Assessment of long-term health impacts of air quality with different guideline values for NO_X in the planned by-pass tunnel Förbifart Stockholm

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SAMMANFATTNING

Bland annat för att förbättra förbindelserna mellan de norra och södra länsdelarna och öka framkomligheten på infartsleder mot Stockholm planeras en 21 km lång förbifart i nord-sydlig sträckning, varav cirka 18 km planerad gå i tunnel. Denna nya led, Förbifart Stockholm, förväntas ge förutsättningar för utveckling och minska trafikbelastningen i områdets centrala delar. Samtidigt visar tidigare analyser att de som kommer att färdas i tunneln kan bli utsatta för höga koncentrationer av trafikföroreningar. Denna rapport redovisar resultat av forskning som är beställd och finansierad av Trafikverket.

För att styra luftkvaliteten i den planerade tunneln har användandet av riktvärden för luftföroreningshalten i tunneln föreslagits, och ett preliminärt förslag från Trafikverket presenterats vid olika möten. Denna studie syftar till att bedöma de potentiella hälsokonsekvenserna som kan förväntas med olikt strängt riktvärde för trafikföroreningar indikerat med halten av kvävoxider, NOx, (1000, 2000, 3000 och 4000 mikrogram/m^3 som maximalt timmedelvärde för tunnelsystemet).

Exponeringen från tunnelpassager uppskattas baserat på de årliga genomsnittliga NO_X-halterna i tunneln, tillbringat tid i tunneln och antal trafikanter. I underlaget beräknas halterna för olika delar av tunneln och olika tid på dygnet. Hälsokonsekvenserna av förändrad exponering har beräknats med etablerade metoder och beräkningsprogrammet AirQ Plus utvecklat av WHO.

På grund av stora trafikflöden och ekonomiska/tekniska begränsningar för ventilationen kan luftföroreningskoncentrationerna i tunneln bli mycket högre än i andra trafikmiljöer. Med minimal ventilation och maximala trafikmängder under rusningstid kan timmedelvärdet för NOx bli till 3500 mikrogram/m^3 och även när maximal ventilation skulle tillämpas, beräknas årsmedelvärdet av dygnets högsta timmedelvärde längs en länk i tunneln bli 1789 mikrogram/m^3. Således är det i princip omöjligt att klara riktvärdet 1000 mikrogram/m^3 överallt i tunnelsystemet. Exponeringen skulle bli lägst vid maximal ventilation, vilket beräknas resultera i 22,2 (95% konfidensintervall: 16.8-30.1) förtida dödsfall per år, motsvarande 480,4 (95% KI: 364,1-650,6) förlorade levnadsår (förutsatt att resenärerna utgörs av åldersgruppen 30-74 år). Om riktvärdet skulle vara 2000 mikrogram/m3, beräknas exponeringen med samma åldersgrupp resultera i 35,2 (95% KI: 26,7-47,6) förtida dödsfall per år, motsvarande med 760.9 (95% KI: 480,4-650,6) förlorade levnadsår.

Bland olika tunnellänkar beräknas den största exponeringen på länk 5N, där 28,6-37,2% (beroende på riktvärdesscenario) av de totala hälsokonsekvenserna kan genereras. Länken 3N har hög NO_X-koncentration, stort antal passagerare och lång exponeringstid. För de separata länkarna kan skillnaderna i exponering mellan riktvärdesscenarier också i hög grad variera beroende på möjligheten att ventilera: medan skillnaderna vara stora för länk 5N, var de ganska små för länk 7N.

Om vi jämför dessa resultat med tidigare beräknad positiv effekt på lokalbefolkningens hälsa beroende på minskad exponering för luftföroreningar (årligen förväntas 23,7 (95% KI: 17,7-32,3) färre förtida dödsfall), är det endast med de mest gynnsamma antagandena såsom färre äldre personer som använder tunneln och med nu beräknad maximal ventilation som tunneln kan ge mindre hälsoeffekter jämfört med alternativet trafik ovan jord längs E4. I alla andra fall förväntas hälsoeffekterna med tunneln i Förbifart Stockholm totalt bli högre. Exponeringen i tunneln väntas här bli något högre jämfört med föregående analys på grund av förbättrad modellering av luftföroreningshalter i olika delar av tunneln, inkluderande även ramperna, samt i konsekvensbedömningen förväntat högre antal passager för vissa tunnellänkar.

ABSTRACT

To meet increased needs of transports in the Stockholm region and reduce the problems with traffic congestion in central parts, a 21 km long by-pass (18 km in a tunnel) is planned. The by-pass is expected to reduce traffic and emissions in central Stockholm, but at the same time tunnel users could be exposed to high concentrations of air pollutants from traffic. Thus to control the air quality in the tunnel system, air pollution guideline values have been proposed. The current study is initiated and funded by the Swedish Transport Administration (Trafikverket), and the aim is to assess the potential health impacts of applying different NO_X guideline values (1000, 2000, 3000 and 4000 µg/m3 as hourly average max values all-over the tunnel system). The passengers' exposure was estimated based on annual average NO_X exposures, time spent in the tunnel and the number of tunnel users. Health impacts were assessed following health impact assessment principles using equations and WHO's software AirQPlus.

With minimal ventilation and maximal traffic amounts during rush hours the NO_X hourly average concentrations could raise up to 3500 µg/m^3 and even when the planned maximum ventilation would be in use, the maximum concentration would stay as high as 1789 µg/m^3. Thus, it is in principle with planned the technology impossible to meet the lowest proposed guideline value of 1000 µg/m^3 in the whole tunnel system. However, the effects would be with this guideline still the smallest, resulting annually in 22.2 (CI 95% 16.8–30.1) more premature deaths and 480.4 (95% CI 364.1–650.6) years of life lost (assuming travellers to come from the age group 30–74). If the guideline value would be 2000 µg/m^3, the exposure would annually in the same age group cause 35.2 (CI 95% 26.7–47.6) premature deaths with 760.9 (480.4–650.6) years of life lost. With the lowest guideline level, passing the whole tunnel during rush hours on working days would increase mortality risk by 7.4% (95% CI 5.5-10.1), on average corresponding to a life expectancy decrease by 0.27 (95% CI 0.20-0.37) years for people aged 30–74 years.

