



Costs and benefits of implementing an Environmental Speed Limit in a Nordic city



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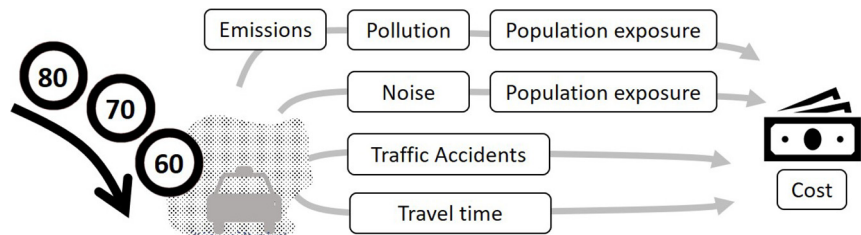
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HIGHLIGHTS

- The implementation of Environmental Speed Limit to reduced PM_{10} levels is evaluated.
- This measure has low to negligible effects on emissions of $PM_{2.5}$, NO_x and CO_2 .
- PM_{10} emissions are reduced by 6–12% and concentration levels reduce by up to 8%.
- Reduction in population exposure and noise convey a net reduction of cost to society.
- The reduction of speed entails a delay to travel journeys with high associated cost.

GRAPHICAL ABSTRACT



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ABSTRACT

We present a comprehensive study on the impacts and associated changes in costs resulting from the implementation of Environmental Speed Limits (ESLs), as a measure to reduce PM_{10} and associated health effects. We present detailed modelled emissions (i.e., CO_2 , NO_x , $PM_{2.5}$ and PM_{10}), concentration levels (i.e., $PM_{2.5}$ and PM_{10}) and population exposure to $PM_{2.5}$ and PM_{10} under three scenarios of ESL implementation for the Metropolitan Area of Oslo. We find that whilst emissions of NO_x and CO_2 do not seem to show significant changes with ESL implementation, PM_{10} emissions are reduced by 6–12% and annual concentration levels are reduced up to 8%, with a subsequent reduction in population exposure. The modelled data is used to carry out a detailed analysis to quantify the changes in private and social costs for the roads in Oslo where ESL are implemented today. This involves assessments related to human health, climate, fuel consumption, time losses and the incidence of traffic accidents. For a scenario using actual speed data from ESL implementation, our study shows a net benefit associated with the implementation of ESLs, whilst for a theoretical scenario with strict speed limit compliance we find a net increase in costs. This is largely due to variation in costs due to time losses between the scenarios, although uncertainties are high.

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1. Introduction

In Oslo, there is extensive winter use of studded tyres that greatly enhances road wear and particle emissions from road traffic. In addition, local climatic and geographical factors make extended periods of inversions likely. Both of these are factors contributing to enhanced pollution

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levels, which result in exceedances of legal limits of particulate matter (*PM*). Authorities are thereby required to implement strategies to limit air pollution to within legal limits. Different policy strategies to reduce local air pollution are implemented, i.e., electrification of the port, shore-power for frequent international ferries, economic incentives to switch to cleaner residential heating installations, a wide range of policy instruments for electric vehicles, fees for the use of studded tyres and, the focus of this study, the implementation of Environmental Speed Limits (ESL) during winter. Maximum (signed) speed limits have been implemented primarily as a traffic safety measure to reduce the number of accidents. In the last decade, maximum speed limits of specific roads have also been reduced to lower the environmental impact of traffic noise and emissions in several European capitals. In Oslo, since 2004, the Norwegian Road Administration has implemented ESLs on certain roads in an attempt to reduce the production and dispersion of non-exhaust *PM*. The ESLs were originally limited to one road in a pilot study (RV4; Fig. 1), but have since been expanded. New ESLs were introduced in 2006 (Ring 3; Fig. 1) and in 2007 (E18; Fig. 1). These roads are considered main arterial roads that experience high traffic volume due to people commuting from residences in the city outskirts to work in the city centre. For these roads, maximum speed limits were originally reduced from 80 to 60 km h⁻¹ during the winter season (i.e., November 1st to April), when studded tyres are allowed due to winter meteorological conditions and slippery road surfaces. In 2012, the ESL was revoked and the signed speed limits set to 70 or 80 km h⁻¹ all year. In 2016, the winter ESL was re-implemented to 60 km h⁻¹, whilst retaining the summer speed limit of 70 km h⁻¹ or 80 km h⁻¹.

Reducing speed is associated with reductions of both exhaust and non-exhaust *PM* emissions. Exhaust or tailpipe emissions are reported to be reduced due to improved driving efficiency, whilst non-exhaust emissions are lowered due to the reduction in wearing processes (e.g., tyre, break and road wear) and a decrease of suspension of deposited particles. However, the real effect on emission reduction of different

compounds (i.e., CO₂, NO_x, *PM*) and on population exposure is still controversial. The dependencies between speed and emissions vary for different pollutants, meaning that reducing speed may have a differing effect on different compounds. For instance, NO_x and CO can have “U-shaped” emission curves as a function of speed with minimum emissions between 60 and 80 km h⁻¹ (Kousoulidou et al., 2010), whereas *PM* exhaust emissions do not seem to be much affected by speed. In contrast, modelled non-exhaust *PM* increases linearly with speed (Denby and Sundvor, 2012b; Denby et al., 2013). Meteorology additionally plays an important role on the pollution concentrations and emissions, e.g., dispersion is influenced by stability conditions and wind speed, and precipitation leads to wet roads that enhance particle retention.

Studies published in the literature on the effects of reducing the maximum speed limit on emissions and pollutant concentration levels show a wide range of results. This reflects an uncertainty that may be related to variations in the methodology and scope of the studies. Most studies address reductions of the maximum speed limit from 120 or 110 to 80 km h⁻¹ in motorways (Bel and Rosell, 2013; Keuken et al., 2010; Dijkema et al., 2008; Gonçalves et al., 2008; Keller et al., 2008; Baldasano et al., 2010), whereas fewer studies focus on lower speeds in urban areas with speeds reduced from 50 to 30 km h⁻¹ (Madireddy et al., 2011). The methodologies used to evaluate the potential effects of implementing ESL are also different, using e.g., statistical approaches (Bel and Rosell, 2013), evaluation of air quality monitoring data (Dijkema et al., 2008) or assessments based on atmospheric dispersion modelling (Gonçalves et al., 2008; Baldasano et al., 2010). Panis et al. (2011) pointed out the discrepancies obtained when using macroscopic or microscopic traffic emission models to assess the effects of reducing speed limits on *PM*, NO_x and CO₂ emissions. Minor changes were obtained for NO_x and CO₂ emissions when using both methods. However, the authors obtained a moderate increase of *PM* emissions when using macroscopic traffic emission models, compared to a significant decrease when the evaluation is based on

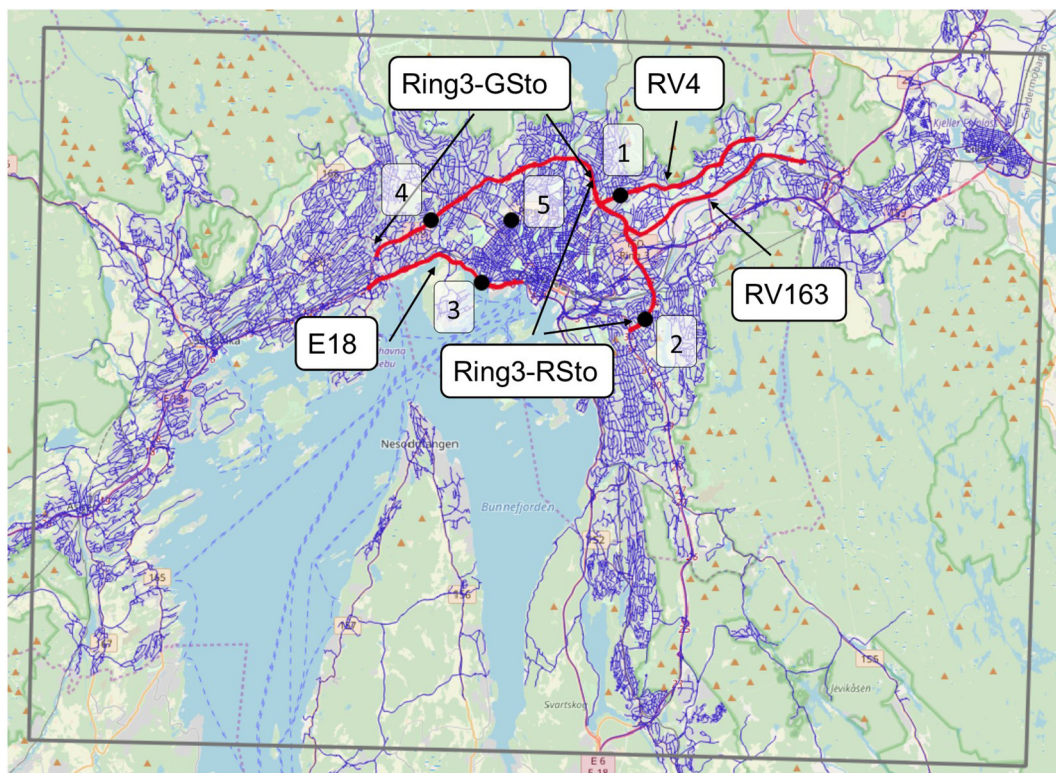


Fig. 1. Locations of the roads where the ESLs are implemented in winter time (red roads). The blue roads represent the complete traffic network in Oslo Metropolitan Area. The square represents the domain for the atmospheric dispersion model. The black dots and corresponding numbers represent the monitoring stations in Fig. 5 (1: RV4, 2: Manglerud, 3: Hjortnes, 4: Smestad, 5: Kirkeveien). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

microscopic models. Studies have also been conducted previously in the Oslo metropolitan area. One showed that the pilot ESL implementation in 2004 decreased PM_{10} and NO_x levels by 35–40% and 12–13%, respectively (Hagen et al., 2005). Since that time, other studies have shown that reducing vehicle speed on specific roads in Oslo from 80 or 70 km h^{-1} to 60 km h^{-1} would reduce the number of exceedances of the PM_{10} daily limit value (i.e., $>50 \mu g m^{-3}$) by 2 to 6 days, and the PM_{10} annual limit value by 0.5–1.5 $\mu g m^{-3}$ (Denby and Sundvor, 2012a).

A main aspect to take into account when analysing the effectiveness of speed reduction measures is any reduction in population exposure to high pollution levels, the subsequent health improvements and the resulting changes in costs to society. Other benefits of lowering the speed limit that should be accounted for are reductions in the number of accidents and noise. Baldasano et al. (2010) established that the reduction of primary pollutants as a result of reducing the speed limit from 120/110 to 80 km h^{-1} would improve the health and welfare of over 41% of the population of the Barcelona Metropolitan Area. Studies quantifying the relationship between vehicle speed and accident risk generally find that the higher the speed the steeper the increase in accident risk (Nilsson, 1982; Nilsson et al., 2004; Kloeden et al., 2002; Elvik, 2019). In addition, road complexity factors (e.g., the number and type of intersections) increase accident risk (Taylor et al., 2000). A power model describing the relationship between changes in speed and changes in the number of accidents, and accounting for varying levels of initial speed and road types has been established by Elvik (2009, 2014, 2019), along with a model that describes the specific effects of ESLs on the number of accidents (Elvik, 2013). The latter study finds that the number of injury accidents with ESL implementation in Oslo is reduced by about 25–35% according to all study designs.

