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The Stockholm Trial

EFFECTS ON AIR QUALITY AND HEALTH

STOCKHOLM OCTOBER 2006

CITY OF STOCKHOLM
ENVIRONMENT AND
HEALTH ADMINISTRATION

STOCKHOLM AND UPPSALA
COUNTY AIR QUALITY
ASSOCIATIONS

Brief summary

It is a well-documented fact that air pollutants, especially particles, have a considerable effect on the health of Stockholmers, both through influences on their airways and their cardiovascular system. The major part of the emissions of air pollutants comes from cars in the Stockholm inner city where most people also live.

One of the aims of the Stockholm Trial is that there should be a reduction in the emissions of carbon dioxide, nitrogen oxides and particles in the inner city. Measurements have clearly demonstrated that the Stockholm Trial has resulted in a reduction in the volume of traffic in Stockholm's inner city. The reduced volume of traffic has led to lower emissions of carbon dioxide, particles and nitrogen oxides, which in their turn in have lowered the contribution from traffic to total levels of particles (PM10) and nitrogen dioxide. This means that, if the trial were to be made permanent, and produced the same reductions in traffic volume, then the traffic in Stockholm would not contribute as much to air pollutants as it would without the congestion tax.

Estimates show that the emissions of particles and nitrogen oxide from road traffic fell by 8%-12% in Stockholm's inner city. For all road traffic in the City of Stockholm this corresponds to between 3%-5%. This means that, with a congestion tax, both the average particle levels for the population of Stockholm and the nitrogen oxide levels would be some percent lower.

Although these differences in air pollutant levels are rather small on average, the effects on health are estimated to be considerable. In total for the entire Greater Stockholm area (1.44 million inhabitants, 35 x 35 km), it is estimated that between 25 and 30 fewer premature deaths would occur per year as a result of a reduction in long-term exposure to particles. The effects on mortality are, of course, just the "tip of the iceberg". Exhaust gases also affect the occurrence of respiratory tract problems and lead to allergies in many sensitive individuals. This too would fall if a permanent charging system were to be introduced in Stockholm.

Many of Stockholm's inner city streets have very high levels of air pollutants. With the Stockholm Trial it is estimated that the situation was improved. Environmental quality standards to protect health will be met to a greater extent than previously as a result of the reductions in emissions. The results of the Stockholm Trial are, however, not sufficient for environmental quality standards to be met everywhere in Stockholm. For this, greater reductions in traffic are needed, or additional measures to reduce the emissions from traffic.

Comparisons between levels of air pollutants measured during the Stockholm Trial 2006 (January to July) and those from corresponding period in 2003, 2004 and 2005, show that variations in levels of pollutants between different years can be significant. This is the result primarily of meteorological conditions being significant when one studies a short time period. The total measured levels during the Stockholm Trial cannot, therefore, provide quantitative information about how great an influence the reductions in emissions from traffic have had for levels of air pollutants. In the long term, for example if the Stockholm Trial becomes permanent, the air quality in Stockholm will, on the other hand, be influenced most by the reduction in emissions.

A more detailed analysis of the measurements on the inner city streets Hornsgatan and Sveavägen during the Stockholm Trial 2006, shows that the contribution of traffic to emissions of nitrogen oxide levels has decreased. However, the additional contribution of the new direct buses could during certain times of day be seen in the measurements on Sveavägen.

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Foreword

On June 2, 2003 Stockholm City Council decided to propose a congestion charge — the Stockholm Trial. On June 16, 2004 the Swedish Parliament, the Riksdag, adopted the Congestion Charge Law (SFS 2004:629). The law makes it possible to charge a congestion tax in Stockholm up to July 31, 2006. On April 28, 2005 the government decided that the congestion charge trial period should begin on January 3, 2006. The main operators in the Stockholm Trial are the City of Stockholm, the National Road Administration, Vägverket, and Stockholm Transport, SL. The trial is financed by the State.

The Stockholm Trial consists of three parts: extended public transport, congestion tax and more park-and-ride sites in the city and the county.

The objectives of the trial are:

- The number of vehicles in the congestion-charging zone during the peak periods of the morning and afternoon should be reduced by 10 to 15%.
- Traffic flows should improve on the most heavily trafficked roads in Stockholm.
- Emissions of carbon dioxide, nitrogen oxides and particles in inner city air should be reduced.
- People residing or staying in the inner city should experience an improvement in the urban environment.

The Congestion Charging Secretariat is the City of Stockholm's project office. Its task is to plan, coordinate, report on and evaluate the trial. In order to provide an answer to the question to what extent the objectives have been reached, and in order to be able to study the effects of the Stockholm Trial, the Congestion Charging Secretariat has, together with the National Road Administration, the Stockholm County Council Regional Planning and Traffic Office, Stockholm Transport, different research institutions and some of the city's administrations, designed a comprehensive program of evaluation. The measurements, analyses and reports have been prepared by public authorities and administrations as well as consultancies specialising in the different sub-areas included in the programme of evaluation. All of the evaluation reports of being published successively on the trial's homepage, www.stockholmsforsoket.se

The project manager for the program of evaluation was initially Joanna Dickinson (Master of Science in Engineering). She was succeeded by Dr Muriel Beser Hugosson and Ann Sjöberg (Licentiate of Technology). Apart from the project managers, Dr Camilla Byström, Annika Lindgren, Oscar Alarik, Litti le Clercq, David Drazdil, Malin Säker and Ann Ponton Klevstedt have also worked on the evaluations.

The effect of the Stockholm Trial on emissions and levels of air pollutants is presented in this report as well as the estimated consequences for health. The report has been compiled by SLB-analys at City of Stockholm Environment and Health Administration. SLB-analys is responsible for the City of Stockholm's fixed monitoring system for air pollutants and is an operator for the regional air pollution control programme in the Counties of Stockholm and Uppsala. Project managers have been Christer Johansson and Lars Burman. Other collaborators at SLB-analys are Tage Jonson, Magnus Brydolf, Billy Sjövall, Karl-Gunnar Westerlund and Boel Lövenheim. Bertil Forsberg of the Department of Public Health and Clinical Medicine at Umeå University has helped in the health effect estimates.

Summary

The Stockholm Congestion Charging Trial took place during the period January 3 to July 31, 2006. The main objectives of the trial were to reduce congestion, increase traffic flow and improve the environment.

In this report an account is given of the effects of the Stockholm Trial on emissions and levels of air pollutants in Stockholm and the long-term significance of the trial for the health of Stockholmers. The report focuses on inhalable particles (PM10), and nitrogen oxides (NOx and NO_2), but estimates of emissions have also been carried out for other air pollutants, such as the greenhouse gas carbon dioxide. The estimates are based on traffic analyses carried out in connection with the trial. Before and during the trial air quality has also been measured at 20 or so sites in the Stockholm area.

Compared with the situation in 2006 with no Stockholm Trial, it is estimated that nitrogen oxides in the Greater Stockholm area (1.44 million inhabitants, 35 x 35 km) would decrease by approx. 55 tons, of which most would be a result of a reduction in emissions in Stockholm’s inner city. For particles, PM10, the corresponding reduction would be approx. 30 tons, of which about two thirds would be a result of reductions in emissions in the inner city. Both particles formed as a result of road surface wear (primarily due to the use of studded tyres), and particles emitted from exhaust pipes would have decreased. It is estimated that carbon dioxide emissions would have fallen by approximately 41,000 tonnes.

For the Greater Stockholm area the percentage reductions in emissions would be approx. 1%-3%, for Stockholm city approx. 3%-5%, and for the inner city approx. 8%-14%. The emissions also include the results of the extended bus traffic associated with the Stockholm Trial (e.g. direct buses to and from inner city).

Table S1. Estimated reductions in emissions from road traffic in Stockholm for a situation for 2006 with the Stockholm Trial.

	Inner city:		**City of Stockholm:**		**Greater Stockholm*:**	
	tons/year	per cent	tons/year	per cent	tons/year	per cent
Nitrogen oxides. NOx	45	-8.5%	47	-2.7%	55	-1.3%
Carbon monoxide. CO	670	-14%	710	-5.1%	770	-2.9%
Particles. PM_{10} total	21	-13%	23	-3.4%	30	- 1.5%
“road wear particles”	19	-13%	21	-3.3%	28	-1.5%
“exhaust particles”	1.8	-12%	1.8	-4.4%	2.1	-2.4%
Volatile organic compounds, VOC	110	-14%	120	-5.2%	130	-2.9%
benzene. C_6H_6	3.4	-14%	3.6	-5.3%	3.8	-3.0%
Carbon dioxide. CO_2	36,000	-13%	38,000	-5.4%	41,000	-2.7%

** defined as an area of 35 km x 35 km across central Stockholm.*

The total reductions in emissions means that the interim target of the Stockholm Trial, namely that emissions of air pollutants would be reduced, has been achieved.

Reductions in emissions from road traffic in Stockholm mean that the air becomes cleaner. The average levels of nitrogen oxides (NOx) are estimated to fall by at most 5-10 µg/m3 (microgrammes per cubic metre of air) and the levels of particles, PM10 by at most 2-3 µg/m3. The greatest improvements in the air quality are estimated to be found along the Klarastrandsleden bypass, Centralbron Bridge, Valhallavägen and Sveavägen, and at the entrances to the Söderleds Tunnel (Figure S1).

The levels of air pollutants increase in an area around the Essingeleden bypass and the Södra Länken bypass, but considerably more Stockholmers now experience reductions in air pollutants and better air quality compared with those who experience increased levels.

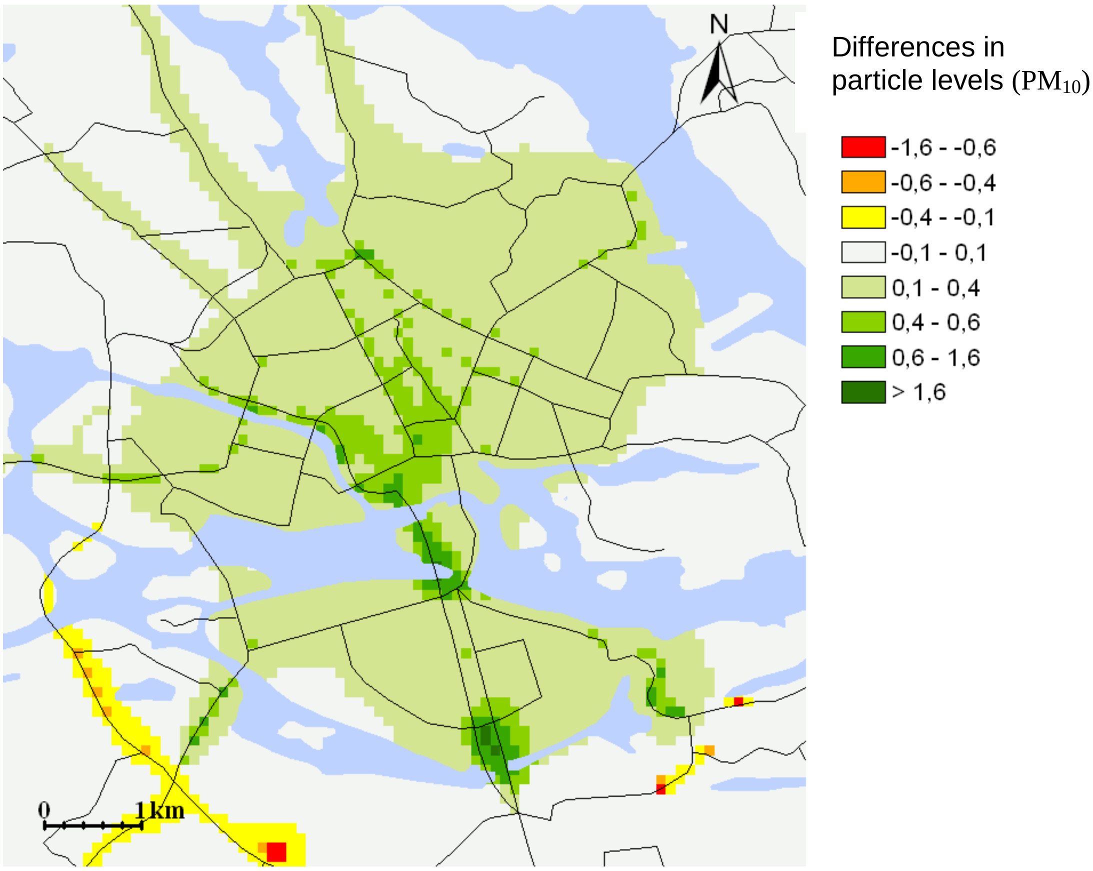

Figure S1. Changes in levels of particles (PM10, mean annual levels) with the Stockholm Trial compared with levels without the congestion charge for 2006. Within the green areas the levels have fallen, within yellow to red areas there is an increase in levels. In the inner city changes refer to rooftop height (not street canyon).

On Hornsgatan it is estimated that levels of nitrogen oxides (NOx) at street level would fall by approx. 7%-8%, levels of nitrogen dioxide (NO_2) by approx. 3%-4% and levels of particles (PM10) by 5%. The improvement is sufficient that the environmental quality standard (to protect public health) as regards the mean annual value for particles, PM10, is not exceeded on Hornsgatan. On the other hand, environmental quality standards are still being exceeded as regards high daily mean values both for particles, PM10, and nitrogen dioxide. Environmental quality standards are legally binding national stipulations whose primary aim is to protect the public against long-term health effects, while daily mean values (and hourly mean values) refer to protection against more acute health effects.

On Sveavägen it is estimated that levels of nitrogen oxides (NOx) at street level would fall by 3%, levels of nitrogen dioxide (NO_2) by approx. 1%-2%, and levels of particles (PM10) by 4%. The improvement is sufficient for the environmental quality standard of the annual mean value for nitrogen dioxide, NO_2, not to be exceeded on Sveavägen. Just as on Hornsgatan, however, the environmental quality standards for high mean daily values are still being exceeded for both particles, PM10, and for nitrogen dioxide.

On Norrlandsgatan the levels of nitrogen oxides (NOx) at street level are estimated to have fallen by 11%, the levels of nitrogen dioxide (NO_2) by approximately 5-6% and the levels of particles (PM10) by 7%. The improvement is sufficient for the environmental quality standard for the annual mean value for nitrogen dioxide, NO_2, not to be exceeded on Norrlandsgatan. Here, too, the environmental quality standard is, however, exceeded as regards high daily mean values both for particles, PM10 and for nitrogen dioxide.

On S:t Eriksgatan (south of S:t Eriksbron Bridge) the air quality is estimated to be unchanged at street level. A little more traffic and somewhat higher emissions are balanced by the fact that the urban background level of air pollutants has fallen. The environmental quality standard for mean annual values is being met, but the standard for high mean daily values of particles, PM10 is being exceeded.

On Valhallavägen (NW of Lidingövägen) the levels of nitrogen oxides (NOx) at street level are estimated to have fallen by 12%, and the levels of nitrogen dioxide (NO_2) and particles (PM10) by approximately 7-8%. The improvement is not sufficient to meet the environmental quality standard for high mean daily values of particles, PM10, on Valhallavägen.

Along the Essingeleden bypass the environmental quality standard for protecting public health is also being exceeded. The increased traffic on this road, with the Stockholm Trial, is estimated to increase daily mean levels by approximately 3 µg/m3 (micrograms per cubic metre of air) for nitrogen oxides, NOx, and up to approximately 2 µg/m3 for particles, PM10. In order to meet the environmental quality standards for particles along the Essingeleden bypass, major reductions in traffic emissions are needed.

For many inner city streets with high levels of air pollutants the situation has been improved by the Stockholm Trial. Environmental quality standards for the protection of public health will be met to a greater extent than previously as a result of reduced traffic. The effect of this trial is, however, not sufficient for environmental quality standards to be met everywhere in Stockholm (apart from on inner city streets, environmental quality standards are exceeded along the city’s major approach roads). To meet the standards requires greater reductions in traffic to cut emissions from road traffic.

