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Health impacts of active commuters' exposure to traffic-related air pollution in Stockholm, Sweden

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ABSTRACT

Introduction: Addressing walking and cycling commuters, this study aimed to measure personal exposure to traffic-related air pollution and analyze the associated health risks.
Method: Diffusive NO_2-samplers were worn by 19 participants as they commuted to work in rush-hour traffic in May 2018 in Stockholm, Sweden (in total 336 trips, 197 h). The average NO_2-concentration per route was measured, and the health impacts were calculated based on previous epidemiological studies of the association between annual NO_2-exposure and premature death.
Result: The measured average concentration per route ranged from 48 to 105 $\mu gNO_2/m^3$, and the average 67 $\mu gNO_2/m^3$ was more than five times higher than the urban background. This corresponded to an annual mean exposure of 16.4 $\mu gNO_2/m^3$, 40% higher than the average exposure at other times. Thus, the increased risk for premature death was 3.3%, with a range of 1.9%–4.8%, as related to assumptions regarding breathing rates and risk relationships between NO_2-exposure and premature death. For active commuters in Stockholm in general, this indicated that one-fourth (23%) of the annual inhaled dose of NO_2 could be attributed to commuting, and that the risk for premature death increased by 2.5% (1.4%–3.7%) due to air pollution. Note that these results were indicative rather than precise. These relationships may be applicable to active commuters in other cities.
Conclusion: The results indicated that active commuting in Stockholm is associated with significant exposure to traffic-related air pollution and that this increases the risk of premature death. It is recommended that future studies consider longer time periods to assess active commuters' personal exposure with higher precision. Policy implications include greater separation between active commuters and motor traffic, and promotion of behavioral changes in favor of emissions free vehicles and active modes of transport.

1. Introduction

The way many urban areas are designed today, active commuting may involve substantial exposure to air pollution. This is incoherent with the SDGs regarding sustainable cities and communities (11) and good health and well-being (3). Globally, air pollution constitutes the greatest risk to human health (Greenstone and Fan, 2018). In the EU, air pollution is the main environmental cause of premature death, accounting for 400 000 deaths per year according to recent data (European Commission, 2017). In Sweden, air pollution reduces the life expectancy by about six months (Public Health Agency of Sweden, 2017). In the capital, Stockholm, it has been estimated that one thousand residents die prematurely each year as an effect of air pollution (Lövenheim, 2017).

The air pollutants that are most harmful to public health in Sweden are inhalable particulate matter (PM), nitrogen dioxide (NO_2), ground-level ozone and hydrocarbons, and of these, PM has the greatest health effects (Swedish Environmental Protection Agency, 2019; Public Health Agency of Sweden, 2017). However, NO_2 is often used as an indicator for other air pollutants from traffic (Hagenbjörk-Gustafsson, 2014). In urban areas, road traffic is the most important local air pollutant source (Public Health Agency of

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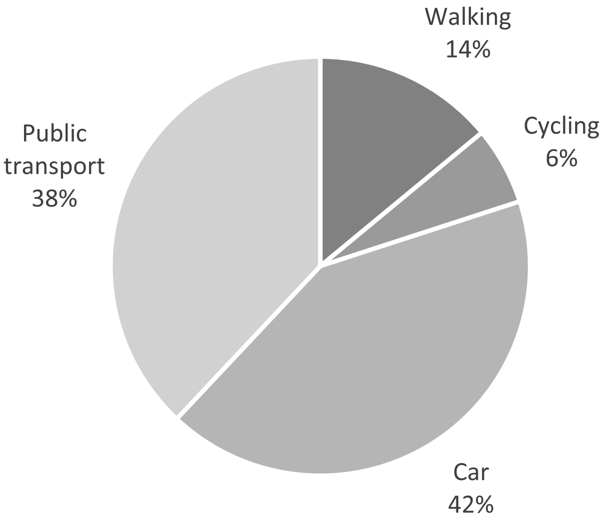

Fig. 1. Modal share of commuters in Stockholm County, with data obtained from Johansson et al. (2017). The total is 923,970.

Sweden, 2017).

Exposure to air pollution increases the overall mortality rate and the risk for cardiovascular and respiratory diseases (Anderson et al., 2012; Lee et al., 2014). PM causes oxidative stress and inflammation, and it decreases lung function and worsens respiratory symptoms (Anderson et al., 2012). Associations have been reported between airborne PM and diabetes, obesity, and chronic pulmonary disease (Dubowsky et al., 2006), and between exposure to NO_2 and lung cancer (Nyberg et al., 2000). Combined exposure of air pollutants and allergens may further cause additive effects on allergies and asthma (Baldacci et al., 2015). Air pollution also leads to lost working days and major healthcare costs (European Commission, 2017).

Walking and cycling to work contributes to achieve the SDGs related to good health, sustainable cities, and reduced climate impact. Active commuting is space-efficient, economical, and it does not cause negative externalities such as noise or air pollution. It allows for daily exercise, and it suits people who are not engaged in organized sports (Stigell, 2011). Most commuters on foot are physically active at least 150 min per week, WHO's recommendation (Stigell, 2011). Additionally, active commuting requires less infrastructure than motor traffic (Swedish Transport Administration, 2016). Healthy environments for active commuting are thus a requirement for sustainable transport. Since 2017, Sweden has a national strategy for increased and safe cycling (Swedish Government, 2017).