Cost-benefit analysis is a systematic approach to account for all effects together (normalised in terms of resulting monetary costs) allowing the strengths and weaknesses of alternatives to be estimated, and has been long applied to determine the favourability of e.g. transport infrastructure (Hyard, 2012), pollution mitigation options (Voorhees et al., 2000) and specific changes to speed limits (Cetin et al., 2018; Morichi et al., 2005; Forester et al., 1984; Kamerud, 1983). It has also been applied previously specifically to investigate ESLs in Norway (NOEPA, 2014; Westby and Folgerø, 2017). This analysis accounted for changes in air quality, time delays associated with lowering speed limit, accidents and other externalities. Whilst Westby and Folgerø (2017) found no socio-economic benefit in Oslo, NOEPA (2014) found that reducing the speed limit has no socio-economic benefit in Bergen and Trondheim, but an associated socio-economic benefit in Oslo. The reason for the different outcomes in NOEPA (2014) is the location of the roads where the ESL was implemented. In Oslo, the roads are located in urban areas and close to areas of high population density, whereas in Bergen and Trondheim, the targeted roads were located in the surrounding areas, meaning that the measures had a low effect on population exposure.

The aim of this article is to establish the impacts, and associated changes to costs, related to the implementation of ESLs in Oslo as a measure to reduced PM_{10} levels. The study will act as support to decide upon the further implementation of ESLs. We first present detailed emissions (i.e., CO_2 , NO_x , $PM_{2.5}$ and PM_{10}), concentration levels from dispersion modelling (i.e., $PM_{2.5}$ and PM_{10}) and population exposure to $PM_{2.5}$ and PM_{10} under three scenarios: 1) the ESL is not implemented (baseline scenario) and observed vehicle speeds are used, 2) the ESL is implemented and we use observed vehicle speed as input data, and 3) the ESL is implemented and we assume full speed limit compliance. We then use the modelled data (and/or vehicle speed/road data) to perform a cost-benefit analysis to quantify the net changes in costs for the roads in Oslo where ESL is implemented today. This involves assessing the costs related to changes in human health, the climate, time losses, incidence of accidents and fuel consumption with reduced speed. Our study thus provides a comprehensive evaluation of the potential effects of implementing ESLs in Oslo.

2. Methodology

2.1. The Environmental Speed Limit

During the Norwegian winter season when drivers are permitted to use studded tyres (i.e., November to April), an ESL is implemented in four main roads in the Oslo metropolitan area and the signed speed limit is reduced (Fig. 1). For the summer season, when studded tyres are not permitted (i.e., April to October), the ESL is lifted.

Fig. 2 shows hourly mean traffic volume (top) and speed (bottom) in 2010 and 2012 from a traffic counting station at Manglerud, a road where the ESL is implemented (Ring3 - RSto, in Fig. 1). In 2010, the summer speed sign was 80 km h^{-1} , whereas in winter (i.e., January to April and November to December), the ESL was implemented reducing the speed sign to 60 km h^{-1} . In 2012, the ESL was revoked, and the speed limit was 70 km h^{-1} the whole year. Taking into account that the ESL period is shorter than the non-ESL period, the year 2010 had a lower average speed than 2012. The mean traffic volume is obtained from the sum of the traffic going inwards and outwards from the city, and the mean speed corresponds to the mean of all lanes, both in and out. Both years have approximately the same traffic volume.

Both 2010 and 2012 have a similar diurnal cycle in annual average traffic speed and volume (Fig. 2 left). The reduction in speed to well below 60 km h^{-1} at morning and evening rush hours indicates that the high traffic volume (at these times) is a major contributing factor towards hourly speed. The peak in speed (and corresponding drop in traffic volume) in July (Fig. 2, middle) corresponds to the national summer holiday; since there is no rush hour and associated congestion, during this month, the speed and volume of traffic resembles a typical weekend (Fig. 2, right). In the ESL months, the monthly speed is higher in 2012 (without ESL) than in 2010 (with ESL). The decrease in speed during winter months in 2012 compared to summer months can be considered as a natural effect of worsening driving conditions during winter with icy and snowy roads. In the scenarios made in this study the traffic volume for all roads are assumed unaffected by the speed change. Speed is assumed to change between scenarios equally at all times. As a consequence of this assumption, the average scenario speed is treated as the signed speed limit.

2.2. The scenarios

To evaluate the potential effects of implementing the ESL, we selected three different scenarios to represent the implementation of the ESL and the compliance by drivers to them (Table 1);

- Scenario 1; observed traffic speed for 2013 when the ESL was not implemented (Baseline Scenario).
- Scenario 2; observed traffic speed represents how drivers actually comply with the ESL.
- Scenario 3; this scenario assumes drivers fully comply with the ESL.

Table 1 shows the signed speed (SS) and observed averaged speed (RS) in winter (W) and summer (S) 2017 for the four roads where the ESL is implemented, and the three scenarios. For two of these roads, the input data have been additionally split. The Ring 3 road is split into two different stretches (i.e., RSto and StoG), as traffic measurements shows different vehicle average speeds for each stretch. Additionally the E18 road is split in two based on temporal variations, since the ESL in winter season is only implemented during day time and lifted during night time and weekends by the use of automatic traffic signs.

Scenario 2 represents the real situation based on average observed speed from hourly traffic counting stations. This scenario shows that the actual vehicle speed reduction from the summer season (without ESL) to the winter season (with ESL) varies among the roads, from a

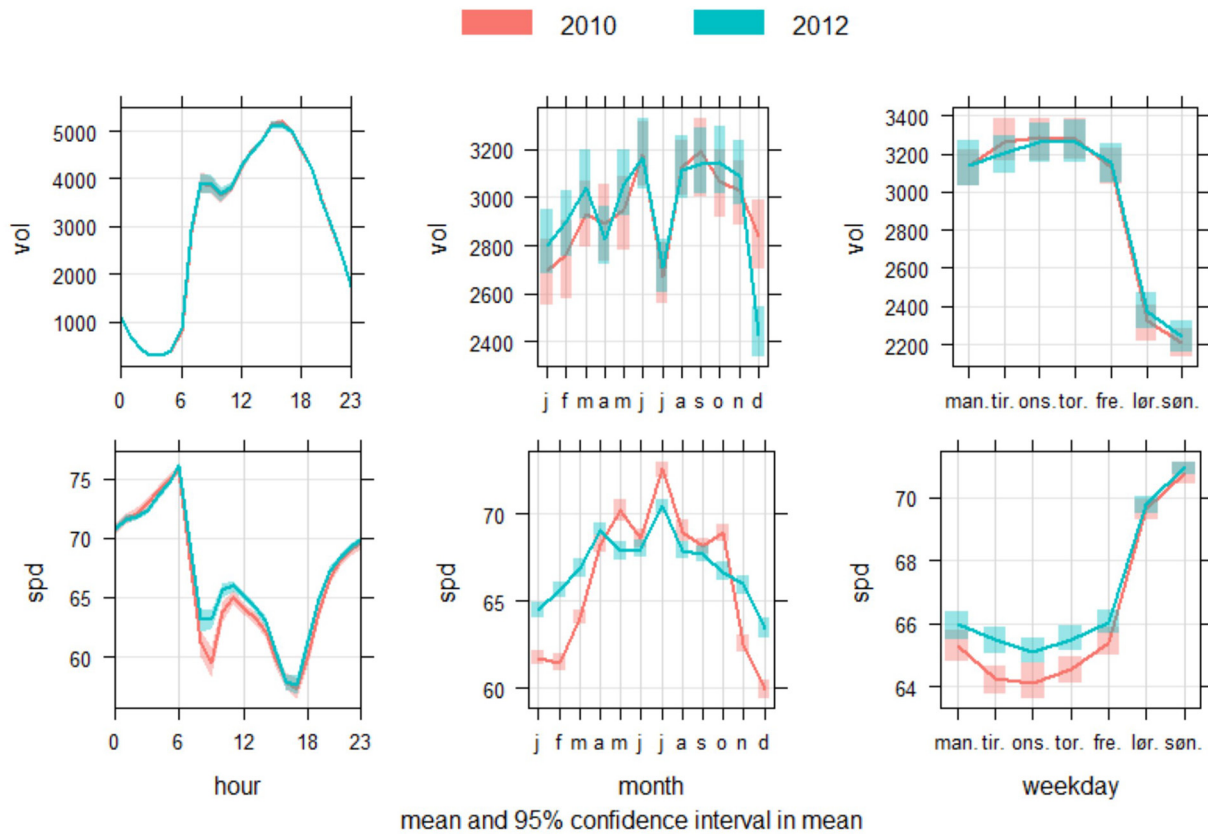


Fig. 2. Hourly traffic volume (top) and mean speed per hour of the day (left), month (middle) and the day of the week (right) for the years 2010 and 2012.

4.97% speed reduction on the E18 (day time) to speed reductions of 7.05% and 10.45% on the RV4 and RV163, respectively. The observed vehicle speed shows that drivers generally comply with the traffic speed signs when they are set at high speed (e.g., 70 or 80 km h⁻¹), whereas they do not comply with speed limits set at 60 km h⁻¹, instead driving up to 20% faster (Table 1). This is also a consequence of the lack of ESL reinforcement by authorities with speed cameras or police controls, making the compliance with the speed limit relatively low.

2.3. Emission inventory

To model total atmospheric concentrations of pollutants, all sources must be considered. A complete emission inventory for the study area (Fig. 1) was used as input for the atmospheric dispersion model. The model setup applied for most emissions in the Oslo area is validated and tested in several studies (Høiskar et al., 2014; Grythe et al., 2019; Tarrasón et al., 2018; Høiskar et al., 2017).

We base our study on the meteorological year 2013 as it is considered the worst case scenario regarding PM pollution levels in the area

of Oslo. During 2013, PM₁₀ daily concentrations exceeded >50 µg m⁻³ for more than 35 days at several measurement stations in Oslo, the limit number of days established by European Air Quality Directive. These exceedences were mainly in spring and occurred on days with large road dust emissions. Emissions for the year 2013 are generally estimated from high resolution input data, that thereafter are aggregated to a 1 km grid, and combined with time variation functions to result in emissions at 1 km² h⁻¹ resolution. The main contributing sectors to PM and NO_x emission and pollution levels aside from traffic are residential wood combustion (RWC), shipping and off-road machinery.

