles.

Wood et al. **[3]** assessed associations between traffic-related air pollutants and respiratory/allergic symptoms amongst 8-9 year-old children living within the London LEZ. Based on data from sites (background and roadside) in and surrounding the study area within the London Air Quality Network, they obtained concentrations for $PM_{2.5}$ (particulate matter with an aerodynamic diameter <2.5 μm), PM_{10}, NOx and NO_2. They targeted areas with high levels of air pollution, and did not find reduction of ambient air pollution levels and thus they did not observe evidence of a reduction in allergic and respiratory symptoms prevalence. The group of children is not representative of all children living the LEZ, but representative of those living in the areas with the highest levels of traffic-related air pollution. Their findings cannot be extrapolated to other age groups. The predicted air quality improvements have not occurred, it could be explained by the delay in implementing the 3rd phase, an increasing proportion of diesel cars in the fleet, and NOx emissions from diesel are not as low as predicted. The predicted improvements could occur at a longer term.

2.2 The Lisbon Low Emission Zone, Portugal

The legal air quality compliance for human health has been the major driver for the implementation of the LEZ in Lisbon. The LEZ affects all vehicles including passenger cars, LDV, HGV, buses, motorcycles regardless to the motorization (diesel or petrol). The Table 2 shows the phases of implementation. This LEZ operates on weekdays from 7 AM to 9 PM. A number of exemptions were admitted (emergency vehicles, residents and commercial vehicles, public transports including taxis *etc.*)

Table 2: Summary of the phases of the implementation of Lisbon LEZ

Date	EU standards required	Zone
July 2011	Euro 1	Zone 1 (city's central area = 1 % of Lisbon City Area)
April 2012	Euro 2	Zone 1
	Euro 1	Zone 2 (1/3 of the city area)
January 2015	Euro 3	Zone 1
	Euro 2	Zone 2

Silva et al. **[9]** described the implementation process of this LEZ. They reported that, in 2012 compared to 2011, on the most polluted station (Avenida da Liberdade) located inside the zone 1, values for annual mean concentrations of PM_{10} were reduced by 16 % and 6 % for NO_2. In 2012, there was 72 days of exceedances for PM_{10}, it was smaller than the 11 past years, but still above the EU limit of 35 days per year. The taxis contributed to 17 % of the light vehicles fleet travelling in the zone, and about one third of the emissions of the light vehicles, thus they expected that the taxis which were identified as a major source of emissions would renew their fleet. But, because of their exemptions, the taxis fleet renewal didn't occur.

Ferreira et al. **[6]** modeled the impacts of the LEZ on emissions of PM_{10} and NOx with three scenarios relying on the behavior of drivers. In the 1st, the owner of pre-Euro 1 vehicles choose to stop driving (there is no fleet renewal, but the traffic inside the LEZ decreases), in the 2nd the owners replace their vehicles, but not all of them with new one, and the 3rd scenario, the owners of pre-Euro 1 vehicle replace their vehicle with the most recent (Euro 5). Although those scenarios are not realistic, they allowed assessing the potential of a measure as a LEZ. As expected, PM_{10} reductions are higher in the first scenario. The 2nd scenario gives modest results and the scenario 3 shows similar reductions to the 1st (motorcycle excepted, for which emission reductions are similar to the 2nd scenario). Concerning the NOx reductions, the 1st scenario gives reduction up to 5 times higher compared to the two other scenarios. They explained this result by a less important reduction in NOx emissions associated to the recent Euro standards (Euro 4 and 5). The results showed that the LEZ could reduce PM_{10} emissions by 25 % to 34 %, and NOx emissions by 1 to 7 %.

In 2015, Ferreira et al. **[17]** compiled air quality data from 2001 to 2013 at the hotspot (Av. Da Liberdade). They compared the results to measurements from two other stations (an urban background station, and a traffic site), outside the LEZ. The results showed that in 2013 there was a reduction in the annual average concentration of PM_{10} of 23 % and 12 % for NO_2 compared with 2011.

Faria et al. **[18]** used real-world data of meteorological conditions, traffic volumes, vehicle speed in an air quality dispersion model (CALINE4). In the absence of local data, they used the characterization of the national fleet for buses, and passenger cars/LCV. They evaluated the impacts of different scenarios on $PM_{2.5}$ concentrations. Among the scenarios, there was the implementation of a low emission zone, and as they expected some traffic reduction within the LEZ, results indicated reduction of $PM_{2.5}$ concentrations by 15 to 43 % within the LEZ according to the strictness of the scenario. They concluded that urban policies such as LEZ (and cordon tolls) are effective in reducing traffic-related $PM_{2.5}$ concentrations and have positive health impacts.

