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What are the Impacts on Air Quality of Low Emission Zones in Denmark?

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Abstract

An evaluation and quantification of the effects for emissions and air quality of introduction of low emission zones in Denmark have been performed using a combination of air quality measurements, dispersion modelling and registration of vehicle number plates. An analysis of measurements of air quality at H.C. Andersens Boulevard in Copenhagen before and after introduction of the low emission zone has been carried out to isolate the effect of the low emission zone. Measurements at selected street and urban background stations have been used to evaluate the performance of the air quality models applied for assessment of the impacts of the low emission zones in selected streets in Copenhagen, Aarhus, Odense and Aalborg. Video recording of vehicle number plates at the street of Åboulevard in Copenhagen was carried out for long periods in 2008/09 and 2010/11, and the number plate information is coupled to the vehicle information from the Central Registry of Motor Vehicles. This method allows for evaluation of how the requirements of the low emission zones influence the distribution of Euro emission classes of affected heavy-duty vehicles and hence the vehicle emission.

1. Introduction

The purpose of establishing the low emission zones is to improve the health of citizens in the largest cities in Denmark by reducing air pollution from particulates. The low emission zone Act requires trucks and buses in a low emission zone to be equipped with particle filters. The requirements apply to trucks and buses that per September 1, 2008 only meet the Euro 2 emission standard (or older standards) and the requirements were tightened further per July 1, 2010 to include the Euro 3 emission standard. The Municipality of Copenhagen and the Municipality of Frederiksberg introduced a common low emission zone from September 1, 2008, Municipality of Aalborg from February 1, 2009, Municipality of Odense from July 1, 2010 and Municipality of Aarhus from September 1, 2010. The National Environmental Research Institute (NERI), Aarhus University (now Department of Environmental Science, Aarhus University) has conducted an evaluation of the effects on air quality of the low emission zones financed by the Danish Environmental Protection Agency. A Mid-term report has been published in 2010 (Jensen et al. 2010) which focused on assessment of the effect on air quality of the low emission zones in Copenhagen and Frederiksberg, that were the first municipalities to implement the low emission zone requirements. In the final report, the effects on air quality are re-evaluated for Copenhagen in light of updated vehicle fleet, traffic information and emission assumptions, and new assessments are carried out for Aarhus, Odense and Aalborg (Jensen et al. 2011). This paper summaries the methodology and results of the final evaluation of the impacts on air quality of the low emission zones in Denmark.

2. Methodology

2.1 Effect assessment based on measurements from H.C. Andersens Boulevard

An analysis of measurements of air quality at H.C. Andersens Boulevard in Copenhagen before and after introduction of the low emission zone has been carried out. The analysis is based on extensive measurements from the Particle Project (Massling et al. 2011) funded by the Danish Environmental Protection Agency with the aim to isolate the effect of the low emission zone. H.C. Andersens Boulevard is one of the busiest streets in Copenhagen and the Particle Project has carried out measurements of different parameters for particulate matter at H.C. Andersens Boulevard and at an urban background location and a regional background location. The idea of the study is to compare an observed reduction in the difference between street and urban background concentrations (named the street contribution) with a modelled emission change calculated with the emission module of the OSPM model (Berkowicz, 2000a) without including the expected emission impact of the low emission zone. If the observed concentration change of the street contribution is greater than the modelled emission change (without the expected emission impact of the low emission zone) then this difference is an indication of an effect of the low emission zone on air quality.

2.2 The effects of the low emission zone on composition of the car fleet based on number plate information coupled to the Central Registry of Motor Vehicles

For the evaluation of effects of the low emission zones in the Mid-term report (Jensen et al., 2010), assumptions were established on how the fleet of heavy-duty vehicles most likely would respond to the low emission zone requirements. How many heavy-duty vehicles would be equipped with particle filters? and how many would be replaced with newer emission standards due to the low emission zone? These assumptions are crucial for estimation of the effects for emissions and air quality. One of the ways in which these assumptions can be tested is through registration of number plates coupled to the Central Registry of Motor Vehicles. Video recording of number plates at the street of Åboulevard in Copenhagen was carried out for long periods in 2008/09 (3 months) and 2010/11 (2 months), and these number plate data is coupled to the Central Registry of Motor Vehicles (Figure 1). The video recording is part of a permanent recording of number plates at various locations used to calculate travel speed towards the city centre of Copenhagen as part of a traffic information system. The Central Registry of Motor Vehicles includes data which makes it possible to determine the emission category (Euro emission standard) of each vehicle. The main purpose of recording of number plates was to evaluate the assumptions initially set up in order to calculate the effect of low emission zones for air quality.

Figure 1. Left and middle: The two video cameras mounted on hanger at the street of Åboulevard in the direction towards the city centre of Copenhagen. Right: The two video cameras.

2.3 Comparison of modelled and observed concentrations

Comparison of modelled and observed concentrations for 2010 for four urban background monitor stations and five street monitor stations under the Danish Air Quality Monitoring Program (NOVANA) (Ellermann et al. 2011) was carried out in order to illustrate the uncertainty in the subsequent model calculations on selected streets in the low emission zones.