The emissions in 2013 from RWC, off-road machinery and shipping are shown in Table 2. RWC is an important contributing source to PM, whereas shipping and off-road machinery mainly contribute to NO_x emissions. Emissions of PM_{2.5} and PM₁₀ from RWC (Table 2) were estimated using the MetVed model (Grythe et al., 2019), based on the wood burning potential at a 250 m grid. Emissions from shipping were estimated following a bottom-up approach based on the port activity registering system (López-Aparicio et al., 2017). Emissions from non-road mobile machinery in construction, industry and residence were originally produced by Statistics Norway, spatially distributed at

Table 1

Vehicle speeds on individual roads where ESLs are applied for each of the Scenarios. Signed speed limit (SS; km h⁻¹) and average observed speeds (RS; km h⁻¹) during the studded tyre season (W; Nov - April) and outside the studded tyre season (S; May - Oct). WE refers to weekends.

Road	SS (W)			SS (S)	
	Sc1 - Sc2 - Sc3	RW (W) Sc1 - Sc2 - Sc3	Sc1-3	RS (S) Sc1-3	
RV4	70 - 60 - 60	74.3 - 69.9 - 60.0	70	75.2	
Ring3 - RSto	70 - 60 - 60	69.9 - 65.4 - 60.0	70	69.9	
Ring3 - StoG	70 - 60 - 60	64.3 - 62.1 - 60.0	70	64.3	
E18 - day	80 - 60 - 60	75.0 - 72.6 - 60.0	80	76.4	
E18 - night and WE	80 - 80 - 60	75.0 - 75.0 - 75.0	80	76.4	
RV163	80 - 60 - 60	80.8 - 72.8 - 60.0	80	81.3	

Table 2

Sectoral emissions of PM_{2.5}, PM₁₀, NO_x and CO₂. Units: t yr⁻¹ for all components except CO₂ which is expressed in kt yr⁻¹. N/R: not relevant. N/A: not available.

Sector	PM _{2.5}	PM ₁₀	NO _x	CO ₂
Residential wood combustion	872.20	872.20	N/R	N/R
Shipping and port activities	18.03	18.03	759.37	56.30
Other sectors (e.g., off-road machinery)	36.33	36.33	733.49	N/A
Traffic emissions non ESL-roads	107	875	N/A	N/A
Traffic emissions ESL-roads (Scenario 1)	9.35	84.34	393.54	101.35
Traffic emissions ESL-roads (Scenario 2)	9.16	80.51	393.84	101.67
Traffic emissions ESL-roads (Scenario 3)	8.78	73.85	400.85	101.50

district level and thereafter gridded at 1 km resolution and updated based on fuel sales or land use changes (Sundvor, 2014).

Traffic volume and numbers on individual road links were simulated by the regional road traffic model RTM23+ (Rekdal and Larsen, 2008), a version of the Norwegian Regional Transport Model, especially adapted for the Oslo area. From this model annual average daily traffic (ADT) in 2013 was derived on each road link separately for light and heavy vehicles. Emissions for each road segment were calculated on an hourly basis, using the time variations from hourly vehicle numbers and speeds, where speed was scaled to each scenario. Emission factors are then interpolated to the nearest congestion level speeds of HBEFA (Keller et al., 2017) to account for congestion in exhaust emissions.

In the traffic simulation, the roads with ESL in winter constitute a length of around 65 km. Although they only make up to 0.2% of the total road network length, they constitute 14.8% of the total vehicle kilometres for light duty vehicle traffic (LDV), and just below 18% for heavy duty vehicle traffic (HDV, including buses), driven on the roads in the domain. HDV traffic makes up 9.8% of the traffic on these roads. The months with ESL have 41% of the traffic volume, so the total percentage of Oslo's traffic affected by the ESL is 6.1% of vkm in the RTM. Although the RTM model parametrizes traffic on small roads, this volume is indicative of the volume of traffic affected.

The exhaust and non-exhaust emissions from on-road traffic, for the three scenarios, are estimated based on highly detailed spatio-temporal data. Exhaust emissions are modelled with HBEFA emission factors (Keller et al., 2017), which are selected for 325 vehicles subsegments and more than 1000 different driving situations, and have dependencies on speed, road-type, slope and congestion. We used the road type "URB city-MW" (urban motorway) speed limit of 60, 70 and 80 km h⁻¹ for all the ESL roads shown in Fig. 1. To account for different driving conditions, we related the HBEFA effective driving speeds at different congestion levels to the hourly driving speed and then calculated hourly emission factors.

The resulting emission factors were then coupled to the vehicle fleet composed of all vehicles officially registered in Oslo municipality in 2017. Each vehicle subsegment was binned, to form a LDV, HDV and bus -emission factor based on the relative contribution of each type of vehicle. The reason for selecting the year 2017 is that the outcome from this study can be used to decide the further implementation of ESL. Since the fleet composition has gone through important changes in Oslo, and in order to support current environmental decisions, we need to represent the current situation regarding vehicle technology. The selection of a 2017 fleet composition (rather than a 2013 composition) will have implications for NO_x and to a lesser extent PM_{2.5} emissions due to the improvement in technology since 2013, but CO₂ and PM₁₀ emissions are less influenced. However, the studded tyre fraction from 2017 is somewhat lower than that in 2013. This has an impact in PM₁₀ estimates and it entails a lower estimation of the modelled results. Based on this, we can say that our setup is a conservative setup.

Non-exhaust emissions and the road dust contribution are estimated with the NORTRIP model, specially developed for Nordic conditions (Denby et al., 2013). NORTRIP calculates the most important parameters that influence the accumulation of road dust in the road surface and also calculates the moisture on the road surface that influences particle suspension. This is done based on input data from meteorology, traffic volume and vehicle distribution, road maintenance and other parameters (for more details see Denby et al. (2013)). In the same study a function was also established to predict traffic speed, with a linear relationship between traffic volume and speed based on observations in Oslo. Thus the average speed is sufficient for estimating the total emissions of road dust emissions (Denby and Sundvor, 2012a). In addition to wear, NORTRIP also has the possibility to include processes such as sanding, salting and snow removal in addition to cleaning. Exact days for these activities were not available, and they were therefore set as periodic occurrences. Cleaning furthermore is set in the model to be partially inefficient as suggested by Denby et al. (2013). This is in

agreement with experimental setups that show that very little of the particle fraction that is suspendable is actually removed by most cleaning processes.

2.4. Dispersion modelling and population exposure

In order to evaluate the impact of implementing ESLs on pollution levels and subsequent population exposure, we use the EPISODE model (Hamer et al., 2019), an off-line Eulerian dispersion model frequently applied to assess air quality in Norwegian cities (Tarrasón et al., 2018). Our study focuses on determining PM (PM₁₀ and PM_{2.5}) pollution levels in 2013 for the three scenarios.

For the EPISODE model, we use as input data the PM_{2.5} and PM₁₀ emissions previously described for the three scenarios, background concentration and meteorology. We use background concentration for 2013 from the MACC project (Marécal et al., 2015) to account for the concentration of PM transported long-range from outside the domain. The meteorology used to drive EPISODE is from the interpolation model MC-WIND (Slørdal and Walker, 2003). This model interpolates meteorological data obtained from available observations in 2013 from 6 meteorological stations and topographic data to produce wind and stability fields.

Population exposure is calculated by combining the modelled PM_{2.5} and PM₁₀ concentration at specific residential addresses with the number of people registered for each building point. The population data at the resolution of building point is provided by Statistics Norway. At each building point, PM_{2.5} and PM₁₀ levels are obtained from the dispersion modelling, and the number of people exposed is extracted. In our study, population exposure is evaluated based on the number of people exposed to annual PM_{2.5} and PM₁₀ levels and daily mean PM₁₀.

2.5. Cost-benefit analysis

There are changes in private and social costs associated with a lower vehicle speed. Increased costs are mainly due to the increased time spent on the road and a delayed arrival at destination. Benefits are mainly due to a reduction in health damages associated with noise and vehicle emissions, as well as a reduced seriousness and frequency of accidents. Wear of vehicle brakes and tyres, as well as the driving surface, is also speed dependent. Many of these effects are quantifiable allowing calculation of associated monetary cost, although quantification of others are more challenging. Here, we calculate the changes in costs associated with key parameters using several approaches. The key parameters relate to changes in NO_x and CO₂ emissions, PM₁₀ population exposure, fuel consumption, noise exposure, traffic accidents and time delays. Net economic impacts of the ESLs are subsequently estimated by comparing scenarios with implementation (i.e., Scenarios 2 and 3) with the baseline (Scenario 1). All results are given in 2019 NOK prices for comparison. The total net cost values are also given in €, considering 1 € = 9.86 NOK (based on the monthly average exchange rate in 2019). A summary of all cost factors used in the cost-benefit analysis is given in the supplementary information.

The changes in social costs associated with air pollution changes between the scenarios are calculated using the emission inventory, dispersion and PM₁₀ exposure modelling as input, and using cost factors derived for use in Norway. NO_x and CO₂ emission costs are based on the quantity emitted, at 416 NOK kg⁻¹ and 508 NOK t⁻¹ (2019 prices), respectively based on Rødseth et al. (2019). The NO_x damage cost is calculated specifically for Oslo (for NO_x deriving from road traffic), and the CO₂ cost is the recommended carbon price for 2019 corresponding to the CO₂ tax of gasoline and diesel (1.18 NOK l⁻¹ and 1.35 NOK l⁻¹, respectively, based on figures from the Norwegian Government). Changes in health costs relating to PM₁₀ exposure are calculated using a summed marginal cost of 0.738 million NOK (MNOK, 2019 prices) per increase in exposure of 1 µg m⁻³ for 1000 persons, following the approach outlined in Rødseth et al. (2019). This value includes mortality and morbidity

costs. For a detailed overview of the methodology involved in calculating these cost-factors, their underlying assumptions, and a breakdown of the types of health damages involved, see Rødseth et al. (2019).

Noise exposure levels are calculated according to the calculation method Nord2000, with implementation in the Norsty software (Randeberg and Olsen, 2007; Vegdirektoratet, 2013). The estimates are made at facade point resolution in the residential areas along the ESL roads. At each facade, noise levels are estimated at several vertical points of each building, with the uppermost calculated level defined for each building as the building's noise level. At each ESL road we set up a corridor for where noise calculations were done. Annual traffic is from 2018, whilst the map basis is from 2011, which we consider to be of minor importance in relation to the 2013 reference year. Calculations are made for an average day and no account is taken, for example, of tyre or weather changes. Largely urban, these corridors' residential buildings cover about 63,800 inhabitants.

The effect of the change in noise between scenarios is quantified as a reduction in the burden of disease, using disability adjusted life years (DALYs). In the past, costs of noise exposure were in Norway associated with willingness to pay, but as the awareness of health effects of exposure to noise has been more understood the costs are now associated with health effects (Aasvang, 2012). The input to these DALY calculations is the decibel (dB) reduction to the inhabitants outside the facade of each building. The procedure for calculating DALY is described in Aasvang (2012), with the cost of one DALY assumed to equal 1.61 MNOK (2019 prices) (Rødseth et al., 2019).