Among different tunnel links, the biggest exposure is expected in link 5N, where 28.6-37.2% (depending on limit value scenario) of the total health impact could be generated. The link 3N has high NO_X concentration, large number of passengers and long exposure time (time spent in the tunnel link). Even the NO_X concentrations are expected to be highest in links 411 and 314, the exposure time there would be shorter and the number of exposed passengers smaller. For the separate links the differences in exposure between limit value scenarios could also vary largely: while the difference was big for link 5N, it was rather small for link 7N.

If we compare these results with the previously estimated beneficial effect on the health of the local population due to decrease of urban air pollution exposure (expecting annually 23.7 (95% CI 17.7–32.3) fewer premature deaths), only with most favourable assumptions as less older persons using tunnel and with highest ventilation the tunnel could have smaller negative health effects compared to the alternative current open road E4. In all other cases the health effects in the by-pass tunnel Förbifart Stockholm are expected to be higher. Also the exposure levels in the tunnel are expected to be somewhat higher compared to previous analysis due to more

enhanced dispersion modelling for the tunnel, including also ramps in the impact assessment and predicting higher numbers of cars than previously.

CONTENTS

1. INTRODUCTION

The planned Stockholm bypass – Förbifart Stockholm – will be a new motorway linking southern and northern Stockholm, which is divided by water. This bypass should meet the growing transport needs due to the increased population in the region. By 2030, the population of the Stockholm region is expected to have increased from 2 million today to roughly 2.4 million. More than 18 km of the total of 21 km of the bypass are going to be road tunnels. When the link opens for traffic it will be one of the longest road tunnels in the world. By 2035, the Swedish Transport Administration (Trafikverket) estimates that Förbifart Stockholm will be used by around 140,000 vehicles per day.

The by-pass is expected to reduce traffic emissions in central Stockholm, but at the same time tunnel drivers could be exposed to high concentrations of vehicle exhaust. An earlier health impact assessment showed the risk being rather high, similar to the beneficial effects of reducing air pollution on open roads (Orru et al., 2015). Thus the idea of an air pollution guideline value in tunnel with automatic ventilation has been proposed by the Swedish Transport Administration to better control the air pollution levels in the Förbifart Stockholm tunnel, and to optimize the tunnel ventilation and operating costs. The current analysis aims to assess the potential health impacts of different proposed air quality levels as guidelines.

It is well established that traffic air pollution has various adverse health effects: mainly associated with respiratory and cardiovascular disease (HEI, 2010). The cardiovascular effects of air pollution include myocardial ischemia, atherosclerosis, infarctions, heart failure, arrhythmias, strokes etc. The respiratory outcomes range from acute symptoms like coughing and wheezing to more chronic conditions such as asthma, chronic bronchitis, chronic obstructive pulmonary disease etc. There is also increasing evidence suggesting vehicle emissions to be associated with the development of cancer, particularly lung cancer, hormonal, and reproductive effects, allergy and birth effects as preterm birth, and low birth weight. Many of these conditions are also associated with the increase in mortality seen in exposed populations. The estimated impact on mortality (and life-years lost) is often used as the health indicator in assessments.

1.1. Exposures in traffic environments and health effects

Traffic induced air pollutants could have substantial impact on personal exposures. The populations who either spend a considerable amount of time in traffic (such as professional drivers and commuters) or who live or work near busy roads are potentially at greatest risk. Often the in-vehicle concentrations are higher than ambient concentrations for most airborne pollutants (Kaur et al., 2007). Also the roadway concentrations are higher compared to ambient concentrations measured at air-monitoring stations; however, highly variable (HEI, 2010). Several studies concentrating on professionals, like taxi and truck drivers, have investigated the air pollution induced health effects associated with driving a vehicle. A study in Denmark of 28,744 men with lung cancer found an increased risk among taxi drivers and truck drivers when compared with other employees, probably due to exposure to benzene (Hansen et al., 1998), and increased levels of respiratory conditions have also been associated with professional driving in Shanghai (Zhou et al., 2001). However, the long-term effects of traffic pollutants on the general population are mainly investigated using the area of residence as basis for the exposure estimation.

1.2. Health impacts assessments and their epidemiological base

The general principle for a health impact assessment (HIA) is to use information on how a change in a specific risk factor (for example an air pollutant) is expected to modify the risk of disease or death in the population. Previously found relative changes in health risks are combined with known base-line frequencies in the population in order to estimate the quantitative impacts. The most important indicator in air pollution HIAs has been long-term exposure impact on mortality, resulting in loss of life expectancy. The major part of the effect on risk of death occurs already after a couple of years. Despite the few cohort studies of long-term exposure and mortality, these studies are considered most relevant for HIA, since the time-series studies of short-term effects on mortality do not fully quantify the number of attributable deaths (Krzyzanowski et al., 2005). Other chronic effects have less often been included in HIAs. Even most HIAs of ambient air pollution have dealt with large populations and areas, often bigger than one country (Anenberg et al., 2010; Boldo et al., 2006; Kunzli et al., 2000; Pascal et al., 2013), some studies have also dealt with parts of a city (Orru et al., 2009) or with specific traffic projects (Johansson et al., 2009).

The most often used exposure indicator in HIAs has been particulate matter (PM) mass concentration for the effects of long-term exposure on mortality, based on exposure-response functions from the American Cancer Society (ACS) cohort (Pope et al., 2002). Even expert reports from WHO Regional Office for Europe have concluded that although studies indicate that some components of PM, especially combustion-derived particles, are more toxic than others, it is currently not possible to quantify the contribution to health effects from different components due to limited epidemiological evidence (WHO, 2013). Though an analysis of ACS participants from Los Angeles County, where traffic-induced particles explain a bigger proportion of gradients in the $PM_{2.5}$ concentrations and where exposure-response function (ERF) are nearly threefold higher coefficient for the same indicator (Jerrett et al., 2005). The use of more specific indicators, such as elemental carbon, results in quite different coefficients per mass concentration (Smith et al., 2009). The coarse fraction and mineral particles do not seem to be associated with the survival of cohort members (Brunekreef and Forsberg, 2005). However, recently road dust particles (coarse fraction of PM_{10}) have been associated with short-term effects on daily mortality in Stockholm (Meister et al., 2012).

