Evaluation of traffic control measures in Oslo region and its effect on current air quality policies in Norway

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A B S T R A C T

Urban air pollution is a challenge in several European cities. For most Norwegian cities, the major challenge is the reduction of the NO_2 annual mean concentration in order to comply with the limit value in the European Directive 2008/50/EC, but also too many high NO_2 hourly values occur during strong inversions in cold winter periods. In Oslo, the main contributor to NO_2 concentration levels is diesel exhaust and hence the proposed measures in this study are targeting road traffic. An extensive array of individual and grouped measures were constructed and we studied the change in traffic and NO_2 concentrations by performing consecutive modelling studies which included traffic, emissions, and dispersion models. These measures were intended for permanent and temporary action. They included increases of the tolls that give access to the inner parts of the city, the establishment of low emission zones (LEZs), allowing for temporary free public transport, odd-even driving, defining priority lanes for low emission vehicles, and imposing higher parking fees. We concluded that the most efficient measures were the creation of LEZs and the increase of parking fees. We also explain how the findings from this work have helped to implement Norwegian air quality control policies.

1. Introduction

Urban air pollution is still a challenge in Europe. The most serious pollutants in terms of harm to human health are particles, nitrogen dioxide (NO_2) and ground-level ozone. In Norway, the major challenge is NO_2 (EEA, 2019)

In Europe (EU-31), 86% of the NO_2 concentrations above the annual mean limit value in the Air Quality Directive 2008/50/EC, 2008 (AQD) are measured at traffic stations. These exceedances have been to a large part attributed to emissions from diesel vehicles (EEA, 2019; Kiese-wetter et al., 2014; Degraeuwe et al., 2016; Høiskar et al., 2014). Jonson et al. (2017) estimated for the year 2013 that almost 10 000 premature deaths from $PM_{2.5}$ and ozone in the adult population can be attributed to NOx emissions from diesel cars and light commercial vehicles in EU-30.

In Fig. 1, we present the NO_2 annual means and the number of hours with NO_2 hourly concentrations higher than 200 μg/m^3 in several Norwegian cities between 2007 and 2017. We can observe how the compliance with the AQD annual limit value has been a challenge in several cities, but especially in Oslo, where the exceedance of the annual

limit is recurrent. Moreover, Oslo also present frequent breaches of the hourly exceedance limit, which occur during strong inversions in cold winter periods. The main source of these high NO_2 concentration levels is traffic (Høiskar et al., 2014; Hagman et al., 2011).

The first action plan for air quality in Oslo was drawn in 2004 by the Norwegian Public Roads Administration (NPRA) East Region branch and the Environmental Department in Oslo Municipality (Oslo Municipality and NPRA, 2004). A second action plan was prepared in 2010 when the AQD came into force. The 2010 action plan was prepared in a collaboration between the NPRA East Region branch and the municipalities of Oslo and Bærum (Dalen and Amundsen, 2010). It included a series of joint measures and accompanying action plan for both municipalities, which the public authorities adopted in 2011. However, the AQD limit for the annual mean NO_2 concentration has continued in breach in Oslo and the maximum AQD limit for the NO_2 hourly exceedances was breached most years (Fig. 1).

In 2015, Norway was summoned by ESA (European Free Trade Association – EFTA - Surveillance Authority) for breaches of the AQD and judged guilty of such by EFTA. The legal judgement explicitly mentioned

the failure in Norway to elaborate appropriate air quality control plans, that is, plans that would decrease air pollution in several Norwegian cities, including Oslo. Following EFTA's ruling, the Municipalities of Oslo and Bærum, NPRA, NILU (Norwegian Institute for Air Research) and Urbanet Analyse started a revision of previous Air Quality Assessments and Action Plans. One objective of the revision was to follow EFTA court's guidance that the air quality control plans would guarantee compliance with the AQD limit values. To be able to show this, alternative plans were elaborated and analysed using a chain of modelling tools. The first study was a modelling-for-policy exercise that included the characterization of air quality for 2013 (reference case), projections for 2020 in a "business as usual" scenario (base case) and one control package scenario set on the base case (Høiskar et al., 2014). The control package in Høiskar et al. (2014) included reduced vehicle speeds, increased share of electric and plug-in-hybrid vehicles, full-operation of existing ventilation towers in tunnels during the day, reducing traffic volumes by 20% and port emissions by 5%. Despite the large number of measures considered, these were not sufficient to comply with annual mean AQD limit value. Exceedances of the NO_2 annual limit value persisted near main roads, tunnel entrances and in

Oslo centre.

This paper presents the additional efforts by the team of researchers and city authorities in Oslo to identify the most efficient measures in decreasing NO_2 concentrations and the lessons learnt in the process. Realistic temporary and permanent measures were discussed and then translated into sensitivity cases in respect to the reference case of 2013. The results of modelling the sensitivity cases led to further discussion iteration and modelling predictions. The policy implementation of some of the control measures required changes in legislation and took into account the voicing of public opinion.

2. Methodology

The co-operative process between local authorities, national road authorities and scientists to identify suitable efficient measures to control air pollution in Oslo was an iterative one. It relied on information from a scientifically sound modelling suite with three models and an open discussion on the traffic control measures to be evaluated.
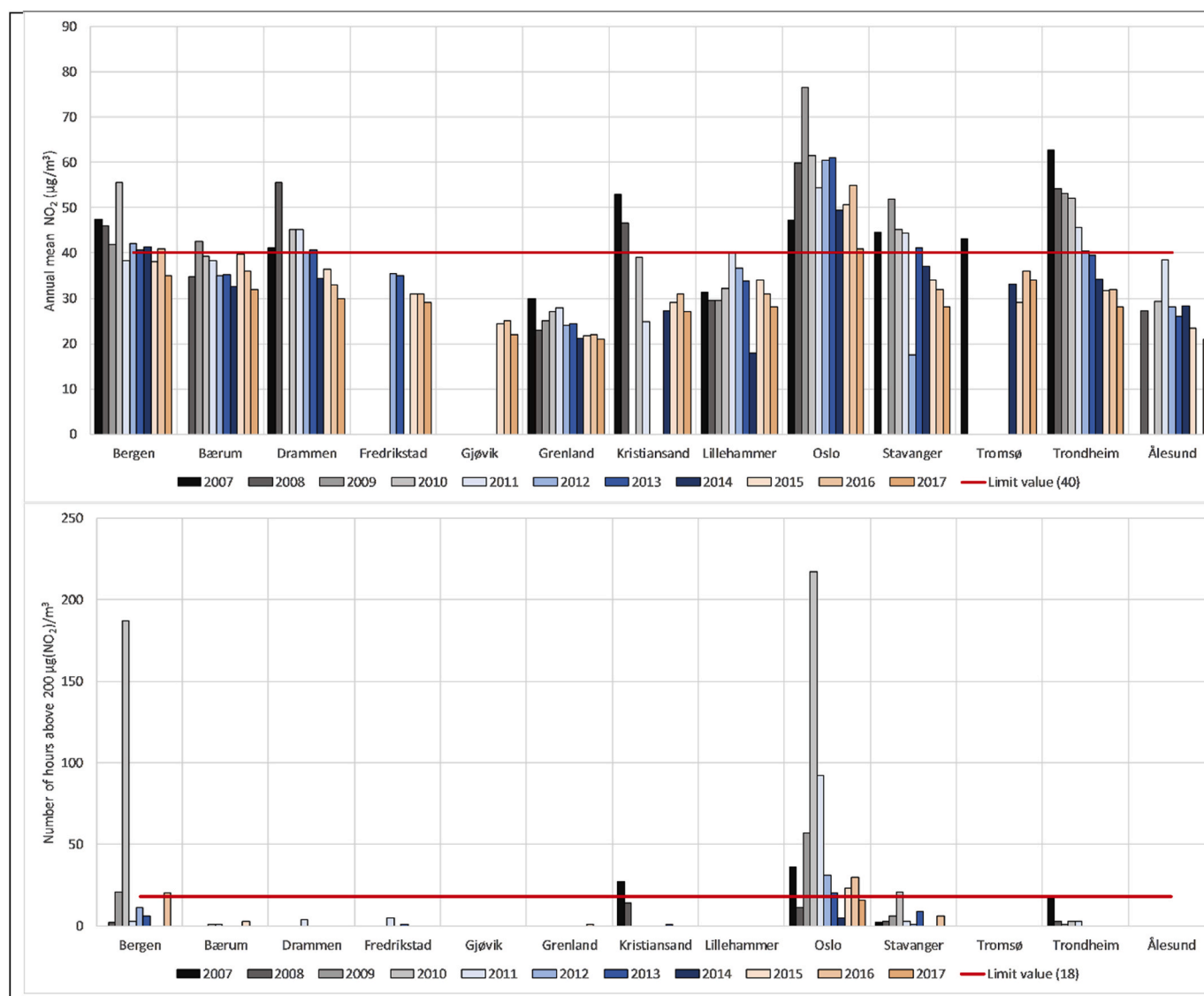