Changes in fuel consumption are calculated on the basis of the modelled CO₂ emissions, by assuming a CO₂ emission ratio of 22% and 78% from gasoline and diesel vehicles respectively. Specific fuel consumption is back-calculated using CO₂ emission factors of 3.13 and 3.17 kg CO₂ kg⁻¹ fuel, and fuel densities of 0.74 and 0.84 t m⁻³, for gasoline and diesel, respectively (Kittilsen et al., 2018). Associated fuel costs are calculated using 15.66 and 14.87 NOK/l for gasoline and diesel, respectively (annual averages for 2019 from Statistics Norway).

Changes in accident prevalence, according to separate categories with fatalities, serious or slight (minor) injuries, are evaluated using the exponential model described in Elvik (2019). These are based on changes in average speed, and allow the expected percentage change in the types of accident to be calculated. The average accident prevalence during winter periods between the years 2007–2018 was derived using recorded data from The Norwegian National Road Database for the roads in the study. Due to the small data sample, years with and without ESL were combined. The predicted change in accident numbers with a change in speed for each scenario was then calculated using model results. Values for the social costs of fatalities, serious injuries and minor injuries are sourced from Rødseth et al. (2019) as 42.2, 10.8 and 0.7 MNOK (2019 prices), respectively.

Time losses associated with ESLs in Scenarios 2 and 3 are calculated using the speed data and length of each road to calculate road travel time, and comparing with Scenario 1. The cost of time losses for each road per day are thereafter calculated by multiplying time cost factors together with the ADT, the time losses per journey, and the number of persons in each type of vehicle. The costs of time losses for light vehicle and bus trips under 70 km are obtained from SVV (2018) for different vehicle and transport purpose categories (NOK person⁻¹ h⁻¹), as well as for trucks (NOK h⁻¹). Transport purposes for light vehicle and bus trips include service journeys, to and from work, and free-time, whilst truck trips are not divided by purpose (see Supplementary Material).

We have assumed 1.15 persons per light vehicle commuting or in service, 1.85 persons per light vehicle in free-time, and 20 persons per bus (Hjorthol et al., 2014). Costs are converted to 2019 prices based on the 2016–2019 Norwegian salary change (data from Statistics Norway).

To enable the time loss calculations of each traffic segment, the ADT was split into the corresponding vehicle and transport purposes. We assume that 1) all light commercial vehicles (LCVs) are used for service journeys, 2) to and from work trips are during weekday rush-hours, defined as 06:30–09:00 and 15:00–17:00, and 3) free time journeys are for all times outside of rush-hour and the weekends. For each road, the hourly time distribution of vehicles was combined with the share of vehicle types to obtain the contribution of light (i.e., passenger vehicles and LCV) and heavy (i.e., buses and trucks) vehicles to total ADT. The time distribution of light and heavy vehicle journeys over a week allows the calculation of the proportion of journeys that occur during rush-hour or free time. Weekdays containing rush-hours are identified from the data due to the bimodal distribution. To allocate journeys in the light vehicle category to passenger vehicles or LCVs, we used the vehicle registered driving partition which allocates 78.7% of light traffic volume to passenger vehicles, and 21.3% to LCVs in Oslo. In the same way, for the HDV category we consider that 26.0% are buses and 74.0% are trucks (Table 3). When combined with the weekly time distribution data, the resulting fraction of passenger vehicles, LCV, bus and truck journeys during rush-hour and non-rush hour is given in Table 3. When considering total cost of time losses per ESL period established by SVV (2018), time loss costs for all roads are summed to give total costs per day, and it is assumed there are 151 days in an ESL period. Discomfort associated with congestion is not accounted for here.

3. Results and discussion

3.1. Impact of the ESL on emissions and PM levels

Tables 2 and 4 show NO_x, CO₂, PM₁₀ and PM_{2.5} traffic emissions at the roads where ESL is implemented for the three scenarios and the changes after ESL implementation compared to the baseline, respectively. NO_x and CO₂ emissions do not significantly change with ESL implementation. Compared to Scenario 1, Scenario 2 changes are almost negligible (0.1% and 0.3%; Table 4), and under a scenario of full compliance to signed speed limits (Scenario 3), we obtain 1.9% and 0.2% increases of NO_x and CO₂ emissions, respectively (Table 4). A similar increase in NO_x emissions with reduction of maximum speed limit has been previously reported by Bel and Rosell (2013).

The main reason for the modelled small changes in NO_x and CO₂ emissions is the congestion level. Whereas HBEFA free flow traffic has higher average emissions for the vehicle fleet at 70 and 80 km h⁻¹ than at 60 km h⁻¹, the speed changes are applied uniformly and affect rush hour speed the same as for all other time periods. This involves a shift of rush hour emissions towards higher levels of congestion, therefore, increasing emissions. Whether this is realistic is questionable as rush hour traffic speed, which comprises 27% of light vehicles and 23% of the heavy vehicles, does not show a discernible difference whether the speed limit is 60, 70 or 80 km h⁻¹. Also, some studies have established the effects of reducing speed limit as a measure to increase capacity and reduce congestion (see review in Soriguera et al. (2017)).

Emissions of PM₁₀ and PM_{2.5} with the implementation of ESL at observed speeds (Scenario 2) are reduced compared to the baseline by

Table 3
Fraction of vehicles driving during rush-hours. LDV: light duty vehicles. HDV: heavy duty vehicles. LCV: light commercial vehicles.

	Passenger vehicle	LCV	Bus	Truck
Category share	78.7% of LDV	21.3% of LDV	26.0% of HDV	74% of HDV
Rush-hour share	21% of LDV	6% of LDV	6% of HDV	17% of HDV
Non rush-hour share	58% of LDV	16% of LDV	20% of HDV	57% of HDV

Table 4

Changes to selected impacts as a result of implementing ESLs, compared to their absence (Scenario 1). *Average noise reduction to inhabitant. **Mortality represents the long-term impact of the number of people who die after a 5-year period 8 years before life expectancy due to cardiovascular and other lung disease. The % reduction in PM levels represent the maximum reduction (see Fig. 4). Reductions in the table are expressed as - values, whilst increases are expressed as + values.

Impact type		Scenario 2	Scenario 3
Emissions	NO _x emissions (%)	<+1	+2
	CO ₂ emissions (%)	<+1	<+1
	PM ₁₀ emissions (%)	-5	-12
	PM _{2.5} emissions (%)	-2	-6
Concentration	PM _{2.5} levels (%)	<-1	<-1
	PM ₁₀	-3	-8
Fuel consumption	Diesel (1 y ⁻¹)	+93,700	+45,393
	Gasoline (1 y ⁻¹)	+30,383	+14,719
Time	Travel time (min/journey)	+2.0	+6.2
Noise exposure	Noise change* (dB y ⁻¹)	-0.5	-1.1
	DALY (DALY y ⁻¹)	-6.2	-15.6
PM ₁₀ exposure	Change in (pers. µg m ⁻³ y ⁻¹)	-38 133	-64 729
	Mortality** (no/y)	-0.4	-0.6
Accidents	Fatality (%)	-24.7	-50.9
	Major injuries (%)	-19.4	-42.8
	Minor injuries (%)	-13.6	-32.3

5% and 2%, respectively (Table 4). For Scenario 3, the PM₁₀ and PM_{2.5} emission reductions are 12 and 6%, respectively (Table 4). These emission reductions are due to a lower suspension of particles with lower speed and therefore, the emission reductions are higher for PM₁₀ than PM_{2.5} since the mass of wear particles is mainly in the coarse PM fraction (i.e., PM_{10-2.5}). These results are similar to findings by (Keuken et al., 2010; Goncalves et al., 2008; Baldasano et al., 2010), when assessing the effects of reducing maximum speed limit in urban motorways from 120 to 80 km h⁻¹ on emissions in the urban area. However, an important difference in our study is that the use of studded tyres in winter enhances the wear processes, increasing the material available for suspension, and thus enhancing the effect even though the speed difference is lower.

Fig. 3 shows daily and monthly PM₁₀ emissions for the three scenarios evaluated in our study. The time variation of emissions shows a clear seasonality as higher emissions are estimated to occur in spring, from March to May. In addition, the emission changes among the scenarios is more pronounced during spring. This supports the purpose of the implementation of the ESL, as it is a measure specially designed to reduce the daily levels of PM_{10-2.5}. Even though the ESL is implemented only in

winter and the targeted days of reducing emissions at specific seasons, the annual average is also affected.

Changes in PM₁₀ and PM_{2.5} concentration levels have been assessed by comparing the annual mean concentration from air dispersion modelling for the three scenarios. Traffic exhaust and RWC are the main sources of PM_{2.5}. Therefore, the differences in annual PM_{2.5} levels among the three scenarios are small. The reduction of the annual PM_{2.5} levels is estimated to be below 1% for both scenarios with implementation of ESL (Table 4). Unlike PM_{2.5}, non-exhaust traffic emissions is the main contributing source to PM₁₀. Fig. 4 shows the annual PM₁₀ concentration in Oslo Metropolitan area (Scenario 1). Annual levels in 2013 (i.e. without implementation of the ESL) are found to be above 40 µg m⁻³ (i.e., the limit value established by the EU Air Quality Directive) only at hot-spots associated with road intersections with intense traffic. In Norway, the limit value for annual PM₁₀ concentration was reduced in 2015 to 25 µg m⁻³, and exceedances of the Norwegian annual limit value are observed on the vicinity of main roads and in Oslo city centre.

Fig. 4B shows the contribution in percentage from the ESL roads (shown in Fig. 1) to the annual PM₁₀ concentration. The contribution diminishes from 40% close to the roads, as the contribution from other roads and sources increases over distance from the ESL-roads. Fig. 4C and D show the percentage change in PM₁₀ annual concentration of scenarios 2 and 3 to Scenario 1. Maximum reductions of PM₁₀ levels are 3% and 8% for scenarios 2 and 3, respectively (Table 4). PM_{10-2.5} results were evaluated to establish if the reduction in emissions associated with the implementation of the ESL is reflected in observation data. Data was selected from five traffic monitoring station for the spring period from 2009 to 2013, when consistent monitoring data is available. Fig. 5 shows the average PM_{10-2.5} concentration in spring (March, April and May) at stations located along the roads with ESL (i.e., Hjortnes in E18, Manglerud in Ring3-Rsto, RV4 in RV4 and Smedstad in Ring3-Gsto) and one station located at a road without ESL (Kirkeveien). The average levels have been split in years without ESL (NoESL(Years) in Fig. 5, 2013) and with ESL (ESL(Years) in Fig. 5, 2009–2012). Three out of the four stations at the roads with ESL show a reduction in the PM coarse fraction in spring of 17–28% (Hjortnes, Manglerud and RV4, Fig. 5) with the implementation of ESL, versus Kirkeveien without ESL, which does not show changes. The fourth station along ESL-road, i.e., Smedstad, does not seem to show changes with ESL. This station is located in Ring3-Gsto (Fig. 1) with high congestion levels. This could explain the lack of effects after the implementation of ESL.