The reduction in emissions and the general improvement of air quality in Stockholm means that Stockholmers’ health will improve in the long-term (i.e. with the permanent introduction of a congestion charge). In long-term exposure to air pollutants even relatively small improvements in air quality can provide appreciable health benefits for a large population. International research ascribes reduced mortality as the most important of these health benefits. Premature death as a result of long-term exposure to air pollutants can, for example, result from cardiovascular diseases and lung cancer.

In order to quantify the effects of the Stockholm Trial as regards its long-term significance for Stockholmers' mortality, a Norwegian study has been used. On the basis of this study it is estimated that improvements in air quality in Stockholm will lead to approximately 20-25 fewer premature deaths per annum for Stockholm's inner city. In total for the entire Stockholm area (1.44 million inhabitants, 35 x 35 km) it is estimated that there will be between 25 and 20 fewer early deaths per annum as a result of the cleaner air. Apart from the long-term effects on Stockholmers' mortality, vehicle emissions also have an effect on the occurrence of illnesses as well as aggravating respiratory conditions in individuals who are prone to these. The cleaner air resulting from the Stockholm Trial means fewer admissions to hospital and fewer cases of distress experiences, i.e. people experiencing the air as irritating, evil-smelling or dirty.

Comparisons between observed levels of air pollutants that have been measured during the Stockholm Trial 2006 (January to July 2006) with corresponding months in 2003, 2004 and 2005 show that the variations in levels of pollutants between different years can be significant. This depends to a great extent on the fact that meteorological conditions are very important when studying a short period of time. Particle levels in the air, for example, depend to a high degree on the humidity of the road surfaces. During the spring of 2006 Stockholm received a large amount of precipitation and the snow melted late, which caused particle levels to be unusually low. The influence of the weather means that the total levels measured during the Stockholm Trial cannot provide quantitative information on how significant the reductions in traffic emissions have been for levels of air pollutants. In the long term, for example if the Stockholm Trial becomes permanent, air quality in Stockholm will be affected most by reductions in emissions.

A more detailed analysis of the measurements on the inner city streets of Hornsgatan and Sveavägen during the Stockholm Trial 2006, shows that the contribution of traffic emissions to nitrogen oxide levels has decreased. However, contributions to emissions from the new direct buses could at certain times be proven in the measurements on Sveavägen.

1 Introduction

The Stockholm Trial has as one of its interim targets the reduction in the emissions to the air of carbon dioxide, nitrogen oxides and particles. After the introduction of catalytic converters in private cars at the end of the 1980s emissions in Stockholm of a number of air pollutants have fallen dramatically, and continue to fall in pace with the replacement of older vehicles. Stockholm’s environment zone has accelerated the development as regards reducing emissions from trucks and buses. For several air pollutants (benzene, carbon dioxide, lead and benzo[a]pyrene) the levels are below the approved environmental quality standards (or the EU directives) even on the busiest streets in Stockholm’s inner city.

The problem remains, however, in Stockholm of high levels of nitrogen dioxide and particles. Nitrogen dioxide levels have not fallen at the same pace as emissions of nitrogen oxides from traffic because the levels are influenced by ozone levels, which in turn have increased steadily (Johansson & Forsberg, 2005). Nor do the particle levels fall in pace with emissions of particles in exhausts falling because the particles to a great extent come from wear of the road surface, which in its turn is a result of the use of studded tyres (Johansson et al., 2004).

Figure 1 below shows photographs of particles formed when studded tyres erode the road surface, and the exhaust particles arising as a result of imperfect combustion of diesel and petrol. The road wear particles are considerably larger than the exhaust particles, and they have quite different shapes and chemical compositions. It is not known exactly which particles are the most damaging to people’s health, but it is well documented that airborne particles affect both poor health and mortality among the population. It has also been demonstrated that particles have a greater significance for public health than the other air pollutants.

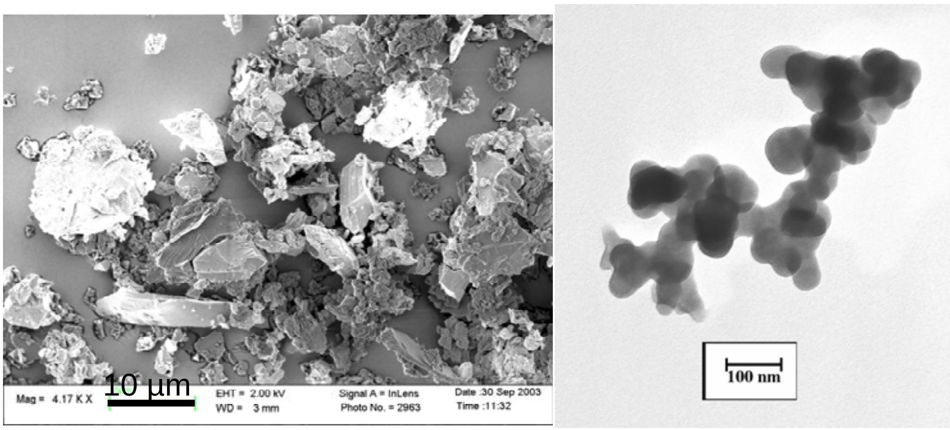

Figure 1. Different types of suspended particles in the ambient air. On the left can be seen fresh particles formed by wear of the asphalt road surface (1 UM equals 1000th of a millimetre). On the right can be seen a diesel particle consisting of several small cylindrical particles which have bunched together and formed a chain-like structure (1 nm is equal to one millionth of a millimetre). The diesel particles are, therefore, considerably smaller than the road wear particles.

Particles are measured as PM10, which means the amount (the mass) of all inhalable particles with a diameter less than 10 µm (ten thousandths of a millimetre). Road traffic is the most important source of particles in Stockholm’s inner city. The greater part of the PM10 levels along the streets in the inner city are the result of cars with studded tyres eroding the road surface. The particles in exhausts from petrol and diesel vehicles are much smaller and do not contribute a great deal to PM10 levels. On the other hand, there are considerably higher numbers of exhaust particles than particles resulting from tyre stud road wear. Road traffic is also the largest source of nitrogen oxides (e.g. NOx and NO_2), but here emissions through exhausts dominate. Nitrogen oxide levels and exhaust particle levels co-vary extremely well, and for this reason nitrogen oxide levels are an indicator of levels of exhaust particles. PM10 levels on the other hand show poor co-variance with nitrogen oxide levels because of completely different factors such as road surface conditions determine PM10 levels (Johansson et al., 2006).

In order to manage the air pollution problems, measures are required which both reduce exhaust emissions and reduce the formation of non-exhaust related particles (primarily particles arising from wear of the road surface). Analyses carried out earlier by SLB-analys show that “congestion taxes” according to a proposal put forward by the Swedish Environmental Protection Agency and “congestion charges” according to the model that the City of Stockholm are now testing out, are expected to provide significant reductions of emissions in both exhaust-related and non-exhaust related air pollutants (see Johansson et al., 2003 and Johansson et al., 2004 respectively). Other measures evaluated in Stockholm include, on the one hand those that only reduce non-exhaust related particles (dust suppression, intensify the street cleaning and a lower portion of studded tyres; Johansson et al., 2005) and on the other measures only reducing exhaust emissions such as, for example, the environmental zone (Burman & Johansson, 2001).

The aim of this report is to analyse the effects of the Stockholm Trial on the emission of air pollutants, on air quality and on the health of Stockholmers. The assessment focuses primarily on particles and nitrogen oxides. Other air pollutants being measured due to their potential health effects are benzene and certain other volatile hydrocarbons (VOC). There is also a description of carbon dioxide (CO_2) emissions, which affect climate.

Comparison of measured levels of air pollutants between periods with different types of weather is not easy as the dilution of the emissions then varies. In the short term, air quality is influenced a great deal by these variations in weather. In the long term, with normal weather conditions, levels of air pollutants are influenced most by the scale of the emissions. For the assessment of the effect of the Stockholm Trial on air quality and its long-term effect on the health of Stockholmers and on environmental quality standards (which apply by calendar year), both measurements and estimates based on air quality dispersion models have been used.

2 Results

2.1 The effects on air pollutant emissions

Estimates of the effects of the Stockholm Trial on emissions of air pollutants by road traffic are presented below. The estimates have been made with the help of Stockholm and Uppsala County Air Quality Associations’ emission databases (LVF, 2006), and traffic measurements (Stockholm Traffic Office 2005, 2006) and estimates of traffic mileage (Road and Traffic Research Institute VTI, 2006, National Road Administration consultant 2006) carried out in connection with the trial.

The total traffic mileage (i.e. the distance over which all the vehicles move in total) in Stockholm's inner city fell during the Stockholm Trial by approx. 15% on an average 24-hour weekday period. For Stockholm County the traffic mileage has fallen by approx. 2% on 24-hour weekday periods. Reductions in traffic mileage in Stockholm mean that emissions of air pollutants from road traffic also decrease.

The Stockholm Trial has therefore meant that traffic has declined along most streets in the inner city. Table 1 shows changes in traffic intensity on some major streets in the inner city with a great deal of traffic and major emissions. On Hornsgatan for example, one of the streets with the highest levels of air pollutants, traffic has fallen by approx. 8% between Ringvägen and Varvsgatan. The traffic on Sveavägen has fallen by approx. 4%-6%. On some streets in the inner city traffic has increased, e.g. on S:t Eriksgatan south of S:t Eriksbron bridge.

As regards approach roads and ring roads, traffic on the Essingeleden bypass has increased by between 3% and 5% on 24-hour weekday periods. For the southern approaches increases are seen on Huddingevägen (north of the Älvsjö interchange), and on the E4/E20 at Västertorp. On Nynäsvägen traffic has fallen somewhat, however. For the northern approaches modest reductions in traffic can be seen.

Table 1. Changes in traffic flows during a 24-hour weekday period on some main streets in Stockholm's inner city during the Stockholm Trial (City of Stockholm Traffic Office 2005, 2006). The average reduction in traffic for a 24-hour weekday period is 15% (VTI, 2006).

Inner city street:	**Site:**	**Change:**
Hornsgatan	Ringvägen-Varvsgatan	-8%
Sveavägen	Vandisvägen-Frejgatan	-6%
	Odengatan-Kungstensgatan	-4%
	Adolf Fredriks Kyrkogata- Kammakargatan	-6%
Norrlandsgatan	Birger Jarlsgatan- Kungsgatan	-1%
	Hamngatan - Mäster Samuelsgatan	-12%
Birger Jarlsgatan	Tegnérgatan- Rådmansgatan	-6%
Valhallavägen	Odengatan - Drottning Kristinas Väg	-14%
Stadsgårdsleden bypass	Tullhusinfarten-Stadsgårdshamnen	-14%
Centralbron Bridge	Herkulesgatan/Söderkopplan - Riddarfjärden	
	exit, entrance	-10%
Söderleden tunnel	Johanneshovsbron Bridge - Söderleden bypass	-7%
Västerbron Bridge	Lorensbergsgatan - Västerbron Bridge descent	-13%
Strandvägen	Artillerigatan - Nybroplan	-11%
S:t Eriksgatan	Norra Stationsgatan - Vanadisplan	-20%
	Vanadisplan - Karlbergsvägen	-12%
	Alströmergatan - S:t Eriksplan	+5%
Drottningholmsvägen	Fredhäll exit- Fredhällsplan exit	-18%
Folkungagatan	Borgmästargatan -Erstagatan	-9%
Folkungagatan	Sågargatan - Tegelviksgatan	- 23%
Cedersdalsgatan	Roslagstull - Sveaplan	- 8%

Table 2. Changes in traffic flows during 24-hour weekday period on approach roads and ring roads during the Stockholm Trial (National Road Administration consultant, 2006)

	Road:	**Site:**	**Change:**
Approaches, N,W	E18	N of Danderyd Church interchange	-6%
	E18	N of Rinkeby	-2%
	E4	N of Järva krog interchange	-2%
	E4	S of Haga Norra interchange	-3%
	Bergshamraleden bypass	E of Ulriksdalsvägen	-2%
	Roslagsvägen	W of Frescati	-6%
	Drottningholmsvägen	Tranebergsbron Bridge	-1%
Approaches S, E	Värmdöleden bypass	E of Skogalund interchange	+1%
	Värmdöleden bypass	At Alphyddan	n/a
	Nynäsvägen	N of Gubbängen interchange	-2%
	Huddingevägen	N of Älvsjö interchange	+5%
	E4/E20	W of Västertorp interchange	+2%
Essingeleden	At Tranebergsbron Bridge	Northbound	+3%
	At Tranebergsbron Bridge	Southbound	+3%
	At Gröndalsbron Bridge	Northbound	+ 3%
	At Gröndalsbron Bridge	Southbound to junction with Södra Länken	+ 5%

Table 3 shows how the changes in traffic resulting from the Stockholm Trial have affected the total emissions from road traffic in different parts of Stockholm. In the estimates the Stockholm and Uppsala County Air Quality Associations' county-wide emissions databases have been used. The databases contain detailed descriptions of the emissions from road traffic for all traffic routes in the region with traffic flows of greater than 1,000 vehicles per 24-hour period. The estimates in Table 3 have not taken into account any changes in speed as a result of the Stockholm Trial. The effects of the extended bus traffic (e.g. the direct buses to and from the inner city) have, on the other hand, been included in the estimates.

Compared with an anticipated situation for the entire year of 2006 without the Stockholm Trial, it is calculated that emissions of nitrogen oxides in the Greater Stockholm area (1.44 million inhabitants, 35 km x 35 km) have decreased by approximately 55 tons, of which most are a result of reductions in emissions in the inner city.

For particles, PM10, the corresponding reduction is about 30 tons, of which approximately two-thirds is a result of reduction in emissions in the inner city. Both particles formed due to road wear from, and particles emitted through exhaust pipe's are falling. The reductions in emissions shown in Table 3 are somewhat smaller as a result of the extended bus traffic in connection with the Stockholm Trial, with for example direct buses to and from the inner city. The effects of this are estimated to be greatest on the emissions of nitrogen oxides. Taken together across the Greater Stockholm area the percentage reductions in emissions are approx. 1%-3%. Taken as a whole for the City of Stockholm these are approx. 4%-5% and for the inner city approx. 8%-14%.

Table 3. Estimated reductions in emissions from road traffic in Stockholm for a situation for 2006 with the Stockholm Trial.

	Inner city:		**City of Stockholm:**		**Greater Stockholm*:**	
	tons/year	per cent	tons/year	per cent	tons/year	per cent
Nitrogen oxides. NOX	45	-8.5 %	47	-2.7 %	55	-1.3 %
Carbon monoxide. CO	670	-14 %	710	-5.1 %	770	-2.9 %
Particles. PM_{10} total	21	-13 %	23	-3.4 %	30	- 1.5 %
"road wear particles"	19	-13 %	21	-3.3 %	28	-1.5 %
"exhaust particles"	1.8	-12 %	1.8	-4.4 %	2.1	-2.4 %
Volatile organic compounds, VOC	110	-14 %	120	-5.2 %	130	-2.9 %
benzene. C_6H_6	3.4	-14 %	3.6	-5.3 %	3.8	-3.0 %
Carbon dioxide. CO_2	36,000	-13 %	38,000	-5.4 %	41,000	-2.7 %

** defined as an area of 35 km x 35 km across central Stockholm.*

2.2 The effects on levels of air pollutants

In this section the estimated effects of the Stockholm Trial on levels of nitrogen oxides and particles will be presented. The estimates are based on the emissions presented above, which in their turn are based on analyses by VTI (the Road and Transport Research Institute) how the Stockholm Trial has affected road mileage. The estimated changes in traffic and corresponding levels of air pollution are annual mean values which would arise if a permanent charging system of the same kind as the Stockholm Trial were to be introduced (i.e. not merely the change in level during the months that the trial took place). For the inner city, with high buildings on both sides of many streets, the change applies to rooftop level (not street level) and for open areas 2 m above the ground. The levels of air pollutants at rooftop level in the inner city (so-called urban background level) provide an indication of the average load on the population of Stockholm. Changes in levels of air pollutants at street level have been estimated separately for a number of inner city streets, and these are shown in section 2.4. Later in the report (Chapter 5) the total measured levels for the Stockholm Trial 2006 (January to July) will be presented.