Fig. 1. Compliance to legislation in Norwegian cities for ambient NO_2 (for Air Quality station with highest values). Top: NO_2 annual mean concentrations in several Norwegian cities for the years 2007–2017 (horizontal line is the limit value in AQD of 40 µg/m³). Bottom: number of hours with hourly NO_2 concentrations higher than 200 µg/m3 (horizontal line is the limit value in AQD of 18). Source: www.luftkvalitet.info.

2.1. Modelling setup

We used a modelling suite with three models to analyse the effects of the designed measures: A traffic model, an emission model, and an urban dispersion model.

The traffic model provides a description of the connection between transport offer and transport demand. We used the regional traffic model RTM (Regional Passenger Transport Model), more specifically the development for Oslo and the region of Akershus called RTM23+. This model aims to capture the relevant traffic parameters for Oslo and Akershus for all journeys under 70 km. In this way, its domain contains several municipalities as can be seen in Fig. 2, forming the larger irregular-shaped outer domain that we call **Total domain**. RTM is widely used in Norway for appraisal of infrastructure projects and scenario evaluations by the authorities, transport professionals and research institutes (e.g., Madslien and Kwan Kwong, 2015; Hansen and Johansen, 2016; Malmin et al., 2016; Malmin et al., 2017; Madslien et al., 2019).[1]

The emission and dispersion models used the inner rectangular domain centred in Oslo and Bærum municipalities shown in Fig. 2. We called it **EPISODE domain.** Its total horizontal size is 38 km × 27 km with a 1 km^2 resolution main gridding. The total vertical height is 3.5 km, with 10 layers and the lowest layer is 20 m thick.

As boundary data for RTM23+ we used data from the National Passenger Transport Model NTM6 (Rekdal et al., 2014). RTM23+ consists of approximately 48 500 links. Its network includes waterways, railways and roads, as well as terminals and stops for public transport. The system consists of five demand models, one for each travel purpose (to work, service, visit, leisure, and other). Each of the models takes into account different factors characteristic of purpose. For example, the demand model for work trips takes into account the choice between period and single ticket. In addition, the model calculates intermediate travel, i.e., travelling with two destinations. The model calculates traffic for five modes: car drivers, car passenger, public transport, bicycle and foot, for five vehicle types, five household types, and twelve age groups (Rekdal, 2007). RTM23+ is designed to capture effects in the mid- and long-term and take into account most of the parameters that affect behaviour as is the case of travel time, travel cost, access to car, gender, age, number of jobs (for calculating work trips), location of leisure activities (leisure trips), etc. The factor that will most affect the traffic model accuracy for the temporary measures simulations will be the level of information and correspondent response of the travellers to the new and short-term rules set by the authorities. High/low levels of information and response will mean a larger/smaller change in traffic values and is a source of uncertainty for the results of the simulations.

The emission model relied on the results from RTM23+ where the most important input data used from the traffic model was the traffic volume and speed per road link as well as the fleet composition. The emission model creates hourly emissions for area, point, and line sources in the EPISODE domain. Area sources included residential heating, off-road traffic (Sundvor, 2014), and shipping. Residential heating and off-road emissions estimates were based on data from Statistics Norway. We used wood consumption by type of stove for Oslo and Bærum and applied emission factors based on national measurements (Haakonsen and Kvingedal, 2001) to get the amount of NOx emitted. These were then geographically distributed based on population density. Based on expert experience we assumed that in the areas around Oslo/Bærum the average wood consumption per person was 3 times higher. Emissions from ships and harbor area were based on activity data on arrivals,
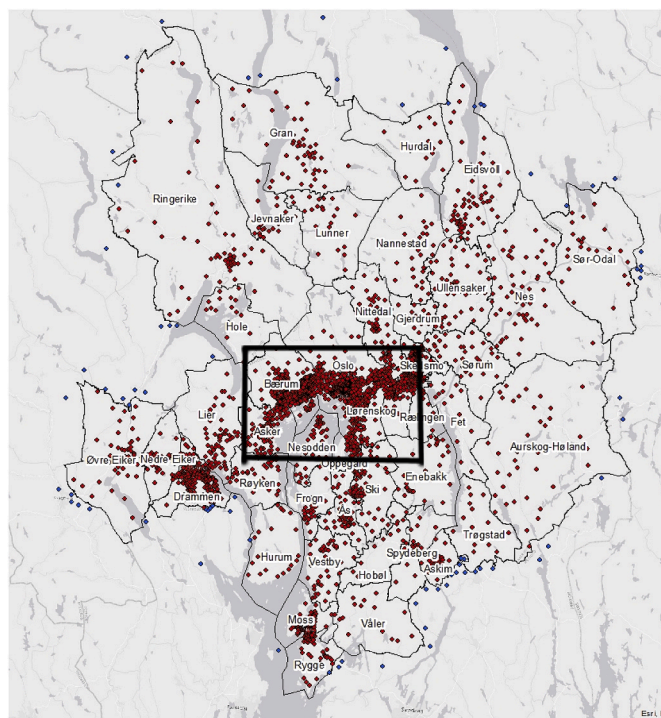
Fig. 2. The domains considered in the modelling system. The traffic model used the larger domain (**Total domain**). The emission and dispersion models EPISODE used the inner rectangular domain (**EPISODE domain**). The polygons represent zones in the traffic model between which travel is estimated, red being zones within and blue outside the traffic model domain. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