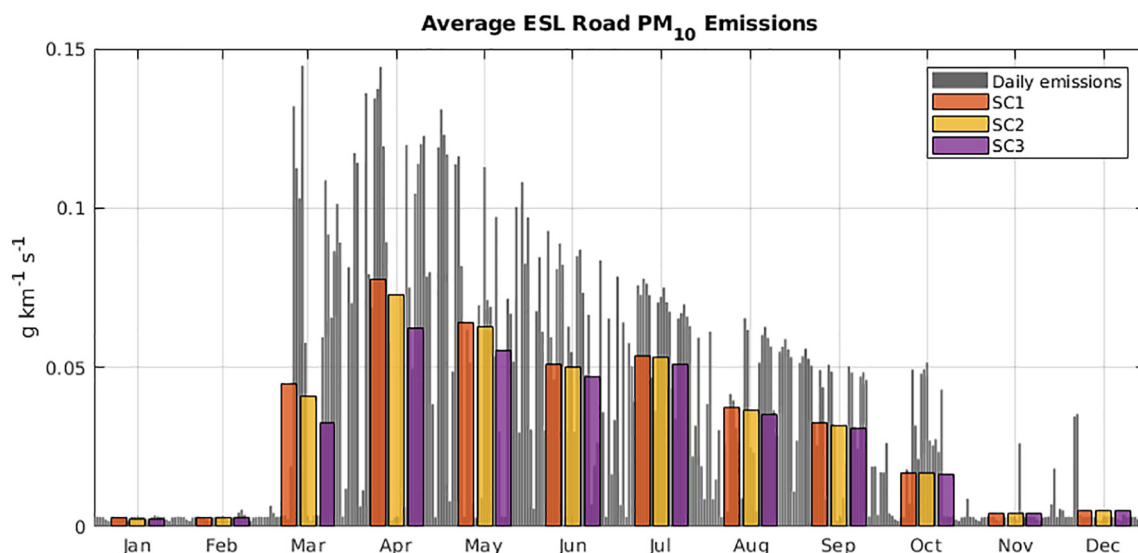


Fig. 3. Daily and monthly PM₁₀ emissions for the three scenarios evaluated in our study.

The modelling results and the observation data indicate that the implementation of the ESLs is an effective measure to reduce non-exhaust traffic emissions, and subsequent PM_{10} pollution levels. These results are in agreement with studies carried out in Barcelona according to variable speed based emissions and dispersion modelling (Gonçalves et al., 2008; Baldasano et al., 2010), but contrast with studies based on statistical analysis and average speed (Bel and Rosell, 2013). Our work thus supports the need for appropriate methods to evaluate the effects of reducing speed limit on air pollution levels (Panis et al., 2011). Comparisons between the results obtained in scenarios 2 and 3 moreover indicate the importance of reinforcing compliance with the ESL towards an effective reduction of PM_{10} pollution levels. This aspect was already highlighted by Keuken et al. (2010), which in their study contributed to a maximum PM_{10} emission reduction of 25% reducing speed from 120 to 80 km h⁻¹.

3.2. Population exposure

The changes in population exposure to $PM_{2.5}$ and PM_{10} levels are shown in Fig. 6. The values are estimated as changes under the implementation of the ESL compared to the baseline (Scenario 1). We have

selected for this assessment the changes in population exposure to the annual mean $PM_{2.5}$ (Fig. 6A) and PM_{10} (Fig. 6C) concentrations, and the changes to daily mean PM_{10} concentration over two days (Fig. 6B). The latter one is selected as the implementation of ESLs is a measure specially designed to reduce daily mean values of PM_{10} .

As previously stated, changes in $PM_{2.5}$ annual concentration levels under the implementation of ESL are low, and therefore this is reflected in small changes in population exposure. When the ESL is implemented and we consider observed speed, the largest change is observed for annual $PM_{2.5}$ levels above $14 \mu\text{g m}^{-3}$ (as population exposure is reduced by 49 persons). When drivers fully comply with the ESL, the population exposure to annual $PM_{2.5}$ levels above $14 \mu\text{g m}^{-3}$ is reduced by 181 persons (Fig. 6). The current Norwegian $PM_{2.5}$ limit value is established at $15 \mu\text{g m}^{-3}$. Therefore the implementation of the ESL will have, even though low, a positive effect on reducing population exposure to $PM_{2.5}$ limit values.

The changes in population exposure are more significant when assessing the PM_{10} concentration levels, particularly regarding the daily mean concentration (Fig. 6). In Norway, the limit value is established at $50 \mu\text{g m}^{-3}$ daily mean concentration, not to be exceeded for more than 30 days. Around 95% of the Oslo population is exposed for

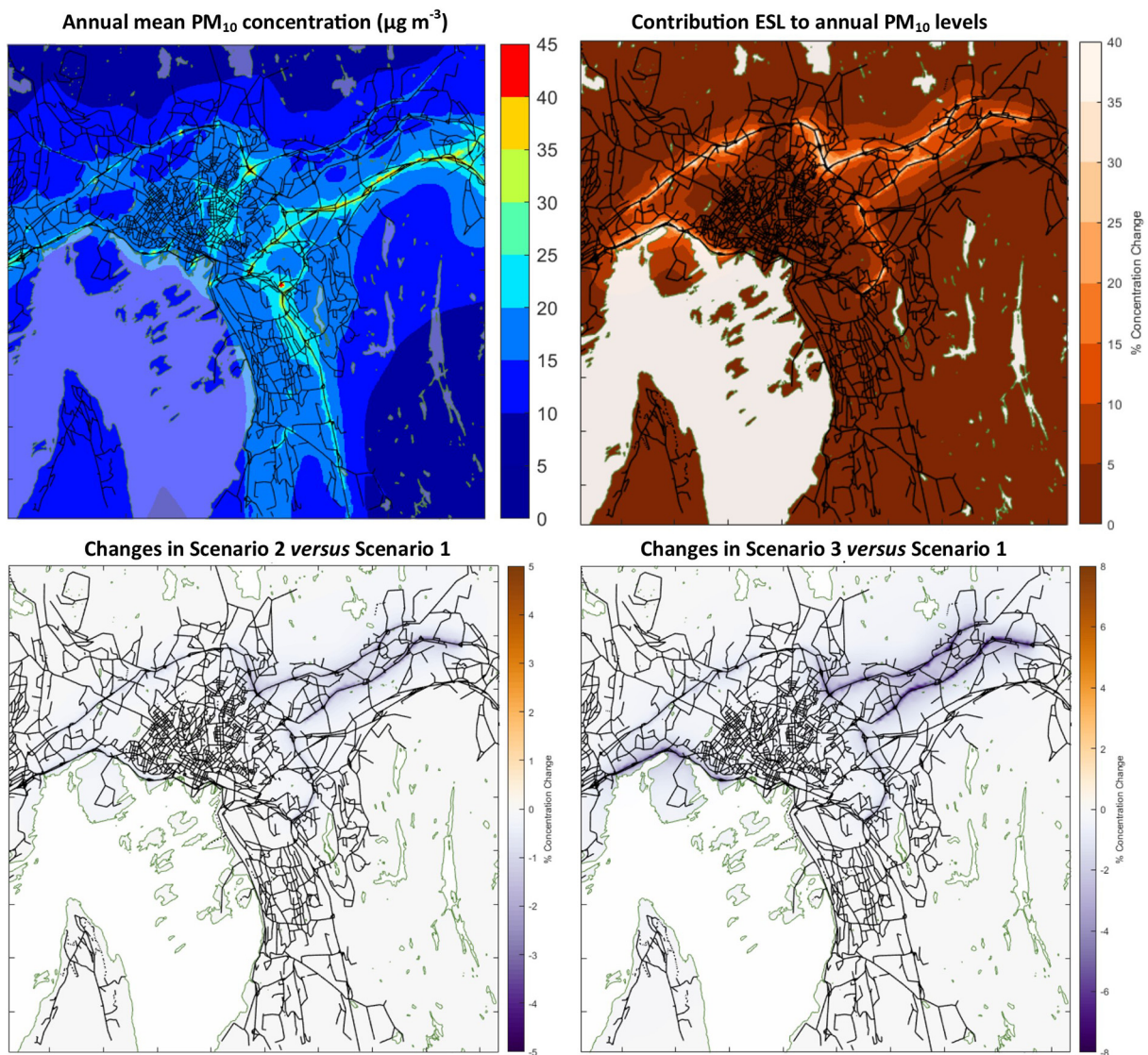


Fig. 4. Annual (2013) mean PM_{10} concentration in the model domain without implementation of ESL (Scenario 1) in Oslo Metropolitan area (top left). Contribution from traffic emissions at roads where ESLs are implemented to annual mean PM_{10} concentration (top right). Changes in PM_{10} annual concentration with the implementation of ESL in Scenario 2 (bottom left) and Scenario 3 (bottom right) compared to Scenario 1. Note that scales in both graphs (bottom) are different.

more than two days to the limit value (i.e., $50 \mu\text{g m}^{-3}$) and this share is the same for all scenarios evaluated in our study, with or without implementation of the ESLs. When evaluating population exposure changes to different daily levels, the largest changes are estimated to be at high daily PM_{10} concentrations, i.e., $65\text{--}85 \mu\text{g m}^{-3}$ (Fig. 6B). The implementation of the ESL will reduce population exposure over two days to PM_{10} daily values between 65 and $85 \mu\text{g m}^{-3}$ by 600–1600 persons (Fig. 6B). Furthermore, if drivers fully comply with the ESL, the population exposure over two days to $65\text{--}85 \mu\text{g m}^{-3}$ would be further reduced by 2500 to 3600 persons (Fig. 6B).

The evaluation of population exposure changes to annual mean PM_{10} concentration also shows important results. The values are less significant than those for exposure to daily mean PM_{10} when compared with regulatory limits. Around 1% of the Oslo population is exposed to levels above the Norwegian limit value (i.e., $25 \mu\text{g m}^{-3}$) with and without implementation of the ESLs. The WHO is clear about PM exposure, it has health impacts even at very low concentration, and therefore, no threshold has been identified under which no damage to health occurs. In this study, the implementation of the ESL will reduce population exposure to $15\text{--}20 \mu\text{g m}^{-3}$ annual mean PM_{10} concentration by approximately 2000 persons (Scenario 2), and by 7000–8000 persons under full compliance with the ESL (Scenario 3; Fig. 6).

For the 63,800 inhabitants in Oslo living in the corridors covered by our noise calculations with NORsty, the average reduction in noise to inhabitants was above 0.5 dB for Scenario 2, and above 1.1 dB for scenario 3. This reduction considers only a reduction for building points which have the ESL roads as their main source of noise. Whilst these are relatively small changes, this reduction is roughly equivalent to reducing the traffic volume by 20 and 40% for scenario 2 and 3 respectively.