Figures 2, 3 and 4 show the geographical distribution of the differences in particle levels (PM10 and exhaust particles) and nitrogen oxide levels between a situation with and without the Stockholm Trial in 2006. The geographical distribution of changes in levels is largely the same, as the estimates are based on the same change in traffic mileage for all substances. The greatest changes in air quality can be seen along the Klarastrandsleden bypass, Centralbron Bridge, Valhallavägen and Sveavägen, and at the entrances to the Söderleden Tunnel.

At their maximum, levels of nitrogen oxides, NOx, fall by approx. 5-10 $\mu g/m^3$ (micrograms per cubic metre of air), and particles, PM10, by up to approx. 2-3 $\mu g/m^3$. Increased levels are found in a restricted area around the Essingeleden bypass. The increases in level are small at most 3 $\mu g/m^3$ for NOx and up to approx. 2 $\mu g/m^3$ for PM10. Many fewer individuals are exposed to increased levels compared with a number who experience reduced levels.

Table 4 shows the estimated mean levels arising as a result of emissions from road traffic, on the one hand in the entire Greater Stockholm area (1.44 million inhabitants, 35 x 35 km), and on the other Stockholm's inner city (350,000 inhabitants, 7 km x 7 km in area, see e.g. Figure 2). The table also shows changes in the levels of particles and nitrogen oxides arising as a result of the Stockholm Trial. The levels are the mean contributions to which the population is estimated to be exposed, and they have been obtained by taking into account where people live in relation to the geographical distribution of the levels. It is clear from the table that the contribution of road traffic to the levels of nitrogen oxides has declined from 4.42 µg/m^3 to 4.19 µg/m^3, i.e. a reduction in the contribution to the level of a good 5%.

For particles the contributions to the level are markedly different depending on whether one merely takes into account the particles emitted through exhaust gases (PM exhaust) or whether one also takes into account those particles formed due to the road wear of the road surface because of the use of studded tyres and wear and tear on brakes and tyres. Road surface particles provide a considerably greater contribution to particle levels compared with exhaust particles. For Greater Stockholm the contribution to the level from the total of road wear particles and exhaust particles from road traffic falls by 1.71 µg/m^3 to 1.65 µg/m^3, i.e. barely 4%. For exhaust particles contributions to levels fall from 0.102 µg/m^3 to 0.0960 µg/m^3, corresponding to a 6% reduction.

If one looks at the estimates for the inner city, then the contributions from road traffic are considerably greater, and the reduction in traffic means more both for particles and for NOx; reaching almost 10% for the population-weighted contributions to levels from road traffic.

The reductions in levels can also be compared with the total levels measured. On Södermalm (monitoring station at Torkel Knutssonsgatan) the total levels of NOx are approx. 20 µg/m^3 on average over a year. Here the levels are estimated to fall by approx. 1.1 µg/m3, which corresponds to barely 6%. For PM10 the total levels are around 18 µg/m^3 and the reduction is estimated at 0.3 µg/m^3 or less than 1%.

Table 4. Mean contributions to total levels of nitrogen oxides and particles from emissions from road traffic with and without charges according to the Stockholm Trial. Mean levels have been estimated by weighting with regard to the number of residents in the area. Unit: µg/m^3.

	2006 without Stockholm Trial	**2006 with Stockholm Trial**	**Difference**
NOx (Greater Stockholm)	4.42	4.19	0.23 (5.3%)
PM_{10} (Greater Stockholm)	1.71	1.65	0.064 (3.8%)
PM exhaust (Greater Stockholm)	0.102	0.0960	0.0062 (6.1%)
NOx (inner city)	8.41	7.60	0.81 (10%)
PM_{10} (inner city)	2.76	2.55	0.21 (7.6%)
PM exhaust (inner city)	0.21	0.19	0.022 (10%)

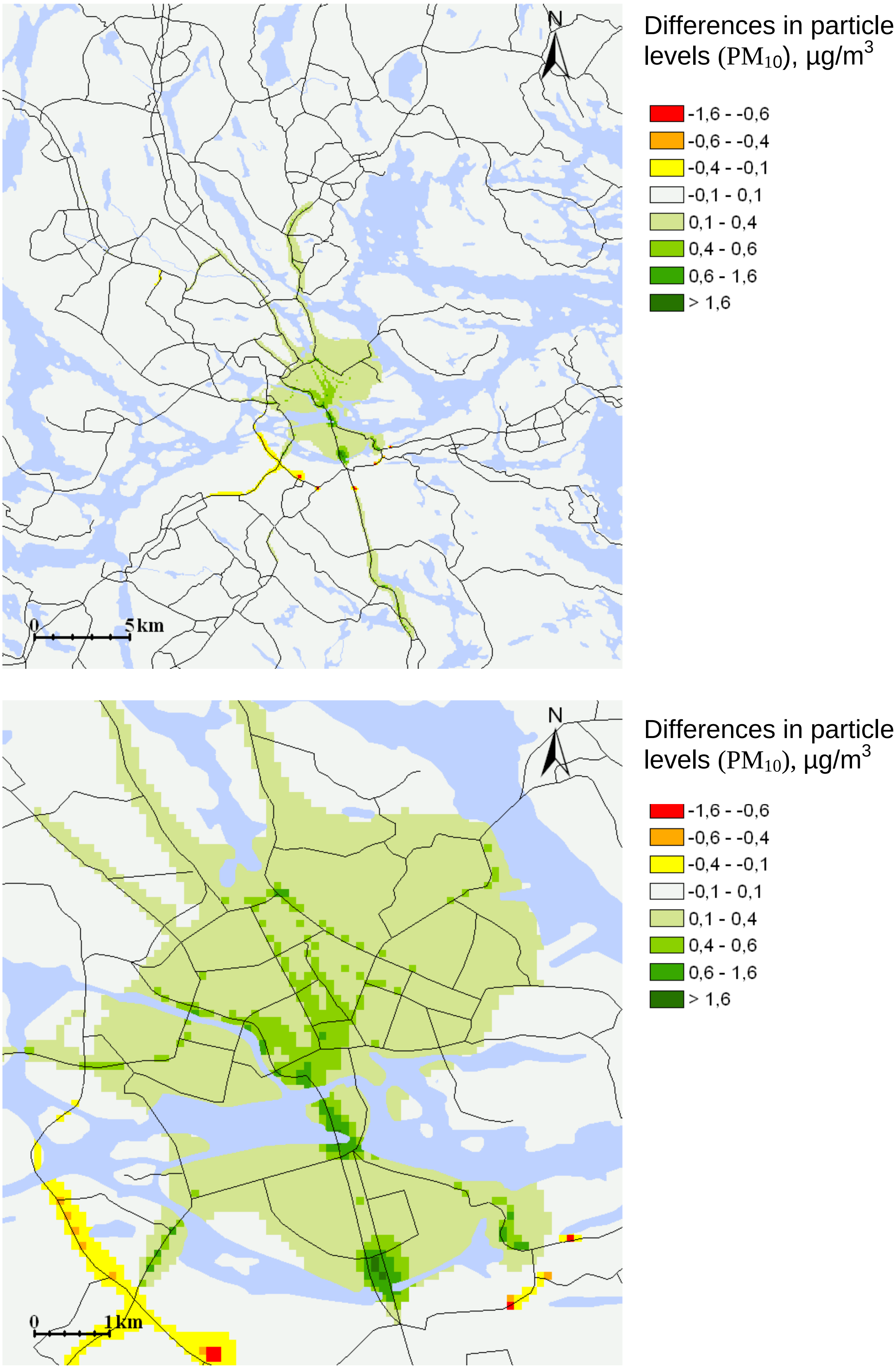

Figure 2. Change in particle levels (PM_{10}, mean annual values) in the Stockholm Trial. The upper picture shows the difference for the entire Greater Stockholm area, and the lower picture shows Stockholm's inner city. Within the green areas the levels have fallen, within yellow to red areas an increase of the levels has occurred.

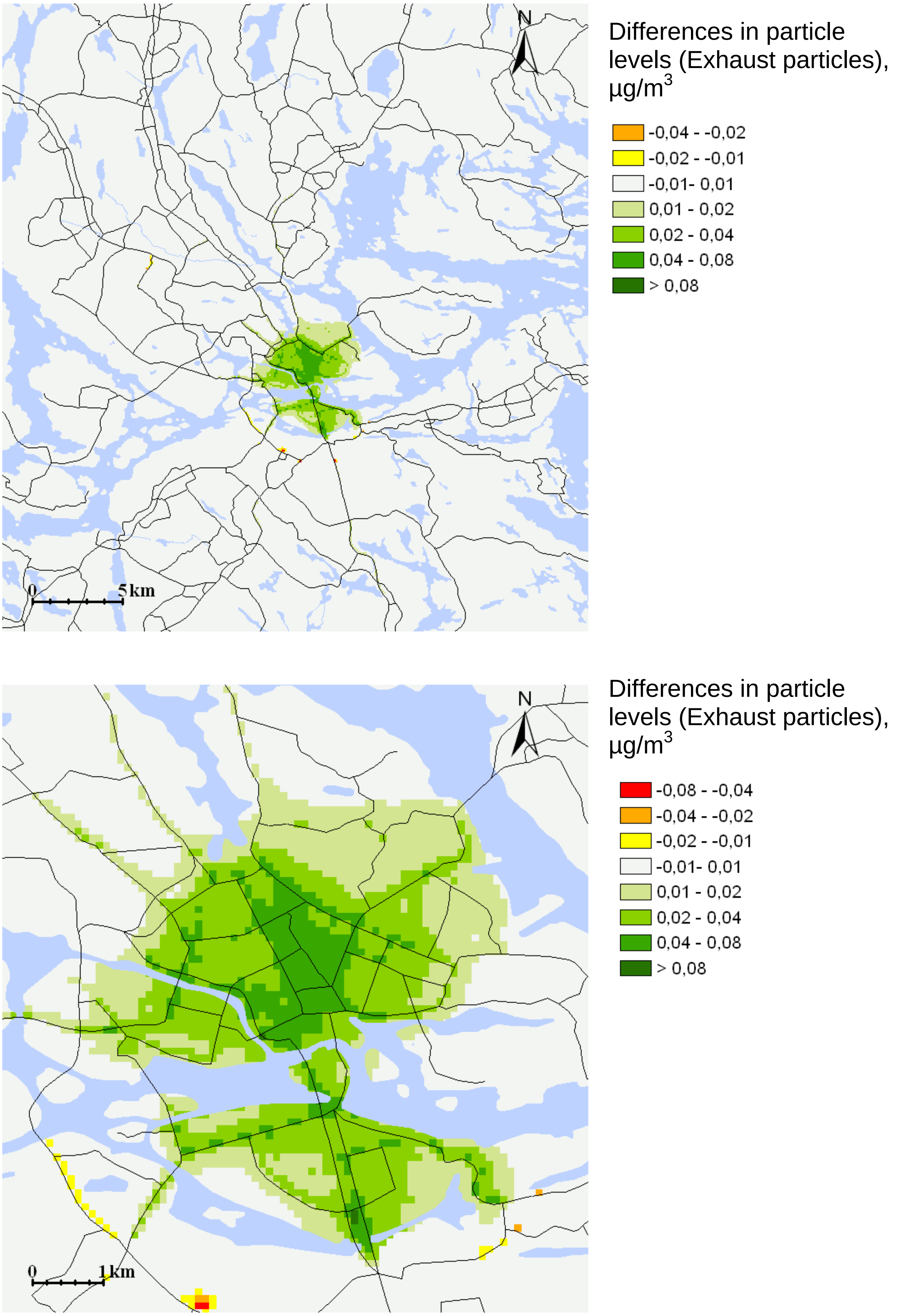

Figure 3. Change in particle levels (exhaust particles, mean annual values) in the Stockholm Trial compared with the levels without charges in 2006. The upper picture shows the difference for the entire Greater Stockholm area, the lower picture shows Stockholm's inner city. Within the green areas the levels have fallen, within yellow to red areas an increase of the levels occurred.

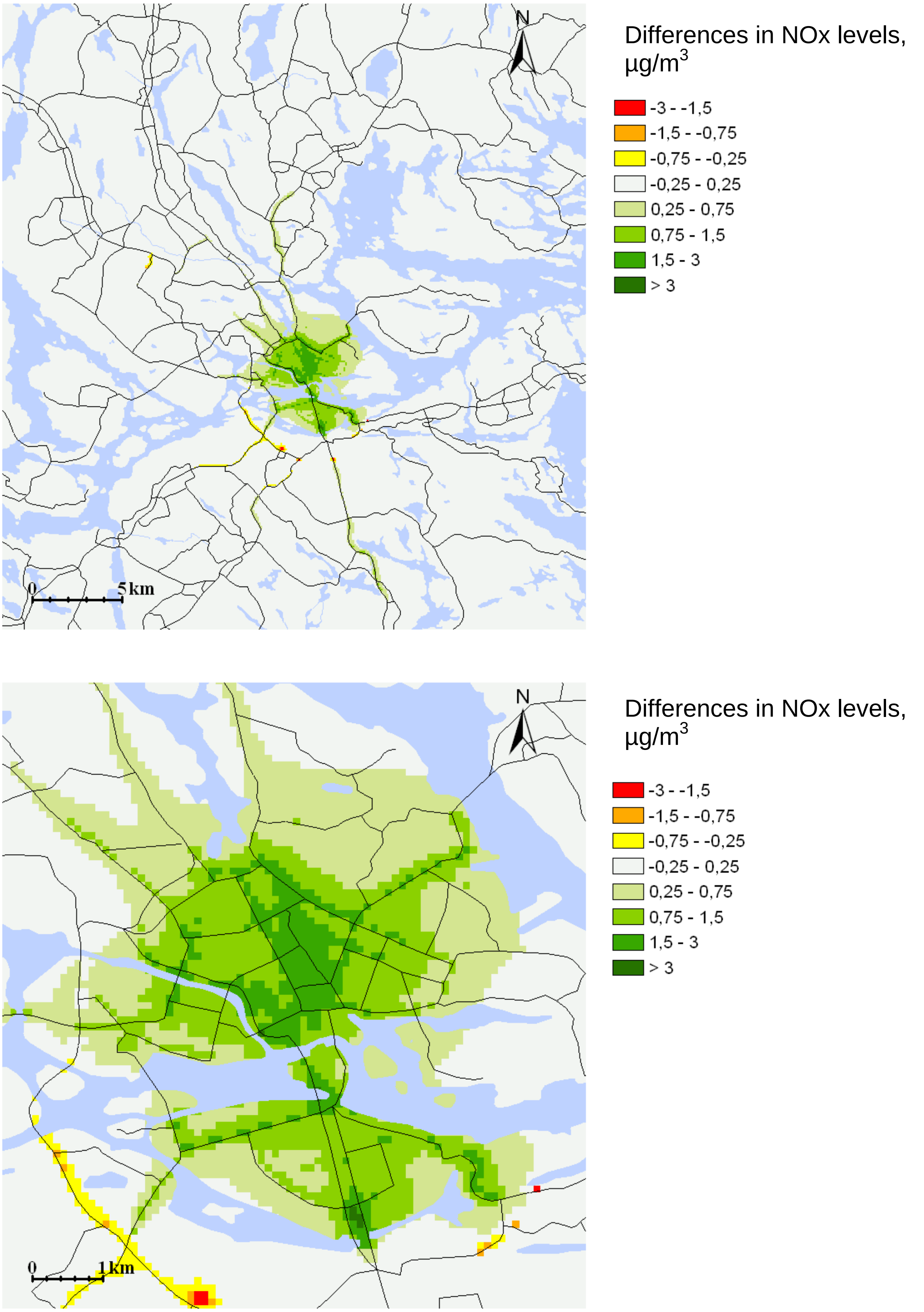

Figure 4. Change in nitrogen oxide levels particle levels (mean annual values) in the Stockholm Trial compared with the levels without charges in 2006. The upper picture shows the difference for the entire Greater Stockholm area, the lower picture shows Stockholm's inner city. Within the green areas the levels have fallen, within yellow to red areas an increase of the levels occurred.