berths and discharge factors provided by Oslo Harbor KF. The vessels were divided into different categories and different activities were considered such as cruising, manoeuvring and at berth (López-Aparicio et al., 2017). We also included land activity. Stack emissions from the combustion plants Haraldrud, Klemetrud, and Hoff were treated as point sources. The emission data for 2013 and other metadata as stack heights, gas velocity and temperature, was provided by the Oslo Municipality. Line sources are the traffic emissions calculated at each road link. In the reference situation, fleet composition, Euro-class distribution and age of petrol cars, diesel cars, trucks and buses, were obtained from the Norwegian Transport Council for Road Traffic AS (OFV). Based on the latter we considered that 30% of the vehicles were under 3 years, for light vehicles we used a distribution for 2013 of 2% electric vehicles, 37% petrol passenger cars, 38% diesel passenger cars and 23% light diesel vans. Each vehicle type was assigned an emission factor based on Hagman et al. (2011) who have used HBEFA (Handbook Emission Factors for Road Transport), including emission factors for real-world driving conditions in an urban area for Euro VI (Hagman and Amundsen, 2013). The resulting emissions per kilometre driven are hence higher than the Euro standards. Emissions from Euro VI heavy-duty vehicles (HDV) and buses were set at around 10–15% of a Euro V. Measurements have verified that Euro VI do keep lower emission levels, but do vary according to brand and make (Weber et al., 2015). During traffic congestion, emissions can increase significantly. This was taken into account with a simple parameterization for queues, based on observations of speed and number of cars per lane by Denby et al. (2014). This leads to traffic emissions in 2013 correspondent to 77% of the total NOx emissions in the 2013 inventory (22% direct NO_2 emission). Moreover, a large fraction of the traffic NO_X emissions (36%) are due to heavy traffic even if these vehicles account for 10% of the traffic volume. For the scenarios, the emissions were calculated by introducing the changes

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[1] https://www.vegvesen.no/fag/trafikk/transport/transportanalyser/persontransportmodell: Selection by NPRA of reports written by different institutes regarding the development, documentation, and validation of the different transport models used in Norway including RTM (last accessed April 29, 2020).

relative to the reference case in traffic volume, speed per vehicle type, and fleet composition calculated with the traffic model RTM23+.

The urban air quality dispersion model EPISODE is used to estimate air concentrations and relies on emissions as input data. EPISODE is a model developed specifically to answer questions regarding air quality legislative compliance and policy development in Norway (Sundvor and López-Aparicio, 2014; Høiskar et al., 2014;Tarrason et al., 2017). It is a 3D Eulerian dispersion model combined with Lagrangian submodels, which allow to refine calculations close to sources (Hamer et al., 2019; Oftedal et al., 2009). This is the case of the line source model, which is an integrated Gaussian type model. The Eulerian part of the model consists of a numerical solution of the atmospheric (mass) conservation equation of the pollutant species in a three-dimensional Eulerian grid. EPISODE calculates hourly average concentrations as gridded values and in a set of irregularly placed receptor points (Slørdal et al., 2003, 2008). The input data for the EPISODE simulations (besides emissions and domain characteristics) are meteorological variables (wind speed and direction, precipitation, air temperature, vertical air temperature gradient, air pressure, cloud cover, and relative humidity) and boundary concentrations. The meteorological variables were hourly measurements from meteorological stations in the EPISODE domain (Hovin, Blindern, Alna, Tryvannshøgda, and Kjeller). With the exception of wind, the meteorological variables were set spatially constant. The variables related to wind and atmospheric stability were used as input to a diagnostic wind field model called MCWIND, which produced the hourly 3D wind field based on the Monin-Obukhov similarity theory. The boundary concentrations were taken from the MACC ensemble reanalysis for 2013 (Marécal et al., 2015). Meteorology and boundary concentrations were the same in all simulations.

2.2. Traffic control measures

Traffic control measures can have permanent or temporary nature. The annual concentration levels are best addressed with permanent measures that act cumulatively throughout the year. They can also contribute in keeping the hourly limit by bringing the urban background concentrations down. However, this may still not be sufficient; therefore, we also designed measures to avoid breaching the hourly NO_2 air concentrations of 200 $\mu g/m^3$. These are temporary measures that can be activated during meteorological events leading to NO_2 accumulation in the surface atmosphere. The temporary measures have little to no effect on the annual levels.

As the main challenge for compliance is the NO_2 ambient levels, we focused on measures that promote the reduction of traffic volumes, promote the phasing-in of cleaner vehicles in the fleet especially targeting diesel vehicles, the main source of NOx emissions (Aas et al., 2012). Vehicles not affected in any measure are service passenger vehicles like taxis and in social work, and HDV with technology Euro VI.

2.2.1. Permanent measures

The permanent measures considered and modelled are listed in Table 1. Measures P1 and P2, which imply an increase of the fees at the tollbooths, were inserted in the traffic model as an added direct cost for the specific vehicles (possible because the demand models include the necessary distinction detail). The creation of priority lanes (P3) was defined for roads with more than one lane per direction. This means that all vehicles when carpooling, hybrids and electric vehicles can use this lane. It was assumed by the working group based on their professional experience that this means an increase in traffic share of 20% for electric and hybrid vehicles and 10% of carpooling. Measure P4 means a change of the level of service in public transport, which translates in a decrease of 50% in headway between vehicles. Parking fees (P5) are a direct zonal data input in the traffic model. The LEZ (P6) was introduced at the emission model stage. There is no traffic change from the reference simulation. The rough assumption is that the HDV circulating in the LEZ are all Euro VI. Accepting only Euro VI was justified by the evidence of

Table 1
Permanent measures modelled.

Measures		Vehicles directly affected	Application point or application area
P1	Doubling toll fees at rush hours[a]	All vehicles	At tollbooths
P2	Doubling toll fees	Diesel vehicles	At tollbooths
P3	Creation of priority lanes	Public transport; all vehicles when carpooling, otherwise hybrid and electric vehicles	All roads with more than one lane per direction
P4	Double frequency in public transport during rush hours.	Public transport vehicles	Selected lines of public transport
P5	Higher parking fees	All vehicles	Oslo city
P6	Creation of LEZ	Heavy-duty vehicles with technology older than Euro VI	Area defined by the tollbooths
Groups of measures			
G1	Measures P3 to P6		
G2	Measures P3, P4, and larger area for LEZ		

[a] Rush hours considered between 6:00–9:00 and 15:00–18:00.

much lower NOx emissions in real driving conditions (Hagman and Amundsen, 2013). The previous assumption means an overestimation of emissions outside the LEZ, because the technology changes would spread to these areas. According to the opinion of the experts, it is not expected a significant reduction of traffic volume in HDV with this measure, because goods have to be delivered at fixed places. There is not the flexibility as for other travel purposes and vehicle modes.

The remaining measures were inserted in the emissions model through the results of the traffic model. Both traffic and emission models have the same net of road links. We used the changes in traffic volumes, speed and fleet composition between the reference simulation and the case scenarios simulations to recalculate the emissions per road link.

Further iteration in the discussions led to the modelling evaluation of two groupings of previous listed permanent measures (Table 1). Group G1 consists of all permanent measures, except the ones that affect toll prices. In group G2, the LEZ affects a larger area of the Oslo metropolitan region combined with the measures relating to the priority lanes and the public transport offer.

2.2.2. Temporary measures

The temporary measures described in Table 2 were designed to accomplish short-term effects. They target different vehicles, are applied at different areas and include or not LEZ (HDV with technology older than Euro VI forbidden within Ring 3 as a permanent measure. The location of the existing tollbooths and Ring 3 is shown in Fig. 3. Prospective tollbooths are not shown, but they were considered to the South and East of Oslo at the municipality borders. The temporary measures were analysed for one winter week (30th January to 8th February 2013). The worst air quality conditions in Norway take place in fall and winter and this week had particularly sustained high NO_2 hourly concentrations for the year being simulated.

In temporary measure T1 (odd-even driving), we used experience from Bergen to define the effect on traffic. In NPRA (2011), it is shown that families have access to multiple cars which allow them to circumvent such a measure. This and non-compliance leads to a traffic volume reduction in the simulations of circa 30% instead of 50%.