2.4 Sensitivity analysis of impacts of different input assumptions on predicted concentrations

An analysis of model results under different input assumptions for H.C. Andersens Boulevard in 2015 has been conducted to illustrate the sensitivity of different input assumptions on predicted concentrations.

2.5 Modelled concentrations at selected streets in the low emission zones

Model calculations have been performed for 138 busy streets in Copenhagen and Frederiksberg, 55 streets in Aarhus, 40 streets in Odense, and 31 streets in Aalborg. Calculations are carried out without and with the low emission zone requirements in 2010, 2015 and 2020.

2.6 Applied air quality model system

Air quality calculations have been carried out with an inter-linked model system consisting of a regional long-range transport model (Danish Eulerian Hemispheric Model - DEHM) (Christensen et al. 1997; Brandt et al. 2001), an Urban Background Model (UBM) (Berkowicz, 2000b) and a street air quality model (Operational Street Pollution Model - OSPM) (Berkowicz, 2000a). The AirGIS system has been used to automatically generate street geometry and traffic input for the OSPM model based on digital maps for roads and buildings, enabling efficient calculations for many locations (Jensen et al., 2001,2009; Ketzel et al. 2011; airgis.dmu.dk).

Modelled meteorological data from the meteorological model MM5 is applied, and emission data for the DEHM model is based on a number of European and global emission inventories.

Emissions for the UBM model are based on a new emission database (SPREAD) (Plejdrup & Gyldenkærne, 2011) developed by the National Environmental Research Institute (now Department of Environmental Science, Aarhus University) which produces a geographical distribution of national emissions on a 1km x 1km grid. The database includes emissions from all sources (traffic, industry, energy, etc.) whereas previous assessments were based solely on traffic sources.

Traffic emissions at street level are calculated by the emission module of the OSPM model which is based on the EU COPERT 4 emission model (EEA 2009). The emission model requires information about the car fleet and its distribution by vehicle category, fuel type and emission standards. The latest updated version of the COPERT 4 model is implemented, and provides a further breakdown of the emission categories into weight sizes for buses and trucks compared to former versions.

The municipalities of the low emission zones have provided updated traffic data for Copenhagen and Frederiksberg and new traffic data for Aarhus, Odense and Aalborg. Traffic data includes Average Daily Traffic (ADT), vehicle composition (passenger cars, vans, trucks and buses), and travel speeds.

3. Results

3.1 Assessments based on measurements at H.C. Andersens Boulevard

In the analysis of measurements at H.C. Andersens Boulevard, the reduction in EC (elemental carbon), benzo(a)pyrene (PAHs), $PM_{2.5}$, N (number of particles), NO_x, CO, benzene and toluene was calculated by linear regression analysis over a three-year period from 2008 to 2010. To isolate the effect of the low emission zone based on analysis of measurements is technically a difficult task. Small concentration changes have to be assessed over a relatively short time period of three years that is affected by factors like meteorology, uncertainty of measurements and data analysis, and an overall reduction in emissions resulting from the continuous renewal of the car fleet. Under these reservations, measured reductions were compared with calculated emission reductions of NO_x, CO, benzene and $PM_{2.5}$ exhaust (excluding the expected emission effect of the low emission zone) as shown in Table 1.

The benzene concentration contribution is reduced as expected according to emission calculations. On the contrary, the measured NO_x and CO contributions are less than expected according to the emission calculations. For NO_X this may be explained by the fact that measurements from the second half of 2010 had to be left out. Furthermore, the emission model may overestimate the emission reduction from 2008 to 2010 due to e.g. less efficient catalysts than assumed in emission calculations.

Ud fra målingerne reduceres benzen som forventet ud fra OSPM modellens emissionsberegninger for perioden 2008-2010. Den målte reduktion af NO_x og CO var derimod mindre end forventet ud fra emissionsberegningerne (Tabel 2.5). Mht. NO_x var det nødvendigt at udelade andet halvår af 2010 fra analysen, hvilket måske kan forklare forskellen. For både CO og NO_x kan dårligt fungerende katalysatorer muligvis forklare de lavere målte reduktioner end beregnet med OSPM modellen emissionsmodul.

According to the emission calculations, $PM_{2.5}$ exhaust is reduced by 19% and non-exhaust is unchanged. The total traffic-related $PM_{2.5}$ emission reduction (exhaust and non-exhaust) is 11% excluding the effect of the low emission zone. The measured reduction is 23% or 1,3 $\mu g/m^3$, that indicates that the low emission zone requirements have led to a reduction of the street contribution of 12% or about 0.7 $\mu g/m^3$ during the period January 2, 2008 to December 15, 2010. For comparison, the street concentration is about 14.3 $\mu g/m^3$ and the street contribution is about 5.8 $\mu g/m^3$ in the beginning of 2008. The reduction 0.7 $\mu g/m^3$ is about 5% in relation to the street concentrations and 12% in relation to the street contribution. PM2.5 is measured with the TEOM method and the street concentrations are therefore about 30% lower than the true concentrations.

The observed reduction in $PM_{2.5}$ is further supported by the fact that related parameters like EC, PAH and particle number concentrations also are reduced.