2.3 Long-term consequences for health

In so-called epidemiological studies researchers worldwide have investigated the link between air pollution levels and different health effects in large groups of a population. In the health consequence analyses the greatest significance is usually ascribed to the effects on mortality, as exposure over a long period (one or several years) has been shown to influence human survival rates.

The first American long-term studies of air pollution levels and survival had a major impact in the literature, but these investigated how differences between towns in levels of particles (PM10, PM 2.5) influence mortality (Dockery et al., 1993; Pope et al., 1995). In this study we are interested in estimating the effects on public health as a result of reductions in particle levels resulting from reduced exposure to road traffic emissions. Recently studies have been presented which use the differences in the level of exposure to exhausts measured as nitrogen dioxide (NO_2) or nitrogen oxides (NOx) in cities. Studies of this kind now exist from Holland, New Zealand, France and Norway. These studies have arrived at very similar so-called level response factor for the importance of traffic emissions for mortality. They found that the increase in mortality is 12%, 13% and 14% per 10 µg/m3 (micrograms per cubic metre of air) increase in nitrogen dioxide, NO_2, respectively in the studies from Holland, England and France. The Norwegian study, carried out on adult men, has been considered the most relevant for the consequence analysis of the effects of the Stockholm Trial. In that study they arrived at an increased premature mortality of 8% per 10 $\mu g/m^3$ increased level of nitrogen oxides, NOx.

It should be observed that it is neither NO_2 nor NOx in itself which is the cause of the effects on mortality that have been reported. As was pointed out in the introduction, it has been shown that particles have a greater significance for public health than other air pollutants. In those studies mentioned above NO_2 and NOx have been used as **indicators** of traffic exhaust. Exactly which component(s) in the exhaust is the cause has not been demonstrated, but a great deal points to the fact that particles are important.

If one accepts the exposure-response function for NOx from the Norwegian study (8% per 10 $\mu g/m^3$) and a mortality frequency of 1,000/100,000 inhabitants per year, then the reduction in level in Stockholm's inner city, with its approx. 350,000 residents, is expected to result in approx. **20 to 25 fewer premature deaths per year**. We have then taken into account that even the low mortality among younger people is influenced to the same extent calculated as a percentage by lower levels, as other studies have shown that particles even affect mortality in children. The fact that younger people are included has however negligible significance on the result. Using the same assumptions for the entire assessment area (approximately Greater Stockholm) with 1.44 million inhabitants (including the inner city), the reduction in level is estimated to result in **avoiding approximately 25 to 30 premature deaths per year.**

Effects on mortality are, of course, merely one of many negative health effects. Vehicle emissions also affect the occurrence of certain illnesses, exacerbate respiratory problems in people prone to these and can cause allergies.

2.4 Effects at street level and comparisons with environmental quality standards

Environmental quality standards are legally binding national stipulations whose primary purpose is to protect people from high levels of air pollutants. Environmental quality standards have been drawn up in connection with the Swedish Environmental Code. Standard values and concepts are based on directives and limits set by the EC for all EU countries.

Environmental quality standards should be met as soon as possible, though before a point in time given for each substance. At present there are environmental quality standards for nitrogen dioxide, particles (PM10), benzene, carbon monoxide, sulphur dioxide, ground-level ozone and lead (Ministry of the Environment, 2001).

The levels of sulphur dioxide, carbon monoxide, benzene and lead in the Stockholm air are so low that they meet the environmental quality standard by a broad margin. The environmental quality standards which are generally regarded as the most difficult to meet in the Stockholm area are those for particles and nitrogen dioxide. These standards are exceeded today along many of Stockholm's inner city streets and approach roads.

For particles, PM10, there are environmental quality standards to protect health both as a mean annual value and as a mean daily value. For nitrogen dioxide there is also an environmental quality standard for mean hourly value. Short-term values (hours, days) are intended to protect the population against acute health effects whilst mean annual values are meant to protect against long-term effects.

Table 5. Environmental quality standards for particles, PM_{10}, which have to be met from January 1, 2005.

Time for mean value	Norm value $\mu g/m^3$	Value must not be exceeded more than
24-hour	50	35 days per calendar year (90th percentile)
Calendar year	40	Must not be exceeded

Table 6. Environmental quality standards for nitrogen dioxide, which have to be met from January 1, 2006.

Time for mean value	Norm value $\mu g/m^3$	Value must not be exceeded more than
1 hour	90	175 hours per calendar year (98th percentile)
24-hour	60	7 days per calendar year (98th percentile)
Calendar year	40	Must not be exceeded

On the pages that follow estimates of the effects of the Stockholm Trial as regards environmental quality standards for particles and nitrogen dioxide are given for some of the most polluted places in Stockholm. Estimates for the inner city refer to levels at street level for each stretch of street (the maps shown earlier referred to levels at rooftop height for the inner city). Levels of pollution at street level in the inner city are always higher than at rooftop height because of the close vicinity of road traffic and the poorer ventilation of the emissions.

The account which follows applies to total levels, which comprise both the contribution from the street (emissions from street traffic) and the urban background level (all other emissions within and outside Stockholm). Comparison is made with the situation in 2005. Between 2005 and 2006 without the Stockholm Trial it is estimated that the emissions of nitrogen oxides would fall slightly, which is a result of the vehicle fleet becoming slightly cleaner year by year (according to the National Road Administration's EVA-model). For particles, PM10, emissions of exhaust particles would fall, but as these, comprise a small proportion of the total PM10 level, this is not visible in the diagrams (PM10 consists primarily of particles from road wear of the road surface by tyres).

With e.g. the 90th percentile we mean the level which is exceeded by only during 10% of the days of the year. When the 90th percentile of the daily mean value for particles, PM10, is shown in the diagrams that follow, this means the mean value on the 36th "worst" day of the year. When the 98th percentile of the daily mean value for nitrogen dioxide, NO2, is shown in the diagrams that follow, this means the mean value on the eighth "worst" day of the year.

On **Hornsgatan** (Ringvägen-Varvsgatan) the levels of particles, PM10, are estimated to **fall by 5%** at street level (Figure 5) during the Stockholm Trial (on an annual basis). The reduction is sufficient for the environmental quality standard of 40 $\mu g/m^3$ (mean annual value of PM_{10}) not to be exceeded. The environmental quality standard 50 $\mu g/m^3$ (mean daily value, 90th percentile) is, despite the improvement, estimated to continue to be exceeded on Hornsgatan.

The levels of nitrogen oxides, NOx, at street level are estimated to fall by approx. 7%-8% in which the Stockholm Trial (on an annual basis). Nitrogen dioxide levels on Hornsgatan are estimated to **fall by approx. 3%-4%**. The reduction is not sufficient to achieve the environmental quality standards for NO_2.

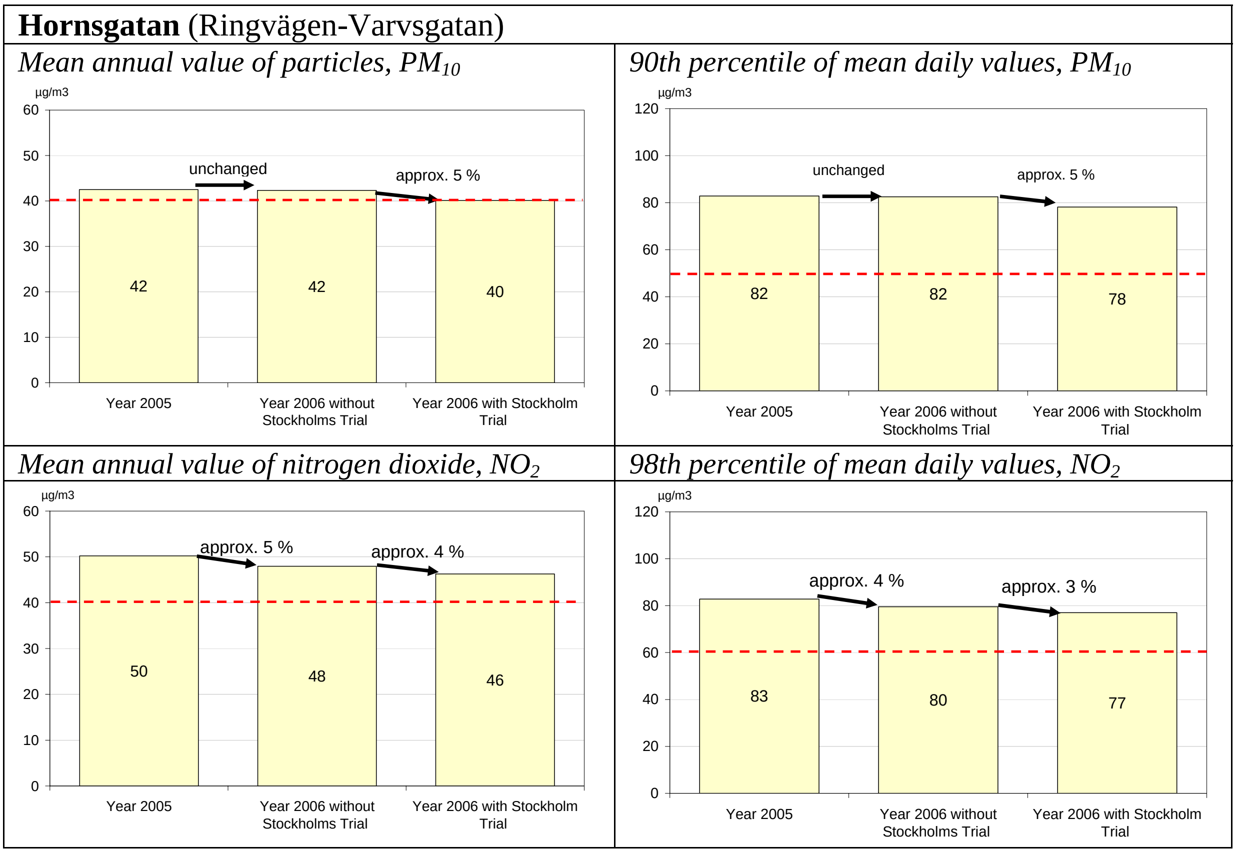

Figure 5. Estimated change in air quality on Hornsgatan and a comparison with environmental quality standards for protecting health (red broken line). Data for 2005 was measured. The values apply to a whole year. Unit: $\mu g/m^3$.

On **Sveavägen** (Kungstensgatan-Rådmansgatan) the levels of particles, PM10, are estimated to **fall by 4%** at street level (Figure 6) during the Stockholm Trial (on an annual basis). The environmental quality standard 40 µg/m^3 (mean annual value) is estimated to be met even without this reduction. On the other hand the environmental quality standard 50 µg/m^3 (mean daily value, 90th percentile) would be exceeded.

The levels of nitrogen oxides, NOx, at street level on Sveavägen, are estimated to fall by 3% during the Stockholm Trial (on an annual basis). The nitrogen dioxide levels are estimated to **fall by approx. 1% to 2%**. The emissions from the new direct buses have also been included in the calculation. Without these buses the nitrogen dioxide levels would fall by 3% (the PM10 levels are, on the other hand, not affected). On an annual basis reduction means that the environmental quality standard 40 µg/m^3 (mean annual value) is not exceeded. On the other hand the environmental quality standard 60 µg/m^3 (mean daily value, 98th percentile) is still being exceeded.

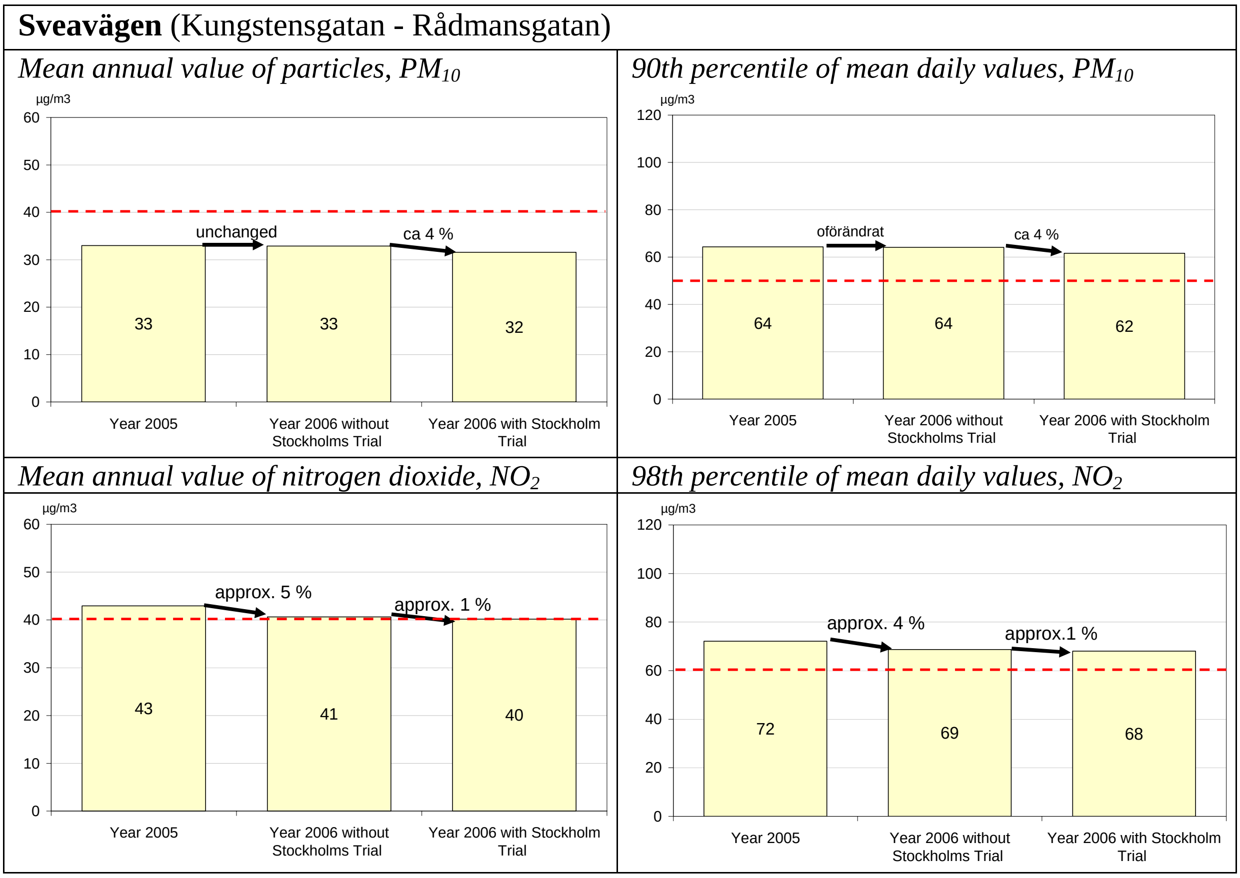

Figure 6. Estimated change in air quality on Sveavägen and a comparison with environmental quality standards for protecting health (red broken line). Data for 2005 was measured. The values apply to a whole year. Unit µg/m^3.

On **Norrlandsgatan** (Birger Jarlsgatan – Kungsgatan) the levels of particles, PM10, are estimated to **fall by 7%** at street level (Figure 7) during the Stockholm Trial (on an annual basis). The reduction is not sufficient to meet the environmental quality standard of 50 µg/m^3 (mean daily value, 90th percentile).

The levels of nitrogen oxides, NOx, at street level on Norrlandsgatan, are estimated to **fall by 11%** during the Stockholm Trial (on an annual basis). The nitrogen dioxide levels on Norrlandsgatan are estimated to fall by approx. 5%-6%. The reduction means that the environmental quality standard 40 µg/m^3 (mean annual value) has not been exceeded . On the other hand, the mean daily value of 60 µg/m^3 is still being exceeded.