3. Results and discussion

In Fig. 3, we present the landmarks that will be referenced along the discussion: the location of the tollbooths, the most trafficked roads, the traffic rings surrounding areas of Oslo and receptor points. The results in this section are presented as changes relative to the reference case in 2013 (Høiskar et al., 2014). Results on both traffic and NO_2 annual mean concentration changes are thus presented in a relative way and are

Table 2
Temporary measures modelled.

| Measures		Vehicles directly affected	Application point or application area	Existence of LEZ within Ring 3 as a permanent measure
T1	Odd-even driving	All vehicles	Oslo municipality	–
T2	10 times increase in toll prices	All diesel vehicles	Existing tollbooths	–
T3	idem	Passenger diesel vehicles	idem	–
T4	idem	idem	idem	yes
T5	idem	idem	Prospective tollbooths and existing tollbooths	–
T6	idem	All diesel vehicles	idem	yes
T7	Free public transport	Public transport vehicles	Oslo municipality	–
T8	10 times increase in toll prices and free public transport	Passenger diesel vehicles and public transport vehicles	Prospective tollbooths and existing tollbooths, and Oslo municipality	–
T9	Ban	Passenger diesel vehicles	Inside Ring 3	–
T10	Ban	All diesel vehicles	Inside existing tollbooths	–

comparable to each other when ranking the measures. Also, for reference we present in Fig. 4 how much the reduction in annual concentration of NO_2 is needed to comply with the annual limit in AQD of 40 µg/m^3.

3.1. Results from permanent measures

Table 3 shows the modelled changes in traffic and NO_X emissions for
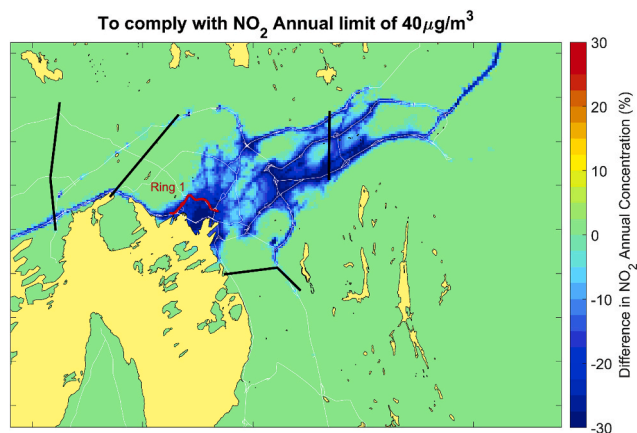
Fig. 4. Percentage change in NO_2 annual concentration necessary in order to comply with the EU legislative limit of 40µg/m3 at and around Oslo (Directive 2008/50/EC). We show the main roads in the region, Ring 1 (roughly defines Oslo centre), and the black lines represent the limits of the tollbooths.
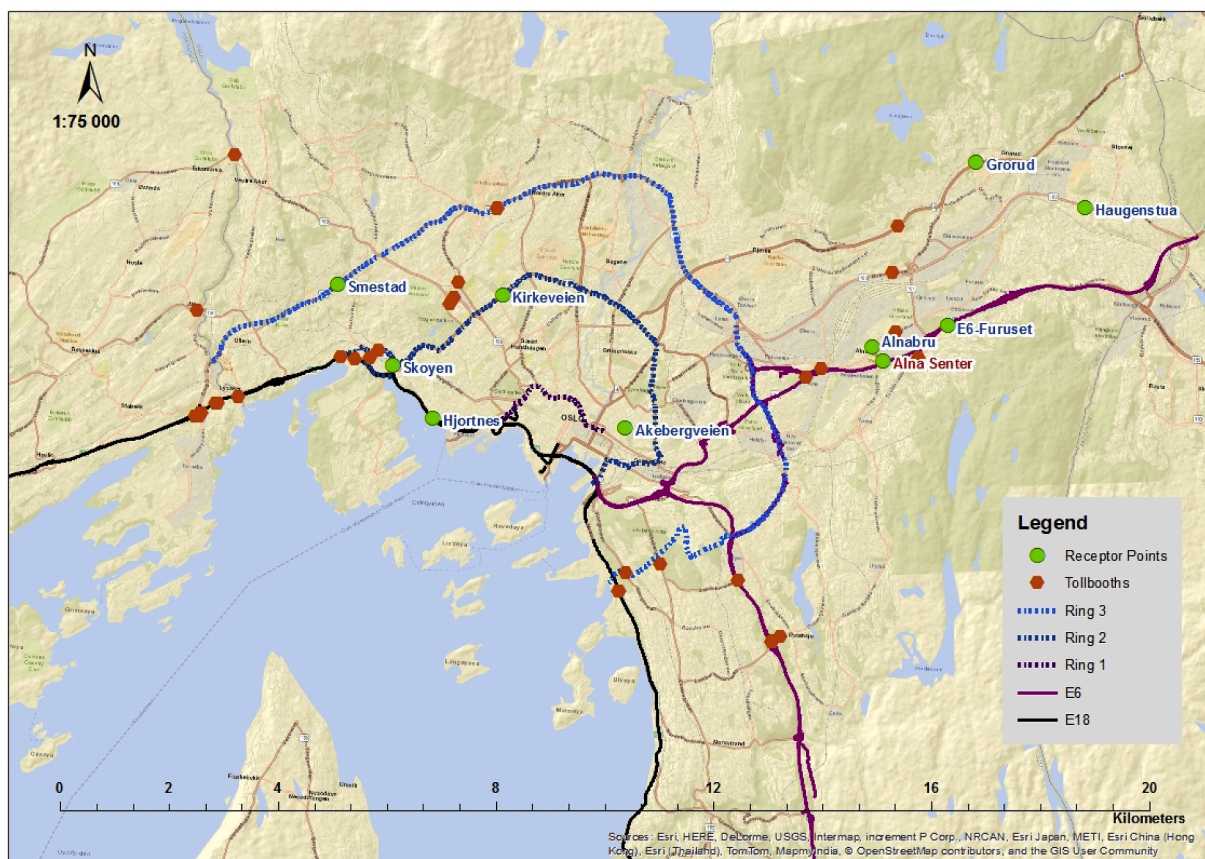
Fig. 3. Map with the indication of the most trafficked roads around Oslo city centre (highways E18, E6, and Ring 2 and Ring 3) and the location of the tollbooths. We also show the location of Ring 1, which roughly defines the city centre and the location of the receptor points used in the dispersion modelling. All shown receptor points are Air Quality stations except E6-Furuset, Grorud and Haugenstua to the East.

each permanent measure and the two groups of measures in Table 1. The number of trips to and from Oslo ("In and out EPISODE domain") changes little between the reference simulation and for each of the sensitivity simulations. The changes in traffic are more apparent within Oslo and its surroundings as encapsulated by the EPISODE domain. No changes in traffic exist for measure P6 (LEZ), because the change in this measure is regarding the technology for the circulating HDV vehicles within the LEZ.

The doubling of costs with tolls at rush hours (permanent measure P1) leads to the positive outcome of more traffic fluidity. Traffic amount decreases during rush hours in the simulation and RTM23+ assumes that 30% of the decrease is transferred to the period outside the rush hour. Such assumption is supported by studies in Bergen and Kristiansand (Ruud, 2009). Also, part of the trips do not cross the tolls and are not affected by a price change. Hence, measure P1 does not change significantly the total traffic volume and therefore the impact on NOX emissions is minimal. For this reason, this measure was not simulated with the dispersion model. Similar happens for measure P4 (double public transport in rush hours), where the increase in public transport trips does not offset the decrease in private car use (roughly +5% versus −1%).