3.3. Cost-benefit analysis

Changes in costs related to changes in emissions, PM exposure, fuel consumption, time losses, accidents and noise exposure for the different ESL scenarios are evaluated and shown in Table 5. An increase in cost values associated with each parameter (after implementation of ESL) is shown as a positive value, whereas all benefits are shown as negative values. As it can be seen, Scenario 2 with ESL and observed speed has a

net benefit, i.e., a reduction in costs compared to the scenario without ESL (Scenario 1), whilst Scenario 3 with speed limit compliance has a net increase in costs compared to Scenario 1 (benefit:cost ratio (BCR) of 1.24 and 0.79, respectively). This is largely due to changes in time losses between the two ESL scenarios. For Scenario 2, the extra costs associated with time losses are offset by cost savings mainly relating to a reduction of PM_{10} and noise exposure. However, in our analysis of Scenario 3 the costs associated with time losses of one journey, defined here as travel along all road lengths, are too large to be offset by the reduction in health damages and other benefits. A breakdown of the non-monetary impacts for each parameter, upon which the costs are calculated, is given in Table 4. The implementation of ESL entails a slight increase in CO_2 and NO_x emissions, due to the increased congestion, and an increase in fuel use (calculated based on the CO_2 emissions). However, there is a reduced annual average exposure to PM_{10} and to noise for the population surrounding the affected roads, resulting in health benefits. Reduced speed from ESL implementation further results in other health benefits due to a reduced calculated accident prevalence. The percentage reductions in fatal, serious and minor injuries calculated here for the ESL scenarios are comparable to the reduction in injury accidents previously calculated by Elvik (2013), and with greatest reductions in the fatal accident category (Elvik, 2014, 2019). Time losses summed along all road lengths are around three times higher with compliance of ESL speed limits.

Our study estimates changes to both private and social costs. We compare the cost associated with time losses, which can be mainly considered as private, to the social benefits of improving human health through reducing exposure to air pollution and noise, and the reduction in traffic accidents. The results of our study support the ‘polluter pays’ principle, which entails that those that produce pollution should bear the costs associated to prevent the damage on human health and the environment. Comparing these results with the literature is challenging due to wide variation in case study scope and methodology. NOEPA (2014) finds that there is a benefit to implementing ESL in Oslo, which they deduce is primarily due to the reduction of PM concentrations in population-dense areas around the ESL due to changes in speed (calculated BCR of 1.4). Similarly, Cetin et al. (2018) find that there are net socio-economic benefits with a lower speed limit for the highway in

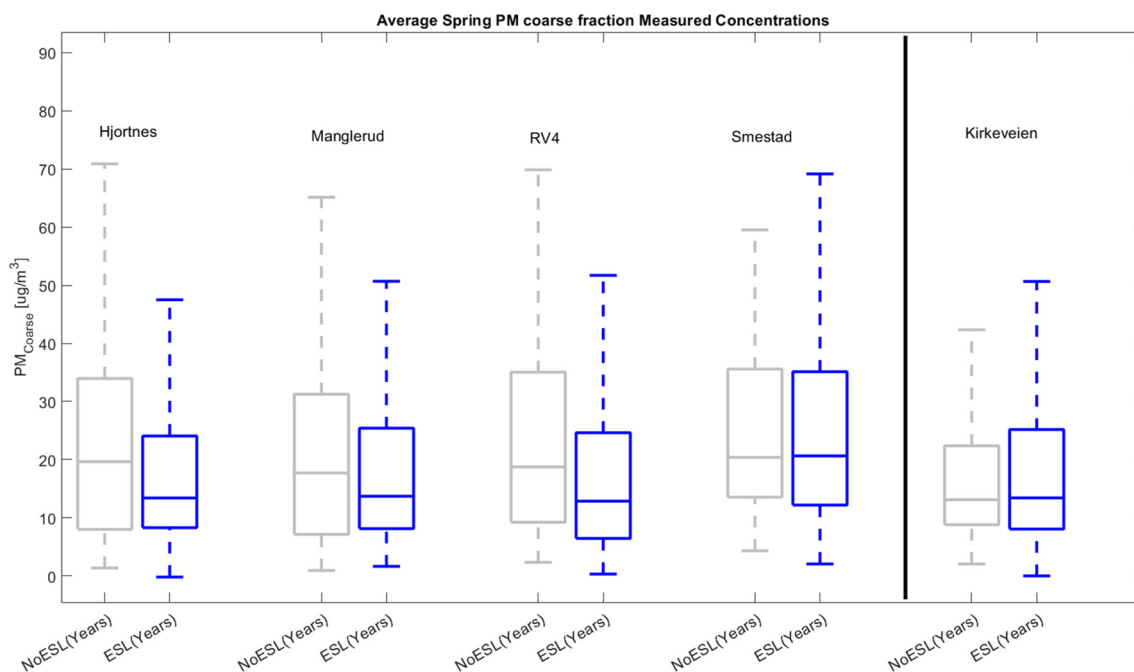


Fig. 5. Average spring $\text{PM}_{10-2.5}$ concentration measured at stations on roads with ESL (Hjortnes, Manglerud, RV4, Smedstad) and at a road without ESL (Kirkeveien). The location of the stations can be seen in Fig. 1. The values are split for years with and without ESL.

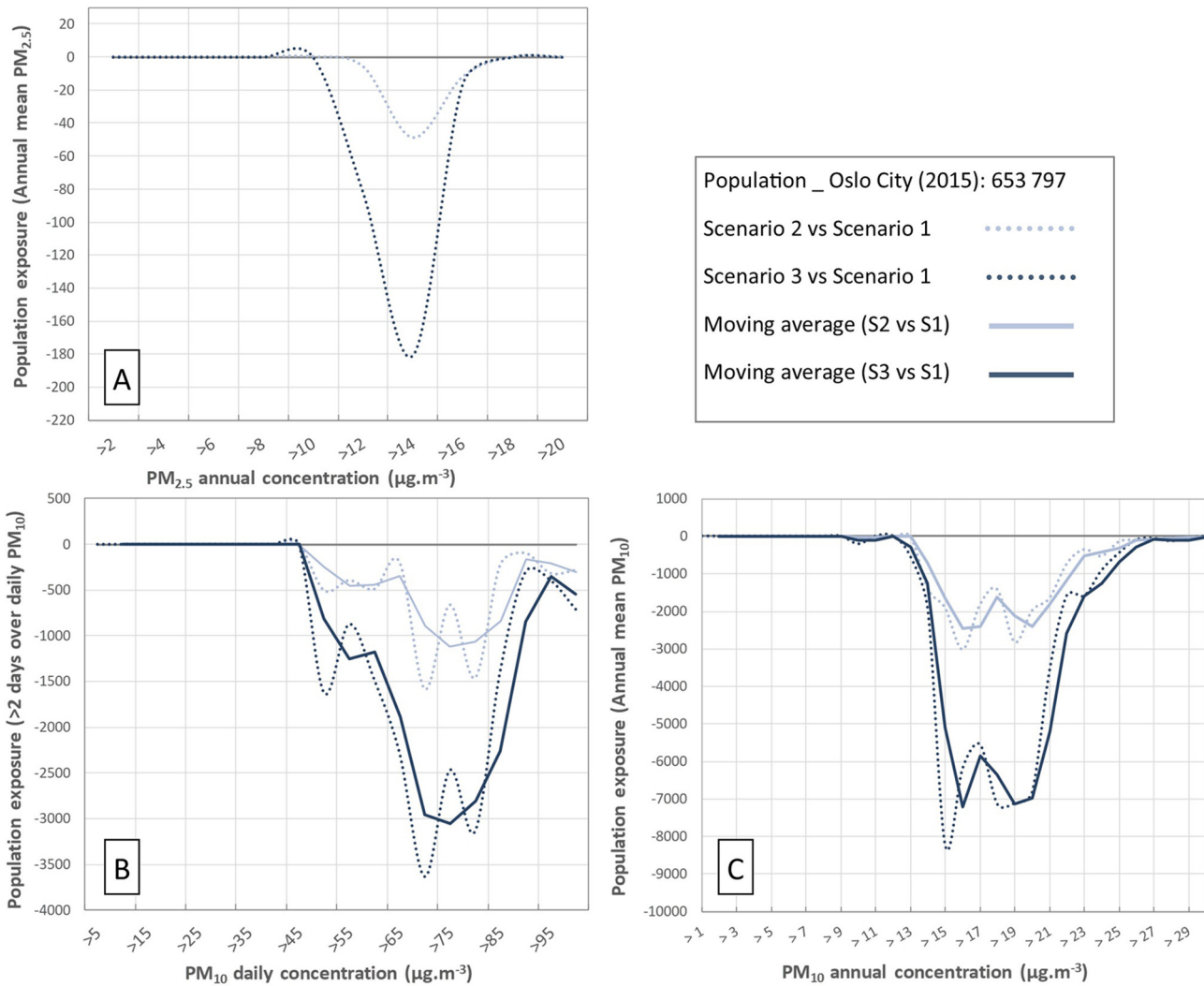


Fig. 6. Changes in population exposure to annual $PM_{2.5}$ concentration (A), PM_{10} daily concentration (B) and PM_{10} concentration (C) in Scenario 2 and Scenario 3 compared to Scenario 1 in 2013. For exposure to PM_{10} daily levels, we select ≥ 2 days to the different PM_{10} levels as selection criteria.

their study in Turkey (with BCRs for the higher speeds of between 0.50 and 0.66). However, net costs were found by NOEPA (2014) in other Norwegian cities (Bergen and Trondheim) with lower speeds associated with ESLs (BCR of 0.3–0.5), and a net cost was also calculated by Westby and Folgerø (2017) in Oslo. Morichi et al. (2005) also found net benefits with upgrading of regulated speeds for a highway in Japan (calculated BCR of 3–4 for their scenarios with the higher speeds). The change in costs relating to time is found as a general rule to be the largest contributing factor in all studies, as is found in the study here.

3.4. Uncertainties and sensitivity analysis

Our study builds on a chain of processes from the design of scenarios of ESL implementation, emission and dispersion modelling, to the estimates of population and noise exposure, time delays and accidents. Each step entails its own level of confidence, thus the overall total outcome shares these uncertainties.

The design of the ESL scenarios is constrained by the speed limits, upon which a uniform change to speed is applied over the ESL period. This implies a similar reduction in speed during rush hour as at other times during the day. Rush hour driving speed on these roads is, however, generally not determined by the speed limit but the traffic density. With private cars having differentiated costs and prevalence during the day, the fact that rush hour vehicle speed reduction is probably

overestimated in this time period leads to a likely overestimation of the cost associated with delay. Furthermore, lowering speed during congestion increases emissions of NO_x and CO_2 emissions, meaning that costs associated with these are likely also overestimated in this study. With the available data, it was however not possible to estimate if and how these non-linear responses were affected.