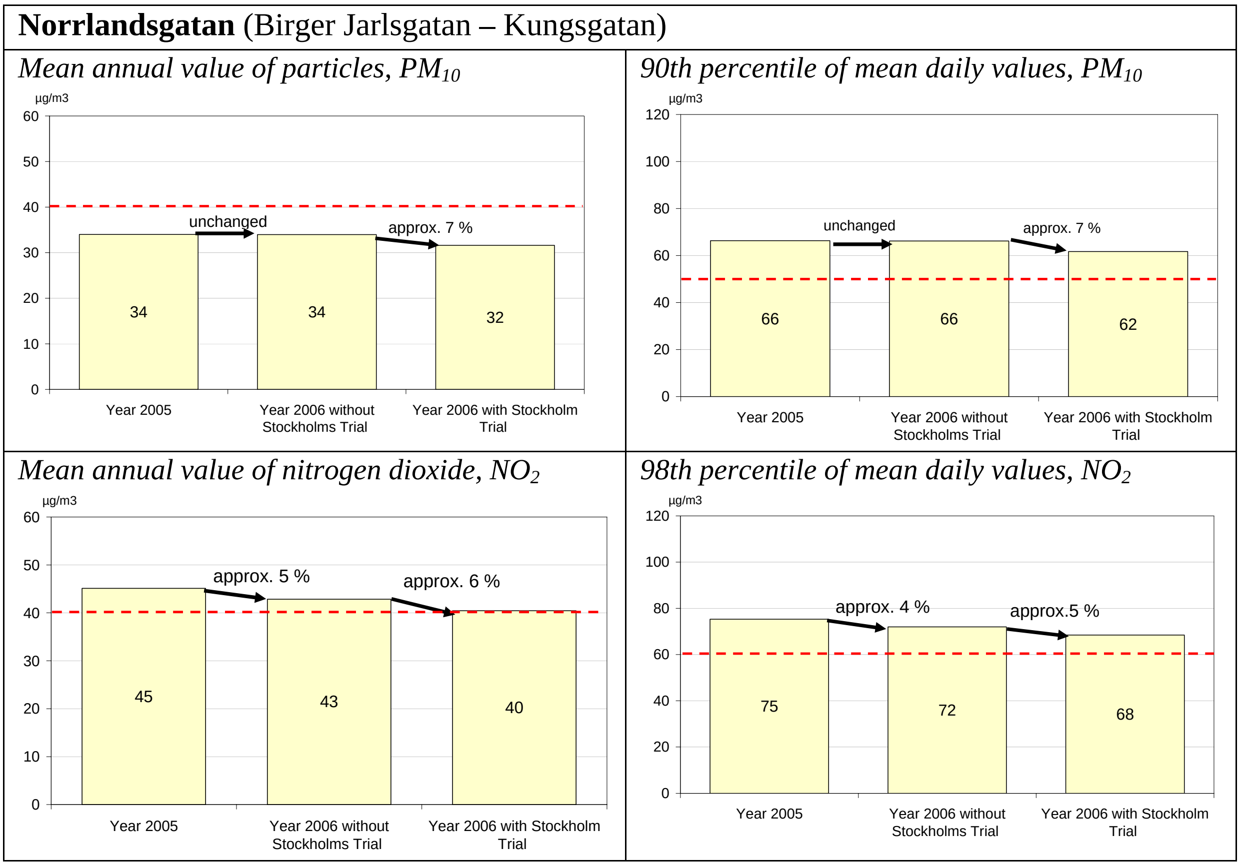

Figure 7. Estimated change in air quality on Norrlandsgatan and a comparison with environmental quality standards for protecting health (red broken line). Data for 2005 was measured. The values apply to a whole year. Unit: µg/m^3.

On **S:t Eriksgatan** (Alströmergatan - S:t Eriksplan) traffic is estimated to have increased slightly during the Stockholm Trial (Table 1). PM_{10} levels are nevertheless estimated to remain unchanged because the increased contribution from street level to the total level of care pollution is compensated for by a reduced background level (Figure 8). It is estimated that the environmental quality standard 40 µg/m^3 (mean annual value) will be met, whilst the standard 50 µg/m^3 (mean daily value, 90th percentile) will be exceeded despite the trial.

Nitrogen dioxide levels are also estimated to remain unchanged during the trial. Environmental quality standards for nitrogen dioxide are met on S:t Eriksgatan.

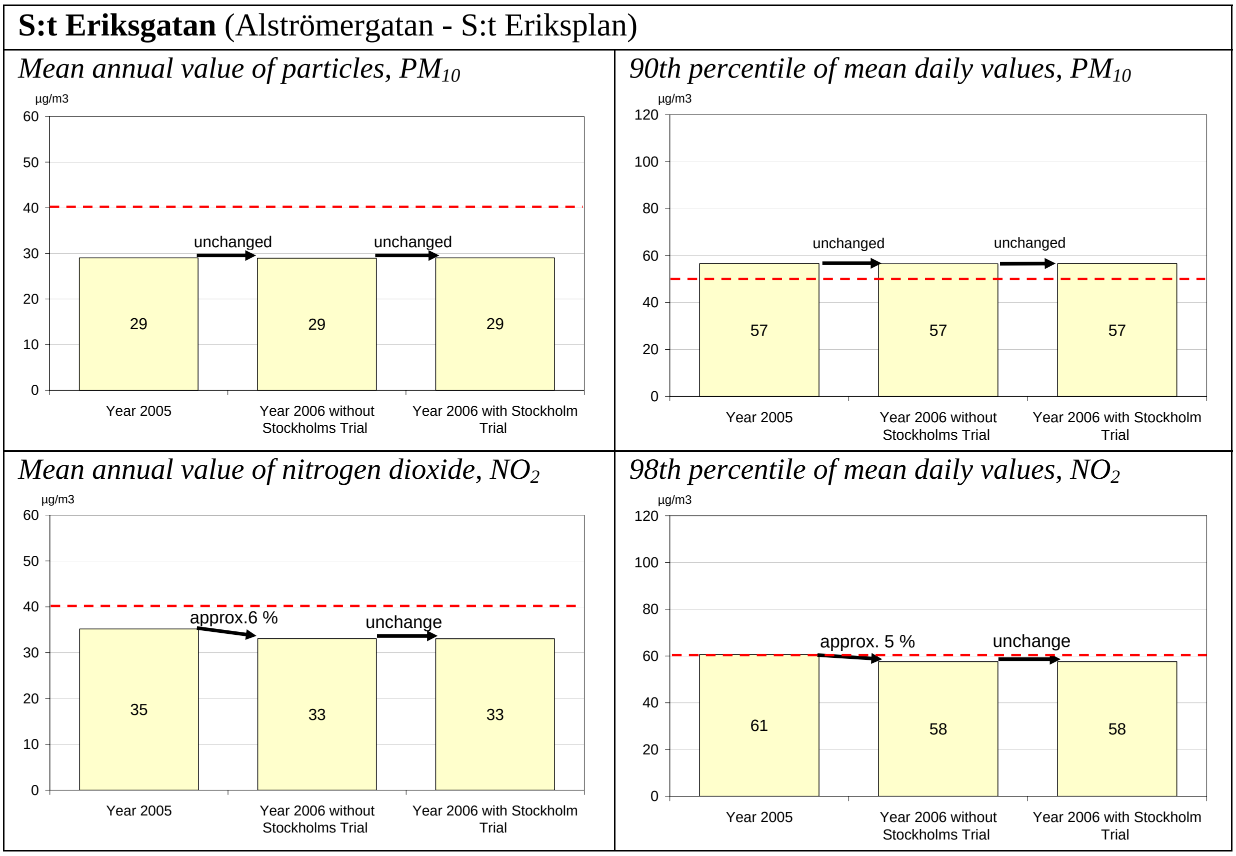

Figure 8. Estimated change in air quality on S:t Eriksgatan and a comparison with environmental quality standards for protecting health (red broken line). Data for 2005 was measured. The values apply to a whole year. Unit µg/m^3.

On **Valhallavägen** (Odengatan - Drottning Kristinas Väg) the levels of particles, PM_{10}, are estimated to fall by 7% at street level during the Stockholm Trial (on an annual basis).
The reduction is not sufficient to meet the corresponding environmental quality standard of 50 µg/m^3.

Levels of nitrogen oxides, NOx, at street level on Valhallavägen are estimated to fall by 12% during the Stockholm Trial (on an annual basis). Nitrogen dioxide levels are estimated to **fall by approx. 7% to 8%**. On Valhallavägen the environmental quality standards for nitrogen dioxide will be met.

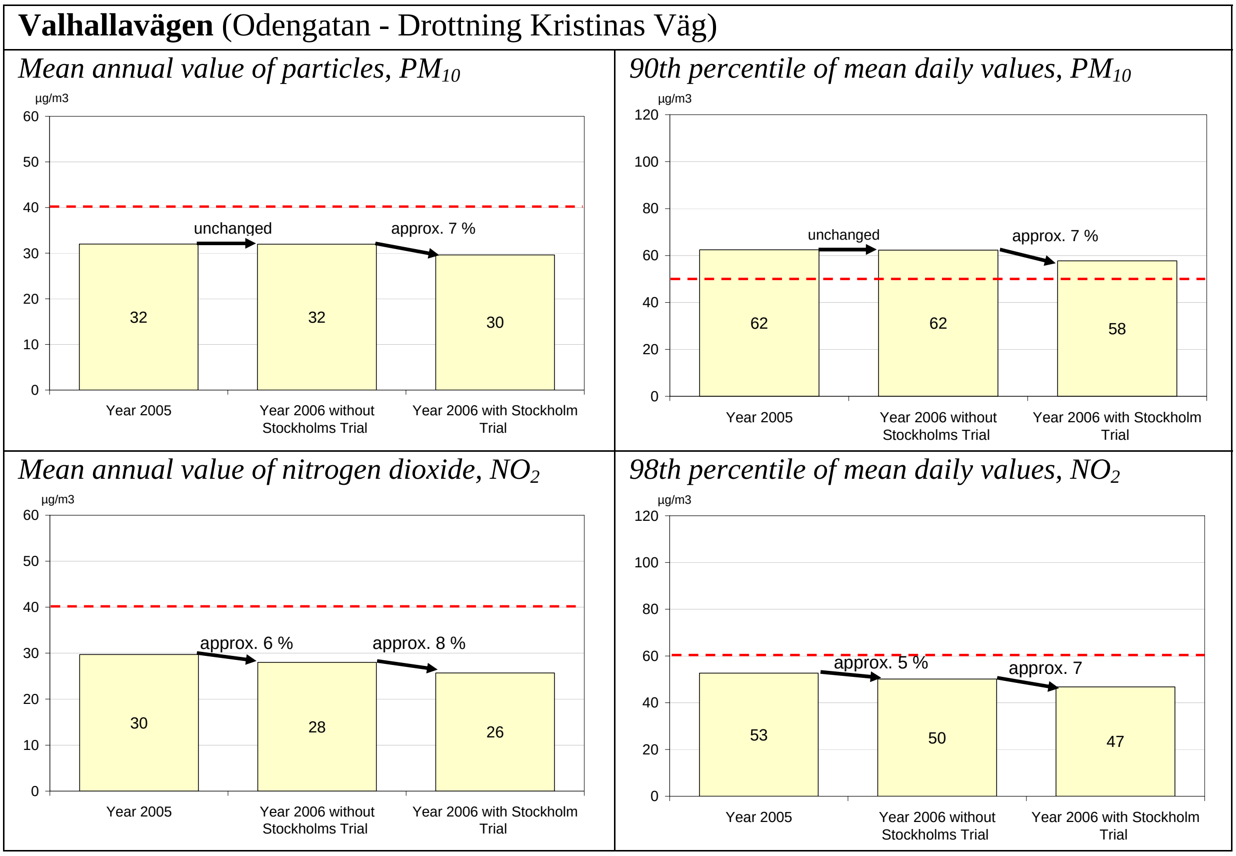

Figure 9. Estimated change in air quality on Vallhallavägen and a comparison with environmental quality standards for protecting health (read broken line). Data for 2005 was measured. The values apply to a whole year. Unit: µg/m^3.

Along the Essingeleden bypass environmental quality standards for the protection of public health are currently being exceeded. The increased traffic resulting from the Stockholm Trial is estimated to mean somewhat raised levels of air pollutants. The increases in level for an average 24 hour period is approx. 3 µg/m^3 (micrograms per cubic metre of air) for nitrogen oxides, NOx, and up to approx. 2 µg/m^3 for particles, $PM_{10,}$ in order to meet the environmental quality standards primarily applying to mean daily values particles, PM_{10}, major reductions in emissions are required along the Essingeleden bypass.

3 Conclusions

The following conclusions have been reached during the study:

- The reduction in traffic volume has led to lower emissions of carbon dioxide, particles and nitrogen oxides, which in its turn has reduced the contribution from traffic to the total levels of particles (PM_{10}) and nitrogen dioxide. This means that if the trial were to be made permanent, and provide the same reductions in traffic volume, then the traffic in Stockholm would not contribute as much to pollution levels as it has without the congestion tax.

- The emissions of particles and nitrogen oxides from road traffic in Stockholm’s inner city are estimated to fall by between 8% and 12%. For road traffic in the City of Stockholm this corresponds to between 3% and 5%. The reductions in emissions of primarily nitrogen oxides would have been higher without the extended bus traffic during the Stockholm Trial.

-

- The reductions in emissions overall mean that the interim target for the Stockholm Trial, that emissions of air pollutants should fall, has been achieved.

The average levels of nitrogen oxides (NOx) are in some places estimated to fall by up to approx. 2-3 µg/m^3. The greatest improvements in air quality are estimated to occur along the Klarastrandsleden bypass, Centralbron Bridge, Valhallavägen and Sveavägen, and at the entrances to the Söderleden Tunnel. Greater levels of air pollutants are found around the Essingeleden and Södra Länken by-passes, but considerably more Stockholmers now have reduced levels of air pollutants and better air quality compared with those who have higher levels.

- Average particle levels for the population of Stockholm (Greater Stockholm) are estimated to be a percentage point or two lower with congestion charging. In total, for the whole of the Stockholm area (1.44 million inhabitants, 35 x 35 km), it is estimated at between 25 and 30 fewer premature deaths each year will result from long term exposure to particles. Emissions from road traffic in Stockholm also cause certain illnesses, exacerbates respiratory problems and leads to allergies among certain sensitive individuals. These are reduced with the congestion tax.

- On many of Stockholm’s inner city streets with very high air pollutant levels the situation has been improved with the Stockholm Trial. Environmental quality standards to protect public health will be met to a greater extent than before with the reductions in emissions. The effects of this trial are however not sufficient for environmental quality standards to be met everywhere within the Stockholm region. For this, greater reductions in traffic are needed or measures reducing emissions from road traffic.

- Comparisons between pollutant levels measured during the Stockholm Trial (the period January to July 2006) with the corresponding period in 2003, 2004 and 2005, show that variations in pollutant levels between different years can be significant. This results in large part from different meteorological conditions. Overall measured levels during the Stockholm Trial therefore cannot provide a quantitative answer as to how great significance the reductions in emissions from traffic on hand for the levels of air pollutants. In the long term, e.g. if the Stockholm Trial is made permanent, the air quality in Stockholm will be affected most by the reduction in emissions. The assessment of the measured air quality during the Stockholm Trial is described in Chapter 5.

4 Method

The most important factors governing air quality and in this way the effects of air pollutants on the population of Stockholm are:

- Emissions in Stockholm, Sweden and Europe in general
- The large scale weather situation which determines the in-transport of pollutants due to emissions outside the region
- Local emissions primarily from road traffic in Stockholm
- The local weather which determines how these local emissions are spread.

A comparison of measured levels of air pollutants between periods with different types of weather is problematical as the spread of the emissions can vary a great deal both continentally, regionally and locally. In the short-term air quality is affected greatly by variations in weather. In the long term, with normal weather conditions, air pollutant levels are affected most by the scale of the emissions. A long series of measurements are therefore necessary in order to provide a good picture of how the levels change because of changes in emissions. Long series of measurements are also required to determine whether environmental quality standards are met or not. As the seven months of the Stockholm Trial in this regard is a short period, the measurements have been supplemented with model estimates. Model estimates are also necessary in order to estimate the exposure of the population and health effects of air pollutants. As regards the effects on health, long term exposure is the most important, i.e. the level the population is exposed to over a year or several years, and not how high the levels of air pollutants happen to be for short periods. This means that estimation models have to be used in combination with measurements in order to evaluate the effects of levels on the health of the population.