Permanent measure P1 has little impact on the number of trips undertaken and the distance driven (Table 3) but may still be important. This is so because of changes in travel patterns like the time at which the trips are undertaken and the increase of traffic outside the area delimited by the tolls, especially East of Oslo. The toll fees necessary to implement for drivers to respond would be politically unmanageable as tolls are already very expensive in Oslo. This permanent measure would have larger impact in a city where tolls did not exist in the reference situation.

With permanent measure P2, we double the cost of tolls for the vehicles with high NOx emissions, namely diesel vehicles, which leads to a total decrease of 3.3% in NO_X emissions in EPISODE domain. Because this measure targets the most polluting vehicles it leads to higher effects than in measure P1 in terms of traffic decreases as we can assess in Tables 3 and 4. We also have higher effects on Air Quality (AQ), however as we can see in Fig. 5a, we have increases in annual concentrations in large areas and more importantly, in the problematic areas where we need to decrease concentrations (areas shaded dark blue in Fig. 4). Even if we get slight increases and decreases of traffic volumes for the total of each of the domains in Table 3, the transfer of traffic within these domains to particular roads when drivers choose to avoid the tolls, actually leads to higher emissions in these particular roads and to an increase around them in NO_2 annual mean concentrations of up to 15%.

The definition of priority lanes in order to promote modal shift (permanent measure P3) leads to a minimal effect in number of trips (Table 3) but has a more important effect on the distance driven, leading to shorter trips within and larger outside Oslo. 69% of the vehicles in circulation have no access to priority lanes. This means a decrease in

capacity for the remaining lanes, which leads to increased traffic congestion. Drivers thus choose to avoid these areas and there is an increase of travel outside the city. The total decrease in NO_X emissions is circa 2.5%. In terms of AQ, large areas show an increase of concentrations (Fig. 5b), specifically areas along main roads. In the Oslo centre road-net, decreases in NO_2 concentrations are sufficient to decrease the exposure of the population to hourly concentrations above the EU legal limit. We probably underestimate the impact of this permanent measure, as it will become apparent in the long-term with drivers avoiding the acquisition of diesel cars and choosing to buy low and zero NO_2-emission vehicles.

The most successful permanent measures are P5 and P6, that is, increasing the parking fees in the city centre and the creation of the LEZ. The most successful permanent measure in decreasing traffic in the city is measure P5 (Tables 3 and 4). The most successful measure decreasing total NOx emissions (Table 3) and decreasing NO_2 concentration levels in the city is P6 (Fig. 5 and Table 4). Extending the LEZ would extend these benefits to the suburbs of Oslo. LEZ is a measure used in a number of countries to reduce pollution (e.g.: exhaust particles and noise) in areas with high traffic (Aas et al., 2012).

Even the permanent measures with success are not sufficient to make Oslo comply with legislative demands. This is why, we did a further investigation of the impact on traffic and air quality when grouping permanent measures (Tables 3 and 4).

The values in Table 3 for Group 1 show that the restrictions imposed by the higher parking fees in the centre of Oslo reduces the traffic that the other permanent measures can affect. There is further avoidance of the city and trips that are not done at all. This has an impact in NO_2 annual concentrations within the city and along the main roads that lead there (Fig. 5c and e). For Group 2, the decrease in number of trips/day is larger than the decrease in km driven/day, which points to drivers deciding to make less trips, but drive further. Moreover, the choice of public transport is more appealing when joined with measure P3, especially in the EPISODE domain where public transport offer is better. "In and out EPISODE domain" the change in number of trips/day is small in Group 2, especially when compared with the results for the individual measures, because the increase in public transport use leads to a recovery in road capacity that is now used for other car trips.

Table 4 shows changes in the city itself, specifically at three points located at high trafficked roads. Again, we can infer the importance of the parking fees cost increase as a measure to decrease traffic in the values for Group 1 versus Group 2, the latter not including parking fees. Both Groups have a substantive effect on NO_2 ambient concentrations (Table 4 and Fig. 5e and f). This is due to the LEZ measure, which does not imply a change in traffic, only in HDV technology. However, the effect on NO_X emissions is large, because as already referred HDV represent 10% of the km driven/day in EPISODE domain in the reference simulation, but 36% of the NO_2 emissions.
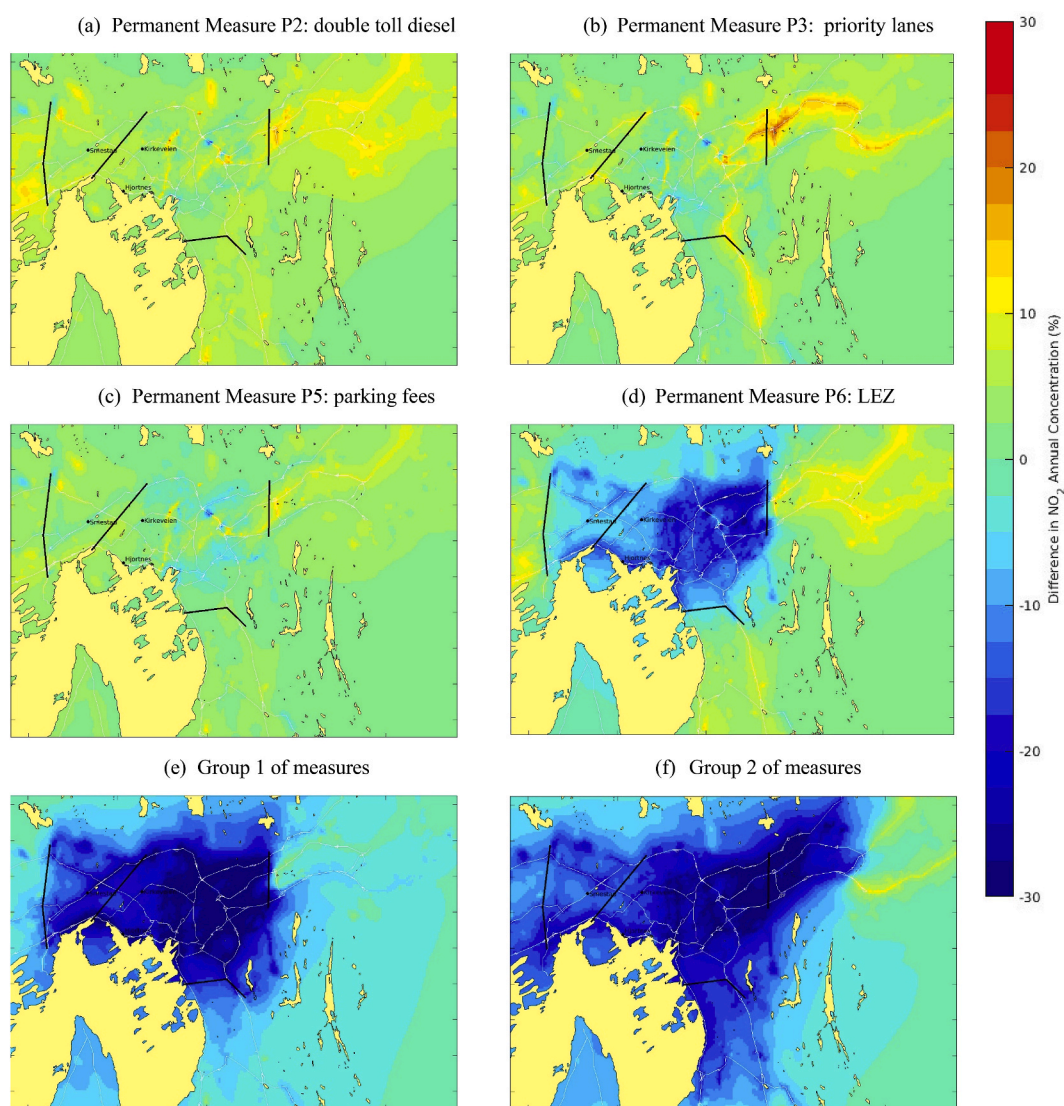
Table 3

Modelled changes in traffic (number of trips/day and length driven/day) and NO_X emissions between the reference case and the introduction of each permanent measure. Fig. 2 shows the domains.

