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Assessment of impact of traffic-related air pollution on morbidity and mortality in Copenhagen Municipality and the health gain of reduced exposure

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ABSTRACT

Background: Health impact assessment (HIA) of exposure to air pollution is commonly based on city level (fine) particle concentration and may underestimate health consequences of changing local traffic. Exposure to traffic-related air pollution can be assessed at a high resolution by modelling levels of nitrogen dioxide (NO_2), which together with ultrafine particles mainly originate from diesel-powered vehicles in urban areas. The purpose of this study was to estimate the health benefits of reduced exposure to vehicle emissions assessed as NO_2 at the residence among the citizens of Copenhagen Municipality, Denmark.
Methods: We utilized residential NO_2 concentrations modelled by use of chemistry transport models to calculate contributions from emission sources to air pollution. The DYNAMO-HIA model was applied to the population of Copenhagen Municipality by using NO_2 concentration estimates combined with demographic data and data from nationwide registers on incidence and prevalence of selected diseases, cause specific mortality, and total mortality of the population of Copenhagen. We used exposure-response functions linking NO_2 concentration estimates at the residential address with the risk of diabetes, cardiovascular diseases, and respiratory diseases derived from a large Danish cohort study with the majority of subjects residing in Copenhagen between 1971 and 2010. Different scenarios were modelled to estimate the dynamic impact of NO_2 exposure on related diseases and the potential health benefits of lowering the NO_2 level in the Copenhagen Municipality.
Results: The annual mean NO_2 concentration was 19.6 $\mu g/m^3$ and for 70% of the population the range of exposure was between 15 and 21 $\mu g/m^3$. If NO_2 exposure was reduced to the annual mean rural level of 6 $\mu g/m^3$, life expectancy in 2040 would increase by one year. The greatest gain in disease-free life expectancy would be lifetime without ischemic heart disease (1.4 years), chronic obstructive pulmonary disease (1.5 years for men and 1.6 years for women), and asthma (1.3 years for men and 1.5 years for women). Lowering NO_2 exposure by 20% would increase disease-free life expectancy for the different diseases by 0.3–0.5 years. Using gender specific relative risks affected the results.
Conclusions: Reducing the NO_2 exposure by controlling traffic-related air pollution reduces the occurrence of some of the most prevalent chronic diseases and increases life expectancy. Such health benefits can be quantified by DYNAMO-HIA in a high resolution exposure modelling. This paper demonstrates how traffic planners can assess health benefits from reduced levels of traffic-related air pollution.

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1. Introduction

Air pollution is recognized as an important risk factor for population health (Cohen et al., 2017; WHO Regional Office for Europe, 2013). Health impact assessments of air pollution have mainly focused on the effects related to fine particulate matter ($PM_{2.5}$) on overall mortality (Boldo et al., 2006, 2011; Davidson et al., 2007; Medina et al., 2009; Logue et al., 2012). The latest Global Burden of Disease study estimated that in 2016, ambient exposure to $PM_{2.5}$ was responsible for 4.1 million deaths representing 7.5% of total global deaths (https://vizhub.healthdata.org/gbd-compare/). In Denmark these figures were 1800 deaths, or 3.4% of total deaths. The majority of these deaths were due to ischemic heart disease (IHD), cerebrovascular disease, chronic obstructive pulmonary disease (COPD) and lung cancer (Cohen et al., 2017). In many urban environments in high-income countries the most important local contributor to air pollution is exhaust emission from internal combustion engines of road vehicles, especially heavy duty diesel powered vehicles. The exhaust contains large amounts of ultrafine particles and nitrogen oxides (NO_x) as well as other toxics, but contributes only moderately to the local levels of total mass of $PM_{2.5}$, which mostly derive from other sources, including biomass combustion and long-range transport of secondary particles (Jensen et al., 2017a). In order to estimate the health impact of local traffic emissions, the nitrogen dioxide (NO_2) level can serve as a proxy of exposure to the combined traffic-related air pollution (European Environment Agency, 2016). The concentrations of NO_2 can be modelled with high resolution at address level and a number of cohort studies provide robust exposure-response functions for mortality and morbidity (Andersen et al., 2011, 2012a, 2012b, 2012c; Beelen et al., 2014; Faustini et al., 2014; Hamra et al., 2015; Raaschou-Nielsen et al., 2010, 2011, 2012, 2013a, 2013b; Roswall et al., 2017). The use of NO_2 exposure also allows assessment of impact of scenarios aiming at reducing traffic related emissions by e.g. environmental zones, road pricing or substituting car-based transport with public or active transport (Johansson et al., 2017). HIA models that use mortality data only underestimate the true health consequences of air pollution by disregarding the consequences related to morbidity. Only a few studies included both mortality and morbidity, for instance an assessment of traffic-related air pollution in Austria, France, and Switzerland (Künzli et al., 2000). Also the Global Burden of Disease study estimates disability-adjusted life years attributable to air pollution (https://vizhub.healthdata.org/gbd-compare/).