Table 1. Comparison of air quality measurements and emission calculations (not including the effect of the low emission zones)

Parameter	Measurements		Emission calculations						
	Street concentration	Street contribution	Total	Passenger car	Taxi	Van	Truck <32t	Truck >32t	Bus
NO_X		-8%	-12%	-11%	-29%	-5%	-14%	-16%	-13%

CO		-9%	-22%	-23%	-2%	-19%	-21%	-35%	-21%
Benzene	-10%	-20%	-24%	-24%	-10%	-24%	-24%	-37%	-23%
N (10-700 nm)	-17%								
$PM_{2.5}$ exhaust			-19%	2%	-91%	-14%	-26%	-31%	-24%
$PM_{2.5}$ total		-23%	-11%						
EC	-13%	-16%							
PAH	-21%								

3.2 The impacts of the low emission zone on the car fleet based on number plate information coupled to the Central Registry of Motor Vehicles

In assessing the impacts of low emission zones, it is of particular interest to know how the low emission zone affects the emission classes of the car fleet and the number of heavy-duty vehicles with retrofitted particle filters. Although the Central Registry of Motor Vehicles in principle should include this information, it turns out that the information is not consistently recorded. For example, only 7.6% of the 1.1 million video registrations had a Euro class registered in the Central Registry of Motor Vehicles. However, 97% of trucks and 81% of buses had Euro class registered whereas passenger cars, taxis and vans only had 4-7%. Therefore, it has been necessary to group the registered vehicles into Euro emission classes based on information about the registration date of the vehicle and start and end dates of the different emission standards, see Table 2.

Table 2. Years different emission classes are assumed to entry into force

Emission class	Passenger car	Van	Truck and bus
Euro 1	1991	1995	1994
Euro 2	1997	1999	1997
Euro 3	2001	2002	2002
Euro 4	2006	2007	2007
Euro 5	2011	2012	2010
Euro 6	2015	2016	2015

Analysis of the subset of vehicles that were registered by Euro emission class in the Central Registry of Motor Vehicles shows that in most cases there was a match between the registration date of the vehicle and the assumed Euro class, but it was also clear that there are some registrations where the registration date was before the entry date of the Euro emission class. This indicates that a new emission standard is sold before it becomes mandatory. It is not possible from the available data to include this effect in the description of the car fleet.

In the Mid-term report (Jensen et al., 2010), the impacts of the low emission zone were established based on assumptions of how the vehicle fleet for the heavy-duty vehicles was likely to respond to the requirements of the low emission zone. Based on the new number plate information it is now possible to test these assumptions. For buses it was assumed that all Euro 3 buses and 50% of the Euro 2 buses would be retrofitted with particle filters and other buses would be replaced by newer buses with the Euro 5 or later. For trucks it was assumed that all Euro 3 trucks would be retrofitted with particle filters and older trucks would be replaced by newer vehicles (Euro 5 or later). The analysis of the number plate information broadly confirmed these assumptions as shown in the following.

In Table 3, Table 4, and Table 5 a comparison is shown between the car fleet as registered with number plates in 2010 (Table 3), the original assumptions set up in the Mid-term report for the evaluation of the low emission zones in 2010 (not adjusted for mileage) (Table 4), and the car fleet based on national statistics in 2010 (adjusted for mileage) (Table 5), respectively.

The emission class EEV refers to Environmentally Enhanced Vehicle and is a voluntary emission standard that corresponds to the Euro 5 for NO_x and PM, but has slightly lower emissions for HC and smoke opacity than Euro 5 (www.dieselnet.com).

Table 3. Car fleet in 2010 based on number plate information at Åboulevard in Copenhagen

	Passenger cars		Taxi		Minibus		Van		Bus	Truck
Euroclass	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Diesel**	**Diesel**
Euro 0	2.7	1.3	0.4	0.0	-	-	6.6	1.8	1.2	1.0
Euro 1	17.8	2.9	2.9	0.0	-	-	20.2	6.4	0.3	1.2
Euro 2	25.2	5.3	11.5	0.9	-	-	20.9	9.4	3.7	7.3
Euro 3	24.2	21.8	31.6	3.5	-	-	38.0	41.7	7.0	25.1
Euro 4	30.1	68.7	49.3	92.6	-	-	14.4	40.4	31.6	41.3
Euro 5	0.0	0.1	4.4	3.0	-	-	0.0	0.2	2.9	22.6
EEV	0.0	0.0	0.0	0.0	-	-	0.0	0.1	53.5	1.6

Table 4. Car fleet with original assumptions in 2010 in Mid-term report (car fleet population not adjusted for vehicle mileage)

	Passenger cars		Taxi		Minibus		Van		Bus	Truck
Euroclass	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Diesel**	**Diesel**
Euro 0	4.8	2.2	0.0	0.0	-	-	7.6	7.6	0.0	0.0
Euro 1	21.5	9.1	0.0	0.0	-	-	13.1	13.1	0.0	0.0
Euro 2	26.1	14.9	0.0	0.0	-	-	14.2	14.2	10.8	0.0
Euro 3	23.0	34.8	0.0	0.0	-	-	32.0	32.0	30.1	30.8
Euro 4	24.6	39.0	50.0	50.0	-	-	33.1	33.1	22.1	23.0
Euro 5	0.0	0.0	50.0	50.0	-	-	0.0	0.0	37.0	46.3
Euro 6	0.0	0.0	0.0	0.0	-	-	0.0	0.0	0.0	0.0