Stockholm is the most populous area in the Nordic countries, and the Stockholm region is one of the fastest growing in Europe (City of Stockholm, 2018a). About one-fifth of commuters in the city walk or cycle to work (Fig. 1) (Johansson et al., 2017). However, about one-third of car commuters has a bicycle journey of less than 30 min, indicating a large potential for increased active commuting (Johansson et al., 2017). The number of bicycle trips passing the city center was three times higher in 2018 than in 1980 (City of Stockholm, 2019). The city's target is that 15% of all journeys in rush-hour traffic will be made by bicycle in 2030, which would reduce traffic congestion (City of Stockholm, 2018b). However, from the commuter's perspective, it is not obvious that increased cycling complies with the SDG to reduce health impacts from air pollution (3.9).

Previous research has evaluated the health effects related to a modal shift from car to bicycle among commuters with a bicycle ride below 30 min to work in Stockholm (Nilsson et al., 2017; Johansson et al., 2017). This has complemented similar studies in other cities (Holm et al., 2012; Rojas-Rueda et al., 2011; de Hartog et al., 2010). Such studies are often based on interpolated maps of air pollution, which use traffic models and measurements at a limited number of static locations. Such maps may be underestimated in some areas, e.g., near tunnel openings, and they do not provide precise data regarding the doses inhaled by people who are moving in space. In order to more accurately assess the health effects related to commuting, it is therefore pertinent to measure *personal* exposure.

This study was conducted from the perspective of the active commuter. Personal exposure in rush-hour traffic was evaluated using diffusive samplers. Active commuters often travel close to motor traffic at times when it is most intense and they breathe air that has not been filtered, which is often the case for car travelers; lastly, they breathe relatively frequently because of the physical effort, and this increases the inhaled dose. Moreover, the measurements were made at times of the day when residents who work indoors are likely to be exposed to traffic-related pollution.

The research questions were:

- Which levels of traffic-related air pollution (indicator NO_2) are active commuters in Stockholm exposed to at rush-hour and how do they vary with different routes?
- How do these concentrations relate to the urban background air pollution concentration in Stockholm, i.e., the ambient level not affected by local sources?
- Which are the related health risk implications, considering previous epidemiological studies?

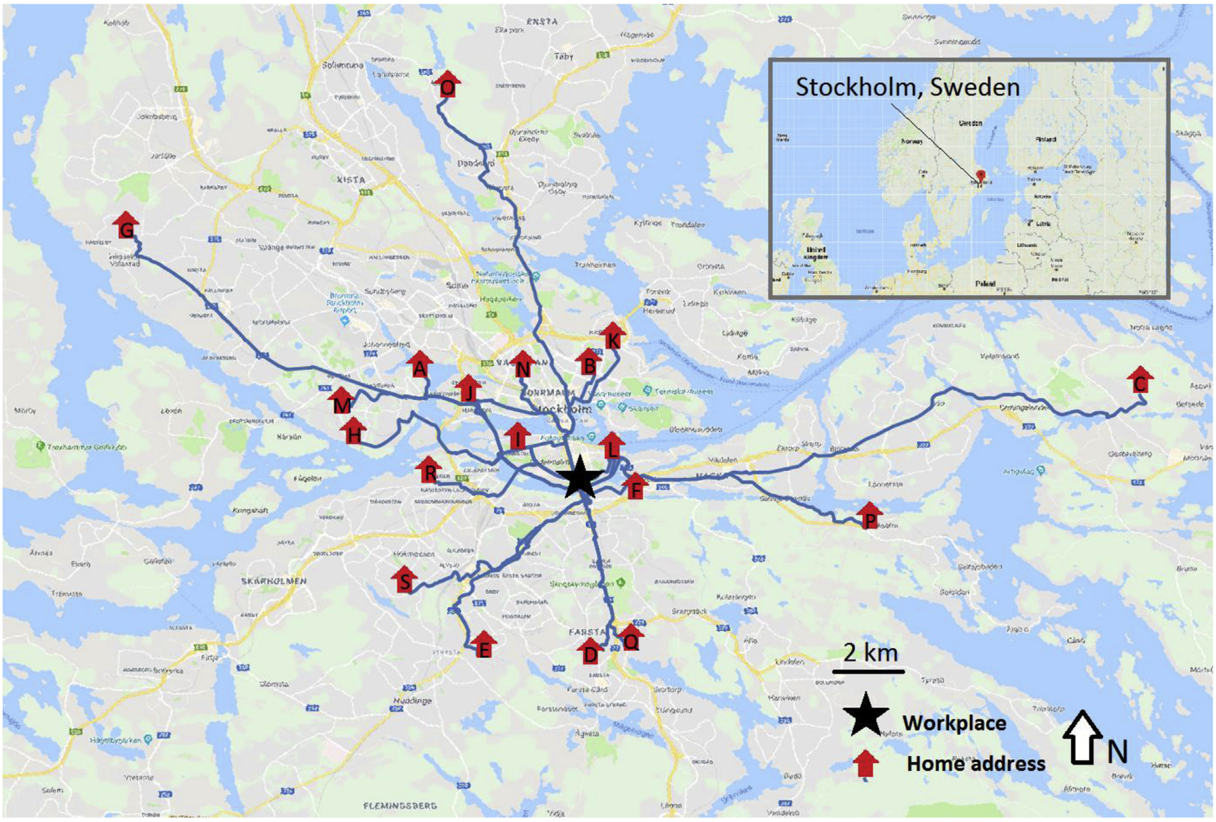

Fig. 2. Sampling routes. The star indicates the workplace and the red houses the residences. Each participant took the same route back and forth. The inset shows the location of Stockholm in Northern Europe. Base map ©2019 Google. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2. Methodology

This section outlines the sampling procedure and the methods used to calculate the health impacts for the participants and active commuters in Stockholm in general.