2.3 The German Low emission zones

Cyrys et al. **[2]** conducted a review of the effects of German LEZ on PM_{10} concentrations and Diesel soot in German cities. The reductions on PM_{10} concentrations modelled in Munich or other German municipalities appeared to be between 2 and 10 % for the first and third stage respectively. Those relatively low reductions were criticized. The first studies, in Cologne, Berlin and Munich analyzing the effects of German LEZ supported results from modeling. However, Cyrys et al **[2]** noted that those analysis were established on short time period, whereas assessment should be done on long enough time period to avoid an influence of meteorological conditions on annual mean concentrations from one year to the next. Moreover, they assessed the relevance of using PM_{10} concentrations to assess the effects of a LEZ. A study in Berlin highlights that Black Smoke (BS) concentrations decreased of 21 to 24 % in 2008, after the first stage, then 52 % in 2010, after the third, in comparison to 2007. They attributed those reductions to the reductions of BS emissions from traffic.

In Munich, to reduce PM_{10} concentrations they introduced a law forbidding the transit vehicles heavier than 3.5 tonnes without final destination in Munich to use a motorway ring around the city area. Moreover, they set up a LEZ which phases are described in Table 3. All vehicles are concerned, and in Germany, the identification for compliance is done with colored badges, corresponding to European emission standards.

Table 3: Summary of the phases of the implementation of Munich LEZ

Date	EU standards required
October 2008	Euro 2 / red sticker
October 2010	Euro 3 / yellow sticker
October 2012	Euro 4 / green sticker

Fensterer et al. **[10]** investigated the effect of the enforcement of a low emission zone and a transit ban for heavy duty vehicles in 2008. They focused on PM_{10}. They compared PM_{10} concentrations before and after the LEZ implementation using a statistical model (a semi-parametric model with first order autoregressive errors). They collected data at two sites located in the LEZ, and at one urban background. The measures were performed before (form February 2006 to January 2008) and after (October 2008 to September 2010) the LEZ was implemented. Results showed the concentrations were higher during winter than summer. Reduction of PM_{10} concentrations were observed on both urban stations (from -2 to -14 % in summer and about -2 % in winter), and a lower decrease at the background station. They observed important changes in car fleet composition, particularly between 2007 and 2008, just before the LEZ implementation. During the 2007 to 2010 period, passenger cars and HGV without any badge (*i.e.* Euro 1 or older) decreased from 9.2% to 2.5% and from 31% to 24 % respectively. In the same time, the vehicles with green sticker increased from 78 to 89 % and from 19 to 36 % for passenger cars and HGV, respectively.

As mentioned in Cyrys et al. **[2]**, Qadir et al. **[11]** assessed the effect of the implementation of the LEZ on concentrations and source contribution of the particulate organic compounds (POC). They observed an effect of the LEZ implementation on POC concentrations, but not significant. However, a Positive Matrix Factorization (PMF) model was used to identify the sources of the POC, and after the LEZ implementation the contribution of traffic had decreased about 60 %. Moreover, the average concentration of EC from traffic, decreased from 1.1 $\mu g/m^3$, before, to 0.5 $\mu g/m^3$ after the LEZ implementation.

Morfeld et al. **[19]** studied the potential effects of LEZ on concentrations of NO_2, NO and NOx in 17 German cities having implemented a LEZ. They analyzed continuous measurements (with half-hour averages) and data from diffuse sampler for NO_2, NO, and NOx concentrations measured inside and outside LEZs. The effect of LEZ introduction on nitrogen oxide concentrations (NO_2, NO, and NOx=NO_2+NO) was not higher than 2 $\mu g/m^3$ at all index stations, that means it was not higher than 4 %. The reduction was only slightly larger for stations close to traffic. Moreover, the four week averages concentrations measured after the LEZ implementation were far above the current EU limit for annual average concentration of NO_2 which is 40 $\mu g/m^3$ and could not be achieved with the 2 $\mu g/m^3$ reduction.