Table 5. National car fleet in 2010 adjusted for annual mileage of vehicles (without low emission zone)

	Passenger cars		Taxi		Minibus		Van		Bus	Truck
Euroclass	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Diesel**	**Diesel**
Euro 0	1.9	0.7	-	-	-	-	5.5	1.3	5.4	2.5
Euro 1	13.0	1.7	-	-	-	-	15.1	5.9	4.3	2.6
Euro 2	22.8	6.1	-	-	-	-	16.7	9.0	19.7	13.1
Euro 3	30.1	27.9	-	-	-	-	46.0	41.7	32.1	33.4
Euro 4	32.3	63.7	-	-	-	-	16.6	42.1	31.3	41.0
Euro 5	0.0	0.0	-	-	-	-	0.0	0.0	7.2	7.4
Euro 6	0.0	0.0	-	-	-	-	0.0	0.0	0.0	0.0

If we assume that the number plate recordings at Åboulevard in 2010 (Table 3) are representative of the car fleet in Copenhagen then the distribution of emission classes at Åboulevard should match the distribution of the assumptions originally set up in the Mid-term report (Table 4) given that the original assumptions are correct.

In the Mid-term report it was assumed that no trucks would be Euro 2 or older. However, the number plate recording shows that 10% of trucks are in this category (Euro 2 accounting for 7%-points). The share of Euro 3 is similar while the share of Euro 4 and 5 are similar in magnitude but interchanged. The Mid-term report assumes a higher share of Euro 5 than registered. Consequently, the assumptions in the Mid-term report lead to higher emissions for trucks compared to emissions based on the registered car fleet.

For buses the assumption in the Mid-term report about very low shares of Euro 0 and 1 are correct but it assumes too high shares of Euro 2 and 3, and too low combined share of Euro 4 and 5 leading to higher emissions compared to emissions based on number plate information.

For passenger cars and vans there is a general trend that the shares of older Euro classes are higher in the Mid-term report than registered at Åboulevard. This will also lead to higher emissions.

For taxis a very high share of Euro 4 (93%) is registered with number plate information but this is an artefact since the year of registration of the vehicle was used to define the Euro emission class. The statutory order about energy and environmental requirements for taxis demands that new taxis have to meet the Euro 5 emission standard after September 15, 2009, and Euro 6 after January 1, 2011. Therefore, there should be a high share of Euro 5 in 2010, and in 2015 100% of all taxis will be Euro 6. In the Mid-term report it was assumed that 50% was Euro 4 and 50% Euro 5. In this case, the Mid-term report gives lower emissions than a car fleet based on number plate information.

In the Mid-term report the car fleet was based on vehicle population statistics from the Central Registry of Motor Vehicles and the car fleet was not adjusted for annual mileage of the different Euro classes. However, since newer cars have higher annual mileage than older cars, then newer cars should be more likely to appear in a street. To test this hypothesis for passenger cars and vans we can compare the car fleet based on number plate registration (Table 3) and the national car fleet in 2010 adjusted for annual mileage of vehicles (without low emission zone) (Table 5). There is a good agreement between the distribution of the car fleet for passenger cars and vans based on number plates and the national car fleet in 2010 adjusted for annual mileage of vehicles. This indicates that a car fleet adjusted for annual mileage gives a better description of the actual car fleet in a street than a car fleet based on national statistics of the vehicle population.

It is also clear that the car fleet registered with number plates (Table 3) have fewer Euro 2 and older and more Euro 5/EEV than the national car fleet (without low emission zone) (Table 5) in accordance with the assumptions of the implementation of the requirements of the low emission zone.

Based on the new information from the recorded number plates and information from the Central Registry of Motor Vehicles new assumptions for the vehicle fleet with and without the low emission zone was established for 2010, 2015 and 2020. These new assumptions are used in the revised calculations of the effect of the low emission zone on air quality, and the assumptions with the low emission zones are summarized for 2010, 2015 and 2020 in Table 6, Table 7, and Table 8, respectively.

Table 6. Car fleet in 2010 based on number plate information (with low emission zone)

	Passenger car		Taxi	Van		Bus	Bus	Truck<32t	Truck<32t	Truck>32t
Euro class	**Petrol**	**Diesel**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Diesel**
Euro 0	1.9	0.7	0.0	5.5	1.3	100	1.2	100.0	1.0	1.0
Euro 1	13.0	1.7	0.0	15.1	5.9		0.3		1.2	1.2
Euro 2	22.8	6.1	0.0	16.7	9.0		3.7		7.3	7.3
Euro 3	30.1	27.9	0.9	46.0	41.7		7.0		25.0	25.0
Euro 4	32.3	63.7	3.5	16.6	42.1		31.5		41.3	41.3
Euro 5	0.0	0.0	92.5	0.0	0.0		56.4		24.2	24.2
Euro 6	0.0	0.0	3.0	0.0	0.0		0.0		0.0	0.0
Fuel distribution	76.7%	23.3%	100.0%	10.9%	89.1%	7.1%	92.9%	1.1%	98.9%	100.0%