Permanent measures	P1 double toll	P2 double toll diesel	P3 priority lanes	P4 double public transport	P5 parking fees	P6 LEZ	Group 1 measures P3 to P6	Group 2 Larger LEZ measures P3 and P4
Number of trips/day								
Total domain	−0.2%	−0.5%	−0.8%	−1.1%	−10%	–	−11%	−7.7%
EPISODE domain	−0.4%	−1.0%	−1.3%	−1.3%	−20%	–	−21%	−14%
Outside EPISODE domain	0.0%	+0.1%	+1.7%	−0.9%	+1.4%	–	+1.6%	−1.0%
In and out EPISODE domain	0.0%	−0.5%	−5.7%	−1.0%	−4.2%	–	−9.9%	+0.1%
km driven/day								
Total domain	−1.1%	−3%	−6.4%	−1.1%	−12%	–	−17%	−5.2%
NO_X emissions								
EPISODE domain	–	−3.3%	−2.5%	–	−8.6%	−24%	−41%	−48%

Table 4

Modelled changes in traffic volume and NO$_2$ annual concentrations (%) at three road points close to three Air Quality traffic stations in Oslo between reference case and the introduction of each permanent measure. Fig. 3 contains the location of the Air Quality stations and the Rings.

Permanent measures	P1 double toll	P2 double toll diesel	P3 priority lanes	P4 double public transport	P5 parking fees	P6 LEZ	Group 1 measures P3 to P6	Group 2 Larger LEZ & measures P3 and P4
Traffic volume								
Hjortnes (E18)	−3%	−7%	−9%	−1%	−13%	–	−19%	−4%
Kirkeveien (Ring 2)	−2%	−5%	−6%	−2%	−17%	–	−21%	−8%
Smestad (Ring 3)	−3%	−7%	−10%	−1%	−13%	–	−20%	−3%
NO$_2$ annual concentration								
Hjortnes (E18)	–	−3%	−6%	–	−5%	−21%	−32%	−28%
Kirkeveien (Ring 2)	–	−2%	−6%	–	−5%	−20%	−32%	−28%
Smestad (Ring 3)	–	−5%	+1%	–	−7%	−17%	−33%	−19%

(a) Permanent Measure P2: double toll diesel

(b) Permanent Measure P3: priority lanes

(c) Permanent Measure P5: parking fees

(d) Permanent Measure P6: LEZ

(e) Group 1 of measures

(f) Group 2 of measures

Fig. 5. Percent differences in NO2 annual concentrations between EPISODE simulations of permanent measures and the reference case at Oslo and its surroundings. Black lines represent the limits of the tollbooths (for an exact location of the tollbooths see Fig. 3).

3.2. Results from temporary measures

Fig. 6 shows the changes in the mean hourly NO$_2$ concentrations calculated for a winter week between the reference case and each of the temporary measures. We show the changes for selected points in the EPISODE domain that are locations of AQ stations and three points outside the area defined by the existing toll system in 2013 (Fig. 3). The latter are E6-Furuset, Grorud, and Haugenstua. Skøyen is an urban background station. Alnabru and Åkebergveien are traffic stations not located close to high traffic roads. Smestad, Hjortnes, and Kirkeveien are located by main arteries.

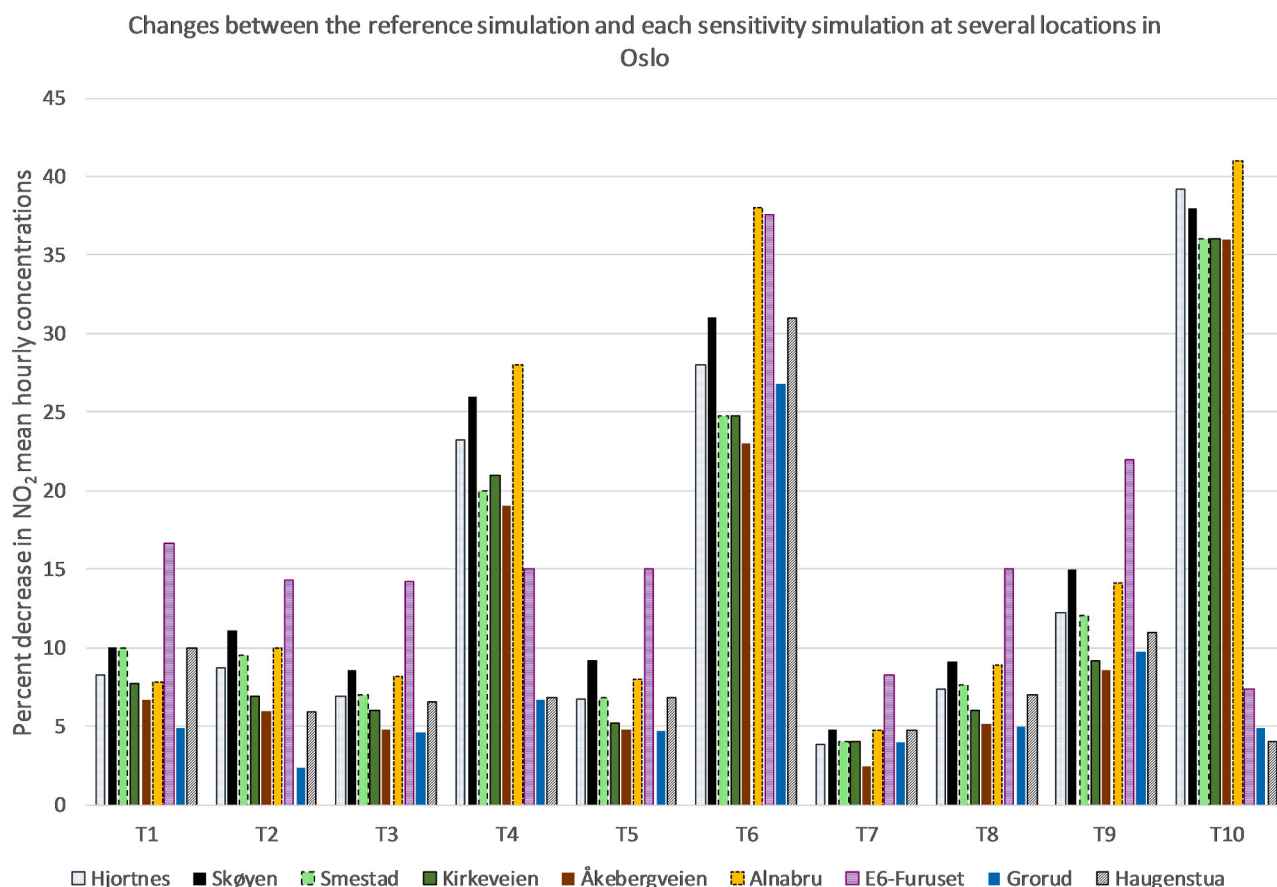We get a reduction in NO$_2$ concentrations for all of the temporary

Fig. 6. Changes in mean NO_2 hourly concentrations (%) in nine locations in Oslo (locations in Fig. 3) between the reference simulation in 2013 and each of the simulations with temporary measures (Table 2). Period of calculation: 30th January to 8th February 2013.

measures tested. The measures more effective in decreasing NO_2 levels include some kind of ban on diesel vehicles (T4, T6, T10). With these measures, the reduction in traffic volume in downtown areas is high, provided that the prohibition is highly complied.