Morfeld et al. also analyzed PM_{10} concentrations from 19 German LEZ **[20]**. They performed half-hour measurement and gravimetric daily measurements of PM_{10} from about 2005 until the end of 2009. The results showed that the LEZ effects estimated were about 0.2 $\mu g/m^3$ at all index stations, i.e., the relative PM_{10} reduction was about 1 %. The highest concentrations near traffic (excluding urban background and industry index stations) were below 1 $\mu g/m^3$ (less than 5 % relative reduction). Thus, the effects were smaller than predicted prior to the introduction of LEZ. The average of total carbon (elemental carbon + organic carbon) concentrations was estimated as 13 $\mu g/m^3$ and LEZ effect estimates were about -0.55 $\mu g/m^3$ (-4.2 %). The $PM_{2.5}$ mean concentration was found at 17 $\mu g/m^3$ and there were no indication of reduced concentrations after the introduction of the LEZ.

2.4 The Dutch Low emission zones

In Netherland, from July 2007 LEZ were gradually implemented in several cities. They aim to comply with EU air quality standards for PM_{10} and NO_2. Most of them are affecting lorries, however, some are starting to include light duty vehicles.

In five cities, Boogaard et al. **[21]** conducted measurements of PM_{10}, $PM_{2.5}$, soot, NO_2, NOx, and elemental composition of PM_{10} and $PM_{2.5}$ at eight streets sites, six urban background and four suburban background sites before and after two years of LEZ implementation. They did not find that LEZ affected traffic-related indicators such as soot or NOx. They exposed several explanations, firstly as the LEZ only affected trucks and the absolute decrease of the number of old trucks was relatively small, the impact might have been too small to be measured. Moreover, the emission factors of NOx appeared to be smaller between Euro classes than expected. The effects of the LEZ could have started in their baseline measurements with the gradual implementation. Furthermore, they hypothesized that the sampling periods could have been too short to reflect significant changes related to the LEZ.

Panteliadis et al. focused their study on the Amsterdam LEZ **[4]**. They studied the effects of the implementation of the LEZ in 2009 on air quality: during a period starting two years before the implementation up to two years after, at two monitoring sites within the LEZ (a street frequently used by HDV, and a urban background site). This LEZ excluded Euro 0, I and II lorries. The results showed that after the LEZ implementation, the traffic contribution to concentrations decreased by 4.9 % for NO_2, 5.9 % for NOx, 5.8 % for PM_{10}, 7.7 % for Absorbance, and 12.9 % for EC. Those results highlighted significant decreases of concentrations of traffic-related air pollutant in the vicinity of a roadside monitoring station. As air pollution is influenced by meteorological parameters, this study adjusted its results with wind speed, wind direction *etc.* However, they did not have traffic counts before the implementation and thus could not exclude that the effects could be biased by a decrease of traffic.

2.5 The Stockholm Low emission zone

In Stockholm, in combination with a LEZ, a Charging scheme has been implemented, and recent studies are focusing on it. However, Rapaport **[5]** analyzed the benefits of the LEZ by modelling the emissions and reviewed the initial evaluation of the Stockholm LEZ conducted by the municipality. The LEZ applied to diesel trucks and buses with a weight over 3.5 tonnes since 1996 in the city center of Stockholm. Rapaport **[5]** evaluated emissions and concentrations of carbon monoxide (CO), NOx, Volatile Organic Compounds (VOC), particles and CO_2 for 1995 (base year), 2001 without the LEZ and 2001 with the LEZ. He used the traffic data sets and models used by the municipality of Stockholm. The results of modeled emissions showed that the LEZ did not affect VOC, CO and CO_2 emissions but particles and NO_2 suffered a significant change decreased but the traffic of heavy vehicles remained a large contributor to traffic emissions. The modeled concentrations highlighted that the LEZ was more effective for particles than NO_2, CO and VOC. He criticized the way the evaluation had been carried out by the municipality before the implementation, particularly the lack of an estimation of the effects on concentration levels. He concluded on the importance of interactions between different groups (stakeholders, researchers, technicians *etc.*) prior to an implementation of an environmental project.