Table 7. Car fleet in 2015 based on number plate information in 2010 and development in national statistics from 2010 to 2015 (with low emission zone)

	Passenger car		Taxi	Van		Bus	Bus	Truck<32t	Truck<32t	Truck>32t
Euro class	**Petrol**	**Diesel**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Diesel**
Euro 0	0.6	0.1	0.0	2.2	0.3	100	0.0	100.0	0.0	0.0
Euro 1	3.1	0.2	0.0	6.9	1.7		0.0		0.0	0.0
Euro 2	10.4	1.8	0.0	10.9	3.7		1.2		2.1	1.5
Euro 3	22.9	12.7	0.0	45.1	25.6		3.5		10.2	6.5
Euro 4	30.6	35.8	0.0	23.0	39.9		18.4		23.8	13.9
Euro 5	27.9	42.4	0.0	11.9	28.9		70.9		57.1	68.5
Euro 6	4.5	7.0	100.0	0.0	0.0		6.1		6.8	9.5
Fuel distribution	66.1%	33.8%	100.0%	7.3%	92.7%	3.7%	96.3%	0.9%	99.1%	100.0%

Table 8. Car fleet in 2020 based on number plate information in 2010 and development in national statistics from 2010 to 2020 (with low emission zone)

	Passenger car		Taxi	Van		Bus	Bus	Truck<32t	Truck<32t	Truck>32t
Euro class	**Petrol**	**Diesel**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Diesel**
Euro 0	0.3	0.0	0.0	1.0	0.1	100.0	0.0	100.0	0.0	0.0
Euro 1	0.6	0.0	0.0	2.0	0.3		0.0		0.0	0.0
Euro 2	2.0	0.3	0.0	3.5	0.7		0.3		0.5	0.3
Euro 3	9.3	4.0	0.0	23.6	7.9		1.2		3.0	1.3
Euro 4	20.2	18.3	0.0	17.7	18.4		9.1		8.5	3.4
Euro 5	21.2	23.7	0.0	14.7	20.5		37.1		29.0	21.2
Euro 6	46.4	53.7	100.0	37.4	52.1		52.3		59.0	73.8
Fuel distribution	58%	42%	100%	4%	96%	2%	98%	1%	99%	100%

3.3 Comparison of modelled and observed concentrations

A comparison of modelled annual concentrations of $PM_{2.5}$, PM_{10} and NO_2 and measurements was carried out at street and urban background monitor stations in 2010 for the cities with the low emission zones to illustrate the uncertainty of the applied model system and input data.

The comparison shows that there is a good agreement between calculated and measured levels of $PM_{2.5}$ and PM_{10} in the regional background (after up-scaling of underestimated regional levels), and modelled urban background concentrations are within -4% to 10% of observed concentrations disregarding Aalborg where measured urban background concentrations are likely to be affected by temporary construction at the harbour front. Street concentrations of $PM_{2.5}$ and PM_{10} are within -7% and 11%, again disregarding Aalborg.

The comparison for NO_2 shows that calculated urban background concentrations are within -21% to 19% of the measurements at urban background stations with an average close to zero. Calculations of street concentrations differ between -16% and 12% with a more systematic underestimation by the model system, since four out of five streets have underestimation of NO_2. Therefore, it is more likely that the model system will underestimate NO_2 concentrations than overestimate. There is a systematic underestimation of NO_x which suggest that traffic emissions are underestimated.

3.4 Sensitivity analysis of the impacts of different input assumptions on predicted concentrations

An analysis of model results under different input assumptions for H.C. Andersens Boulevard in 2015 has been conducted to illustrate the sensitivity of different input assumptions on predicted concentrations. H.C. Andersens Boulevard is one of the busiest streets in Copenhagen and it has the highest measured NO_2 concentrations among available street monitor stations. 2015 is of particular interest since the Danish government has applied to the EU Commission for an extension from 2010 to 2015 for compliance with the NO_2 limit value (40 µg/m^3). The analysis is based on calculations carried out within the last few years in different projects. The calculations show a range of NO_2 concentrations from about 40 µg/m^3 to 46 µg/m^3 depending on the assumptions (see details in Jensen et al. (2011)). The latest assessment of annual NO_2 concentration in 2015 for H.C. Andersens Boulevard is 40.45 µg/m^3 which is just below the threshold value which must exceed 40.5 µg/m^3 to be recorded as an exceedance. This assessment includes the latest assumptions for the vehicle fleet, emission factors and traffic and is the most likely based of the existing knowledge, and is equivalent to the assessment presented as part of the final evaluation of the low emission zones (Jensen et al., 2011).

3.5 Modelled concentrations at selected streets in the low emission zones

Effects of the low emission zone on particle emissions were assessed for H.C. Andersens Boulevard in 2010, 2015 and 2020. Tail-pipe emissions from heavy-duty vehicles were reduced by 60% in 2010 due to a combination of the low emission zone in 2010 and environmental requirements to public bus service. This is a result of some Euro 3 and older vehicles being retrofitted with particle filters and some being replaced with newer Euro 5 vehicles which have lower emission standards. The reduction in exhaust emissions are 16% compared to total emissions from all vehicle categories. The total reduction in emission of PM_{10} (exhaust and non-exhaust) and $PM_{2.5}$ (exhaust and non-exhaust) are 4% and 8%, respectively. The reduction is less for PM_{10} compared to $PM_{2.5}$ since exhaust emissions for PM_{10} constitutes a smaller proportion of the total emission (exhaust and non-exhaust). Non-exhaust includes road, tire and brake wear and re-suspension of particles. The reductions are smaller than predicted in the Mid-term report due to different assumptions about the vehicle fleet, emission factors and traffic data.