While waiting for motor traffic specific ERFs for PM to become available, other indicators may be used to indirectly assess the effect of traffic related particles. Road traffic contributes to atmospheric particle pollution in several ways. There are emissions of particles and combustion gases which results in an increased concentration of ultrafine particles (< 100 nm). These particles usually only cause a small increase in the local mass concentration expressed as PM_{10} or $PM_{2.5}$, but a large increase in the particle number concentration (PNC) (Johansson et al., 2007). Due to the common major source (traffic exhaust) there is a good correlation between PNC and NO_X in Stockholm (Johansson et al., 2007). Exhaust gases also form secondary particles such as nitrates and sulphates, but this process occurs on a regional scale (Wexler et al., 1994). A third type of traffic particle is road dust, mainly road wear material but also brake and tire wear. In Stockholm the local contribution to the PM_{10} levels of road dust is approximately 10 times higher than the mass concentration of exhaust particles (Johansson et al., 2007). Nevertheless, a recent study has shown that only a small fraction of the coarse particles will penetrated into vehicles in tunnels, causing marginal increase in exposure (Johansson et al., 2013).

Thus the motor vehicle emissions of primary exhaust particles have a major local influence and their effect on long-term effects exposure should be studied with a fine spatial resolution. However the ACS results that are frequently used for HIAs do not examine associations at the intra-community level. Epidemiological studies from Europe that use a fine spatial resolution which can capture the gradients in exposure to local traffic pollutants indicate an important effect of local traffic emissions, resulting in high relative risks. Of particular interest is a Norwegian study of 16,000 men from Oslo, of whom 25 % died during the follow up, which used modelled nitrogen oxides (NO_X) in the residential area as the exposure indicator (Nafstad et al., 2004). This cohort, with people of between 40–49 years of age at the start of the study, was followed from 1972/73 through 1998. NO_X was estimated in a model with 1000 m grids, and a street contribution added for the largest streets. When the NO_X concentration for 1974–78 was used (median 10.7 μgm^{-3}), the relative risk for total non-violent mortality was 8 % per 10 μgm^{-3} (95% CI 6–11%). There is also a study that obtained similar results for men in Gothenburg aged 48-52 years of age (a bit older than in the Oslo study) at the start of follow up in 1973, where non-accidental mortality increased by 6 % (95% CI 3%-9%) per 10 µg m-3 NOx (Stockfelt et al., 2015).

In a city like Oslo, NO_X is a good indicator of the gradients in levels of motor vehicle exhaust. Due to its long atmospheric lifetime (days) it may be considered as inert and modelled without considering photochemical processes, as in the Norwegian cohort study. Moreover, on a yearly basis there is in general a good spatial correlation between NO_X and NO_2. Other studies from the Netherlands (Hoek et al., 2002), Germany (Gehring et al., 2006); later follow up by (Heinrich et al., 2012)), France (Filleul et al., 2005), US (Hart et al., 2011), Toronto (Jerrett et al., 2009) and Auckland (Scoggins et al., 2004) have found deaths from non-external causes to increase by 12–14% per 10 $\mu g/m^3$ of NO_2 (however using slightly different exposure metrics), which are in line with the Norwegian result.

The short-term associations between NO_2 and daily mortality remain in many studies after adjustment for PM_{10} or $PM_{2.5}$. The WHO REVIHAAP report (WHO, 2013) concludes ”As there is consistent short-term epidemiological evidence and some mechanistic support for causality, particularly for respiratory outcomes, it is reasonable to infer that NO_2 has some direct effects.”

In order to avoid double counting when calculating effects on mortality, we choose to use one of the most relevant pollution indicators only – in our case NO_X that has also been applied in country-wide air pollution health impact assessment in Sweden (Gustafsson et al., 2014).

Excess mortality associated with vehicle exhaust exposure (exhaust particles) is also in the newly developed DALY model used by The National Transport Administration calculated using NOx as the indicator pollutant and the relative risk from Nafstad et al, 2004.

2. METHODS

2.1. Tunnel links and air pollution guideline scenarios for the tunnel

Air pollution levels in the tunnel are planned to be regularly monitored in order to modify air exchange rates depending on the concentrations and any air quality guidelines for tunnels. This study was planned to investigate the health impacts associated with four different NO_X guidelines for the maximum concentration in the tunnel:

- 1000 µg/m^3
- 2000 µg/m^3
- 3000 µg/m^3
- 4000 µg/m^3

The tunnel itself is a complex system consisting of different tunnel links with ramps (Figure 1). The NO_X levels were modelled for every tunnel road link and ramp as hourly average concentrations. Latter health effects were also assessed for those links and ramps.