2.6 The Italian Low emission zones

As in London or Stockholm, the municipality of Milan enforced a zone where the most pollutant vehicles have to pay to charge when entering, the action was named Ecopass. Even if this is not a Low Emission Zone, Invernizzi et al. **[22]** brought some useful insights about assessment of an action aiming at improving air quality linked to traffic emissions. He studied the effects of the zone on black carbon (BC) concentrations. Indeed, the previous studies did not demonstrate reduction in PM_{10}

concentrations, in the Ecopass zone. They assume that the lack of measurable air quality improvements could be due to the limited area of the zone (4,5 % of the total area of Milan municipality) or because of the homogeneous distribution of PM concentrations, as a large amount comes from regional sources and formation of secondary aerosols processes. Thus, PM concentrations are not an appropriate indicator for local variations of emissions within an urban area. The results highlighted that the sites within a pedestrian zone showed low BC concentrations than the Ecopass zone, and the Ecopass zone had reduced BC concentrations compared to unrestricted traffic zones. They concluded that BC is able to distinguish levels of traffic related concentrations at several close urban sites.

Rome enforced a limited traffic zone of 6 km^2 (LTZ) in 2001 where all vehicles were prohibited from 6:30 to 18:00 during weekdays and from 14:30 to 18:00. A second zone was implemented in January 2002, restricting old diesel vehicles to enter the area during daytime. In July 2002, all vehicles without catalytic converter were prohibited during daytime, and form January 2003, at any time of day. A third zone is now enforced, and the restrictions have evolved, but Cesaroni et al. **[12]** studied this first intervention. They studied the impact of the policy on the fleet composition using data from 2001 to 2005 from the national Automobile Association. They considered three scenarios of the fleet composition in the area, the first was a « without policy scenario », a second was an « optimistic scenario » where all Euro 0 were replaced with Euro 4, and a « pessimistic scenario » where 10 % of Euro 0 were still in the fleet, and 90 % were replaced by Euro 1 to 4 cars. They calculated emissions with Copert III, they modelled concentrations of NO_2 and PM_{10} and estimated population exposures and quantified mortality impacts. They found that the total number of car decreased slightly, but this tendency was observed in central Italy too. However, the Euro 0 decrease and Euro 3 increase were higher in Rome than in central Italy. The calculations showed that PM_{10} and NO_2 emissions were 33 % and 58 % lower in the intervention area, but the changes in concentrations were modest in the city significantly but larger in the intervention area. However, the differences between the two scenarios with intervention were slight, they concluded that the main impact on concentrations was due to the removal of Euro 0, whatever the class of replacement car. Since the pollution concentrations changes were modest, the predicted gains in life expectancy at city level were small.

2.7 Conclusion

In conclusion of this review, the studies aiming at assessing LEZ are often focusing on PM_{10} and NO_2 emissions and concentrations, because PM_{10} are largely present in background concentrations and NO_2 did not decrease as much as expected with recent Euro standards. Thus, most of the time the studies of the implementation did not allow to observe the major expectation that is to achieve EU limit values. Cyrys et al. **[2]** and Invernizzi et al. **[22]** showed that traffic-related indicators as BC or BS would be more pertinent to assess an action as a LEZ which is focusing improving air quality by modifying traffic emissions. However, some pollutants, as NO_2, are involved in adverse health effects, and the assessments must demonstrate if the policies implementations have a positive impact on them. Moreover, the assessment should take into account a delay between the implementation and the effects, since LEZ are enforced in phases from the less severe to the strictest. Indeed several studies did not emphasize any improvement due to short term experimentations. Most of the papers did not study health impacts, that is explained by the main goal of the LEZ which is to respect EU limits for NO_2 and PM_{10} concentrations.

3 Hierarchization of LEZ Mechanisms, Impacts and External Factors

Low Emission Zones aim at achieving EU air quality targets, thus to improve air quality and population health. According to Tögel and Špička [13], the causal relationship between emission reductions, air quality improvement, and health improvement must be taken into account with the uncertainties related to external factors. Indeed, the effects of those external factors may significantly modify the results of an implemented action. It appears to be important to establish a hierarchy of mechanisms and impacts of the LEZ to identify on which of them external factors are acting. Indeed, the "cause and effect" relationships from the implementation of the policy to the health effects are induced by mechanisms. Transport for London [15] and Tögel and Špička [13] introduced a hierarchy of impacts, with primary, secondary and tertiary impacts. In this section we will try to extend the reflection.

3.1 Mechanisms and impacts of a Low Emission Zone

Firstly, a Low Emission Zone has a principal mechanism from which other mechanisms and then all impacts are ensuing. The first mechanism is the restriction to vehicles which are the most polluting, in general the oldest one in a defined area.