Street concentrations of $PM_{2.5}$ and PM_{10} are both reduced by 0.3 µg/m^3 at H.C. Andersens Boulevard in 2010 due to the low emission zone. The modelled reduction of 0.3 µg/m^3 is less than estimated in the analysis of measurements (0.7 µg/m^3, see section 3.1). For comparison, the modelled street concentrations of $PM_{2.5}$ and PM_{10} with the low emission zone are 19.6 µg/m^3 and 29.9 µg/m^3, respectively.

The average effect on air quality of $PM_{2.5}$ and PM_{10} are about 0.2 µg/m^3 for all streets in all the cities with low emission zones in 2010, and the maximum effect is up to 0.7 µg/m^3. The average reduction in street concentrations of $PM_{2.5}$ is equivalent to 1.5% and 1% for PM_{10}. The reason why the reduction is larger for $PM_{2.5}$ compared to PM_{10} is due to the fact that none-exhaust emission is a smaller fraction of total particulate emissions for $PM_{2.5}$ compared to PM_{10}. These estimates are lower than estimated in the Mid-term report since assumptions of the Mid-term report had relatively older vehicles and higher emission factors in the vehicle fleet than in the updated version, and the assumptions about the car fleet and traffic are also different.

The average effect in 2015 is only about 0.1 µg/m^3 and even less in 2020. This is expected as the low emission zone corresponds to an earlier introduction of Euro standards for heavy-duty vehicles than otherwise would have taken place and this effect will level off in time.

Although reduction of NO_x emissions is not the primary objective of the low emission zone, these emissions are reduced due to a shift in emission classes of the heavy-duty vehicles. For H.C. Andersens Boulevard, NO_x emissions are reduced by about 17% for smaller trucks (<32t), 8% for larger trucks (>32t) and 40% for buses due to the low emission zone in 2010 due to a shift from older to newer trucks and buses. Total NO_x emission from heavy-duty vehicles is reduced by 25%. The total reduction in NO_x emissions is 8% when considering all vehicle categories. This is slightly lower than estimated in the Mid-term report due to the same reasons as stated for particle emissions. The reduction of NO_x emissions of 40% for buses is not only driven by the requirements of the low emission zone but also environmental requirements to urban bus services as part of public procurement. These may be minimum requirements for emission standards and additional incentives to use newer emission standards. It is not possible to separate the impact of the low emission zone requirements and the environmental requirements to bus services based on the existing data collected.

The effects of the low emission zone for NO_2 concentrations were assessed for all the streets where air quality monitoring is carried out. The reduction was about 1 $\mu g/m^3$ for H.C. Andersens Boulevard and Jagtvej in Copenhagen, 4 $\mu g/m^3$ for Banegårdsvej in Aarhus, 2 $\mu g/m^3$ for Albanigade in Odense, and 3 $\mu g/m^3$ for Vesterbro in Aalborg. The percentage effect of the low emission zones in 2010 are reductions of 4% for H.C. Andersens Boulevard and 3% for Jagtvej in Copenhagen, 11% for Banegårdsvej in Aarhus, 4% for Albanigade in Odense, and 7% for Vesterbro in Aalborg. Differences are primarily due to different shares of heavy-duty vehicles.

The differences between with and without low emission zone is reduced to 1-2 $\mu g/m^3$ in 2015 and close to zero in 2020 for NO_2 concentrations. The effect of a low emission zone corresponds to an accelerated introduction of newer Euro emission standards than otherwise would be the case. This effect diminishes in time. There is still a minor effect of the low emission zone in 2015 but in 2020 there is only a marginal difference between without and with the low emission zone.

An impact assessment of the low emission zone on air quality has been carried out based on model calculations for 138 busy streets in the cities of Copenhagen and Frederiksberg, 55 streets in Aarhus, 40 streets in Odense, and 31 streets in Aalborg.

The effects of the low emission zones are summarized in Table 9 for NO_2. In Copenhagen the low emission zone reduces the number of exceedances of the NO_2 limit value from 47 to 29 in 2010 out of 138 selected streets. In Aarhus the low emission zone reduces the number of exceedances from 20 to 11 out of 55 selected streets and in Odense from 1 to 0 exceedances out of 40 selected streets, and none exceedances are seen in Aalborg.

In 2015 the low emission zone reduces the number of exceedances from 8 to 6 and from 2 to 0 in Aarhus while there are no exceedances in Odense and Aalborg. These calculations include the effects of the low emission zone and also new regulation of taxis that requires all new taxis in 2011 to comply with the Euro 6 emission standard. There are no predicted exceedances in 2020.

Estimation of the number of exceedances is subject to considerable uncertainty due to uncertainty in the model system and input data.