2.1. Diffusive NO_2-samplers

To measure exposure, diffusive (passive) IVL samplers were used, which contain an impregnated filter that adsorbs gas molecules due to molecular diffusion (Ferm and Svanberg, 1998; IVL Swedish Environmental Research Institute, 2018a, 2018b). The functioning of such diffusive samplers (low dose) has been further described in Ferm and Svanberg (1998). The average concentration of NO_2 for each route could be determined based on measures of the accumulated NO_2 in the samplers, the total sampling time, and the average temperature during sampling. Diffusive samplers are small and light, and they require no electricity or prior calibration, as described in further detail by Pienaar et al. (2015) and Hagenbjörk-Gustafsson (2014). Previous research based on this technology includes Carmichael et al. (2003), for example. The samplers were in total 25 mm in diameter and 12 mm in height. They were prepared and analyzed by IVL Swedish Environmental Research Institute, an accredited laboratory.

2.2. Sampling procedure

Volunteers were engaged through an internal recruitment campaign at the headquarters of the Folksam Insurance Group, which is located at Skanstull on the island Södermalm in central Stockholm (the star on Fig. 2). With regards to the sampling time, it was a prerequisite that the commutes took at least 20 min in one direction. The participants, fourteen bicyclists and five pedestrians, were recruited in order of application. They commuted to and from work and their places of residence. The same route was taken back and forth. Commutes included the inner city of Stockholm as well as suburbs (Fig. 2).

Each participant carried a brooch at chest level with two fixed diffusive samplers, filters pointing downward. The brooch was put on at the start of the commute, and it was removed when the journey was terminated. After each trip, the brooch was stored in an air and waterproof plastic jar (150 ml). In the jar lay also two tightly closed plastic cylinders (38 ml each) to minimize sampling of the surrounding air. Between uses, the plastic jar was stored in a traveling case to protect it from light.

For each commute, start and stop times and temperatures were recorded. Temperatures may affect the sampling rate (Ferm and Svanberg, 1998). The presented results were concentrations at Standard Temperature and Pressure (STP). In total, air was sampled for 336 commuting trips over nearly 197 h. The commutes occurred at times that are common for commuting in Stockholm, from 06:30 a.m. to 08:30 a.m., and from 3:30 p.m. to 6:00 p.m. Sampling was conducted as often as possible from April 27 to May 30 2018. In this period, temperatures at the time of commuting were generally within the range of 15 °C–25 °C. Sampling was not conducted during rainfall.

2.3. Health impact calculations

The health risk increase due to elevated levels of air pollution during commutes were calculated assuming that everything else was equal, including the level of physical exercise. The benchmark scenario was that the commutes would have taken place in environments with NO_2-concentrations corresponding to the average at other times. The time-weighted exposure per participant over a year was calculated in accordance with Orru et al. (2015):

$$E_i = \sum_{j=1}^{J} C_j \, t_{ij} \tag{1}$$

where E_i is the average exposure for person i; C_j is the pollutant concentration in environment j, e.g., at work or at home; t_{ij} is the time that person i spends in environment j; and J is the total number of environments for this individual.

In this study, two environments were considered ($J = 2$), commuting and otherwise, and a higher breathing rate during commutes than otherwise was accounted for. Based on *eq*. 1, each participant's annual average exposure, E_{annual_i}, was calculated as:

$$E_{annual\_i} = (C_{com\_i} v_i + C_{oth\_i}(1 - v_i))w + C_{oth\_i}(1 - w) \tag{2}$$

where C_{com_i} was the measured average NO_2 concentration for participant i during commutes; C_{oth_i} was the calculated average concentration at other times; v_i was the share of ventilation during commutes in an average workweek, as dependent on the commuting duration and the relative respiratory rate; and w was the annual proportion of workweeks.

The values for C_{com_i} and v_i were specified as the mean for each participant (Table 1), assuming a relative respiratory rate of three for all commuters. The latter was based on previous studies: minute ventilation at all times except during commutes was assumed to correspond to levels at rest, with 0.5 l/breath (Carroll, 2007) and 15 breathes/min, i.e., 7.5 l/min; and Zuurbier et al. (2009) reported that the respiration rate among cycling commuters was in average 23.5 l/min (n = 33), i.e., three times higher.

2.3.1. Participants

To calculate C_{oth_i}, an air pollution map of average annual NO_2-exposure in 2015 was examined in detail, focusing on the workplace and each commuter's home neighborhood (Fig. 3). The former was specified to 15 $\mu gNO_2/m^3$. Annual levels were generally between 5 and 20 $\mu gNO_2/m^3$. It was assumed that the time spent at home and at work during an average workday was 14 h and 9 h, respectively.

The risk increase was calculated from the difference between each participant's calculated average annual exposure, E_{annual_i}, and other concentration, C_{oth_i}. The risk relationship between NO_2-exposure and premature death was specified as 7% per 10 $\mu gNO_2/m^3$, as obtained from a meta-analysis of European studies in Faustini et al. (2014).