The increase of toll prices does not have a high effect on pollution levels (average decrease in NO_2 concentration of around 8%) or even traffic volume. It only decreases traffic volume passing through the tollbooths, while traffic volume increases in and outside the toll-ring. Only measure T9 shows a decrease in traffic volume in the city proper. The concept of a second layer of tollbooths only gives small improvements in the area between the existing and the conceptual toll systems. This is explained because the 10 times increase of prices in the existing toll system is already high and therefore the extra payment has little effect.

The panoply of experiments let us conclude that the ban of only diesel passenger vehicles is per se not a sufficient measure (NO_2 air concentrations decrease by roughly 13%). This is an important conclusion for the authorities in Oslo, who desire to affect minimally the transport of goods. The addition of HDV with technology older than Euro VI to the ban is effective in decreasing pollution levels, which is a reflection of emissions from heavy traffic being 36% of the traffic emissions total in the reference case while being 10% of the traffic volume.

There is little difference between temporary measures T2 and T3, that is, introducing the 10-times increase of toll prices for all vehicles or only for diesel passenger vehicles. This is mainly because the traffic model only calculates changes in route choice for freight, not including effects on demand. In this way, freight trips passing through the tollbooths are taking place regardless of the toll price. There is no

independent assessment of freight model in this project, but it is believed that commercial transport will have a relatively high willingness to pay, so that the reduction in traffic volume passing the tolls will be low.

The effect of odd-even driving is of the same magnitude as a 10-times increase in toll rates for diesel vehicles despite the fact that the measure is not targeted towards vehicles with high NOx emissions. This is because in measure T1 it is assumed that the odd-even driving applies to the entire municipality. The measure affects thereby a larger area than in most other examples considered here, providing a traffic volume reduction as a whole greater than for the other temporary measures.

Free public transportation had very little effect on traffic volume, as the main mode change occur for the bikers and the walkers, not the drivers.

4. Air quality control policies in Oslo

The consequent challenge after identifying measures that will have the intended effect on the levels of pollution is the political and economic difficulties of applying the measures on the ground. In Norway, the political decisions regarding the different measures fall under the central government prerogative and under the district/city responsibility and power. The change of toll pricing had to go to a parliamentary vote and differentiation of prices between vehicles demanded changes in regulations. The only toll pricing measure that was under the responsibility of the municipalities was the discrimination between rush hours and other hours of the day. Parking pricing was also under the city control and it is a very good tool for traffic regulation. Hjorthol et al. (2014) showed that availability/cost of parking close to work has an indirect correlation with use of public transport (instead of

private car). Measures relative to public transport is under the district power of action, but involves large budgeting options that lead this measure to be also under the central government decision umbrella.

The pressure on Norwegian authorities by the EFTA court judgement put pressure for political decisions. In May 20, 2015 (Oslo City Council item number 116/15), the Oslo City Council adopted an Air Quality Action Plan, where the most important intended actions affecting NO_2 concentrations were: (1) introduction of toll fees discriminating between vehicles with different pollution potential (the environmentally differentiated fees) and the time of the day; (2) increase of public transport offer in Oslo; (3) decrease of the legal speed on the main roads in winter time (targeting road dust production by studded tyres).

In our study, the most effective measure in controlling NO_2 pollution involved the creation of an LEZ. A Regulation on LEZ was adopted by the Ministry of Transport and Communications in December 2016 with a release in the following February of a guidebook by the NPRA (NPRA, 2017). The purpose of the regulation is to provide the framework for introducing, managing, controlling and enforcing municipal LEZ established to improve air quality in an area exposed to local air pollution from vehicles. The regulation gives the municipalities the opportunity to determine the fee, zone size and define exceptions. In this context, the LEZ is a permanent measure. By March 2016, the Department of Environment and Transport of the Oslo Municipality had already requested the Agency for Urban Environment a study to analyse possible LEZs that would fulfil the main AQ goal. This analysis involved members of our team for the AQ simulations and resulted in OKB (2016). This document, the local regulations draft and comments to the latter by NPRA were for public consultation in the summer of 2017. From this process, it was decided a LEZ covering all the municipality of Oslo, in which a fee would have to be paid by HDV.

A change in traffic legislation was realized by the Norwegian Government in 2017[2] which made it possible for environmentally differentiated toll fees. Since then, there were updates to the AutoPASS system to allow the automatization of such measures.[3] The AutoPASS system will also allow for a comprehensive overview of the fleet composition, which then can be used in readjustments of toll pricing.

Oslo started with environmentally differentiated toll fees in October 1st, 2017. In this system of tolls, vehicles started paying different prices depending on the fuel type, the EURO standard, the type of car (heavy-duty, light) and time of day (rush hour, not rush hour). The price for diesel vehicle was set to 59 NOK which is about double the price in 2013, quite similar to our permanent measure 2. However, in implementation also petrol vehicles pay a larger fee, but less than diesel. One can get a discount if the vehicle is equipped with an AutoPASS-tag. Electric vehicles could pass for free. The authorities view this as the path to a faster replacement of polluting diesel vehicles[4] by zero emission vehicles and less traffic at rush hours. By 2019, the share of electric vehicles in new vehicle sales was circa 42% in Norway.[5] Electric vehicles will start to pay a small amount by 2020. Oslo Municipality also proposed a LEZ for HDV only allowing Euro VI. It was planned for the winter 2017/2018, but was postponed. It is now likely that it will not be implemented. For every year passing the amount of Euro VI trucks in the fleet is increasing, and a LEZ would have less effect.

Oslo Municipality governing coalition wants to proceed to a so-called "city-living without cars".[6] This plan was already in their original proposals when the coalition took office in 2015. The area defined is slightly smaller than the area delimited by Ring 1 (Fig. 3). In 2017, around 350 street parking spaces were removed in this area and further work continues in 2019. The removal is opening spaces that the Oslo Municipality wants to use for biking lanes, playgrounds, green areas, benches and for outdoor ludic activities.

In the actions of the Norwegian authorities, we observe compromise in policies that limit the use of vehicles and the avoidance of prohibition. The "city-living without cars" zone is not closed to traffic, but the traffic is limited by the decrease in parking spaces. Also promoting low emission is national regulation which removes taxes on electric vehicles making them an economically competitive choice for most users. The incentives for battery electric vehicles are the reason for the high fraction of electric vehicles in the Norwegian fleet today.

Our study showed that actions on the tollbooths were not efficient. One of the reasons for this is that the distribution of tollbooths around the city (Fig. 3) allow extensive driving within the city without the driver having to pass any tollbooth (three trips in four). Therefore, emissions in the city do not decrease. However, there is another issue of social nature: the burden of actions on tolbooths do not affect equally the drivers responsible for the emissions in Oslo. In this way, the study COWI (2017) was commissioned to analyse, among other points, a new distribution of the tollbooths that would allow for a fairer distribution of the financial burden, that is, a larger fraction of drivers polluting Oslo city centre pay for it. With the new devised toll system, COWI (2017) estimated a 11% decrease in km-driven in Oslo in 2020 compared with an estimate for the same year with the old toll system. The change was implemented in 2019, including a system of 83 toll crossing points in a 3-ring system and is expected to keep the pressure for a cleaner vehicle fleet and overall limit traffic volumes. Such environmentally differentiated toll system can be considered as a form of LEZ.