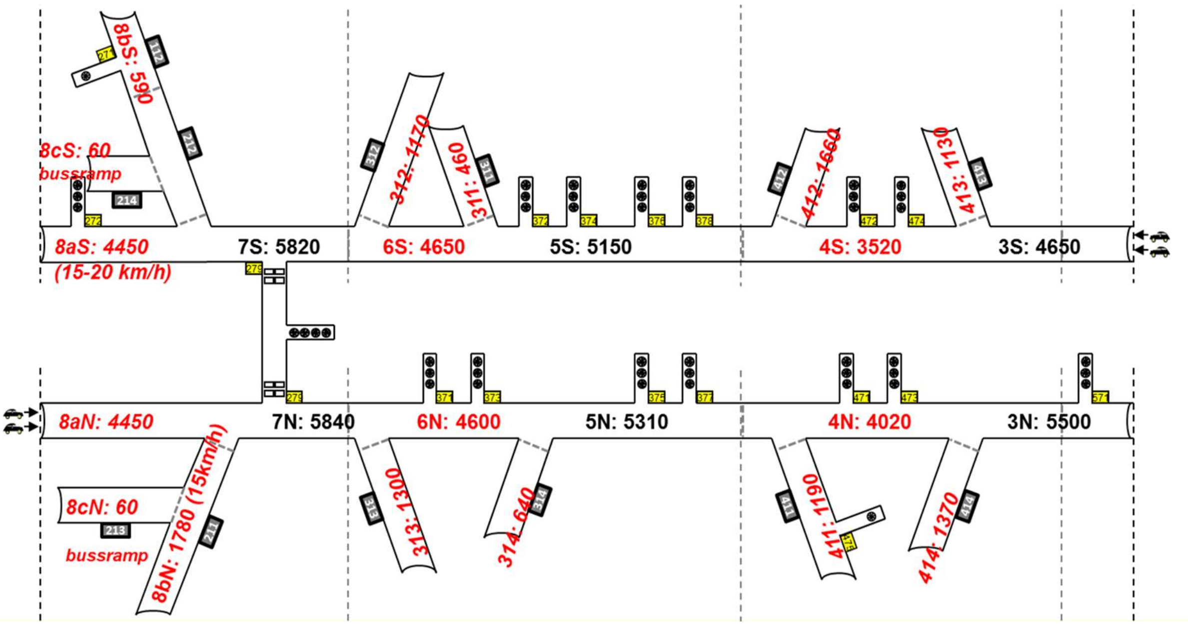

Figure 1. Different road tunnel links with ventilation stations (•), ramps and expected mean traffic flows between 07 and 08 in the morning in the year 2030.

2.2. Assessment of additional exposure from short-term high concentrations of air pollutants in traffic

The calculated NO_X concentrations along the by-pass including the road links in the tunnel have been modelled for The Swedish Transport Administration. The details of the air pollution modelling are given in the report by Brandt and Lucchini (2016). In the current impact analyses these recently modelled NO_X levels were used as the air pollution indicator.

As only the concentrations in northbound tunnel link were modelled, the latter health impact assessment results were multiplied by two.

In the calculations the contributions of those modelled short-term very high concentrations of air pollutants to regular exposure, the time-weighted average micro-environmental (tunnel) exposure (Kornartit et al., 2010) concept was used

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

Where,

E*i* is the time-weighted average air pollutant dose for person *i* over the specified time period;

C*j* is the air pollutant concentration in microenvironment *j* (e.g. tunnel link);

t*ij* is the aggregate time that person *i* spends in microenvironment (e.g. tunnel link);

J is the total number of microenvironments (e.g. tunnel links) that the person *i* moves through during the specified time period in transit.

Moreover, the micro-environmental exposures per average traveller were adjusted to contribution to the annual total exposure, weighted by number of cars, and time spent in different road links as well as ramps in the tunnel. In these calculations hourly average concentrations in the tunnel were used which enabled more exact calculations than previously (Orru et al., 2015).

When assessing the additional risk for users of the by-pass road tunnel, the corresponding exposure using the current E4 (as main alternative passing Stockholm) was subtracted (see more details in Orru et al., 2015).

2.3. Population exposure, baseline mortality, and morbidity data and calculating the health effects

Impact calculation

For the quantification of the health impacts the following equation was used:

$\Delta Y = (Y_0 \times pop) \times (e^{\beta \times X} - 1)$,

where Y_0 is the baseline rate; *pop* the number of exposed persons; β the exposure-response relationship (relative risk) and X the estimated excess exposure.

The number of Years of Life Lost (YLL) was assessed using the WHO software AirQPlus that uses the life-table approach.

Exposure-response relationships and baseline frequencies

For non-external mortality analysis the following exposure-response (E-R) relationship from previous studies was used: RR=1.08 (95% CI 1.06–1.11%) for 10 μg/m^3 increase of annual mean NO_X concentration (Nafstad et al., 2004).

The baseline non-external mortality (A00–R99) in Stockholm County was retrieved from the databases of The National Board of Health and Welfare of Sweden for year the 2011. This baseline data is in line with the previous analysis (Orru et al., 2015) to keep the current results comparable with the earlier health impact assessment.

We have no projection for the future age distribution. Thus, the health effects in the tunnel were assessed for three different age distributions as in the previous analysis:

- expecting that tunnel users would be aged 30–69 with the same probability to travel;
- expecting that tunnel users would be aged 30–74 with the same probability to travel;
- expecting that tunnel users would be aged 30–84, adjusted for the probability to travel, being 50% for persons between 70–79 and 25% for persons aged 80–84 years.

The rush hours were defined as previously 06.00-9.00 and 15.00-18.00 (Orru et al., 2015).

3. RESULTS

3.1. Air pollution exposures in the tunnel

Due to limited ventilation, the air pollution concentrations in the tunnel can be very high (Figure 2). With minimal ventilation and maximal traffic amounts during rush hours, the annual mean of daily 1-hr maximum concentrations could raise up to 3500 µg/m³ in parts of the tunnel (Figure 2). If the maximal proper ventilation would be applied, the average daily maximum 1-hr concentration would decrease to 1789 µg/m³. Nevertheless with the planned ventilation solution, it is not possible to keep the maximum NO_X values below 1000 µg/m³ (Figure 2). Thus the referred lowest guideline scenario is not actually a maximum 1000 µg/m³ scenario, but a maximum 1789 µg/m³ scenario.

The earlier air pollution dispersion modelling showed that during the day the pollutants concentrations were highest during morning (around 8.00) and evening rush hours (around 17.00) (Figure 2). The concentrations were lowest at night, where they stayed below 1000 µg/m³ in all scenarios, even with minimal or no ventilation.