The restriction of circulation to the oldest vehicles applies to the vehicles circulating in the LEZ: those coming from the inside and those from the outside of the LEZ. Thus, this first mechanism is highly dependent on the behavior of car owners and transport firms. Before the implementation they can choose to anticipate and buy newer vehicles. Once the LEZ is implemented, owners that did not anticipate can cancel their travel or if they must usually travel in the LEZ, they must choose between: make the travel and buy a new car, a modal shift (using public transportation) or not fulfill the law and risk a sanction, and the transport firms can redistribute non-compliant vehicles outside the zone. For owners, who used to pass through the zone but did not stop within, a last choice is given: to circumvent the zone, which would induce traffic shifting around the LEZ, and could locally increase the traffic and congestion. The choice to risk a sanction depends on the means used to check if vehicles are compliant with the minimum standards required, and the level of the charge to pay for the non-compliant vehicles. Thus, the other mechanisms are the induced car fleet turnover, the traffic shifting, modal shifting, cancellation of travel and maybe the fraud.

According to Ellison et al. [16], we can assume that the major choice is the replacement of oldest vehicles by newer. Consequently, the second mechanism directly induced by the implementation is the fleet turnover. They emphasized the anticipated renewal before the LEZ, but the impacts of anticipation on emissions, concentrations and exposition are transitory. Thus, to assess the fleet evolution and its impacts, it is not necessary to take into account the transitory phase, but only data sets before and after the implementation is permanent. We may distinguish two cases: the private owner, and the transportation firms. The private owner that has to change its vehicle will buy either a car that complies with the most recent EU standards or a car complying with the LEZ without being among the last Euro categories. The firms have those two choices too or can redistribute the non-compliant vehicles away from the LEZ. According to Cruz and Montenon [23], in London the largest firms that operate in all United Kingdom redeployed their oldest vehicles where no restrictions applied, while the newest came to London. The local firms, that could not redeploy their fleet had to buy vehicle depending on the purchase they could afford. The redeployment in Germany was not possible because of the national plan that led to LEZ implementation in many cities. After, having bought new cars, whether the rate of the fleet turnover will be less important than before, and after few years the number of recent vehicles will be the same as the one without the LEZ, or the rate will remain the same (owners will replace cars at the same rate as they would have done without the LEZ). The second hypothesis has been verified for transport firms by Ellison et al. [16], but has not been observed for private owners. Thus, a regular strengthening is necessary.

Then, the expected impact of the fleet renewal expected is a decrease of emissions of vehicles operating within the zone. If we assume that the number of kilometers performed in the LEZ remains the same before and after the implementation (i.e. modal shift, circumvention, travel cancellation *etc.* are negligible), the number of kilometers performed with newer vehicles will increase at the expense of kilometers made with older cars. Outside the LEZ, on the principal axis leading to the zone, improvements should also be observed. If emissions are modified by the LEZ, they impact concentrations of traffic related air pollutants. However, the concentrations depend on many parameters: the area covered by the LEZ, meteorology, regional sources and background levels *etc.* Finally, the last impact of a LEZ concerns public health.

3.2 External factors impacting the mechanisms and impacts

The policy enforced can be affected by many external factors as described by Cartier et al. [24]. The first link of the chain, which is the restriction of circulation, can be affected by behaviors, the public transportation network *etc.* Then, the second link, the car fleet turnover, depends on socio-economic factors, behaviors, the set-up of a scrappage incentive to buy a vehicle with the most recent EU standards. The third link of the causal chain is the emissions. It is influenced by parameters that we assume to be invariant, or at least not directly affected by the LEZ, as the driving behavior, urban planning, evolution of demand, population and total number of travels made within the zone in the future. The concentrations of pollutants are depending on multiple factors as the meteorology (temperature, wind speed and direction, rainfall), or the local topography. Moreover, regional sources can affect concentrations. The last link is the health impacts, which depend on the population exposure. The activities, behaviors, the socioeconomic position, age *etc.* are factors that modify the vulnerability and thus health impacts. Most of those factors are considered as invariants during the assessment of an action, this will be explained on the following discussion.

4 Discussion to improve the framework of evaluation

The causal chain described previously reflects the complexity of a policy such as the Low Emission Zone. Indeed, it can affect travels, congestion, modal shift and emissions, concentrations, exposure and health impacts.