2.3.2. Active commuters in general in Stockholm

The measured concentrations were likely to be relevant for other active commuters in Stockholm, since the participants were selected randomly in order of application, and they worked at a large and representative employer in terms of its location near the city center. The sampled routes in Fig. 2 were compared to tracking data of cycling and running activity (Strava, 2019), which confirmed that the participants typically had traveled on common routes. However, their commutes lasted in average 36 min, while the mean in Stockholm is more likely to be 25 min, as inferred from data for 1872 active commuters reported by Stigell (2011).

Accounting for this, the annual exposure for active commuters in general in Stockholm, E_{annual_Sthlm} was calculated ($i = 1$ in eq. (2) and specified as *Sthlm*), and C_{oth_Sthlm} was set to the population-weighted annual average concentration in the City of Stockholm (Table 2). The benchmark scenario was that commuting would occur in environments with this level of exposure.

Table 1
Parameter values used in the health impact calculations for each of the participants.

Parameter	Description	Assumed value [unit]	Comment
C_{com_i}	Average concentration while commuting	Personal exposure as measured in this study [$\mu gNO_2/m^3$]	Average of two diffusive samplers
C_{oth_i}	Average concentration at all other times	Each participant's individual value, as calculated [$\mu gNO_2/m^3$]	Inferred from air pollution maps of yearly averages at the home address and the workplace (SLB-analys, 2018a)
v_i	Commuting's share of a workweek's total ventilation	Each participant's individual value [-]	Based on the commuting time, and an overall assumed relative breathing rate of three, as inferred from Zuurbier et al. (2009)
w	Annual proportion of workweeks	47/52 [-]	Five weeks of vacation annually was assumed

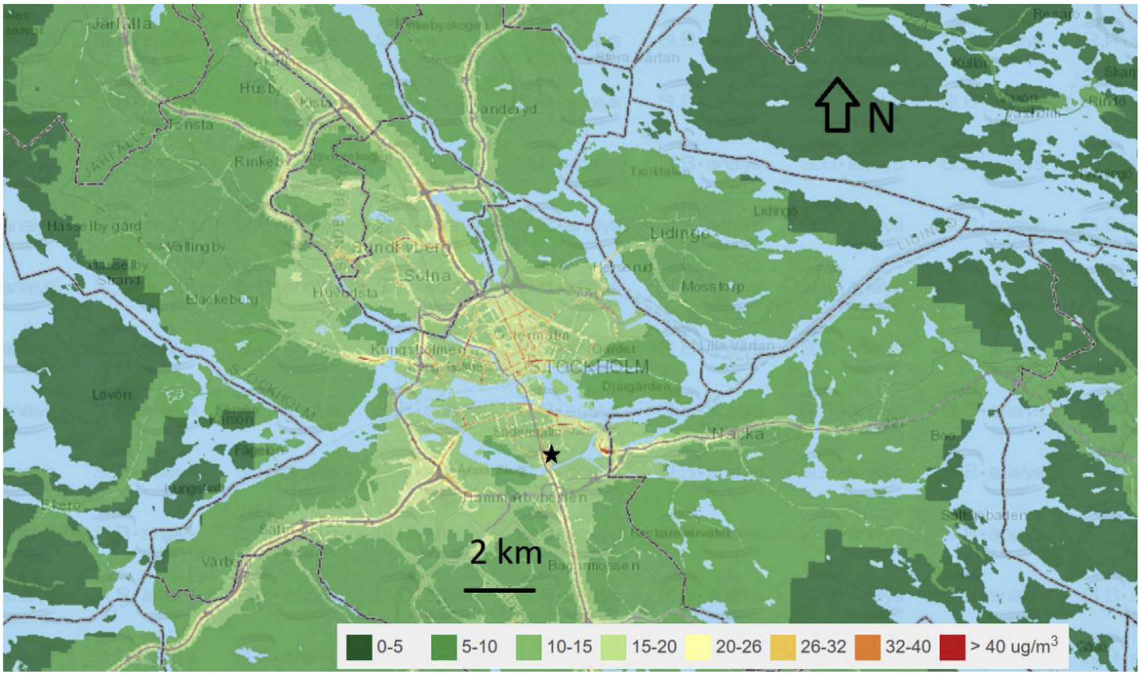

Fig. 3. Air pollution map of the annual average concentration of NO_2 in 2015. The star shows the workplace location. The map has been developed by Stockholms Luft-och Bulleranalys (SLB-analys) (2018a), as commissioned by Östra Sveriges Luftvårdsförbund. Base map powered by ©Esri.

Table 2
Parameter values used in the health impact calculations for active commuters in general in Stockholm.

Parameter	Description	Assumed value [unit]	Comment
C_{com_Sthlm}	Average exposure while commuting	Average of C_{com_i} [$\mu gNO_2/m^3$]	Average of the measured personal exposures
C_{oth_Sthlm}	Average exposure at all other times	12.1 [$\mu gNO_2/m^3$]	Population-weighted annual average concentration in the City of Stockholm (Lövenheim, 2017)
v_{Sthlm}	Commuting's share of a workweek's total ventilation	7 [%]	Assuming 25 min of commuting in one direction (Stigell, 2011) and a relative ventilation rate of three
w	Annual proportion of workweeks	47/52 [-]	Five weeks of vacation annually assumed

3. Results and discussion

This section presents the average measured concentration of NO_2 for each sampled route and the implicated health impacts for the participants and active commuters in general in Stockholm.