4.1 Measurements of the levels of air pollutants

The effects of the Stockholm Trial on air quality and health have been assessed by making use of:

- Fixed continuous monitoring of air pollutants and meteorology in Stockholm with a high time resolution, i.e. hour by hour.

- Monitoring of air pollutants before and during the Stockholm Trial along main streets and approach roads, partially with lower time resolution, day or month.

- Estimates of emissions from road traffic with emission factors according to the National Road Administration and traffic data from traffic monitoring during the Stockholm Trial and the Road and Traffic Research Institute's model estimates.

- Estimates of levels and exposure with diffusion models in the Air Quality Association's system (the Meteorological and Hydrological Institute Airviro).

The Air Quality Association's system is a complete geographical information system for the evaluation and monitoring of air quality in the region. Every year data is stored about which pollutants are emitted into the atmosphere and where and when the emissions occur. Apart from information about emissions, the estimates in the system are based on meteorological data.

Model estimates with input data on both emissions and meteorology have been used to determine how air quality has been affected by the Stockholm Trial. In this way the weather has been kept constant and normal, while only the changes in emissions from road traffic have varied. Measurement of air pollutants have, for example, been used to validate estimated results.

4.2 Estimates of emissions and levels

The emissions database in 2006 without the Stockholm Trial comprises traffic data stored in the latest updated emissions database of Stockholm and Uppsala counties. For this, just as for the emissions database comprising the trial, the composition of the level of exhaust emission control of Stockholm traffic is according to those emission factors applying to 2006 according to the National Road Administration's EVA-model.

Apart from the exhaust particles, particles are also generated and spread primarily from wear of the road surface but also wear and tear on tyres and brakes. Emission factors for PM_{10} excluding exhaust particles (i.e. road wear particles) have been obtained from measurements on Hornsgatan in central Stockholm. These emission factors are expected to remain unchanged as long as measures are not taken to reduce the formation and diffusion of these particles.

In estimates of emissions and levels of air pollutants from traffic no allowance has been made for the effects of alterations in speed because of the Stockholm Trial. Greater speeds can increase wear of the road surface and thereby increase emissions but it may also increase the ventilation due to the turbulence generated by the vehicles. The emissions of other substances can fall with a reduction in traffic queues and a more even pattern of driving. The Stockholm Trial also involves extended bus traffic. The approx. 200 new so-called direct buses for the trial run on diesel fuel (a few use biogas). Their engines fulfil the exhaust requirements of "Euro 3" and are fitted with particle filters. The traffic mileage of the buses (total distance covered) has been obtained from the Road and Traffic Research Institute's estimates, 2006.

For a description of the air quality dispersion models, we refer to previous studies (Johansson et al., 2003). Estimates have been made for nitrogen oxides, NOx, and particles, PM_{10} exhaust particles, on the one hand for the entire Greater Stockholm area, and on the other for an area covering the inner city and also areas outside the inner city (i.e. outside the congestion charge zone). Estimates of levels for the inner city have been made with a resolution of 25 metres. The resolution in the population data is, however, 100 metres, so in addition estimates were made with a resolution of 100 metres in order to be able to estimate population-weighted exposure levels. More detailed description of the population data used to be found in Forsberg *et al*., 2003.

5 Data - measured air quality in connection with the Stockholm Trial

The air quality before and during the Stockholm Trial (including the congestion tax) has been monitored at 20 sites in the central area of Stockholm (Figure 10). Nitrogen dioxide (NO_2) has been measured at all of these monitoring sites, whilst the level of nitrogen oxides (NOx) has been measured at five of them and particles (PM_{10}) at 10 sites. The entire monitoring program for the Stockholm Trial and monitoring methods are described in Appendix 2. A more detailed description of the monitoring results for traffic flows, pollution levels and meteorological records from the fixed monitoring stations during the Stockholm Trial is to be found in Appendix 3. Other measurements during the trial have been made with a daily or monthly resolution during seasons as comparable from a weather point of view as possible: January to July 2005 and January to July 2006 during the trial. The analysis results obtained for these are also presented in Appendix 3.

Hornsgatan, Sveavägen, Norrlandsgatan, E4-Essingeleden bypass and Torkel Knutssonsgatan (rooftop height level) are fixed monitoring stations, which means that, e.g. particles (PM_{10}) and nitrogen oxides (NOx and NO_2) are monitored continually hour by hour. This generates a long series of measurements with data which, can for some monitoring sites, be compared many years into the past.

Figure 11 shows the average levels of nitrogen oxides (NOx and NO_2) and carbon monoxide (CO) on Hornsgatan and Sveavägen during the Stockholm Trial 2006, and corresponding months in the previous three years. It is clear from the figures that the levels of CO and NOx have gradually decreased, which has to do with **reduced emissions** from the entire vehicle fleet, as a result of there being fewer old cars. The differences between the years also result from **meteorological conditions**. The influence of meteorology is particularly significant when one is looking at a short time period. For NO_2 levels it is not primarily the emissions of NO_2 which are decisive but photochemical reactions in the air in which ozone levels play a decisive role (Johansson & Forsberg, 2005). Overall one can say that comparisons of measured total levels between different years do not provide quantitative answers as to the significance of the reductions emissions from traffic in the inner city have made on levels. This is estimates are required which can distinguish between the significance of meteorology and the emissions for levels.

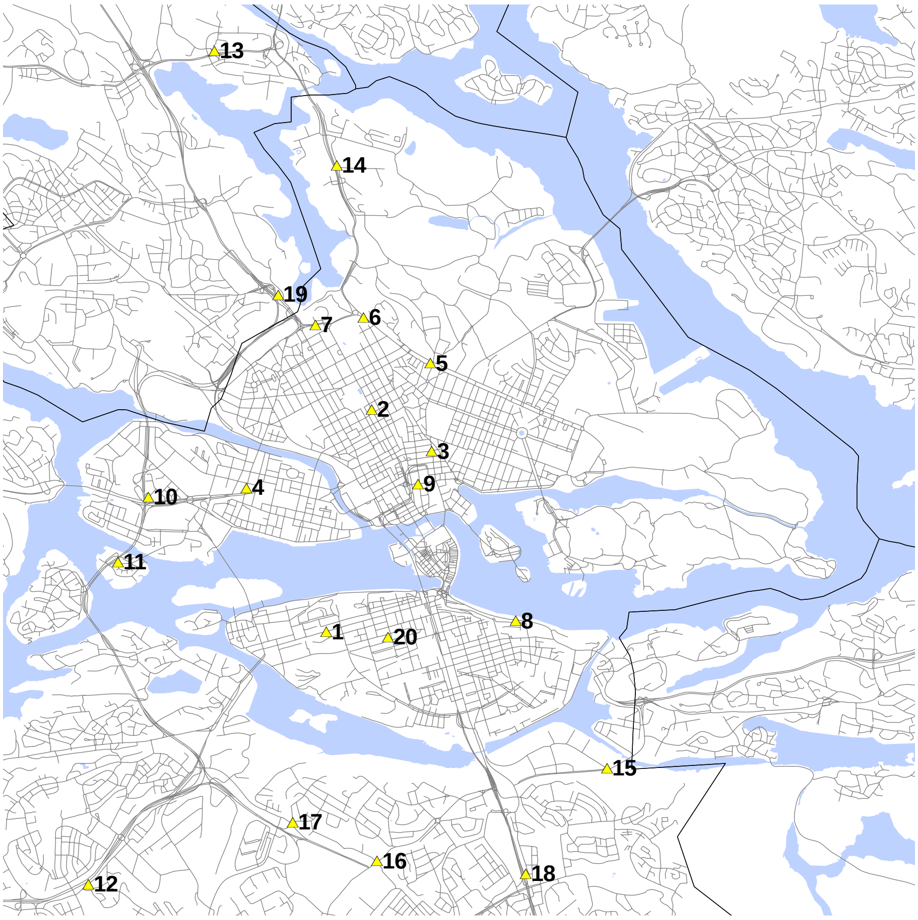

Figure 10. Map of monitoring sites for air quality measurements in connection with the Stockholm Trial. See also descriptions in Appendix 2.

By instead analysing the meaning daily variations in levels arising only as a result of traffic on certain streets one can get some idea of the significance of traffic changes and/or emissions. The mean variations in levels of NOx during weekdays between the Stockholm Trial 2006 and corresponding period in 2005, on Hornsgatan and Sveavägen, can be seen in Figure 12 and Figure 14. Note that these are not the total levels but only the levels which in large part are the result of local traffic on each street (i.e. the levels at rooftop height have been subtracted). The average total measured traffic flows (vehicles per hour) for a 24-hour weekday period for Hornsgatan and Sveavägen are given in Figure 13 and Figure 15.

For Hornsgatan the change between 2005 and 2006 in the contribution from traffic to NOx levels is very similar to the change measured in traffic flows. During the daytime between 0800 and 1900 hours the contribution to the levels is lower during January to July 2006 compared with the same period in 2005. To some extent the change in the NOx level is the result of lower emissions because of fewer vehicles, but also because of lower emissions from vehicles thanks to a more modern (cleaner) vehicle fleet. Differences between the meteorological conditions in the two years also has an influence, and as the wind speeds were lower in 2006 compared with 2005 this provides the opposite effect.

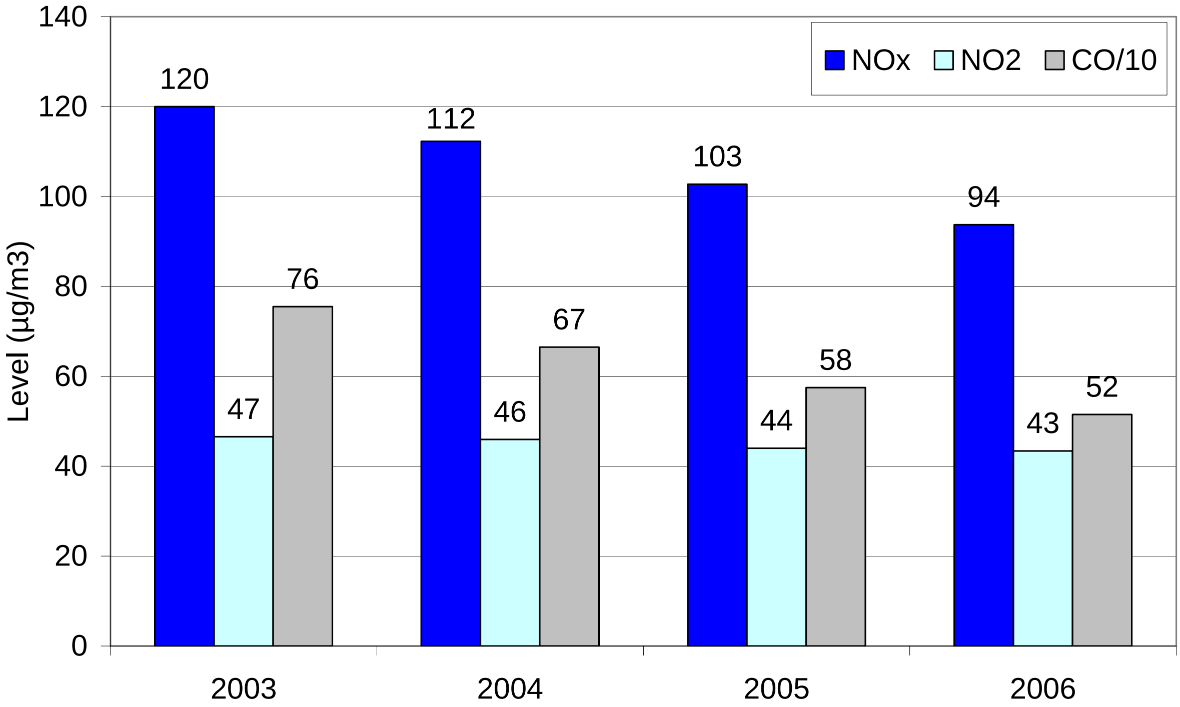

Figure 11. Average levels of NOx, NO_2 and CO during the Stockholm Trial 2006 and corresponding months in the previous three years. The levels are mean values of date from the fixed monitoring stations on Hornsgatan and Sveavägen where measurements were made on both sides of the street approximately 2.5 m above the pavement

For Sveavägen on the other hand the change deviates in the local contributions to levels from the altered volume of traffic (compare Figures 14 and 15). The contributions to levels from traffic on Sveavägen are lower in 2006 compared with 2005 during the night and a period in the middle of the day, but higher contributions can be noted for 2006 in the morning and for a couple of hours in the afternoon. This may be explained by increased emissions because of the new direct buses introduced in connection with the Stockholm Trial. The 565 bus route passes the monitoring station every 10 minutes between 0600 and 0900 and every 15 minutes between 1530 and 1830. The 561 bus route passes every 12 minutes between 0630 and 0900 and 1530 to 1830. Taken as a whole this means a good 20 bus passages per hour during the morning and afternoon. Even though this is admittedly very few vehicles in comparison with the total number of vehicles, which is approximately 1,400 vehicles per hour, the emissions of NOx from diesel buses are considerably higher than from cars.

It is estimated that the new buses increase emissions by around 20%, which is approximately the same as the increase in the contribution to the level during the morning hours (if one compares with the contribution to the level in the middle of the day when no direct buses pass by). The theory that it is emission from the buses that explains the additional contribution to levels in the morning and afternoon is also supported by the fact that the additional contributions to levels of NOx appear at the same time as the introduction of the buses during the autumn of 2005, but not before that. A further factor supporting the theory that it is diesel emissions, is that a corresponding estimated contribution for CO shows no peak during the morning and afternoon for 2006 compared with previous years — CO is emitted primarily from petrol vehicles, not diesel vehicles (as in the newly introduced buses).

It should, however, be noted that total emissions from all the new buses in the inner city provide a small contribution to the total NOx levels from private cars. That is to say, it is only locally during rush-hour on the streets where new buses have been introduced that the emissions may increase somewhat.

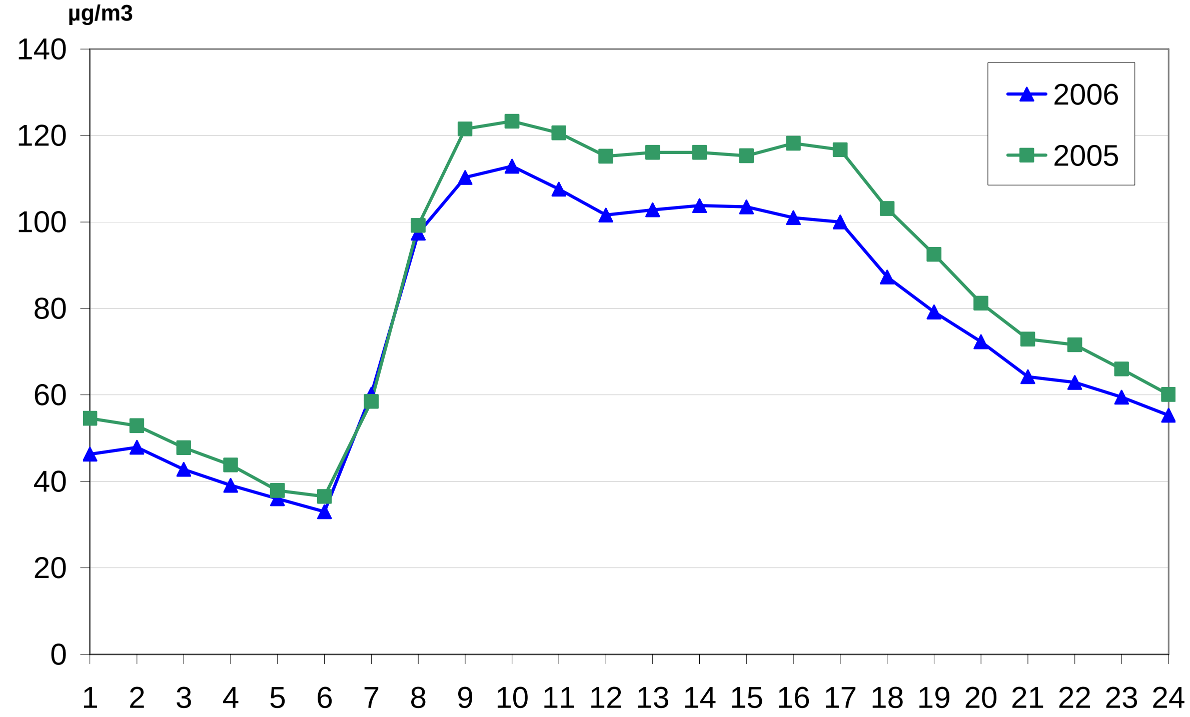

Figure 12. Average variations in levels of NOx on Hornsgatan during a 24-hour weekday period (Mondays to Thursdays), during the Stockholm Trial 2006 and corresponding period 2005. Rooftop level measurements are subtracted from levels measured on the street and only northerly winds had been taken into account in order to obtain the local contribution to the level from traffic on Hornsgatan.