4.1 LEZ definition and initial state

To avoid some bias due to the evolution of external parameters, or the implementation of another action or policy, the LEZ must be defined precisely: the area covered, the types of vehicles restricted, emissions categories, exemptions, time of applicability, sanctions foreseen for non-compliant vehicles that enter the LEZ. Moreover, representative data sets of traffic, fleet composition, emissions, meteorology and pollutant concentrations in the zone of interest before the intervention must be available to define the initial state. In a first approach, the zone of interest can be limited to the LEZ itself. For further observations of impacts, the zone could be extended to the principal roads surrounding and accessing the LEZ, but the profits could be diluted, thus the choice of the area is important. It is also relevant to choose a control zone that will not be affected by the restriction area, some parameters between the zone of intervention and the control zone might be different and must be studied. Concerning travel itineraries, the mobility surveys can bring useful information about itineraries, the modal split and as demonstrated in Carteret et al. [25] the ability to define local fleet characteristics depending on socio-economic criteria.

As described in Carteret et al. [25], the approach by modelling to assess *a priori* a LEZ that was proposed by Transport for London [15] brings some useful insights for the assessment. Firstly, it is necessary to define a population of interest which is the potentially-affected vehicles operating in the LEZ. Thus, the knowledge of the total volume of vehicles in the zone and the fleet composition are necessary. To assess correctly the effects of a LEZ on the emissions from traffic, the knowledge of the evolution of the fleet that can be expected is decisive. Few studies take an active interest on the local fleet composition and its evolution. This lack leads to a poor inclusion of local specificities and leads to neglect external factors as the socio-economic position of car owners, or simply to not consider the natural renewal of the fleet. Yet when comparing the fleet turnover due to the LEZ and the natural renewal that would occur without the LEZ, the profits must decline over time. Ellison et al. [16] for London, Panteliadis et al. [4] in Amsterdam, Boogaard et al. [21] in several Dutch cities, and Wolff [26] in Germany observed the fleet evolution of the vehicles concerned by the restriction. Moreover, as illustrated in the report by Carteret et al. [25] the car fleet composition can be variable locally and influence emissions. Thus, the local knowledge of fleet composition and its geographical distribution is necessary. Moreover, the fleet composition is naturally evolving, thus a LEZ will accelerate the renewal, but the difference between the natural and the « forced » turnover will disappear with time, unless the LEZ become stricter and is spatially extended with time. The automatic number plate recognition with cameras allows to have data sets of local fleet composition and to observe its evolution with time. In the lack of a recording campaign of number plates, mobility surveys have the ability to analyze local fleet composition, when data are recent.

4.2 Modelling approach for assessing LEZ

The first step of modelling concerns the travels, traffic quantities and spatial distribution. A LEZ will affect the travels and itineraries on a zone. Chevallier et al. (2012) [27] proposed a methodology for assessing the travels that can be summed up:

- Itineraries are modelled by a multimodal commuting model, relying on origin-destination matrix derived from mobility surveys
- Distinguish two categories of travels: those impacted by the LEZ (itineraries that transit the LEZ) and those unchanged.
- Among the impacted travels, we identify the travels performed with a vehicle banned from the LEZ, and those performed with an authorized one.
- Then, some assumptions must be done about the replacement of the banned vehicle, the modal shifting, or itinerary shifting
- Finally, new matrices are performed impacted travels.

This approach emphasize the importance of the ability to estimate the behaviors (avoid the LEZ, replace its vehicle, choose public transports *etc.*), and to quantify the potential of these choices. Feedbacks and behavior surveys could give some useful clues to quantify *a priori* the choices that will be made. However, feedbacks may pose some limits as each territory has its own specificities (surface area of the city, availability of public transports as subways, tramways, or road infrastructures, parking outside the zone *etc.*).

Then, the vehicle-kilometers driven in the zone must be quantified and shared out with Euro standards, motorization *etc.* to establish the characteristic emissions of the vehicles. Once the fleet composition and vehicles.kilometer are known, the emissions of traffic related pollutants can be estimated.

The impacts of the LEZ on air quality must be assessed, and not only in term of number of days exceeding EU limits. Indeed, in the absence of a threshold below which no health impacts occur, days of exceedance or concentrations above EU limits are not the only responsible for health effects. As noted by Malina and Scheffer [7] the effects of the implementation of a LEZ are depending on local conditions, thus for cities that are slightly exceeding EU limits, a LEZ could allow to respect it, but as those limits are not sufficient to ensure the absence of health impacts, the assessment must show that the intervention is associated with a decrease of pollution levels by using models of dispersion.