Compared to the Mid-term report, fewer exceedances are calculated in 2010 and 2015 due to the updated information about the vehicle fleet, emission factors, and traffic data, and further the assumption about constant traffic from 2010 to 2020 that all in all give slightly lower emissions.

Table 9. Number of exceedances of the limit value of NO_2, and average, maximum and minimum modelled NO_2 concentrations in 2010, 2015 and 2020 without and with the low emission zone (LEZ).

		NO_2 ave. ($\mu g/m^3$)	NO_2 max. ($\mu g/m^3$)	NO_2 min. ($\mu g/m^3$)	Number of Exceedances[1]
Copenhagen	**138 streets**				
	Reference 2010	38	66	19	47
	LEZ 2010	36	63	19	29
	Reference 2015	31	54	15	8
	LEZ 2015	30	53	15	6
	Reference 2020	21	35	12	0
	LEZ 2020	21	35	12	0

Aalborg	**31 streets**				
	Reference 2010	31	39	19	0
	LEZ 2010	30	37	18	0
	Reference 2015	24	30	15	0
	LEZ 2015	24	30	15	0
	Reference 2020	16	20	11	0
	LEZ 2020	16	20	11	0
Aarhus	**55 streets**				
	Reference 2010	34	52	16	20
	LEZ 2010	32	49	16	11
	Reference 2015	27	41	14	2
	LEZ 2015	27	40	14	0
	Reference 2020	19	27	10	0
	LEZ 2020	18	27	10	0
Odense	**40 streets**				
	Reference 2010	27	43	15	1
	LEZ 2010	26	40	15	0
	Reference 2015	22	34	13	0
	LEZ 2015	21	33	13	0
	Reference 2020	16	24	11	0
	LEZ 2020	16	24	11	0

[1] Number of exceedances of NO_2 limit value of 40 µg/m^3 counted as exceedances of the value 40.5 µg/m^3.
'Reference' is without LEZ requirements.

There are not calculated any exceedances of the air quality limit values for $PM_{2.5}$ (25 µg/m^3 in 2015) and PM_{10} (40 µg/m^3 in 2005), see Table 10.

Table 10. Modelled concentrations of $PM_{2.5}$ and PM_{10} in 2010, 2015 and 2020 without and with low emission zones (LEZ).

		$PM_{2.5}$ ave. (µg/m^3)	$PM_{2.5}$ max. (µg/m^3)	PM_{10} ave. (µg/m^3)	PM_{10} max. (µg/m^3)
Copenhagen	**138 streets**				
	Reference 2010	18.1	22.1	27.1	35.1
	LEZ 2010	17.9	21.5	26.8	34.5
	Reference 2015	17.7	20.9	26.6	33.9
	LEZ 2015	17.6	20.7	26.5	33.7
	Reference 2020	17.3	19.9	26.2	32.8
	LEZ 2020	17.3	19.8	26.2	32.8
Aalborg	**31 streets**				
	Reference 2010	13.3	14.3	22.4	24.6
	LEZ 2010	13.0	14.0	22.1	24.3
	Reference 2015	12.9	13.8	22.1	24.1
	LEZ 2015	12.8	13.7	22.0	24.0
	Reference 2020	12.7	13.4	21.8	23.7
	LEZ 2020	12.7	13.4	21.8	23.7
Aarhus	**55 streets**				
	Reference 2010	15.5	18.0	23.6	28.6
	LEZ 2010	15.2	17.2	23.3	27.9
	Reference 2015	15.0	17.0	23.2	27.7

	LEZ 2015	14.9	16.7	23.1	27.4
	Reference 2020	14.7	16.2	22.9	26.9
	LEZ 2020	14.7	16.1	22.8	26.8
Odense	**40 streets**				
	Reference 2010	16.5	18.3	25.0	28.4
	LEZ 2010	16.3	17.9	24.8	28.1
	Reference 2015	16.2	17.7	24.7	27.9
	LEZ 2015	16.2	17.6	24.7	27.8
	Reference 2020	16.0	17.3	24.5	27.5
	LEZ 2020	16.0	17.3	24.5	27.5

An example of the geographic distribution of annual NO_2 concentrations for 138 selected streets in Copenhagen is shown in Figure 2 for 2010 including the effects of the low emission zone.