In this study the health impact assessment model, DYNAMO-HIA (Boshuizen et al., 2012; Lhachimi et al., 2012), was used to quantify the potential health impact of reducing exposure to traffic-related air pollution assessed as NO_2 in Copenhagen Municipality. The model combines micro-simulation of the exposure information with macro-simulation of diseases, and allows users to assess detailed exposure simulations without the need for large simulated populations because of the relative rareness of chronic disease events. The exposure-response functions used in this study were mainly derived from the large Danish Diet, Cancer and Health cohort study (Tjønneland et al., 2007) addressing total mortality, diabetes, cardiovascular diseases, and respiratory diseases in relation to residential NO_2 concentrations (Andersen et al., 2011, 2012a, 2012b, 2012c; Roswall et al., 2017). The exposure-response function for mortality from this study is very similar to the meta-analysis derived estimate from other European and global cohort studies (Faustini et al., 2014; Hamra et al., 2015). Furthermore, the Danish cohort study (Tjønneland et al., 2007) based on local cohorts (Copenhagen and Aarhus) allowed us to use gender specific exposure-response functions.

The aim of the study was to quantify health effects of air pollution in Copenhagen Municipality and to explore scenarios quantifying the effect of exposure reduction on incidence and prevalence of diseases, life expectancy and disease-free life expectancy. Moreover, the study demonstrates the usefulness of the DYNAMO-HIA model in traffic planning and the results might be important also for other cities in Europe and worldwide.

2. Materials and methods

2.1. DYNAMO-HIA

The DYNAMO-HIA model is a Markov-type multi-state simulation software that estimates the effects of change in risk factor exposure on population health by comparing intervention scenarios to a reference scenario (Boshuizen et al., 2012; Lhachimi et al., 2012). An intervention scenario is defined by changing the prevalence of risk factor exposure and/or by modifying transition rates between risk factor exposure states. The reference scenario represents business-as-usual without changes in exposure. Health effects are modelled by linking risk factor exposure with disease incidence and mortality by use of relative risk estimates.

The model requires input data on population size and number of future new-borns, data on incidence and prevalence of diseases, cause specific and all-cause mortality, prevalence of risk factor exposure and relative risks for associations between exposure and specific diseases and all-cause mortality. Model output is future risk factor exposure, disease incidence and prevalence, mortality rates, life expectancy and summary measures of population health such as disease-free life expectancy and disability-adjusted life expectancy. The output for the whole population represents the reference and intervention scenarios, and the differences between the reference and an intervention scenario represents the consequences of change due to the intervention. Output is presented as development over time for the population and can be scrutinized by age and gender for each calendar year. Migration is ignored in the model calculations and for populations with a sizable migration this should be accounted for. The specifications of the model have been described in detail elsewhere (Boshuizen et al., 2012; Lhachimi et al., 2012).

2.2. Data

The population of Copenhagen Municipality comprised 569.600 people in 2014 with a projected 2040-population size of 755.000. The DYNAMO-HIA model for Copenhagen Municipality including local data on several (lifestyle) risk factors and diseases has been implemented previously (Holm et al., 2014). The model has not been used to assess the potential impact on diseases and mortality from reduced exposure to air pollution. In this study the focus was on health benefits of reduced exposure to traffic related air pollution assessed as NO_2 exposure.

The implementation of the DYNAMO-HIA model for the population of Copenhagen Municipality utilized the Danish national registers. In particular, demographic data and data on disease incidence and prevalence, and mortality for people living in Copenhagen were extracted from Statistics Denmark (Statistics Denmark, 2014), The Danish National Patient Register (Schmidt et al., 2015), and the National Diabetes Register (Carstensen et al., 2011). Cause-specific mortality statistics were obtained from the Danish Register of Causes of Death (Helweg-Larsen, 2011).