The pollutants that must be studied are traffic-related pollutants as PM10, PM2.5, NOx and NO_2. Cyrys et al. [2] and Invernizzi et al. [22] highlighted that traffic-related indicators as BC, BS or EC and OC fractions in PM would be pertinent to assess an action as a LEZ which is focusing improving air quality by modifying traffic emissions. Simultaneously, in situ measurements must be conducted in the area of interest to observe the evolution of concentration levels. Then, a comparison before/after the implementation must be done. Moreover, the concentrations measured must be compared with concentrations on the control zone assumed to be non-affected by the LEZ. However, as BC or BS are not among the regulatory monitored compounds, less measures are available than for PM_{10}, $PM_{2.5}$ and NO_2, and specific measurements must be conducted. Duyzer et al. [28] and Morfeld et al. [29] concluded that all LEZ measurement stations should be studied, and not only traffic stations which are not representing the urban area, and consequently the overall population exposure in the city. Giles et al. [30] suggested that gradients of air pollutant concentrations are important and must be taken into account. The definition of the initial state of the zone affected by the LEZ, and the description of a control zone (supposed to be not affected by the LEZ) are clearly justified at this point of the assessment: the comparisons of concentrations “before”/”after” and “in the zone of interest”/”in the control zone” are necessary to show that the LEZ association with decreasing levels of pollution is not biased by other factors. Moreover comparison at the immediate vicinity but outside the LEZ can show an adverse effect as Dias et al. [31] demonstrated that air pollution levels could increase outside the centre as a consequence of the changes of travels induced by the implementation of the LEZ.

4.3 Invariants

It appears to be difficult to take into account a number of parameters that can evolve on short or long term in modelling. In general, for an *ex-ante* assessment we assume that the total number of travels will not be affected, that background air pollution, regional contribution or other sources as agriculture, industries, heating do not change, as the population, demand, urban planning, infrastructures or meteorology. However, all those parameters are actually evolving, thus when we compare measures of concentrations, or health indicators, on an ex-post evaluation, if data are not available, we must have in mind that conditions might have evolved.

5 Conclusion

Low emission zone aim at reducing traffic contribution to air pollutants concentrations by accelerating the fleet turnover. The analysis conducted in this paper showed that the assessments conducted are often focused on PM_{10} and NO_2 concentrations. The effects are often limited to few percent and not always statistically significant or they are influenced by bias as meteorology, other change in the zone or another action. Thus, few statistical methodologies based on significant studies and results could be proposed and compared for adjusting measurements. In the case of an action that aims at improving air quality by managing traffic components as fleet composition, one should study pollutant as BC and smaller particle fractions as Ultra Fine Particles in addition to PM_{10} and $PM_{2.5}$.

The assessment of such an action meets a number of difficulties. Indeed, a Low Emission Zone is generally implemented in phases, from the softest to the strictest, and a problem with a long term action, is that a long term follow-up is needed, but in the same time, longer is the follow-up, bigger the risk of bias is. Besides, the choice of control zone is challenging, as many factors are influencing concentrations, exposure and vulnerability. Behaviors are also delicate to foresee, while they influence car fleet renewal, modal or traffic shifting, hence the LEZ effects. For instance Ellison et al. **[16]** showed an unexpected consequence of the LEZ focusing on Heavy Good Vehicles, which was their replacement by more Light Duty Vehicles. Another difficulty is the availability of data, to compare sites inside and outside, or before and after the LEZ implementation, a lot of data are necessary for traffic flows, fleet composition, emissions, meteorology etc. However, the decomposition of an action on mechanisms should help to foresee those kind of consequences. The accelerate fleet turnover appears to be the main consequence of the mechanism of restriction. And, as local fleet composition has important consequences on emissions and socio-economic criteria are highly influencing local fleet composition, the analysis of composition appears to be necessary before assessing *a priori* the effects of a LEZ. Further work will be lead to establish the quantifiable potential of all the mechanisms considered in the study should enable a better quantification of their impacts and then the impacts of a LEZ. Moreover, the decomposition into mechanisms and association with numerical potential of other actions could help to compare the efficiency of several actions to implement.

In the future, as the EU standards of exhaust emission are improving, emissions from non-exhaust sources (as brake or tire wear or resuspension) will remain high, but are not targeted in such a scheme, while according to Bukowiecki et al. **[32]**, non-exhaust particles may represent up to 50% of the PM_{10} emitted by road traffic. Thus, we can wonder if the LEZ will be an effective policy to improve air quality or at least to help cities to comply with EU limit values.

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