3.1. Air pollution exposure

All the participants commuted near motor traffic during at least a part of their commute (Fig. 4; Table 3). The route with the lowest and highest concentration was C-Gustavsberg with 48 $\mu gNO_2/m^3$, and R-Aspudden with 105 $\mu gNO_2/m^3$, respectively. For comparison, air pollution maps were examined (SLB-analys, 2018b) (Fig. 5) and it was noted that the average exposures for many of the participants were similar to the highest mean hourly average exposure in 2015 (98-percentile) at the most polluted locations in Stockholm, as indicated by the dark orange (72–90 $\mu gNO_2/m^3$) and red areas (> 90 $\mu gNO_2/m^3$) on Fig. 5.

The average personal exposure was 67 $\mu gNO_2/m^3$, which was more than five times higher than the average concentration at the urban background station in central Stockholm (12.2 $\mu gNO_2/m^3$) and the population-weighted annual average in Stockholm City (12.1 $\mu gNO_2/m^3$) (Lövenheim, 2017). The latter were like the participants' calculated average other exposure (11.7 $\mu gNO_2/m^3$) (Table 3). Note that these values also corresponded quite well with the estimated mean concentration for the general Swedish population (2000–2008), 14.1 $\mu gNO_2/m^3$, as measured by means of personal sampling using diffusive NO_2-samplers (Hagenbjörk-Gustafsson, 2014). For comparison, Bernmark et al. (2006) found that bicycle messengers in Stockholm were exposed to 51 $\mu gNO_2/m^3$ in average. This was slightly lower than the current result, which may relate to commuters traveling when motor traffic is relatively intense.

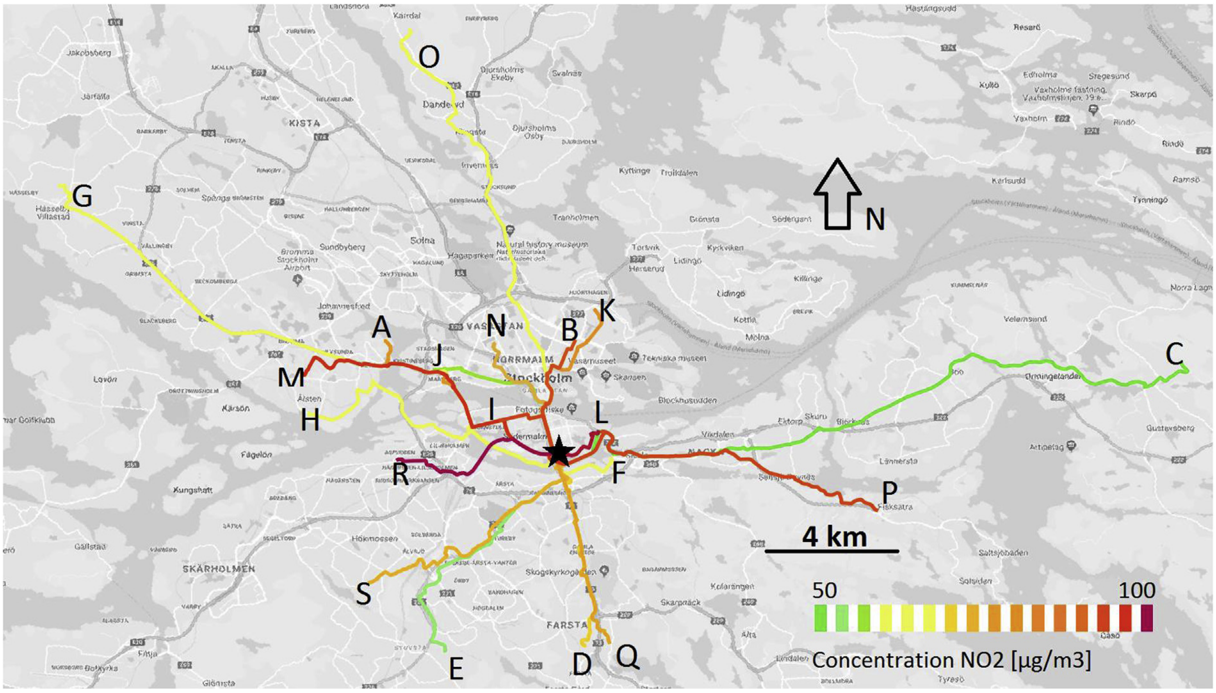

Fig. 4. Measured average level of NO_2 [μg/m^3] per route, with letters according to Table 3. The star shows the workplace location. Base map data ©2019 Google.

3.2. Health impacts

The participants' mean annual exposure, average E_{annual_i}, was 16.4 μgNO_2/m^3, which was 40% higher than their average annual concentration at other times, C_{oth_i} (11.7 μgNO_2/m^3) (Table 3). This suggested that their average risk of premature death was increased by 3.3% as compared to the benchmark scenario with commuting concentration C_{oth_i}. This value was sensitive to assumptions regarding the comparative breathing rate and the assumed risk relationship between annual NO_2-exposure and premature death. A lower estimate was 1.9%, assuming a relative breathing rate of two and a 6% risk increase per 10 μgNO_2/m^3 in annual exposure, and an upper estimate was 4.8%, assuming a relative breathing frequency of four and a risk relationship of 8%.