Uncertainties in the overall results therefore relate to both input data and the cost functions applied, and may result in over- and

Table 5

Changes to costs as a result of implementing ESLs, compared to their absence (Scenario 1). The values represent totals as MNOK (2019 prices), with net total also given in euro. Benefits (reductions in cost) are expressed as - values, whilst increases to cost are expressed as + values. B:C: benefit to cost ratio.

Impact type	Scenario 2	Scenario 3
Fuel consumption	+1.9	+0.9
Travel time	+36.1	+114.7
Health effects (PM exposure)	-28.1	-47.8
Health effects (NO_x emissions)	+0.1	+3.0
Climate (CO_2 emissions)	+0.1	+0.1
Noise exposure	-10.1	-25.1
Traffic accidents	-9.2	-20.6
Total net (MNOK)	-9.2	+25.4
Total net (M€)	-0.93	+2.57
B:C	1.24	0.79

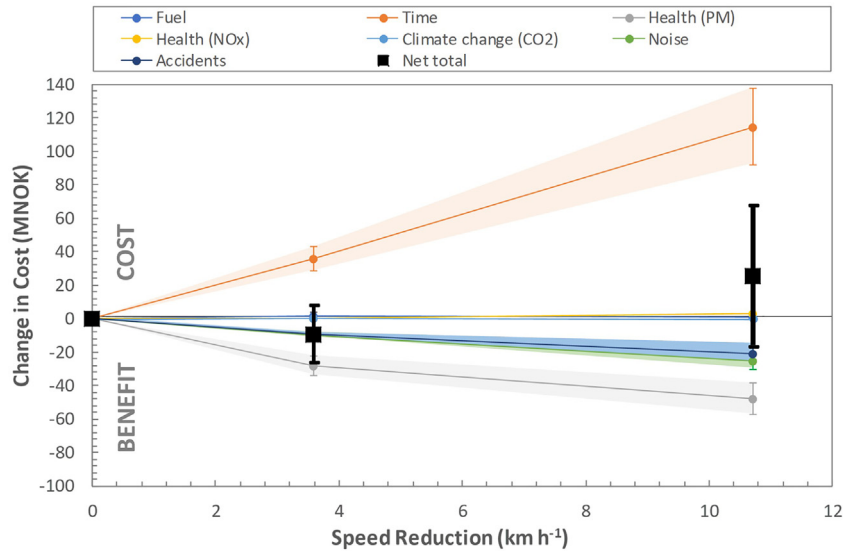


Fig. 7. Changes in individual parameter costs (circles), as well in changes in overall net total costs (black squares), with reductions in speed. Effects of parameter variation ($\pm 20\%$) is shown as the shaded range. The certainty ranges for the net total results were calculated by varying all parameters by a maximum of 20% in either direction, to identify highest and lowest net values possible.

under-estimated individual costs and benefits for various key parameters. Time losses and reductions in health damages from PM_{10} exposure represent the largest single extra cost and benefit, respectively, associated with ESL implementation. Variation in their values can therefore affect the main result. Time costs calculated here likely represent a worst-case scenario due to the use of average daily speed for all periods in calculations. Regarding costs of health impacts, since the ESL mostly affects the daily PM_{10} maximum values, it may be that health benefits relating to PM_{10} are conservative as the calculations are based on PM_{10} annual values. Nonetheless, differences in exposure to (and relative effects) of specific PM fractions ($PM_{2.5}$, PM_{10}) leads to uncertainty, as well as possible overlap in health effects from short and long-term exposure and for damages from PM and NO_x (Henschel et al., 2013). For the latter, since the modelled change in NO_x here is small (with opposite

magnitude to PM_{10}), this is not likely to significantly affect results. Excluding short-term health effects from the analysis (regarding PM_{10} exposure) also did not change the main results.

To indicate the robustness of the study, a sensitivity analysis was carried out where all cost-factors (shown in Table S1) were varied both individually and combined, and overall net results compared. No certainty ranges are available, but in this study conservative and high estimates of each factor were generated using a 20% margin of error (see Table 6 for the sensitivity analysis results and Fig. 7 for a visual representation of the uncertainty ranges). Results show that in general where conservative or high estimates are used, no major changes to net favourability result. As expected, varying the cost of time has the largest effect on the result, although the net favourability of main results is unchanged at the $\pm 20\%$ level. However, when parameters are co-varied, changes in

Table 6

Sensitivity analysis to show the change in benefit:cost ratio (BCR) in Scenario 2 and Scenario 3 versus Scenario 1 with variation of underlying cost factors. *Lower and upper bounds are $\pm 20\%$, respectively. **Maximum and minimum are +20% costs and -20% benefits, and -20% costs and +20% benefits, respectively. Values are shaded to indicate a net cost (red) or a benefit (green).

Cost factor variation			B:C ratio		
Parameter		Bounds	Scenario 2	Scenario 3	
Individual cost factors	Costs	Fuel	Lower*	1.3	0.8
			Upper*	1.2	0.8
		Time	Lower*	1.5	1.0
			Upper*	1.0	0.7
		Health (NO _x)	Lower*	1.2	0.8
			Upper*	1.2	0.8
	Benefits	Climate change (CO ₂)	Lower*	1.2	0.8
			Upper*	1.2	0.8
		Health (PM)	Lower*	1.1	0.7
			Upper*	1.4	0.9
		Noise	Lower*	1.2	0.7
			Upper*	1.3	0.8
Grouped cost factors	Costs	Lower*	1.3	0.8	
		Upper*	1.3	0.8	
	Benefits	Lower*	1.2	0.8	
		Upper*	1.3	0.8	
	Costs and benefits combined	Maximum**	0.8	0.5	
		Minimum**	1.9	1.2	

net favourability can result. When all parameters for each scenario were varied by a maximum of 20% in either direction, to identify the net results with highest costs or highest benefits within these boundaries, there does exist the possibility of a change in favourability for both scenarios. The spread of possible results for Scenario 2 (reflecting the change in net costs compared to Scenario 1) was calculated as -26 to 8 MNOK (BCR of 1.9 to 0.8), whilst the spread of possible results for Scenario 3 was calculated as -17 to 68 MNOK (BCR of 1.2 to 0.5).

4. Conclusions

This study comprises an assessment of the impacts and associated changes in costs related to the implementation of Environmental Speed Limits (ESLs) in the Metropolitan Area of Oslo. The effect of changing the speed on the roads that currently have ESL was studied with three different speed scenarios. We used emission modelling to investigate changes in emissions. Atmospheric concentrations were modelled with dispersion modelling and combined with population exposure at building points, and noise was evaluated based on acoustics modelling. The differences between scenarios were analysed in an economic framework using cost-benefit analysis.

We find that ESLs have low to negligible effects on the emission of $PM_{2.5}$, NO_x and CO_2 at the speeds considered in our scenarios. The sign of the change is dependent on potential small differences in congestion. However, PM_{10} emissions and noise levels are significantly reduced. PM_{10} emission reduction occurs primarily between Mar-May and is connected to the end of the studded tyre and ESL season, when roads, loaded with road dust, dry up. Stations near ESL roads show an average reduction in coarse PM in spring of about 16%. This is in agreement with the modelled emissions reductions and the changes in modelled atmospheric concentration in spring. The implementation of ESLs has an effect in reducing modelled annual PM_{10} emissions on the ESL roads (5–12%), concentration levels near these roads (3–8%) and, subsequently, population exposure to PM_{10} levels. Likewise, noise levels and the subsequent exposure are lowered for the time period when ESLs are in place.

Changes in costs between the scenarios were calculated in relation to human health and the incidence of traffic accidents, climate, fuel consumption and time losses. Reductions in social costs associated with population exposure to pollution (PM_{10}) and noise were estimated for both scenarios 2 and 3 compared with the baseline (Scenario 1). In addition, we estimate that the implementation of ESL entails a reduction in the number and seriousness of traffic accidents, with an associated reduction in social cost. However, the reduction of speed associated with ESL implementation entails a delay to travel journeys that has a high associated cost. Each type of calculated cost has a number of uncertainties attached to it, for instance, resulting from the scenario design entailing a uniform change to speed over the ESL period or changes in effects from PM fractions.

In summary, we find that ESLs in Oslo convey a benefit to society when implemented as a measure to reduce air pollution (with reduced population exposure to PM levels, noise exposure and traffic accidents). However, the cost associated with time delays is not always offset by these benefits. Our study shows a benefit (net reduction in costs) associated with the implementation of ESLs where observed speed data from Oslo during ESL periods is used. However, when modelling a theoretical scenario with strict compliance with ESL speed-limits, we find a net increase in costs resulting from ESL use. This difference in net outcome is due to the cost of time losses more than the increase in social benefits. When all parameters for each scenario were varied by a maximum of 20% in either direction, to identify the net results with highest costs or highest benefits within these boundaries, the possibility exists of a change in favourability for both scenarios. Results are specific to Oslo, since previous studies have demonstrated the importance of evaluating the effectiveness of ESL measures to e.g. PM_{10} population exposure on a case-by-case basis NOEPA (2014).

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CRediT authorship contribution statement