Data on prevalence and incidence of IHD (ICD-10: I20-I25) and stroke (ICD10: I60-I69, G45) were obtained from the Danish National Patient Register, which holds data on all hospital contacts since 1979 (inpatient, and since 1995 outpatient and emergency). Respiratory diseases included were COPD (ICD-10 codes: J44 and for hospitalizations J96 with J44 as secondary diagnosis), asthma (ICD-10 codes: J45-J46), and lung cancer (ICD-10 codes: C33-C34). Data on prevalence and incidence of diabetes were obtained from the National Diabetes Register, which combines information on all persons registered with diabetes from other Danish national registers, since 1995 (Danish National Patient Register, The Danish National Prescription Registry, and The Danish National Health Service Register). The National Diabetes Register does not distinguish between type 1 and type 2 diabetes, but in the older age groups, described here, it can be assumed that the majority of incident cases are type 2 diabetes. Because the

National Diabetes Register comprises no data after 2012, incidence and prevalence were estimated based on data before 2013.

Disease incidence was defined as all new cases identified during the period 2010–2014 (2008–2012 for diabetes) among persons with no previous record of the specific disease ten years preceding and who had lived in Copenhagen Municipality at some time within this period. Prevalence of a given disease among persons alive and living in Copenhagen on 1 January 2014 (31 December 2012 for diabetes) was defined as the number of persons with at least one record of that disease in the relevant register in the period 2000–2014 (1998–2012 for diabetes). For every disease excess mortality rates were calculated as the mortality rates of persons with the disease minus the mortality rates of persons without the disease among persons living in Copenhagen Municipality sometime within the period 2010–2014 (2008–2012 for diabetes).

The relative risk estimates linking NO_2 exposure with the selected diseases were obtained from local epidemiological studies on health effects related to long-term exposure to NO_2 based on a large Danish Diet, Cancer and Health cohort, with over 50,000 subjects recruited in the period 1993–97 from the two largest urban areas of Denmark, Copenhagen and Aarhus (Tjønneland et al., 2007). The relative risk estimates were based on a long-term exposure to NO_2 at residence, defined as a 30–39 years mean of annual NO_2 levels at residential addresses, between 1971 and end of follow-up in 2006, 2009, or 2010, in different studies (see Table 1), taking account of changes in addresses. The relative risks of an annual average increment of the NO_2 concentration by 1 μg/m^3 for diabetes, IHD, stroke, COPD, asthma, and lung cancer are shown in Table 1. The effect on mortality caused by NO_2 exposure was calculated through the excess mortality due to the diseases under study and all-cause mortality (Raaschou-Nielsen et al., 2012). Dynamo-HIA splits all-cause mortality into disease-related mortality (i.e. the diseases included in the model) and other mortality. The relative risk of all-cause mortality is used to calculate for each gender and age group a relative risk for other mortality. This is done by subtracting the disease-related mortality from the all-cause mortality at each risk factor level to obtain the other cause mortality. Finally, relative risks are divided into the other mortality at the reference level.

The Danish Diet, Cancer and Health cohort study allowed estimation of gender specific relative risks and to present results both for relative risks combined and for gender specific estimates. The reason for adding results from a model with gender specific relative risks was for taking into account that men and women have different underlying mortality and morbidity rates for all diseases under study, that activity patterns differs between genders implying different exposure to air pollution as well as gender differentials in underlying susceptibility to effects of air pollution.

DYNAMO-HIA allows the prevalence of one disease to increase the risk of other diseases. The risk of IHD and stroke is elevated among persons with diabetes, and this was modelled by including relative risks from meta-analyses causally relating diabetes to IHD (Peters et al., 2014a) and stroke (Peters et al., 2014b). Because only a small part of the population has diabetes the relative risks for IHD and stroke were not adjusted for diabetes (the double counting is negligible).

NO_2 exposure was modelled by use of chemistry transport models to calculate contributions from emission sources to air pollution and is a subset from an earlier, nationwide air quality map. The annual mean concentration of NO_2 in 2012 was modelled within an air quality mapping of all Danish addresses to provide information to the general public as well as authorities, and to serve as a screening tool for air quality assessment. As described in Jensen et al. (2017b) a multi-scale modelling approach was used to estimate air pollution at address level by a hierarchical model where the output of regional background estimates were used as input for urban background modelling, providing input to estimate street concentrations. The national address dataset (2010 levels) used was thinned out to reduce the calculation time of the street concentrations, considering mainly buildings nearby road links

Table 1
Relative risks per μg/m^3 increase of annual average NO_2 concentration.