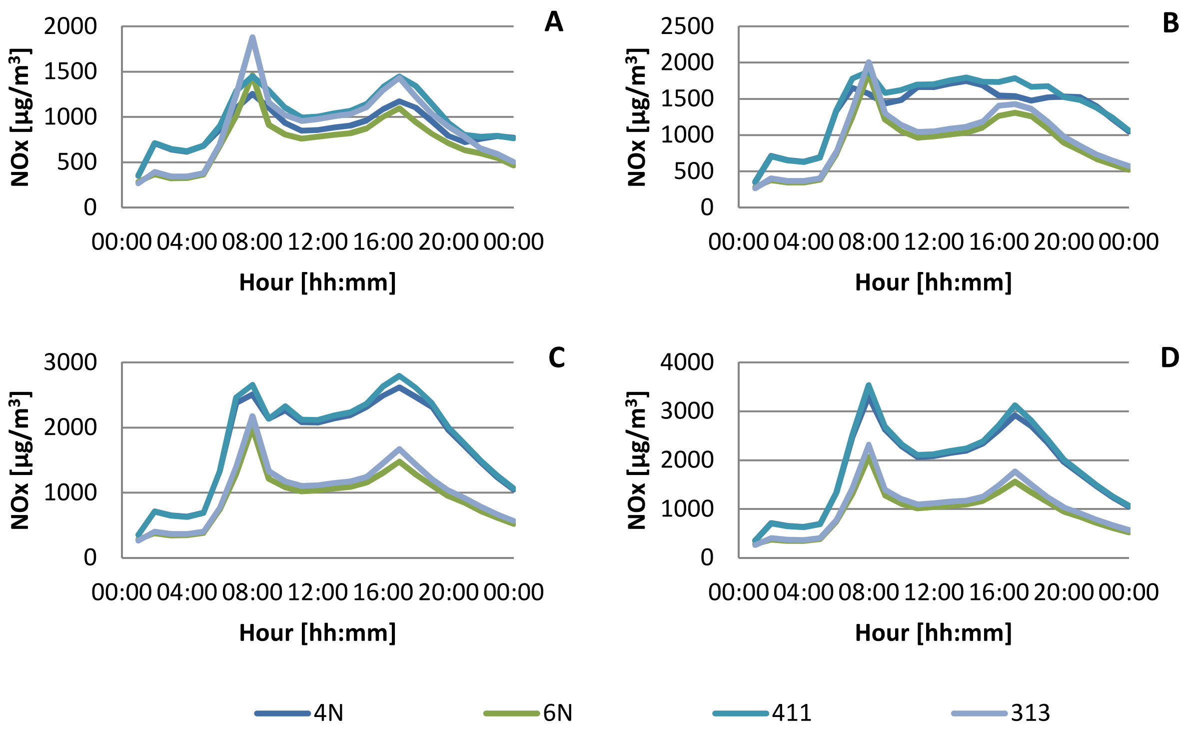

Figure 2. NO_X concentration in different northern tunnel road links (4N, &N, 411, 313) during the day on different times (annual mean hourly concentrations) with four different guideline values: (A) 1000 µg/m³, (B) 2000 µg/m³, (C) 3000 µg/m³ and (D) 4000 µg/m³.

It appeared that the concentrations would be different also in different tunnel links (Table 1). They would be highest in links 4N and 411 with busy traffic and far from entrances and lowest in links 414 and 314 that are ramps with less traffic and close to entrances.

Table 1. Travel time, daily mean number of vehicles and mean concentrations of NO_X in different northbound tunnel links and ramps with different guideline scenarios (1000, 2000, 3000 and 4000 µg/m^3 as maximum 1-hr concentration)

Tunnel link	Travel time in link (sec)	Daily mean number of vehicles	NO_X annual average concentrations (µg/m^3)			
			Max 1000	Max 2000	Max 3000	Max 4000
3N	96.1	64009	601.7	1246.1	2008.2	2305.2
4N	70.1	49077	979.8	1521.5	2150.5	2306.7
5N	218.2	65199	599.2	1165.2	1412.5	1471.0
6N	35.9	56639	885.4	1113.3	1168.2	1195.5
7N	154.4	73133	590.2	601.9	636.2	653.2
8aN	109.7	51382	208.9	188.2	195.7	204.5
8bN	146.8	21751	299.2	428.9	469.7	410.4
8cN	53.5	754	175.7	403.3	281.7	229.6
414	37.8	14932	109.8	128.8	133.2	138.0
411	64.9	16122	1147.3	1637.9	2229.2	2385.6
314	80.2	8560	131.4	137.5	139.0	139.1
313	121.6	16494	1110.4	1202.3	1273.8	1310.2

Passing the tunnel would on average increase the annual NO_X dose by 15.76-29.48 µg/m^3 (depending on limit value scenario) among tunnel users (Table 2). The contribution would be smallest with 1000 µg/m^3 limit value scenario and largest with 4000 µg/m^3 limit value scenario. Passing the Stockholm with current alternative open road E4, would increase the annual NO_X dose by 1.88 µg/m^3.

Table 2. Contribution (µgm^{-3}) in tunnel to the annual NO_X exposure for travellers (daily mean number) in different northbound tunnel links and ramps with different limit value scenarios (Max 1000, 2000, 3000 and 4000 µgm^{-3}) and with current alternative open road E4.

Tunnel link	NO_X annual average exposure (µg/m^3)				Contribution (µg/m^3) on E4 with similar distribution over time
	1000	2000	3000	4000	
3N	0.67	1.39	2.23	2.56	0.08
4N	0.79	1.23	1.74	1.87	0.06
5N	1.51	2.94	3.57	3.71	0.17
6N	0.37	0.46	0.48	0.50	0.03
7N	1.05	1.08	1.14	1.17	0.12
8aN	0.27	0.24	0.25	0.26	0.09
8bN	0.51	0.73	0.80	0.70	0.12
8cN	0.11	0.25	0.17	0.14	0.04
414	0.05	0.06	0.06	0.06	0.03
411	0.86	1.23	1.67	1.79	0.05
314	0.12	0.13	0.13	0.13	0.06
313	1.56	1.69	1.79	1.84	0.10
Total northbound	**7.88**	**11.42**	**14.04**	**14.74**	**0.94**
Total tunnel	**15.76**	**22.84**	**28.08**	**29.48**	**1.88**

3.2. Expected air pollution health impacts in the tunnel

As people while travelling on the by-pass with long tunnels are exposed to high concentration of exhaust pollutants, this will be also reflected in health effects. Nevertheless, the majority of users will be of working age and younger seniors, and likely not many from the oldest and most sensitive group. Recently in congestion charging borders there has been counted 1.3 persons per car, which we assume in the calculations. But due to buses and the expected higher costs to travel this number of persons per vehicle could be assumed to be bigger, e.g. 1.5.

It appeared that the results are highly sensitive to the used guideline scenario (Table 3). The smallest effects are expected if the max available ventilation will be used (guideline scenario 1000 µg/m^3). Then the annual mean exposure in the tunnel Förbifart Stockholm compared to the corresponding traffic on current roads (E4) would cause 22.2 (CI 95% 16.8–30.1) additional premature deaths annually assuming travellers to come from the age group 30–74 (Table 3).