For active commuters in general in Stockholm the average annual exposure, E_{annual_Sthlm}, was calculated to 15.6 μgNO_2/m^3, 29% higher than the population-based average in the city. This indicated that nearly one-fourth (23%) of the annual inhaled amount of NO_2 may be attributed to commuting (32% per workweek). This result corresponded with Dons et al., (2012) reporting that transport accounted for 30% of the daily amount of Black Carbon inhaled by 62 individuals in Belgium. Current findings indicated that the risk for premature death in Stockholm among active commuters increases by 2.5% (range 1.4–3.7%) due to air pollution during commutes. A 2.5% higher mortality risk among active commuters in Stockholm implies eight premature deaths annually (ranging from four to eleven), considering the basic risk of premature death of 168/100,000 between the ages of 15–64 years (Public Health Agency of Sweden, 2018).

3.3. Comparison with car commuters

Previous findings have indicated that active commuters inhale higher levels of air pollution than commuters by car (Chaney et al., 2017; Apparicio et al., 2018; de Hartog et al., 2010). For example, Chaney et al. (2017) reported that inhaled doses of PM2.5 were 9 times higher for cyclists and 21 times higher for pedestrians than for car drivers in Salt Lake City, U.S.

Note that this does not imply that it is preferable from a health perspective to travel by car. Rojas-Rueda et al. (2012) reported that a change in travel mode from car to bicycle in Barcelona (n = 141 690) would result in an increase of 1 death due to air pollution and a reduction of 67 deaths thanks to increased physical activity. In a cohort study from the U.K. (n = 263 540), it was concluded that bicycle commuting, as compared to passive commuting by car or public transport, was associated with a 41% lower risk of premature death overall (Celis-Morales et al., 2017).

3.4. Recommended measures

It is suggested that the distance between active commuters and motor traffic increases, and that the emissions from exhaust are reduced. The first may be addressed by a greater separation between motor traffic and walking and bicycle paths, which has been

Table 3
The investigated commuting routes and measured concentrations, average of two samplers per route. *C = cycling, W = walking; **Based on air pollution maps of average annual NO_2-concentrations at the home address and the workplace (SLB-analys, 2018a), assuming five working days per workweek and work during all but five weeks per year.

	Place of residence*	n trips	Sampling time	Description of route	Average exposure [$\mu g NO_2/m^3$]			
					Commutes, measured C_{com_i}	Other**, calculated C_{oth_i}	Annual, calculated E_{annual_i}	Risk increase [%]
A	Bromma (C)	21	9 h 35min	Route that included the highway Road 275, with relatively high traffic intensity, and two heavily trafficked bridges, Tranebergsbron and Västerbron, as well as city roads with high traffic intensity, Hornsgatan and Ringvägen.	66.3	9.1	13.1	2.8
B	Östermalm (C)	22	8 h 53min	Central route along roads with low speed limits, but with relatively high traffic intensity.	73.3	16.4	19.9	2.5
C	Gustavsberg (C)	22	20 h 30min	A long route along roads with relatively low traffic intensity.	48.4	5.5	11.2	4.0
D	Hökarängen (C)	29	14 h 41min	Long stretch along the highway Road 73, which has a high traffic intensity; however, a noise barrier may have reduced exposure.	59.6	9.1	13.0	2.7
E	Stuvsta (C)	26	13 h 43min	Long stretch near Road 226, with a relatively high traffic intensity.	51.4	9.1	12.4	2.3
F	Hammarby Sjöstad (W)	13	6 h 15min	Route along Hammarby Avenue, a road with moderate traffic.	53.6	12.8	15.7	2.0
G	Hässelby Villastad (C)	18	15 h 20min	A large share of the route took place along the highway Road 275, with relatively high intensity traffic.	54.2	5.5	11.5	4.3
H	Ålsten (W, running)	8	10 h 10min	Route partly along a city highway, Essingeleden, and partly in a large green area, Tantolunden.	54.1	9.1	17.1	5.6
I	Hornsgatan (W)	8	4 h 10min	Central route along roads with low speed limits, but with high traffic intensity, Götgatan and Hornsgatan.	86.5	24.8	29.7	3.4
J	Thorildsplan (W)	19	18 h 55min	A central trip along roads with low speed limits, with traffic intensity that varied from relatively low to high levels at Hantverkargatan and Götgatan.	52.8	16.4	21.6	3.6
K	Gärdet (C)	15	6 h 59min	A central route in areas with medium traffic flow at Gärdet and Östermalm.	69.1	12.8	16.7	2.7
L	Londonviadukten (W)	13	4 h 21min	A central route along roads with relatively low traffic flow.	90.3	16.4	20.2	2.7
M	Abrahamsberg (C)	22	11 h 1min	Route close to high traffic flows along highway Road 275, two heavily trafficked bridges, Tranebergsbron and Västerbron, as well as Hornsgatan and Ringvägen, with high traffic flow.	78.9	9.1	14.4	3.7
N	Vasaparken (C)	22	9 h 23 min	A central route along roads with intense traffic in the city center, Fleminggatan and Munkbroleden.	70.6	12.8	16.5	2.6
O	Sollentuna (C)	11	10 h	Bicycle path along the highway E18 and a route through central Stockholm.	54.0	9.1	15.0	4.1
P	Fisksätra (C)	14	7 h 36 min	Long stretches along Värmdövägen and Saltsjöbadsvägen, with relatively low traffic flow.	76.6	9.1	14.6	3.8
Q	Sköndal (C)	22	11 h	A long stretch along the highway Road 73, which has a high traffic intensity; however, a noise barrier may have reduced exposure.	67.6	9.1	13.6	3.1
R	Aspudden (C)	12	4 h 20 min	A stretch close to the merging of two highways, E20 and Road 75, and along Hägerstensvägen and Ringvägen with relatively high traffic flows.	105.0	16.4	21.2	3.4
S	Älvsjö (C)	19	9 h 50 min	Route close to Road 226 with relatively high traffic flows.	64.7	9.1	13.5	3.1
	Total	**336**	**196 h 42 min**	**Average**	**67.2**	**11.7**	**16.4**	**3.3**