Susana Lopez-Aparicio: Conceptualization, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Henrik Grythe:** Conceptualization, Formal analysis, Investigation, Writing - review & editing, Visualization. **Rebecca J. Thorne:** Formal analysis, Investigation, Writing - review & editing. **Matthias Vogt:** Formal analysis, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Aasvang, G., 2012. Helsebelastning som skyldes veitrafikkstøy i norge. Rapport fra Folkehelseinstituttet.
- Baldasano, J.M., Gonçalves, M., Soret, A., Jiménez-Guerrero, P., 2010. Air pollution impacts of speed limitation measures in large cities: the need for improving traffic data in a metropolitan area. *Atmos. Environ.* 44 (25), 2997–3006.
- Bel, G., Rosell, J., 2013. Effects of the 80 km/h and variable speed limits on air pollution in the metropolitan area of Barcelona. *Transp. Res. Part D: Transp. Environ.* 23, 90–97.
- Cetin, V.R., Yilmaz, H.H., Erkan, V., 2018. The impact of increasing speed limit in Turkey: the case of Ankara-Sivrihisar road section. *Case Studies on Transport Policy* 6 (1), 72–80.
- Denby, B., Sundvor, I., 2012a. Modelling non-exhaust emissions of PM10 in Oslo. Impact of the environmental speed limit using the nortrip model. NILU Report, 47. <https://www.nilu.no/apub/27233/> (41/13).
- Denby, B.R., Sundvor, I., 2012b. Nortrip Model Development and Documentation. Norwegian Institute for Air Research (NILU OR 23/2012) URL www.nilu.no.
- Denby, B., Sundvor, I., Johansson, C., Pirjola, L., Ketzel, M., Norman, M., Kupiainen, K., Gustafsson, M., Blomqvist, G., Omstedt, G., 2013. A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (nortrip). Part 1: road dust loading and suspension modelling. *Atmos. Environ.* 77, 283–300.
- Dijkema, M.B., van der Zee, S.C., Brunekreef, B., van Strien, R.T., 2008. Air quality effects of an urban highway speed limit reduction. *Atmos. Environ.* 42 (40), 9098–9105.
- Elvik, R., 2009. The Power Model of the Relationship Between Speed and Road Safety: Update and New Analyses. No. 1034/2009. The Institute of Transport Economic, Norway.
- Elvik, R., 2013. A before–after study of the effects on safety of environmental speed limits in the city of Oslo, Norway. *Saf. Sci.* 55, 10–16.
- Elvik, R., 2014. Fart og trafikksikkerhet. Nye modeller. TØI rapport 1296, p. 2014.
- Elvik, R., 2019. A comprehensive and unified framework for analysing the effects on injuries of measures influencing speed. *Accid. Anal. Prev.* 125, 63–69.
- Forester, T.H., McNow, R.F., Singell, L.D., 1984. A cost-benefit analysis of the 55 mph speed limit. *South. Econ. J.* 631–641.
- Gonçalves, M., Jiménez-Guerrero, P., López, E., Baldasano, J.M., 2008. Air quality models sensitivity to on-road traffic speed representation: effects on air quality of 80 km h⁻¹ speed limit in the Barcelona metropolitan area. *Atmos. Environ.* 42 (36), 8389–8402.
- Grythe, H., Lopez-Aparicio, S., Vogt, M., Vo Thanh, D., Hak, C., Halse, A.K., Hamer, P., Sousa Santos, G., 2019. The metved model: development and evaluation of emissions from residential wood combustion at high spatio-temporal resolution in Norway. *Atmos. Chem. Phys.* 19 (15), 10217–10237 URL <https://www.atmos-chem-phys.net/19/10217/2019/>.
- Hagen, L., Larssen, S., Schaug, J., 2005. Miljøfartsgrense i oslo. Effekt på luftkvaliteten av redusert hastighet på rv 4.
- Hamer, P.D., Walker, S.-E., Sousa-Santos, G., Vogt, M., Vo-Thanh, D., Lopez-Aparicio, S., Ramacher, M.O.P., Karl, M., 2019. The urban dispersion model episode. Part 1: a eulerian and subgrid-scale air quality model and its application in nordic winter

- conditions. Geoscientific Model Development Discussions 2019, 1–57 URL <https://www.geosci-model-dev-discuss.net/gmd-2019-199/>.
- Henschel, S., Chan, G., Organization, W.H., et al., 2013. Health Risks of Air Pollution in Europe-HRAPIE Project: New Emerging Risks to Health From Air Pollution—Results From the Survey of Experts.
- Hjorthol, R., Engebretsen, Ø., Uteng, T.P., 2014. Den nasjonale reisevaneundersøkelsen 2013/14: nøkkelrapport. Transportøkonomisk institutt.
- Høiskar, B.A.K., Sundvor, I., Strand, A., 2014. Tiltaksutredning for luftkvalitet i oslo og bærum 2015–2020. NILU Report 49/2014. URL <https://nilu.brage.unit.no/nilu-xmlui/bitstream/handle/11250/2507476/49-2014-BAH.pdf?sequence=1>.
- Høiskar, B.A.K., Sundvor, I., Grythe, H., 2017. Luftkvalitetsberegninger for oslo. faglig innspill til revidert tiltaksutredning for luftkvalitet i oslo 2017–2020. NILU rapport.
- Hyard, A., 2012. Cost-benefit analysis according to Sen: an application in the evaluation of transport infrastructures in France. *Transp. Res. A Policy Pract.* 46 (4), 707–719.
- Kamerud, D.B., 1983. The 55 mph speed limit: costs, benefits, and implied trade-offs. *Transportation Research Part A: General* 17 (1), 51–64.
- Keller, J., Andreani-Aksoyoglu, S., Tinguely, M., Flemming, J., Heldstab, J., Keller, M., Zbinden, R., Prevot, A.S., 2008. The impact of reducing the maximum speed limit on motorways in Switzerland to 80 km h⁻¹ on emissions and peak ozone. *Environ. Model Softw.* 23 (3), 322–332.
- Keller, M., Hausberger, S., Matzer, C., Wüthrich, P., Notter, B., 2017. Hbepa Version 3.3. Background Documentation, Berne 12.
- Keuken, M., Jonkers, S., Wilminck, I., Wesseling, J., 2010. Reduced NOx and PM10 emissions on urban motorways in the Netherlands by 80 km/h speed management. *Sci. Total Environ.* 408 (12), 2517–2526.
- Kittilsen, M.O., Moe, S.H., Fedoryshyn, N., 2018. Energiregnskap og- balanse. Dokumentasjon av statistikkproduksjonen fra statistikkår 1990 og fremover. Statistisk sentralbyrå.
- Kloeden, C., McLean, A., Glonek, G., 2002. Reanalysis of Travelling Speed and the Rate of Crash Involvement in Adelaide, South Australia (No. CR 207). Australian transport safety bureau, canberra, act.
- Kousoulidou, M., Ntziachristos, L., Hausberger, S., Rexeis, M., 2010. Validation and improvement of CORINAIR's emission factors for road transport using real-world emissions measurements. *LAT Report* 10.
- López-Aparicio, S., Tønnesen, D., Thanh, T.N., Neilson, H., 2017. Shipping emissions in a Nordic port: assessment of mitigation strategies. *Transp. Res. Part D: Transp. Environ.* 53, 205–216.
- Madireddy, M., De Coensel, B., Can, A., Degraeuwe, B., Beusen, B., De Vlieger, I., Botteldooren, D., 2011. Assessment of the impact of speed limit reduction and traffic signal coordination on vehicle emissions using an integrated approach. *Transp. Res. Part D: Transp. Environ.* 16 (7), 504–508.
- Marécal, V., Peuch, V.-H., Andersson, C., Andersson, S., Arteta, J., Beekmann, M., Benedictow, A., Bergström, R., Bessagnet, B., Cansado, A., Chéroux, F., Colette, A., Coman, A., Curier, R.L., Denier van der Gon, H.A.C., Drouin, A., Elbern, H., Emili, E., Engelen, R.J., Eskes, H.J., Foret, G., Friese, E., Gauss, M., Giannaros, C., Guth, J., Joly, M., Jaumouillé, E., Josse, B., Kadygrov, N., Kaiser, J.W., Krajsek, K., Kuenen, J., Kumar, U., Liora, N., Lopez, E., Malherbe, L., Martinez, I., Melas, D., Meleux, F., Menut, L., Moinat, P., Morales, T., Parmentier, J., Piacentini, A., Plu, M., Poupkou, A., Queguiner, S., Robertson, L., Rouil, L., Schaap, M., Segers, A., Sofiev, M., Tarasson, L., Thomas, M., Timmermans, R., Valdebenito, A., van Velthoven, P., van Versendaal, R., Vira, J., Ung, A., 2015. A regional air quality forecasting system over Europe: the MACC-II daily ensemble production. *Geosci. Model Dev.* 8 (9), 2777–2813 URL <https://www.geosci-model-dev.net/8/2777/2015/>.
- Morichi, S., Masuda, S., Acharya, S.R., Hibino, N., 2005. Cost benefit analysis of speed limit regulation for highways in Japan. *J. East. Asia Soc. Transp. Stud.* 6, 1008–1020.
- Nilsson, G., 1982. The effects of speed limits on traffic crashes in Sweden. *Proceedings of the International Symposium on the Effects of Speed Limits on Traffic Crashes and Fuel Consumption*. Organisation for Economy, Co-operation, and Development (OECD), Dublin. Paris.
- Nilsson, G., et al., 2004. *Traffic Safety Dimensions and the Power Model to Describe the Effect of Speed on Safety* (Ph.D. thesis, Univ).
- NOEPA, 2014. Grenseverdier og nasjonale ml. forslag til langsiktige helsebaserte nasjonale ml og reviderte grenseverdier for lokal luftkvalitet. Report M-129 URL <https://www.miljodirektoratet.no/globalassets/publikasjoner/m129/m129.pdf>.
- Panis, L.L., Beckx, C., Broekx, S., De Vlieger, I., Schrooten, L., Degraeuwe, B., Pelkmans, L., 2011. PM, NOx and CO2 emission reductions from speed management policies in Europe. *Transp. Policy* 18 (1), 32–37.
- Randeberg, R.T., Olsen, H., 2007. Støyberegner-Teknisk dokumentasjon. SINTEF IKT, Norway URL <https://trafikksiden.motocross.io/informasjon/SINTEF/rapporter/STFA4142.html>.
- Rekdal, J., Larsen, O., 2008. Rtm23+, regional modell for oslo-området. Dokumentasjon av utviklingsarbeid og teknisk innføring i anvendelse. MFM rapport 806 2008.
- Rødseth, K., Wangsnæs, P.B., Veisten, K., Elvik, K., Klæboe, R., Thune-Larsen, H., Fridström, L., Lindstad, E., Rialland, A., Odolinski, K., Nilsson, J.-E., 2019. Skadekostnader ved transport. TØI rapport 1704 (/2019).
- Slørdal, L.H., Walker, S.E., 2003. The Urban Air Dispersion Model Episode Applied in AirQUIS2003, Technical Description. 12. Norwegian Institute for Air Research, NILU TR.
- Soriguera, F., Martínez, I., Sala, M., Menéndez, M., 2017. Effects of low speed limits on free-way traffic flow. *Transportation Research Part C: Emerging Technologies* 77, 257–274.
- Sundvor, I., 2014. Arealkilder for oslo. Kjeller, NILU Report OR 13/2014.
- SVV, 2018. Konsekvensanalyser. Haandbok v712. v712. The Norwegian Road Administration URL https://www.vegvesen.no/_attachment/704540/.
- Tarrasón, L., Sousa Santos, G., Vo, D.T., Vogt, M., Lopez-Aparicio, S., Denby, B., Tønnesen, D.A., Sundvor, I., Røen, H.V., Høiskar, B.A.K., 2018. Air Quality in Norwegian Cities in 2015. Evaluation Report for NBV Main Results. NILU Rapport.
- Taylor, M., Lynam, D., Baruya, A., 2000. The effect of drivers speed on the frequency of accidents. TRL Report TRL421. Transport Research Laboratory.
- Vegdirektoratet, V., 2013. Støybygg III: Brukerveileder. The Norwegian Road Administration URL <https://vegvesen.brage.unit.no/vegvesen-xmlui/handle/11250/2557936>.
- Voorhees, A.S., Araki, S., Sakai, R., Sato, H., 2000. An ex post cost-benefit analysis of the nitrogen dioxide air pollution control program in Tokyo. *J. Air Waste Manage. Assoc.* 50 (3), 391–410.
- Westby, B.S., Folgerø, I.K., 2017. Environmental Speed Limits: Do Temporary Speed Limits Improve Air Quality? (Master's thesis)