Disease incidence	RR	RR		Reference
	Men and women combined	Men	Women	
Diabetes	1.008	1.002	1.014	Andersen, Z.J., Raaschou-Nielsen, O., Ketzel, M., Jensen, S.S., Hvidberg, M., Loft, S., Tjønneland, A., Overvad, K., Sørensen, M., 2012. Diabetes Incidence and Long-Term Exposure to Air Pollution. A cohort study. *Diabetes Care* 35, 92–98.
Ischaemic Heart Disease (IHD)[a]	1.010	1.014	1.003	Roswall, N., Raaschou-Nielsen, O., Ketzel, M., Gammelmark, A., Overvad, K., Olsen, A., Sørensen, M., 2017. Long-term residential road traffic noise and NO2 exposure in relation to risk of incident myocardial infarction - A Danish cohort study. *Environmental Research* 156, 80–86.
Stroke[a]	1.009	1.005	1.011	Andersen, Z.J., Kristiansen, L.C., Andersen, K.K., Olsen, T.S., Hvidberg, M., Jensen, S.S., Ketzel, M., Loft, S., Sørensen, M., Tjønneland, A., Overvad, K., Raaschou-Nielsen, O., 2012. Stroke and Long-Term Exposure to Outdoor Air Pollution From Nitrogen Dioxide: A Cohort Study. *Stroke* 43, 320–325. Supplemental Material, ALL STROKE.
COPD	1.013	1.016	1.012	Andersen, Z.J., Hvidberg, M., Jensen, S.S., Ketzel, M., Loft, S., Sørensen, M., Tjønneland, A., Overvad, K., Raaschou-Nielsen, O., 2011. Chronic Obstructive Pulmonary Disease and Long-Term Exposure to Traffic-related Air Pollution. A Cohort Study. *American Journal of Respiratory and Critical Care Medicine* 183, 455–461.
Asthma[b]	1.021	1.033	1.016	Andersen, Z.J., Bønnelykke, K., Hvidberg, M., Jensen, S.S., Ketzel, M., Loft, S., Sørensen, M., Tjønneland, A., Overvad, K., Raaschou-Nielsen, O., 2012. Long-term exposure air pollution and asthma hospitalisations in older adults: a cohort study. *Thorax* 67, 6–11.
Lung cancer	1.008	1.008	1.008	Raaschou-Nielsen, O., Andersen, Z.J., Hvidberg, M., Jensen, S.S., Ketzel, M., Sørensen, M., Loft, S., Overvad, K., Tjønneland, A., 2011. Lung cancer incidence and long-term exposure to air pollution from traffic. *Environmental Health Perspectives* 119, 860–5.
All-cause mortality	1.008	1.015	1.003	Raaschou-Nielsen, O., Andersen, Z.J., Jensen, S.S., Ketzel, M., Sørensen, M., Hansen, J., Loft, S., Tjønneland, A., Overvad, K., 2012. Traffic air pollution and mortality from cardiovascular disease and all causes: a Danish cohort study. *Environmental Health* 11, 60.

[a] The risk of IHD and stroke is elevated among persons aged 40+ with diabetes: RR for IHD is 1.85 and 2.63 for men and women, respectively, and for stroke 1.83 and 2.28 for men and women. (Peters et al., 2014a; Peters et al., 2014b).
[b] RR = 1 for age ≤ 30.

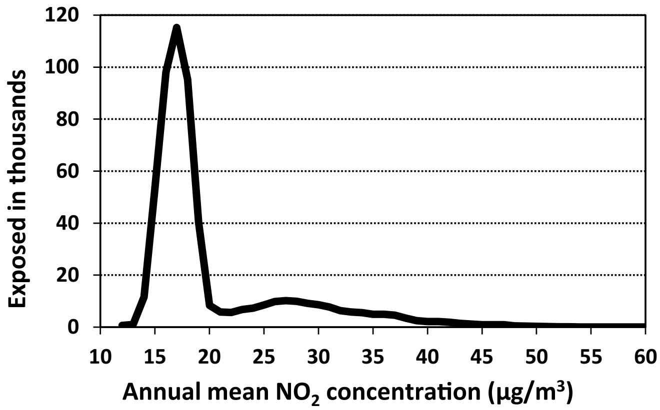

Fig. 1. Number of persons exposed to NO_2 in Copenhagen Municipality.

and using a minimum annual average daily traffic of > 500 vehicles. Buildings that had not been considered for the street concentration model were assigned with the corresponding urban background value (Berkowicz, 2000).

The annual mean NO_2 concentration was 19.6 µg/m^3. Fig. 1 shows the distribution of exposure to NO_2. The majority (70%) of the population was exposed to a concentration between 15 and 21 µg/m^3. Fig. 2 shows the distribution by age of annual mean exposure (and standard deviation). The mean concentration varied between 18.5 µg/m^3 and 20.5 µg/m^3 and was highest among young adults (age 20–30), where the NO_2 concentration exceeded 20 µg/m^3. This may reflect that a high share of young people, mainly students, with low income settle for cheap and poorly situated dwellings.