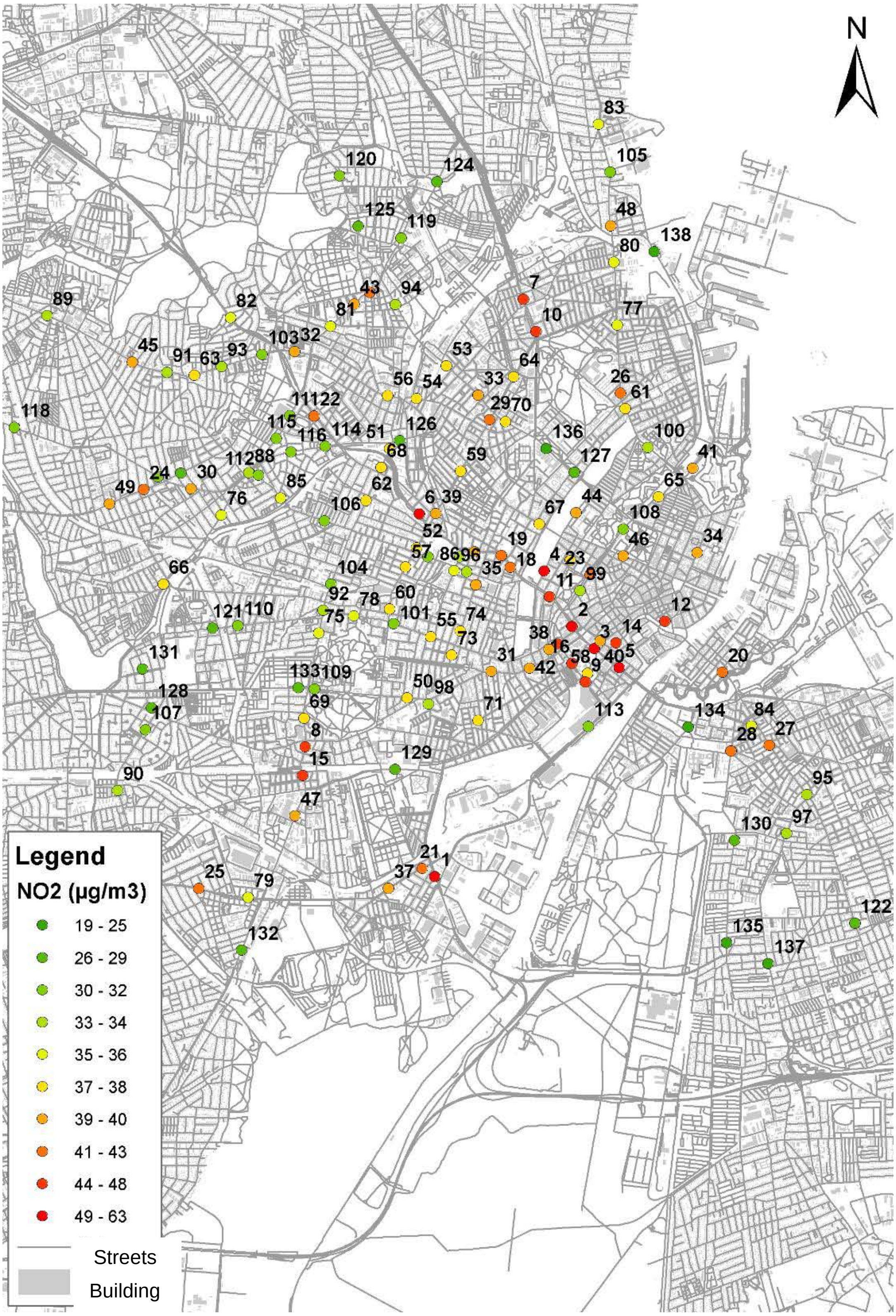

Figure 2. Modelled annual means of NO_2 in 2010 for 138 selected streets in Copenhagen including the effects of the low emission zone. Numbers refer to street names given in Jensen et al. (2011).

4. Conclusion

An evaluation and quantification of the effects for emissions and air quality of introduction of low emission zones in Denmark have been carried out using a combination of air quality measurements, dispersion modelling and registration of vehicle number plates. An analysis of measurements of air quality at H.C. Andersens Boulevard in Copenhagen before and after introduction of the low emission zone has been carried out to isolate the effect of the low emission zone showing a reduction of about 5% in street concentrations of $PM_{2.5}$ equivalent to 0.7 µg/m^3. Measurements at selected street and urban air quality measurement stations have been used to evaluate the performance of the air quality models applied for air quality assessment of the impacts on air quality in selected streets in Copenhagen, Aarhus, Odense and Aalborg of the low emission zones. Modelled street concentrations of $PM_{2.5}$ and PM_{10} are within -7% and 11% of measurements disregarding Aalborg that is affected by construction at the harbour front. Calculations of street concentrations differ between -16% and 12% with a more systematic underestimation by the model system indicating that the model system is likely to slightly underestimate predicted NO_2 levels. Video recording of number plates at the street of Åboulevard in Copenhagen was carried out for long periods in 2008/09 and 2010/11, and these number plate data is coupled to the vehicle information from the Central Registry of Motor Vehicles for evaluation of how the requirements for heavy-duty vehicles of the low emission zones have influenced the distribution of Euro emission classes and hence the vehicle emission. Initial assumptions about how the low emission zone requirements would affect the distribution of heavy-duty vehicles in Euro emission classes were largely confirmed. Calculations of the effect of the low emission zones at selected streets in Copenhagen, Aarhus, Odense and Aalborg show that the low emission zones reduces annual levels of $PM_{2.5}$ and PM_{10} modestly and NO_2 somewhat. The number of exceedances of the limit value of NO_2 (40 µg/m^3) were reduced in Copenhagen and Aarhus in 2010 and 2015 whereas Odense and Aalborg did not have exceedances. No exceedances were modelled in 2020 for NO_2. There are not calculated any exceedances of the air quality limit values for $PM_{2.5}$ (25 µg/m^3 in 2015) and PM_{10} (40 µg/m^3 in 2005) in 2010, 2015 and 2020.

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