Table 3. Additional risk from using the tunnel in different age groups (number on annual premature mortality cases, 95% CI)

Guideline scenario	30–69	30–74	30–85 adjusted*
1000	16.7 (12.7–22.6)	22.2 (16.8–30.1)	30.2 (22.9–40.9)
2000	26.5 (20.1–35.8)	35.2 (26.7–47.6)	47.8 (36.3–64.7)
3000	33.9 (25.7–45.8)	45.0 (34.1–60.8)	61.2 (46.4–82.2)
4000	36.1 (27.4–48.8)	47.9 (36.4–64.8)	65.5 (49.5–88.1)

*From age 30–69 all, from age 70–79 half and from age 80–84 quarter using the tunnel.

This would mean 480.4 (95% CI 364.1–650.6) years of life lost for the society. If we expect tunnel users to be younger (30–69) or older (30–84 adjusted), the effects would be smaller or bigger: 16.7 (95% CI 12.7–22.6) and 22.9 (95% CI 22.9–40.9) premature deaths, respectively (Table 3). If we expect 1.5 persons in the vehicle, the effects would be 15% larger.

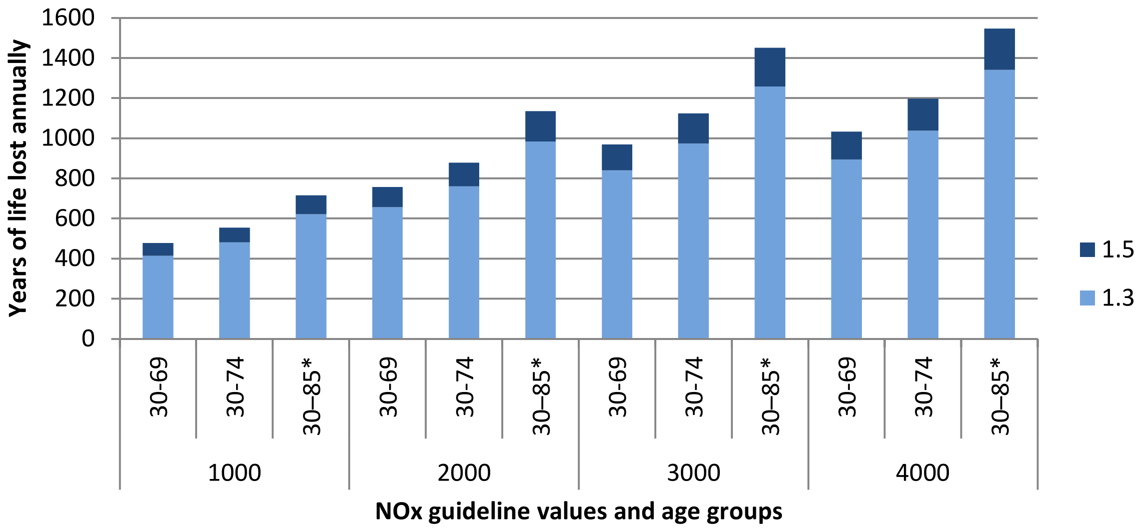

Figure 3. Years of life lost annually (95% CI) due to using the tunnel in different age groups (with 1.3 and 1.5 persons per vehicle)

As in practice keeping the guideline values under 1000 µg/m³ is impossible and it is related to very high power consumption, the more realistic guideline value scenario has been suggested to be 2000 µg/m³ (Brandt and Lucchini, 2016). Then the annual mean exposure in Förbifart Stockholm compared to the current route E4 would cause 35.2 (CI 95% 26.7–47.6) premature deaths with 760.9 (480.4–650.6) years of life lost annually assuming travellers to come from the age group 30–74 (Table 3). If we expect less many elderly to travel or all tunnel users to be aged 30–69, the effects would be smaller and if we expect tunnel users be older or more than 1.3 persons in cars, the effects would be larger (Table 3, Figure 3).

With the guideline value scenario 3000 µg/m³ health effects would be two times higher than with the guideline value 1000 µg/m³ and with the value 4000 µg/m³, even higher (Table 3, Figure 3).

Table 4. Number of exposed travellers, additive NO_X exposure in the tunnel compared to E4 and annual premature mortality cases (95% CI) due to additive exposure in the whole tunnel (both northern and southern bound) with different guideline value scenarios (1000, 2000, 3000 and 4000 µg/m³)

Tunnel link	Exposed passengers	Additive to E4 NO_X annual exposure in tunnel (µg/m³)				Annual premature mortality cases due to additive exposure in tunnel			
		1000	2000	3000	4000	1000	2000	3000	4000
3	166 423	1.19	2.62	4.31	4.98	2.77 (2.10-3.75)	6.10 (4.62-8.25)	10.01 (7.60-13.5)	11.53 (8.75-15.6)
4	127 600	1.48	2.36	3.38	3.63	2.64 (2.00-3.58)	4.21 (3.19-5.70)	6.02 4.56-8.14)	6.47 4.90-8.75)
5	169 517	2.68	5.54	6.79	7.08	6.36 (4.82-8.60)	13.06 (9.92-17.6)	15.97 (12.3-21.6)	16.66 (12.7-22.5)
6	147 261	0.68	0.87	0.91	0.94	1.40 (1.06-1.90)	1.79 (1.36-2.43)	1.89 (1.43-2.56)	1.93 (1.46-2.62)
7	190 146	1.86	1.91	2.03	2.09	4.97 (3.76-6.73)	5.08 (3.85-6.88)	5.40 (4.10-7.32)	5.57 (4.22-7.54)
8a	133 593	0.36	0.30	0.32	0.35	0.67 (0.51-0.91)	0.57 (0.43-0.77)	0.61 (0.46-0.82)	0.65 (0.49-0.88)
8b	56 553	0.78	1.22	1.36	1.16	0.62 (0.47-0.84)	0.97 (0.74-1.32)	1.08 (0.82-1.46)	0.92 (0.70-1.25)
8c	1 960	0.13	0.41	0.26	0.20	<0.01 (<0.01-0.01)	0.01 (0.01-0.02)	0.01 (0.01-0.01)	0.01 (0.01-0.01)
413/414	38 823	0.04	0.05	0.06	0.06	0.02 (0.01-0.03)	0.03 (0.02-0.04)	0.03 (0.02-0.04)	0.03 (0.03-0.05)
411/412	41 917	1.62	2.36	3.24	3.48	0.95 (0.72-1.29)	1.38 (1.05-1.87)	1.90 (1.44-2.57)	2.04 (1.54-2.76)
311/314	22 256	0.12	0.13	0.13	0.13	0.04 (0.03-0.05)	0.04 (0.03-0.05)	0.04 (0.03-0.06)	0.04 (0.03-0.06)
312/313	42 884	2.93	3.19	3.39	3.49	1.76 (1.33-2.38)	1.91 (1.45-2.59)	2.03 (1.54-2.75)	2.09 (1.59-2.83)
Total		13.9	21.0	26.2	27.6	22.2 (16.8-30.1)	35.2 (26.7-47.6)	45.0 (34.1-60.8)	47.9 (36.4-64.8