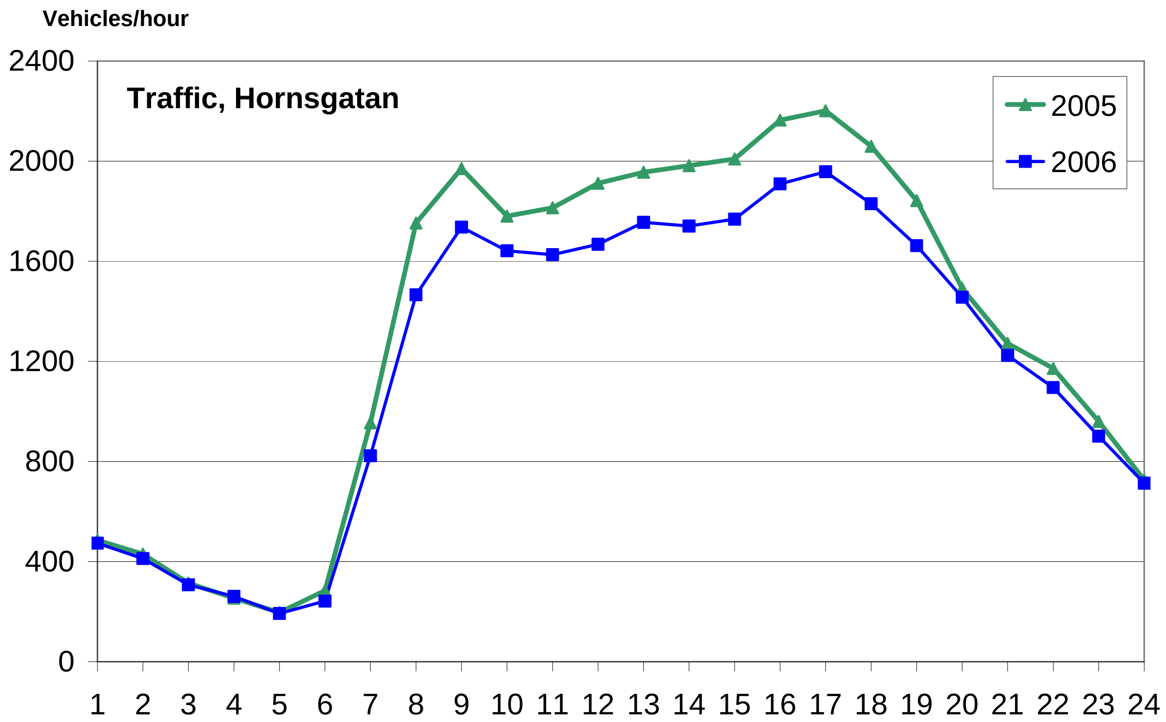

Figure 13. Average variations in traffic flow during a 24-hour weekday period (Mondays to Thursdays) during the Stockholm Trial 2006 and corresponding period 2005, at the fixed monitoring station on Hornsgatan.

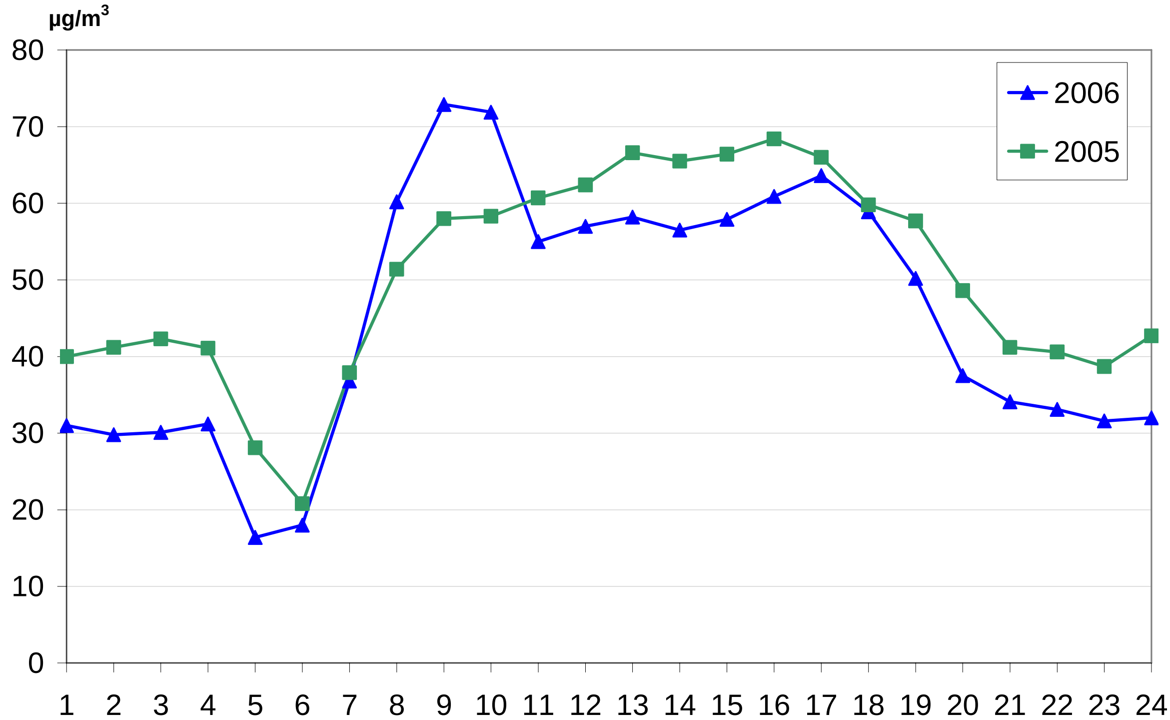

Figure 14. Average variations in levels of NOx on Sveavägen during a 24-hour weekday period (Mondays to Thursdays) during the Stockholm Trial 2006 and corresponding period 2005, at the fixed monitoring station on Sveavägen. Rooftop level values have been taken into account in order to obtain the local contribution to the level from traffic on Hornsgatan.

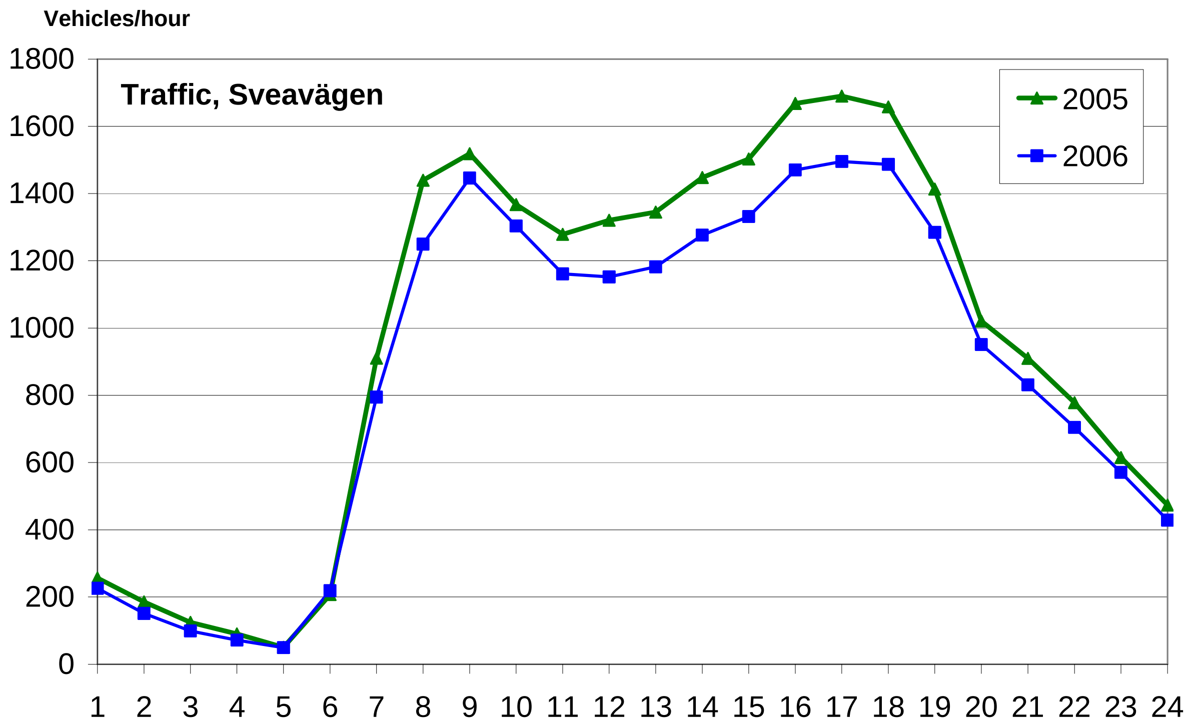

Figure 15. Average variations in traffic flow during a 24-hour weekday period (Mondays to Thursdays) during the Stockholm Trial 2006 and corresponding period 2005, on Sveavägen (between Adolf Fredriks kyrkogata and Kammargatan)

Figure 17 shows the average particle levels (PM_{10}) on Hornsgatan, Sveavägen and Norrlandsgatan. From the figure it is clear that the levels were lower in 2006 compared with similar periods in previous years. This is to a great extent because of meteorological factors. During the spring PM_{10} levels on streets are to a large extent determined by the humidity of the road surface. Particles emitted by vehicles through exhaust gases contribute very little to the PM_{10} levels. Particles formed through the wear of asphalt contribute to PM10 concentrations when the road surface is dry. On moist road surfaces there is still road wear, but the particles accumulate on the road surface until it once again dries out. The proportion of the time when the road surface is dry has a decisive importance for the levels measured.

Figure 16 shows precipitation amounts and the proportion of the time with precipitation during the Stockholm Trial 2006 and corresponding months 2005. In 2005 March and April were unusually dry months in southern Sweden. In Stockholm precipitation amounts were just half of the normal. During March and April PM10 levels are normally at their highest. In 2006 levels were unusually low because of large amounts of precipitation during these two months. The Meteorological and Hydrological Institute observed that all of Götaland and southern Svealand had considerably greater reservoirs of snow than normal at the end of March 2006. Roads in the inner city were wet or icy for a large part of the time from January to March, and the snow was still lying for an unusually long period that spring. This meant that PM_{10} levels were low.

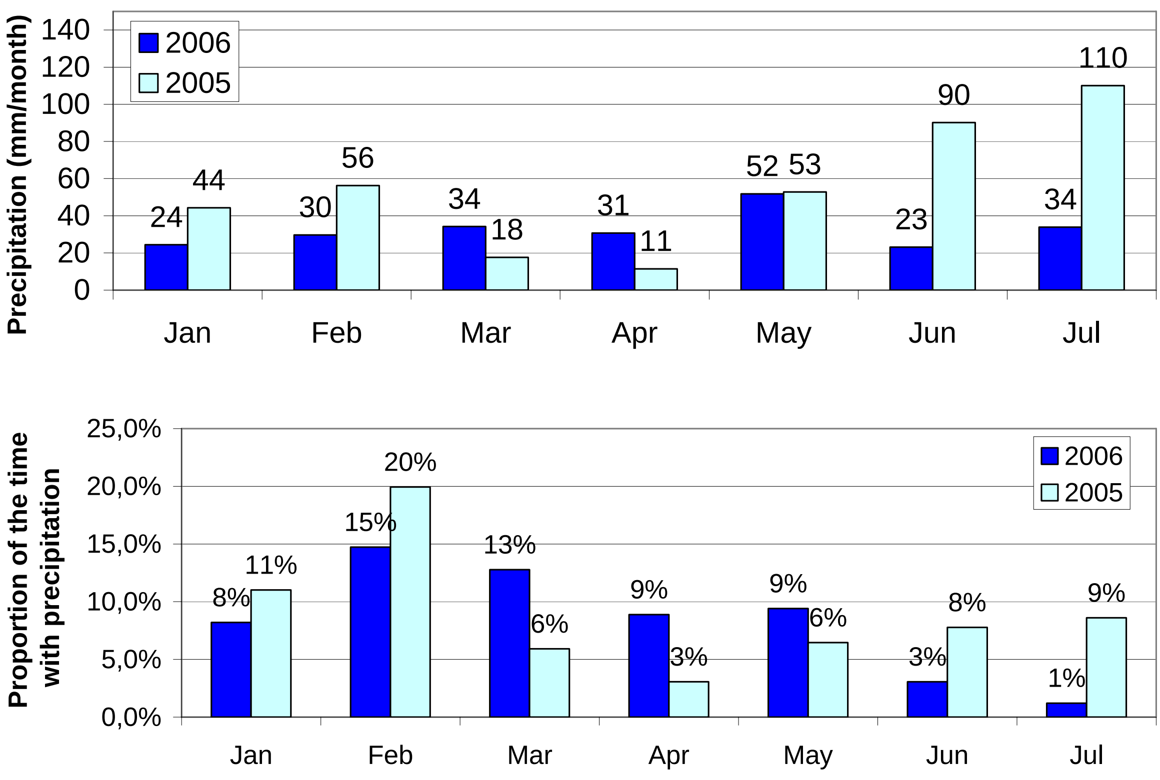

Figure 16. Comparison between amount of precipitation and the percentage share of the total number of hours with precipitation during the Stockholm Trial 2006 and corresponding months 2005. Measurements from Högdalen in southern Stockholm

At the same time as the average levels were unusually low, there were fewer days with levels higher than 50 µg/m^3 during the Stockholm Trial 2006 compared with previous years (see Figure 18). According to the environmental quality standard 50 µg/m^3 may only be exceeded on 35 days per calendar year. Over the last three years during January to July on between 45 and 71 days mean levels in excess of 50 µg/m^3 have been measured, whilst in 2006 mean levels above 50 µg/m^3 were noted for the same month on 41 to 50 days. To a certain extent the high levels have been cushioned by a dust-binding agent (calcium magnesium acetate, CMA) spread along the main streets in the inner city and also along the major approach roads. CMA has also replaced ordinary road salt as an anti-skid agent in the inner city. CMA has the ability to retain moisture, binding particles and in this way reduce the emissions of particles into the air. The importance of this for particle levels in comparison with the unusually long winter period and wet spring has as yet not been assessed.

The reduction in traffic volume as a result of the congestion tax has had less significance for the unusually low levels of particles during this period compared with the influence of meteorology on road surface conditions.