Fig. 3 illustrates the dynamic demographics in Copenhagen Municipality in 2013, with immigration of young adults in their early 20s, and emigration for older age groups, which stresses the relevance of taking migration into account in the analyses and interpretations of long-term health effects of exposure and interventions. As mentioned above, the relative risk estimates used in this study are based on the average NO_2 concentrations for over 30 years, which takes into consideration moving patterns of the study population. The graphs in Figs. 2 and 3 are shown for both genders as no gender difference could be observed (or expected).

The effects of NO_2 exposure on the morbidity and mortality for the population of Copenhagen in terms of risk of diabetes, IHD, stroke, COPD, asthma, and lung cancer were estimated by DYNAMO-HIA. The presented results for 2040 take into account the forecasted change in population size as reported by Statistics Denmark (http://www.statistikbanken.dk). The reference scenario was compared with two scenarios: 1) reduction of NO_2 to the minimum level of 6 µg/m^3 (the

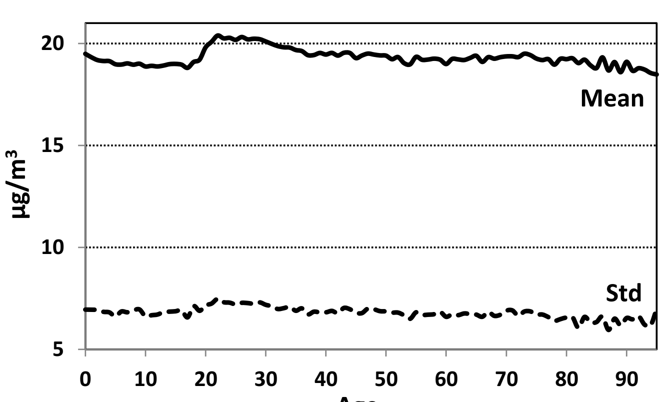

Fig. 2. Annual mean NO_2 concentrations and standard deviation (Std) by age in Copenhagen Municipality.

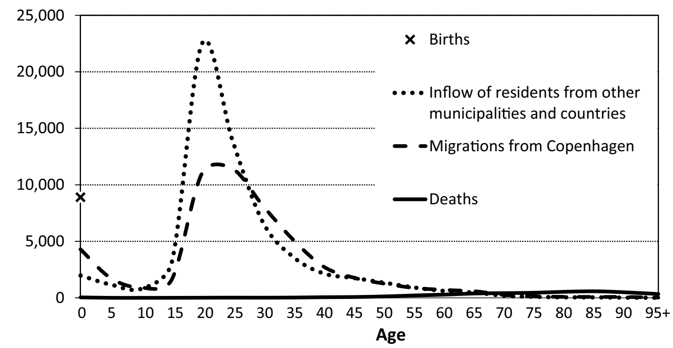

Fig. 3. Migrations into and out from Copenhagen Municipality in 2013.

lowest NO_2 concentration measured in rural areas of Denmark, at station Roskilde), and 2) a reduction of NO_2 exposure by 20%, equivalent to an annual mean NO_2 concentration of 15.7 µg/m^3.

3. Results

The impact of reducing exposure to traffic-related air pollution assessed by NO_2 as indicator on disease incidence and prevalence is shown in Table 2A (with no division of relative risk estimates by gender) and Table 2B (with gender specific relative risk estimates) for the calendar year 2040. It appears from Table 2A that diabetes incidence would be reduced by 35 cases (8.6%) per 100.000 for men and by 29 cases (9.1%) for women if NO_2 concentration was reduced to the level of rural areas (6 µg/m^3). The prevalence of diabetes would be reduced by 543 (8.0%) and 451 (8.2%) per 100.000 for men and women, respectively (Table 2A). The considerable gender difference in diabetes incidence shown in Table 2B (8 cases (2.0%) per 100.000 for men and 49 cases (15.4%) per 100.000 for women) reflects the difference in the risk of diabetes in the model with gender specific relative risks (Table 1). The prevalence of diabetes would be reduced by 125 (1.8%) and 780 (14.1%) per 100.000 for men and women, respectively (Table 2B). The impact of reducing NO_2 concentration by 20% would be around 10 fewer new diabetes cases per 100.000 among both men and women in the model with combined relative risks (Table 2A), whereas it would be a reduction of 2 and 15 new cases in the model with gender specific relative risks (Table 2B). The gender difference in diabetes was reversed for IHD. Thus, for the 20% reduction scenario incidence would be reduced by 19 (4.2%) and 5 (1.5%) incident cases per 100.000 for men and women, respectively. The prevalence of IHD would be reduced by 261 (4.2%) and 63 (1.4%) per 100.000 (Table 2B).