Other finding in this study was the ineffectiveness of free public transport as a temporary measure to decrease traffic volumes. This is corroborated by Fearnley (2013). Moreover, there was the concern from the public transport company for Oslo and Akershus (Ruter #) that days with free public transport could be perceived as problematic by those who use public transport on a daily basis as they buy month or year passes. In this way, the citizens that do not contribute to the pollution receive no benefit with such a measure but those who normally use their cars and contribute to the pollution might. To readdress this, there should be some refunding also for pass holders, which might be very costly.

The Environmental Ministry ordered the Oslo City Council to prepare another Air Quality Action Plan that would substitute the one of 2015. The reason for this demand was because as stated in the Oslo City Council case number 18/00225-2 (January 30, 2018), the estimates done of the effects of the Air Quality Action Plan adopted in 2015 did not show that it would lead to the compliance of the regulatory NO_2 limits. Today, this is verified from observations (Fig. 7) even if levels are closer to the limit than before. In this way, a new proposal was presented by the Oslo Council in case number 18/00225-2 containing a revised Air Quality Action Plan intended to replace the one in 2015. In this document, the continuation of the measures already implemented is supported and additional measures were proposed. The latter ones that affect NO_2 concentrations in Oslo are focused on incentivizing further low and zero-emission vehicles and on the implementation of charging infrastructures for boats and ships at the Oslo Port (which is located at the city centre).

Also in case number 18/00225-2, it is defined that when it is forecasted a high pollution event lasting longer than 2 days and covering a large geographical area temporary measures to implement include the ban of diesel vehicles with technology older than Euro 6/VI in the city, increased fees at tollbooths for the referred vehicles, and free and more frequent public transport offer.

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[2] cf. Prop. 82 L (2016–2017) Changes in Road Law and Road Traffic Act (urban traffic jams).

[3] Electronic system at tolls for the automatic collection of fees from the vehicle owners.

[4] https://www.vegvesen.no/om+statens+vegvesen/presse/nyheter/nasjonal t/regelverk-for-lavutslippssoner (Last accessed on August 2, 2019).

[5] https://elbil.no/elbilstatistikk/.

[6] https://www.oslo.kommune.no/politikk-og-administrasjon/slik-bygger-vi -oslo/bilfritt-byliv/(Last accessed on August 2, 2019).
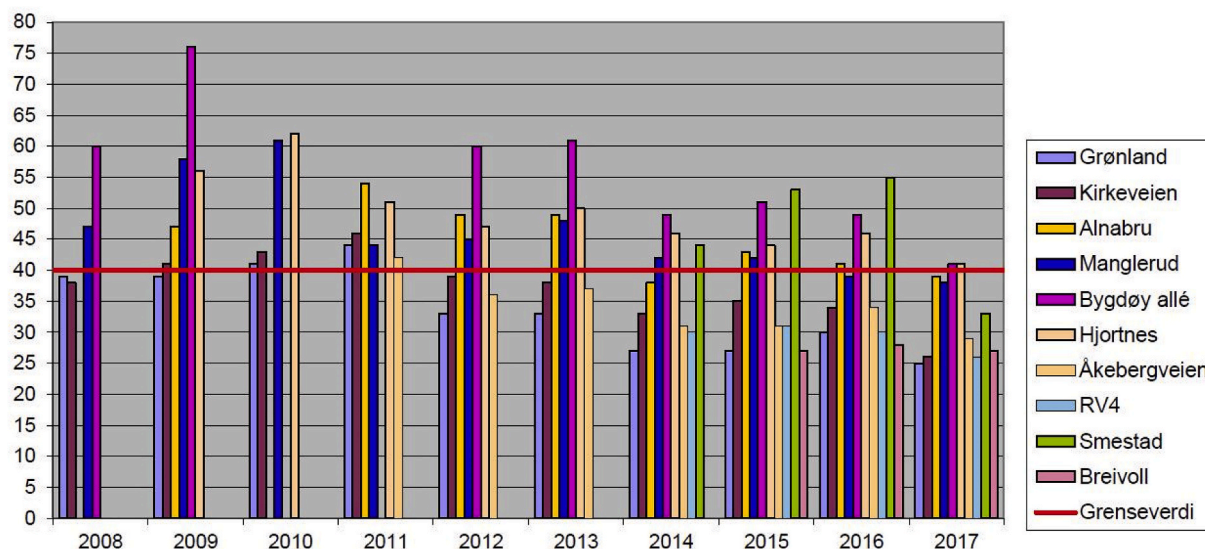
Fig. 7. Annual averages of NO$_2$ concentrations ($\mu g/m^3$) in several Air Quality stations in Oslo from 2008 to 2017. The red horizontal line is the legal limit in AQD (2008). Figure taken from Løseth (2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Conclusions

This article presents a quantified evaluation of different traffic control measures to reduce NO$_2$ concentrations in the Oslo area. The measures have been compared to each other and ranked according to a common methodology based on a suite of traffic, emission and dispersion models. The main findings are:

1) The most effective permanent measure to decrease NO$_2$ air concentrations was the creation of a LEZ.
2) The second most effective permanent measure was to increase parking fees in the city centre. Parking fees were effective in decreasing traffic into the city and therefore also emissions and NO$_2$ annual concentrations in the city.
3) All other permanent measures were not considered effective in lowering the NO$_2$ annual means.
4) To avoid peak NO$_2$ hourly concentrations the most effective temporary measure was a ban of diesel vehicles.
5) No individual measure was sufficient to comply with legislative demands.
6) The grouping of measures does not give a cumulative effect of the individual measures.
7) To comply with the legislative European limits the necessary decrease in NOx emissions has to be large in Oslo region. In our study, a reduction in 48% relative to the emissions of 2013 was not sufficient.

Even if the selected measures on public transport were ineffective, other possible measures on public transport could be considered. Limiting the private vehicles transit by offering an improved public alternative to commuters can be used as a political leaver to make restrictions more acceptable. Moreover, this and other measures targeting modal shift will probably show its positive effects in the long-term by cementing changes in behaviour. The increase of public transport frequency will decrease crowding, standing on board, time spend waiting for a transport and in this way make public transportation a more acceptable way of travel.

The implementation of control measures demanded agreement across several political parties and required revision of legislation at different governance levels. The toll system in Norway is negotiated in relation to both toll revenues for financing larger road construction projects as well as public transport projects. The costs of the

implementation of the measures are also an important aspect in the negotiations. The effectiveness in reducing air pollution was hence only one of several considerations in the process of deciding upon different measures. Our results in air quality showed that the limit values were not reached and were used as an argument for rather strict measures. The results were actively used in forming the measures finally implemented and also to gain support by the public.

The results in this paper are specific for the city of Oslo but the methodology and approaches used are applicable to other cities to help identify effective traffic control measures to combat NO$_2$ pollution.

CRediT authorship contribution statement

G. Sousa Santos: Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **I. Sundvor:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing - review & editing. **M. Vogt:** Visualization. **H. Grythe:** Writing - review & editing. **T.W. Haug:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing - review & editing. **B.A. Høiskar:** Conceptualization, Project administration, Funding acquisition. **L. Tarrason:** Conceptualization, Supervision, Funding acquisition, Writing - review & editing.

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