If we study in more detail the health effects in different tunnel links, the biggest effects are expected in link 5N, where 28.6-37.2% (depending on limit value scenario) of the total health effects could appear in the group 30–74 (Table 4). The link 5N has high NO_X concentrations, large number of passengers and long exposure time. Even the NO_X concentrations are expected to be highest in links 411 and 314, the exposure time there would be shorter and the number of exposed passengers smaller – thus the total effect is expected much smaller (Tables 2, 4). The differences in tunnel links between guideline value scenarios could also largely vary: e.g. while the difference was more than four times in link 3N, it was around 12% in link 7N.

We also calculated the risk for daily commuter, using different tunnel links on working days during morning and evening rush hours (Table 5). We also found the worst case scenario, where the commuting person would pass the whole tunnel (more specifically the links: 3, 4, 5, 6, 7 and 8b). In this case, on average the risk of death with the smallest NO_X guideline value (1000 µg/m^3) would be increased as much as 7.4% (95% CI 5.5-10.1) at least from some year after the exposure started. If the guideline value would be increased to 2000 µg/m^3, the mortality increase would be 11.2% (95% CI 8.3-15.3). With other higher guideline values, the health effects would be even larger.

Among the different tunnel links, the biggest effects are expected in links 5 and 7, where altogether more than half of the total effects are expected in worst case scenario (Table 5). Among the ramps the biggest effects are expected in sections 312/313 that would increase the mortality by 2.45% (95% CI 1.82-3.36) with the NO_X limit value 1000 µg/m^3, being around 1/3 of the total worst case scenario effects (Table 5).

In general exposure to NO_X in the by-pass tunnel Förbifart Stockholm would cause health effects in all cases, but the magnitude of effects would depend on guideline scenario (lower values give less effects), exposure time (smaller exposure times give less effects) and number of passenger (higher number will increase health effects in the society). Using the tunnel every day for commuting could also significantly decrease one’s life expectancy.

Table 5. Increase in mortality among adults (95% CI) in intermediate age group (30–74) in different tunnel links (both northern and southern bound) with different limit value scenarios (1000, 2000, 3000 and 4000 µg/m^3) while commuting twice a day 5 times a week during rush hours

Tunnel link	NO_X yearly mean exposure (µg/m^3)				Increase in mortality (%)			
	1000	**2000**	**3000**	**4000**	**1000**	**2000**	**3000**	**4000**
3	1.05	1.97	3.46	4.52	0.85 (0.63-1.16)	1.59 (1.18-2.18)	2.79 (2.07-3.83	3.64 (2.70-5.00
4	1.33	1.80	2.85	3.25	1.07 (0.80-1.47)	1.45 (1.08-1.99)	2.29 1.71-3.15)	2.62 1.94-3.59)
5	2.57	4.84	6.23	6.71	2.07 (1.54-2.84)	3.90 (2.90-5.35)	5.02 (3.73-6.89)	5.40 (4.02-7.42)
6	0.65	0.82	0.86	0.90	0.52 (0.39-0.72)	0.66 (0.49-0.91)	0.69 (0.51-0.95)	0.72 (0.54-1.00)
7	2.13	2.15	2.29	2.38	1.71 (1.27-2.36)	1.73 (1.29-2.38)	1.84 (1.37-2.53)	1.92 (1.42-2.63)
8a	0.65	0.54	0.56	0.60	0.52 (0.39-0.72)	0.43 (0.32-0.60)	0.45 (0.34-0.62)	0.48 (0.36-0.66)
8b	1.41	2.29	2.79	2.36	1.14 (0.84-1.56)	1.84 (1.37-2.53)	2.25 (1.67-3.08)	1.90 (1.41-2.61)
8c	0.17	0.60	0.34	0.21	0.14 (0.10-0.19)	0.48 (0.36-0.66)	0.27 (0.20-0.38)	0.17 (0.13-0.23)
413/414	0.08	0.08	0.08	0.09	0.06 (0.05-0.09)	0.06 (0.05-0.09)	0.06 (0.05-0.09)	0.07 (0.05-0.10)
411/412	1.60	2.04	3.01	3.42	1.29 (0.96-1.77)	1.64 (1.22-2.26)	2.42 (1.80-3.33)	2.75 (2.05-3.78)
311/314	0.19	0.20	0.20	0.20	0.15 (0.11-0.21)	0.16 (0.12-0.22)	0.16 (0.12-0.22)	0.16 (0.12-0.22)
312/313	3.04	3.26	3.50	3.66	2.45 (1.82-3.36)	2.62 (1.95-3.60)	2.82 (2.09-3.87)	2.95 (2.19-4.05)
***Worst scenario**	9.14	13.87	18.48	20.12	7.36 (5.47-10.11)	11.17 (8.30-15.34)	14.88 (11.06-20.43)	16.20 (12.04-22.25)

*Passing the whole tunnel, more specifically links: 3, 4, 5, 6, 7 and 8b.

4. DISCUSSION

4.1. Guideline values

Clearly the smaller guideline values result in smaller risk for public health (Table 3, 4). In the total tunnel system the risk between smaller and largest guideline value could be little more than two times (Table 3), but in some tunnel links the difference is more than four times (Table 4). However, in some other tunnel links the difference in health effects between guidelinevalue scenarios is only 12%.

As it was previously discussed by Brandt and Lucchini (2016), keeping hourly average NO_X concentrations anywhere in the tunnel below 1000 µg/m^3 is with current planned ventilation solutions impossible (µg/m^3). Nevertheless increasing guideline value from 1000 to 2000 µg/m^3, would increase health effects in the whole tunnel system by 58%. Thus keeping the guideline and exposure as low as possible, would be important for public health.