For men, the largest effect on disease incidence from reduced NO_2 exposure was seen for IHD, COPD and asthma, whereas for women it was for diabetes, stroke and COPD. Reduction in lung cancer incidence was low compared with the other chronic diseases, and due to high mortality among individuals with lung cancer, the prevalence was relatively low too.

Table 3A and B present life expectancy and disease-free life expectancy for the reference population and for the two scenarios with NO_2 reductions. According to the model with no division of relative risks by gender, life expectancy would increase by 1.1 years for both genders if NO_2 exposure was reduced to rural level (Table 3A). Disease-free life expectancy would increase by 1.4 years without IHD for both genders and by 1.5 and 1.6 years without COPD for men and women, respectively. The gain of asthma-free life expectancy would be 1.3 and 1.5 years for men and women (Table 3A). If NO_2 exposure was reduced by 20% the gain in life expectancy was 0.3 years for both genders and the disease-free life expectancy would be between 0.4 and 0.5 years for the different diseases (Table 3A). According to the model with gender specific relative risks life expectancy would increase by 2.0 years for men and by 0.4 years for women if NO_2 exposure was reduced to rural level, and by 0.6 and 0.1 years, respectively after a reduction of NO_2 by

Table 2A
Disease incidence and prevalence in Copenhagen Municipality 2040 in the reference population and decrease after two scenarios in reduction of NO_2 exposure. Model with no division of relative risks by gender.

Health benefits	Reference population (adjusted by forecast of Statistics Denmark)		Minimum exposure (NO_2 concentration 6 μg/m^3)		NO_2 concentration reduced by 20%	
	Disease incidence per 100.000		Reduction in disease incidence (cases) per 100.000			
	Men	Women	Men	Women	Men	Women
Diabetes	406	318	35 (8.6%)	29 (9.1%)	10 (2.5%)	9 (2.8%)
IHD	448	325	51 (11.4%)	38 (11.7%)	15 (3.3%)	11 (3.4%)
Stroke	400	371	42 (10.5%)	39 (10.5%)	13 (3.3%)	12 (3.2%)
COPD	416	350	60 (14.4%)	50 (14.3%)	18 (4.3%)	15 (4.3%)
Asthma	165	212	19 (11.5%)	27 (12.7%)	6 (3.6%)	9 (4.2%)
Lung cancer	92	77	9 (9.8%)	7 (9.1%)	3 (3.3%)	2 (2.6%)

Health benefits	Reference population (adjusted by forecast of Statistics Denmark)		Minimum exposure (NO_2 concentration 6 μg/m^3)		NO_2 concentration reduced by 20%	
	Disease prevalence per 100.000		Reduction in disease prevalence (cases) per 100.000			
	Men	Women	Men	Women	Men	Women
Diabetes	6784	5528	543 (8.0%)	451 (8.2%)	162 (2.4%)	134 (2.4%)
IHD	6290	4602	678 (10.8%)	510 (11.1%)	204 (3.2%)	154 (3.3%)
Stroke	4879	4427	489 (10.0%)	436 (9.8%)	147 (3.0%)	131 (3.0%)
COPD	5569	4891	735 (13.2%)	648 (13.2%)	225 (4.0%)	198 (4.0%)
Asthma	5234	7160	320 (6.1%)	476 (6.6%)	103 (2.0%)	153 (2.1%)
Lung cancer	1183	1107	112 (9.5%)	104 (9.4%)	34 (2.9%)	31 (2.8%)

IHD – ischemic heart disease, COPD – chronic obstructive pulmonary disease.

Table 2B

Disease incidence and prevalence in Copenhagen Municipality 2040 in the reference population and decrease after two scenarios in reduction of NO_2 exposure. Model with gender specific relative risks.

Health benefits	Reference population (adjusted by forecast of Statistics Denmark)		Minimum exposure (NO_2 concentration 6 μg/m^3)		NO_2 concentration reduced by 20%	
	Disease incidence per 100.000		Reduction in disease incidence (cases) per 100.000			
	Men	Women	Men	Women	Men	Women
Diabetes	406	318	8 (2.0%)	49 (15.4%)	2 (0.5%)	15 (4.7%)
IHD	448	325	62 (13.8%)	18 (5.5%)	19 (4.2%)	5 (1.5%)
Stroke	400	371	20 (5.0%)	50 (13.5%)	6 (1.5%)	15 (4.0%)
COPD	416	350	72 (17.3%)	47 (13.4%)	22 (5.3%)	14 (4.0%)
Asthma	165	212	28 (17.0%)	21 (9.9%)	10 (6.1%)	7 (3.3%)
Lung cancer	92	77	8 (8.7%)	8 (10.4%)	2 (2.2%)	2 (2.6%)