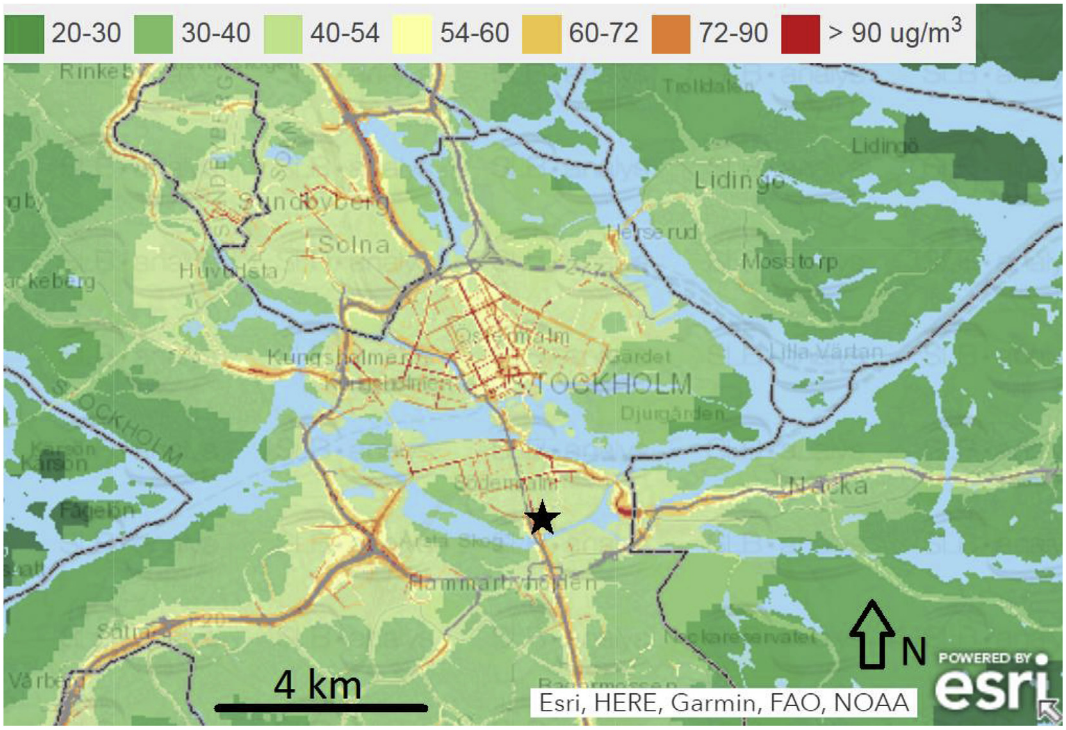

Fig. 5. Air pollution map of the hourly average concentration of NO_2 considering the 176:th most polluted hour in 2015 (98th percentile). The star indicates the workplace location. The map has been developed by SLB-analys (2018b), as commissioned by Östra Sveriges Luftvårdsförbund. Base map powered by ©Esri.

shown to have a significant impact on cyclists' exposure to air pollution (Boogaard et al., 2009; Apparicio et al., 2018; Cole-Hunter et al., 2012). Roorda-Knape et al. (1999) reported that concentrations of NO_2 and black smoke decreased rapidly within distances of around 100 m from the roadside in Delft in The Netherlands.

The second would likely be realized by means of a larger share of low-emission vehicles, such as electric or biogas-powered cars. Reduced rush-hour use of motor vehicles in the city center would also be effective, for example by transportation of goods during the night, using electric trucks. Heavy vehicles have a major impact on pollution. They account for about 40% of NO_x emissions on Hornsgatan in central Stockholm but only 3% of the traffic, according to the City of Stockholm (2013). Reduced exposure may also be achieved through mindful city planning; in King County, Washington, U.S., a 5% increase in walkability was associated with a 5.6% reduction of NO_x emitted, where walkability accounted for factors such as land use mix and street connectivity (Frank et al., 2007).

4. Limitations

As the results in this study are interpreted the issues discussed below should be considered.

4.1. Sampling

For feasibility, the study considered 19 commuters who worked at the same place and one month of sampling. The former caused an over sampling of routes near their employer, which was a shortcoming; then again, there was no reason to assume that the cycling and walking paths neighboring the headquarters of the Folksam Insurance Group were substantially different from other areas in Central Stockholm (Figs. 3 and 5).

The latter implied that sampling times were relatively short, 10 h in average (Table 3), while diffusive samplers are generally used 24 h or longer (Yu et al., 2008). However, for 8 h sampling, IVL samplers have a detection limit of 9 $\mu gNO_2/m^3$ (Lewné et al., 2011), which is lower than current observations. IVL samplers may be used in indoor environments with low concentrations and no wind. For sampling during at least one month, they have a measurement uncertainty of 10% and a detection limit of 0.1 $\mu gNO_2/m^3$ (Yu et al., 2008; IVL Swedish Environmental Research Institute, 2018b). The sampling rate of diffusive samplers has been found to increase with higher wind velocities, which apply for personal sampling outdoors (Hagenbjörk-Gustafsson, 2014).