The solution could be following:

1. Increasing ventilation on certain links with very high NO_X concentrations and high number of passengers
2. Allowing exceedances on certain links on rush hours or having different limit value for rush hours

4.2. Increased risk in the tunnel Förbifart Stockholm compared to reduced risk for the Greater Stockholm population

The previous analyses showed that bypass Förbifart Stockholm would avoid among Greater Stockholm population (who's air pollution exposure would decrease due to reduced traffic on E4) 23.2 (95% CI 17.6–31.5) premature death due to decrease in NO_X exposure (representing traffic exhaust) and 0.5 (95% CI 0.1–0.8) premature death due to decrease in PM_{10} (representing road dust) exposure. This would mean altogether 23.7 premature deaths.

If we expect tunnel users being between ages 30-74, it would even with smallest guideline value (1000 µg/m^3) result in 22.2 (95% CI 16.8–30.1) premature deaths annually (Table 3). This means that only in most conservative scenarios (tunnel users are relatively young, there would be not more than 1.3 passengers per car) we can expect a total reduction in air pollution effects for the population. If the guideline would be higher (e.g. 2000 µg/m^3), we expect mortality effects being around 50% bigger (35.2, 95% CI 26.7–47.6, premature deaths annually) due to tunnel exposure compared to the lower mortality associated with the lower pollution levels in parts of Stockholm.

In conclusion, only in most conservative scenarios we can expect advantageous effects of the improved air quality; however, in most scenarios and presumptions we can expect increase in air pollution exposure and related health effects.

4.3. Difference in the air pollution exposure and the related health effects with the previous assessment

In the previous analysis we could see beneficial effects of the road tunnel in most scenarios (Orru et., 2015). However, there have been several enhancements in the tunnel exposure assessment (see Brandt and Lucchini, 2016) that have increased the exposure:

1. The planned tunnel ventilation systems have been in more detail taken into account in air pollution modelling;
2. Several ramps have been included in the analysis (previously there was largely only the main tunnel) that has increased the number of exposed;
3. The number of tunnel users in main links has been increased;
4. The exposure time has been decreased due to increased speed, but due to increase in exposure and exposed people, still the effects are expected larger than previously;
5. All other factors (e.g. population age, mortality rated etc) besides exposure characteristics have been kept constant for the best comparison.

4.4. Critical assumptions

The critical assumptions have in more detail discussed earlier by Orru et al. (2015). Nevertheless, the main concerns are related to age distribution among users, and number of tunnel users that are susceptible to air pollution. If we presume tunnel users to be older (several up to 85 years), the effects could be almost two times higher compared to being mainly at working age (30-69). As the life-expectancy at birth in Sweden is projected to be around 85 years at 2030 (Statistics Sweden, 2015), it is expectable that tunnel users would be older, which could increase the proportion of vulnerable among the tunnel users. On the other hand, baseline mortality for the age group 30 years and older in Stockholm county has a declining trend, minus 4 percent from 2011 through 2014. Moreover, elderly may travel less often during rush hours and thus be less exposed than the average tunnel user. It is for these reasons difficult to speculate about the most realistic assumption.

Another assumption is related to in-cabin exposure. In different studies the infiltration factors have ranged from 0.1 to 0.95 (Hoek et al., 2013; Hoek et al., 2008), but they have been especially high for particle number concentrations indicating very high infiltration rate for very small exhaust particles (Fuller et al., 2013). The recent measurements in Stockholm have also confirmed that exhaust particles have high infiltration but wear coarse particles have a negligible infiltration rate, thus we did not calculate any additional impacts from PM_{10} in traffic (Johansson et al., 2013). For vehicle exhaust, it is reasonable to use concentrations in tunnel air and relative risk per µg/m3 without adjusting for in-cabin reduction, since people in the epidemiological studies spent most of their time indoors (usually 90-95%), with infiltration rates usually in the same order as for cars. Nevertheless, the infiltration rates in 2030 could be significantly different due to technical improvements in vehicle ventilation.

Also using long-term exposure-response coefficients assessing the effect of short-term very high exposures could be questioned. There is certainly the lack of data on effects of very short exposures, as discussed in the recent WHO REVIHAAP project (2013). There are very few epidemiological studies of shorter than daily air pollution exposures, especially since daily 1-hour maximum values and daily means usually have a high correlation. A few panel studies have associated short term changes in ambient or personal particle exposure to adverse physiological effects that occur within hours of changes in PM exposure (Burgan et al., 2010; Delfino et al., 2010; Schneider et al., 2010). In the most susceptible persons, these changes might further lead to more serious exacerbations of chronic disease, but these toxicological experimental studies are not possible to use for statements on the role of repeated, short high exposures for the cumulative effects on mortality or induction of new cases.

A few small human exposure studies have also been done in current Stockholm road tunnels. First, in healthy subjects 2 hours of exposure to 64 µg/m^3 $PM_{2.5}$ (median concentration) resulted in airway inflammatory response (Larsson et al, 2007). Second, in asthmatics a 30 minutes exposure session with 95 µg/m^3 $PM_{2.5}$ (median concentration) resulted in increased hyper-responsiveness to inhaled allergens (Svartengren et al, 2000), and in a later study asthmatics showed increased symptoms and decreased peak expiratory flow after 2 hours in 80 µg/m^3 (median level) $PM_{2.5}$ (Larsson et al, 2010). Nevertheless, the relevance of such studies is limited in several ways, e.g. if the high peak exposures trigger more or less of severe and fatal events than a linear association would suggest. These are questions that should be answered in further studies.

Finally, depending on the future vehicle fleet and fuel, emissions from motor vehicles may be different that we today expect.

5. CONCLUSIONS

The analysis indicated that only with most conservative assumptions as less older people using tunnel and with the modeled maximal ventilation, the planned tunnel could result in a reduction of health effects from air pollution exposure in the study area. In all other cases the tunnel exposure and related increase in mortality is expected to be bigger than the reductions in mortality related to lower pollution levels in the ambient air.

The higher the concentrations of harmful pollutants are in the tunnel, the longer the total time spent in the tunnel is (especially during more congested situations during rush hours), and the larger the number of users will be, the bigger the adverse health effects would be.

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