Health benefits	Reference population (adjusted by forecast of Statistics Denmark)		Minimum exposure (NO_2 concentration 6 μg/m^3)		NO_2 concentration reduced by 20%	
	Disease prevalence per 100.000		Reduction in disease prevalence (cases) per 100.000			
	Men	Women	Men	Women	Men	Women
Diabetes	6788	5529	125 (1.8%)	780 (14.1%)	36 (0.5%)	240 (4.3%)
IHD	6281	4586	864 (13.8%)	210 (4.6%)	261 (4.2%)	63 (1.4%)
Stroke	4880	4429	261 (5.3%)	546 (12.3%)	76 (1.6%)	167 (3.8%)
COPD	5562	4894	884 (15.9%)	604 (12.3%)	273 (4.9%)	184 (3.8%)
Asthma	5231	7162	467 (8.9%)	374 (5.2%)	159 (3.0%)	117 (1.6%)
Lung cancer	1182	1108	111 (9.4%)	105 (9.5%)	33 (2.8%)	32 (2.9%)

IHD – ischemic heart disease, COPD – chronic obstructive pulmonary disease.

Table 3A

Life expectancy and disease-free life expectancy in years in Copenhagen Municipality 2040 in the reference population and after two scenarios in reduction of NO_2 levels. Model with no division of relative risks by gender.

	Reference population		Minimum exposure (NO_2 concentration 6 μg/m^3)		NO_2 concentration reduced by 20%	
	Men	Women	Men	Women	Men	Women
Life expectancy	76.6	81.4	77.7	82.4	76.9	81.7
Without diabetes	69.8	75.1	71.1	76.4	70.2	75.5
Without IHD	70.1	75.7	71.5	77.1	70.5	76.1
Without stroke	71.6	76.0	72.8	77.2	71.9	76.3
Without COPD	71.3	75.8	72.8	77.4	71.7	76.3
Without asthma	72.8	75.7	74.1	77.2	73.2	76.2
Without lung cancer	75.3	79.9	76.4	81.1	75.6	80.3

Table 3B

Life expectancy and disease-free life expectancy in years in Copenhagen Municipality 2040 in the reference population and after two scenarios in reduction of NO_2 levels. Model with gender specific relative risks.

	Reference population		Minimum exposure (NO_2 concentration 6 μg/m^3)		NO_2 concentration reduced by 20%	
	Men	Women	Men	Women	Men	Women
Life expectancy	76.6	81.4	78.6	81.8	77.2	81.5
Without diabetes	69.8	75.1	71.3	76.3	70.2	75.4
Without IHD	70.1	75.7	72.3	76.3	70.7	75.9
Without stroke	71.6	75.9	73.2	76.9	72.0	76.2
Without COPD	71.3	75.8	73.6	76.8	72.0	76.1
Without asthma	72.8	75.7	75.1	76.5	73.5	75.9
Without lung cancer	75.3	79.9	77.2	80.4	75.9	80.1

20% (Table 3B). Among men, the gain in disease-free life expectancy would be greatest for lifetime without IHD (2.2 years), COPD (2.3 years), and asthma (2.3 years) if NO_2 exposure was reduced to rural level (Table 3B). The greatest gain among women would be for lifetime without diabetes (1.2 years) and without stroke (1.0 years). Lowering NO_2 exposure by 20% would increase disease-free life expectancy by 0.4–0.7 years for men and by 0.2–0.4 years for women due to lower prevalence of the diseases (Table 3B).

4. Discussion

This study quantifies the potential health gain in terms of reduction in incidence and prevalence of diabetes, cardiovascular and respiratory diseases, achieved by two scenarios of lowering NO_2 exposure. NO_2 reductions were used as a proxy for overall reductions in air pollution mainly due to exhaust emissions from vehicles. The population of Copenhagen Municipality was exposed to annual average NO_2 concentrations varying between 18.5 and 20.5 μg/m^3. If the exposure was reduced to the level of rural areas (6 μg/m^3), the average life expectancy and disease-free life expectancy would increase markedly. The model with gender specific relative risks showed considerable gender differences of the impact of NO_2 exposure on life expectancy and occurrence of diseases, particularly diabetes, IHD, and stroke.