IVL's diffusive NO_2-samplers have been used in several previous studies with a limited sampling time of 8 h. This includes Lewné et al. (2011) and Lewné et al. (2007), studying workers exposed to motor exhaust; Bernmark et al. (2006) focusing on bicycle messengers; and Lewné et al. (2006) focusing on taxi, bus and lorry drivers. Considering the current study's aim of assessing personal exposure during commutes as compared to background levels, it was concluded that the IVL samplers had acceptable detection limit and accuracy. Nevertheless, the measurement uncertainty might be higher than 10%. The results should hence be considered indicative rather than precise.

4.2. Seasonality

In the health risk calculations, it was assumed that exposure over the year were like levels in May, and this was a simplification. NO_2-levels in Stockholm are generally somewhat higher in summer than in winter due to a higher access to ozone that speeds up the conversion from NO to NO_2 (SLB-analys, 2017). On the other hand, air pollution in general at the street level is typically lower in summer than in winter due to a lower amount of motor traffic and combustion (SLB-analys, 2017). This matters since NO_2 was assumed to be an indicator of air pollution from traffic in general in the health impact estimates. Even so, it is recommended that future similar studies consider longer periods of sampling and a larger group of commuters – preferably selected randomly from the population of active commuters in a city.

4.3. Health risk relationships

Epidemiological studies are based on correlation, and therefore causal relationships are sometimes difficult to validate. In this study a 7% risk relationship between annual NO_2-exposure and premature death was assumed. Both higher (Grazulevicine et al., 2004) and lower (Stockfelt et al., 2015) values have been reported. Nafstad et al. (2004) calculated a risk ratio of 8% per 10 $\mu gNO_x/m^3$ concentration at the home address in a cohort of Norwegian men. A review study found that the random effects summary estimate for all-cause mortality was 5.5%- per 10 $\mu gNO_2/m^3$ (Hoek et al., 2013). This motivated presenting the results as a range rather than a specific value.

Further, it was assumed that exposure when not commuting could be represented by outdoor values. These levels are often higher than indoors, particularly for PM. About half of the air pollution from road traffic penetrates nearby buildings (Wichmann et al., 2010). If the current study would have measured PM2.5, it is likely that the share of air pollution attributable to commuting would be higher than the value of one-fourth reported for NO_2 in the current study,

4.4. Relative ventilation rates

The health impact analysis was sensitive to the assumption that the relative ventilation rate was three times higher during commutes than otherwise; this may be both an underestimate and an overestimate, as inferred from Apparicio et al. (2018). Bernmark et al. (2006) reported that bicycle messengers' pulmonary ventilation was five times higher during cycling than at rest, which would imply that the health risks were underestimated in the current study.

Except during commutes, it was considered that ventilation corresponded to levels at rest, which was a simplification; nevertheless, the estimates would not change substantially with a few hours of physical effort per day. For a person with a physically strenuous occupation, the proportion of NO_2 attributable to commuting per workweek might however be lower than the value reported here.

Lastly, note that oral breathing while cycling or walking was not accounted for, which might imply that the health impacts were underestimated. At submaximal exercise with minute ventilation of around 35 l/min, breathing goes from predominantly nasal to predominantly oral, which may increase the inhaled pollutant dose and worsen the health effects (Giles and Koehle, 2014).

5. Summary and conclusions

Focusing on the global SDGs related to health (3) and sustainable cities (11), this study presented measurements and evaluations of active commuters' exposure to NO_2 in Stockholm, Sweden. The motivation was that many previous studies have reported of correlations between annual NO_2-exposure and common public diseases in heart, vessels and lungs. The methodology used was distinctive in that average personal exposure was measured per route to work.

The average exposure to NO_2 in rush-hour traffic in Stockholm among the participants (67 $\mu gNO_2/m^3$) was more than five times higher than the urban background air pollution concentrations. This indicated that their an annual mean exposure was 16.4 $\mu gNO_2/m^3$, and that their risk for premature death was increased by 3.3%, with a range of 1.9%–4.8% due to assumptions regarding the relative breathing rate and the risk relationship between annual NO_2-exposure and premature death.

Assuming that the same exposure applies to the population of active commuters in general in Stockholm, nearly one-fourth (23%) of the annual inhaled dose of traffic-related air pollution could be attributed to commuting, and the increased risk for premature death would be 2.5%, or 8 deaths between the ages of 15–64 annually in Stockholm. The increased risk for premature death among active commuters due to traffic-related air pollution ranged from 1.4% to 3.7%. The findings in this study are likely to be of importance for active commuters in Stockholm and in other cities.

In summary, these results put forward that a higher priority should be placed on active commuters' exposure to air pollution in traffic and infrastructure planning. Their exposure may be reduced by decreasing or redirecting motor traffic at rush-hour, or by increasing the share of emissions free vehicles. Greater separation between motor traffic and paths for pedestrians and cyclists is also recommended. These results are particularly important considering that active commuting is advocated by many municipalities and public authorities worldwide. In Stockholm, the target is that the proportion of journeys made by bicycle in high traffic will be doubled by 2030. The results in the current study have shown that air quality needs to be improved for Stockholm to reach the goal of sustainable transport for all.

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Conflicts of interest

We have no conflicts of interest to disclose.

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