The impact of active tobacco smoking and exposure to exhaust emissions (as assessed by NO_2) can be compared, since both have similar toxicological properties and lead to similar adverse health effects as the diseases included in the model. While exposure to smoking is confined mostly to active smokers and those passively exposed, NO_2 exposure is ubiquitous affecting all citizens, and thus resulting in significant burden on population health. A previous study based on the DYNAMO-HIA model, estimated the potential health effects of intervention against smoking in Copenhagen Municipality. If an intervention against smoking could reduce the smoking prevalence from 21% in 2010 to 4% in 2025, then the life expectancy would increase by 1.2 years for men and by 0.9 years for women (Holm et al., 2014). The same study found that the reduction of the prevalence of cigarette smoking to 4% in 2040 would reduce prevalence of lung cancer by 606 per 100.000 and of COPD by 334 per 100.000 in men.

Because exposure to traffic-related air pollution was only assessed as NO_2 exposure in this study, the health effects might have been underestimated. However, in a recent study from Sweden similar estimates of health improvements by shifting car traffic to active transport (cycling, public transport, walking) were derived using modelled NO_2, NO_x or black carbon for population exposure (Johansson et al., 2017). In urban setting with vehicle emission as the dominant local source of particulate matter, black carbon represents mainly the particulate emissions from vehicles. Nevertheless, it is almost impossible to capture all air pollution components in the complex interaction of particles and gasses/chemicals. NO_2-related exposure has been associated with other diseases than those included here, such as dementia, but the evidence on exposure-response relationships is still mixed and weak. On the other hand, as NO_2 exposure is considered the main contributor to traffic-related air pollution, the results are relevant for urban traffic planning. In this respect it should also be taken into account that road traffic noise which is closely related to traffic air pollution, also increases the risk of myocardial infarction and stroke (Sørensen et al., 2011, 2012).

An important strength of this study is the use of exposure-response relationships derived from the same population and area as the target population for the HIA, which gives high credibility. The exposure-response estimates used for mortality related to NO_2 are almost identical to the meta-analysis-based estimate from other similar European cohort studies (Faustini et al., 2014). Moreover, the traffic-derived input data for exposure assessed as NO_2 for both exposure-response relationships and HIA in Copenhagen Municipality were essentially the same (Jensen et al., 2017b). Thus, changes in traffic patterns with subsequent potential reductions in NO_2 emissions can reliably be translated almost directly into improvement in health. The gender difference in disease pattern, mortality and activities related to various exposures probably lead to differential health risks related to air pollution. Because the Danish Diet, Cancer and Health cohort study made it possible to estimate gender specific relative risks with a notable difference for some diseases we presented results from models both with and without division of relative risks by gender.

We implemented the DYNAMO-HIA model to the population of Copenhagen Municipality with high quality data on hospitalisation and mortality rates from nationwide registers. Air pollution was based on NO_2 concentration at each address aggregated to annual average exposure. The model calculations integrated the excess death rates among those suffering from the diseases, however, no overall trends in future mortality, which might be expected to follow the past decline, were included in the calculations. Thus, the future gender and age specific all-cause mortality rates were held constant for the reference population as well as for the scenario populations except for the impact of NO_2-related exposure.

A challenge in using the DYNAMO-HIA is how to take into account the potential effects on population health of changes in social and structural health determinants and community level policy, and in particular how to handle migration between geographical areas and explicitly quantify potential differential effects. The dynamic demography of Copenhagen Municipality with renewal of young adults (Fig. 3) and movements between districts within Copenhagen and between inner Copenhagen and suburb areas with different exposure levels, imply that exposure level would not be permanent or long-lasting for all citizens. Thus, the full latent period with the same specific level of exposure will not be experienced for many individuals in the population. In the current model no adjustment was made for demographic changes. However, the strength of our approach is in using relative risk estimates based on long-term exposure to NO_2 at residence for over 30–35 years, which accounted for moving and changing in residential address for a large population of Copenhagen Municipality. These relative risks represent 'real' exposures over many years, which are facilitated by data available from Danish Central Population registry on address changes since 1971, not possible elsewhere in Europe or globally. The modelled NO_2 exposure was assessed as the concentration at the front door of all addresses in Copenhagen and may not represent indoor exposure. Furthermore, linking information on NO_2 exposure at work and other locations was not possible. Thus, the NO_2 exposure only substitutes the true individual exposure and may be subject to misclassification.

The conclusion of the study was that lowering the NO_2 exposure by reducing traffic-related air pollution would reduce incidence and prevalence of major chronic cardiovascular, respiratory and metabolic diseases and lung cancer, and increase disease-free life expectancy. The full potential of health gain by reducing NO_2 exposure level to that of rural areas would increase life expectancy in Copenhagen between one and two years for men and between a half year and one year for women. These results combined with previously recognized negative health effects of noise from road traffic are relevant to take account of in planning of future urban traffic.

Declarations of interests

None

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