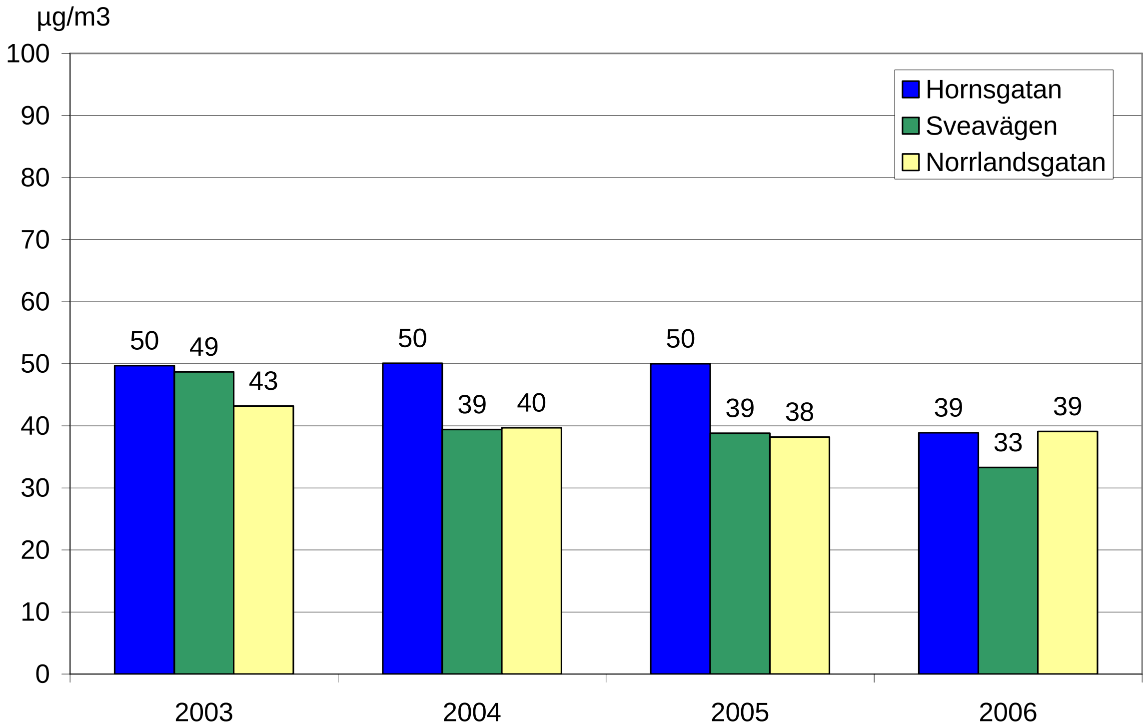

Figure 17. Total PM_{10} levels on Hornsgatan, Sveavägen and Norrlandsgatan during the Stockholm Trial 2006 and corresponding period 2003, 2004, and 2005.

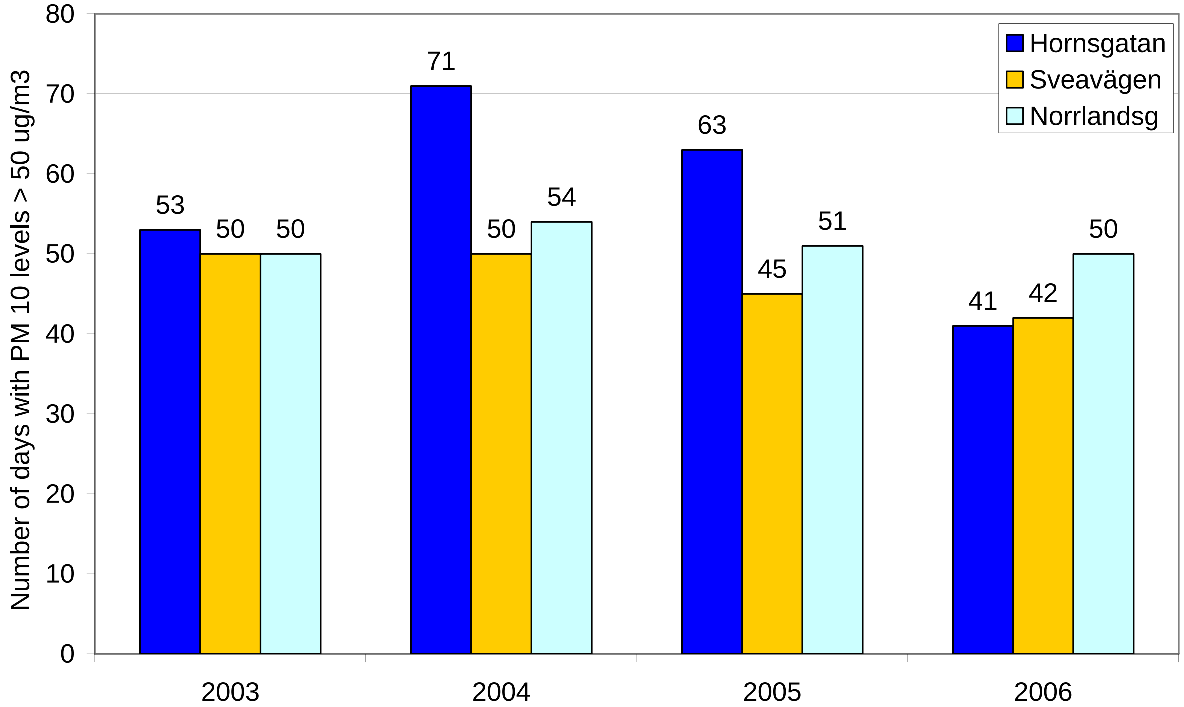

Figure 18. Number of days with levels above 50 µg/m^3 during the Stockholm Trial 2006 and corresponding period 2003, 2004, and 2005, on Hornsgatan, Sveavägen and Norrlandsgatan. The environmental quality standard states that 50 µg/m^3 may not be exceeded more than 35 times during a calendar year (January to December).

Figure 19 shows the average contribution to the PM10 levels from traffic on Hornsgatan, Sveavägen and Norrlandsgatan during the Stockholm Trial 2006 and corresponding period 2005. Considerably lower contributions are noted for 2006 because of the wet roads compared with 2005. Note also the differences in daily variations for PM_{10} levels and NOx levels; the contributions from traffic to PM_{10} levels are at their maximum during the afternoon when the road surfaces are normally dry and when traffic flows are still high. During the morning hours the road surfaces are often still damp, which moderates PM_{10} emissions from the road surface.

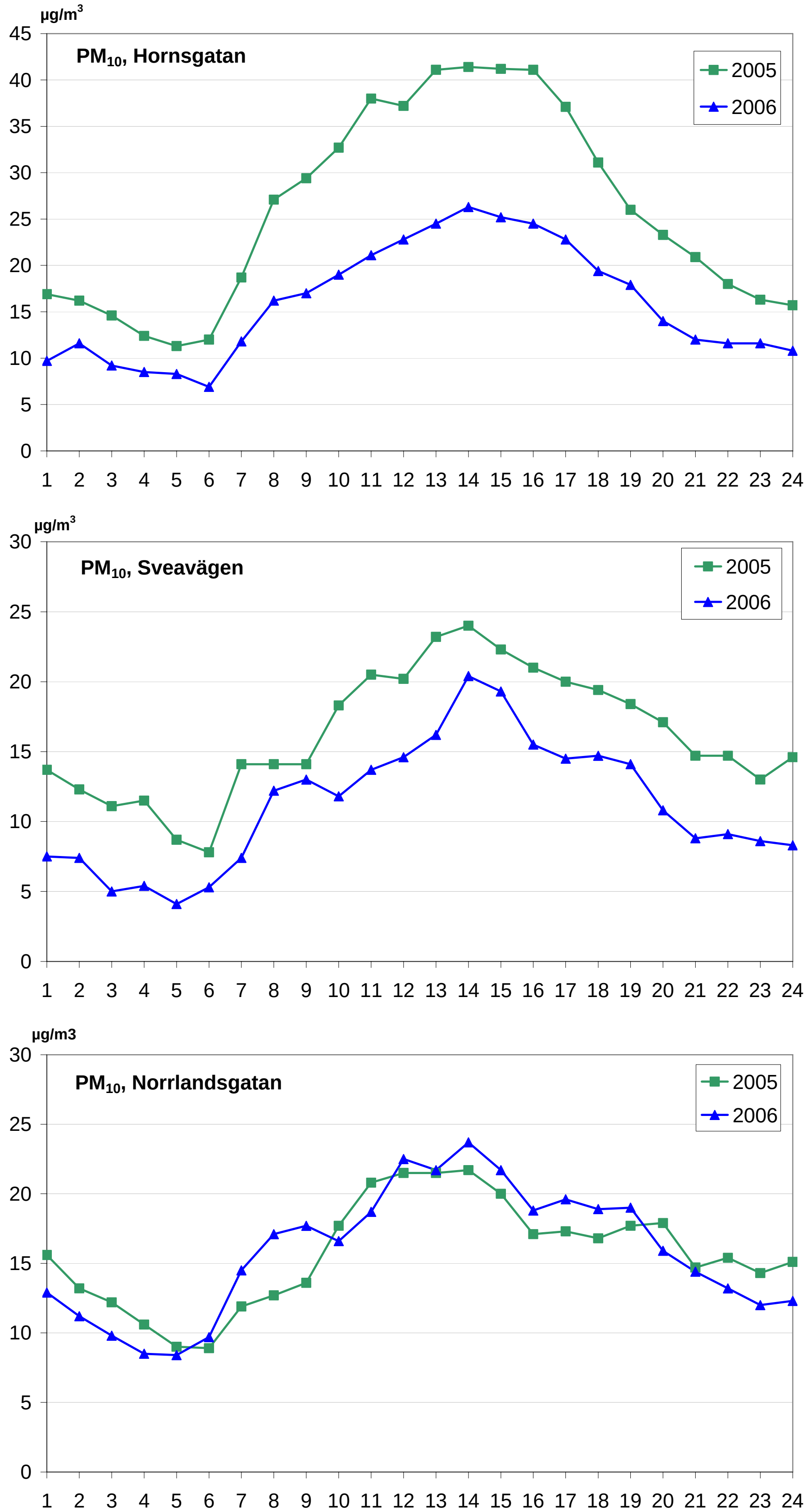

Figure 19. Average variations in the local contributions from traffic to levels of PM_{10} during 24-hour weekday periods (Mondays to Thursdays) during the Stockholm Trial 2006 and corresponding period 2005, on Hornsgatan, Norrlandsgatan and Sveavägen.

5.1 Discussion and conclusions

As has been pointed out previously it is impossible merely on the basis of measurements to assess how much the Stockholm Trial has affected levels of air pollutants, as variations in levels are determined by many factors simultaneously; fluctuations in emissions resulting from temporary local conditions, variations in meteorological conditions influencing the dilution of the emissions and variations in polluted air arriving in the region from other countries.

The only way of finding out the extent to which reductions in traffic as a result of the Stockholm Trial have affected the levels of different pollutants is to make emission estimates and model calculations of the levels. This means that the following estimates are carried out:

1. The reduction in traffic caused by the Stockholm Trial is estimated on the basis of measurements of traffic flows with and without the Stockholm Trial. As traffic monitoring is not carried out on all the streets in the region, certain estimates have to be made of how the traffic is influenced on streets where measurements are lacking.

2. The reductions in emissions of different substances as a result of reduced traffic flows are estimated with the help of known correlations which describe how the emissions from different vehicles change in different traffic conditions.

3. The extent of the effect of estimated reductions in emissions of different substances is, finally, estimated with the help of diffusion models taking into account meteorological conditions and other circumstances affecting the diffusion of air-polluting emissions.

Using the methodology above, the effects of the Stockholm Trial on air quality have been evaluated. The results are to be found in Chapter 2 (Results).

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7 Appendix 1. List of Definitions

List of definitions employed in this report:

Level	The level of air pollutants is stated in the weight of the pollutant per volume of air, usually in $\mu g/m^3$ (millionths of a gram per cubic metre)
Emission	Emissions are usually given in mass amounts per unit of time, commonly in tons per annum.
Nitrogen oxides, NOx	The sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2). The emissions occur for the most part in the form of NO (85-95%). In air NO is oxidised to the more health-endangering NO_2 in a reaction primarily with ozone.
Particles, PM_{10}	The air contains particles of differing sizes and chemical compositions. Inhalable particles are named PM_{10} and comprises the bulk of all particles less than 10 µm (µm = one millionth of a metre) in diameter. PM_{10} in an urban environment consists of mostly of particles from road surfaces, but also wear and tear from brakes and tyres.
$\mu g/m^3$	Micrograms per cubic metre of air ($10^{-6} g/m^3$). The commonest unit expressing the level of an air pollutant.
Mean annual levels	Average levels of a certain pollutant in a particular year.
(Urban) background level	The level of air pollutant for the urban background provides an indication of average loading in a built-up area. For the inner city the urban background is measured or calculated at rooftop height.
Street contribution, local contribution	The level deriving from emissions from traffic on the street.
Total level	Background level + street contribution (local contribution).
Percentile	Statistical concept often used in an air quality context.
Population-weighted level	An average level attained by weighting the level of pollution against the size of the population. This means that the level where more people live acquires greater significance for the average level compared with fewer in inhabitants.
Environmental quality standard	A juridical control measure in Swedish legislation introduced in connection with the Environmental Code in 1999. Its main purpose is to protect people against high air pollution levels.
Emission factor	Usually emission per kilometre for a type of vehicle with a certain degree of exhaust treatment, speed and driving style.
Traffic mileage	The distance (in kilometres) that vehicles move in total (vehicle traffic mileage) during a certain period.
24 hour weekday period and average annual 24-hour period respectively	A 24 hour weekday period is an average weekday (24-hours, Monday to Friday). Average annual 24-hour period corresponds to an average day in a particular year.

8 Appendix 2. Monitoring equipment and descriptions of monitoring sites

Monitoring component:	Equipment:	Time resolution:	Measurement principle/ analytical method:
Nitrogen dioxide, NO_2	Diffusion sampler (passive)	1 month	Wet chemical spectrophotometry
Nitrogen oxides, $NOx/NO_2/NO$	Environnnement S.A., AC31M (active)	1 month	Chemiluminescence
Particles, PM_{10}	Filter sampler (active)	1 day/1 week	Weighing (gravimetric)
Particles, PM_{10}	TEOM*) 1400	1 hour	Weighing (gravimetric)

*) *Teom = Tapered element oscillating microbalance.*

Monitoring site:	Monitoring method: PM_{10}:	NO_2:	Description of location:
1. Hornsgatan	TEOM	Active, incl NOx	No. 108. W of Ringvägen.
2. Sveavägen	TEOM	Active, incl NOx	No 59. N of Rådmansgatan.
3. Norrlandsgatan	TEOM	Active, incl NOx	No 29. N of Kungsgatan.
4. S:t Eriksgatan	-	Passive	No 33. Drottningholmsvägen - S:t Göransgatan.
5. Valhallavägen	Filter sampler	Passive	Nr 74. Near Engelbrektsskolan.
6. Roslagstull	-	Passive	Just S of Roslagstull.
7. Sveaplan	-	Passive	Between Sveaplan and Norra Stationsgatan
8. Stadsgårdsleden	-	Passive	8 m S of the road.
9. Hamngatan	-	Passive	Outside Gallerian.
10.Essingeleden–Fredhällst	-	Passive	Approx. 100 m S of the Fredhäll Tunnel.
11. Essingeleden – Lilla Essingen	TEOM	Passive, Active, and NOx	At the access from Lilla Essingen.
12. E4 - Västberga	Filter sampler	Passive	30 m SE of E4, 4 m NW of Kontrollvägen
13. Bergshamravägen	Filter sampler	Passive	Approx. 50-100 m W of GC bridge across road. North side.
14. Roslagsvägen	Filter sampler	Passive	By Museum of Natural History, 5 m E of the road.
15. Hammarbyvägen	Filter sampler	Passive	Approx. 100 m from the mouth of Södra Länken Tunnel towards Nacka. N side of road.
16. Enskedefältet	-	Passive	Approx. 20-20 m S of mouth of Södra Länken Tunnel towards Huddinge.
17.Åmänningevägen	-	Passive	Junction of Storsjövägen and Åmänningev. Approx. 100 m frrom Södra Länken exit to E4.
18. Nynäsvägen	-	Passive	On Nynäsvägen, approx. 25 m E of the road
19. E4 Haga Tingshus	-	Passive	At Haga Södra interchange.
20.Torkel Knutssonsgatan (rooftop height)	TEOM	Active, and NOx	Approx. 20 m above street level in middle of Södermalm. Measures urban background level in Stockholm.

9 Appendix 3. Measurements during the Stockholm Trial and comparisons with previous years

The diagrams below show the results of measurements of nitrogen oxides, NOx, nitrogen dioxide, NO_2 and particles, PM_{10} at street level on the inner city streets Hornsgatan, Sveavägen and Norrlandsgatan during the Stockholm Trial. Measurement data for 2006 (blue line) in the diagrams below show a corresponding period from previous years. Other measurement data for nitrogen dioxide and particles are to be found in section 9.1 and 9.2 respectively. In order to examine the effects of the weather on the air quality measurements in connection with the Stockholm Trial, meteorological factors have also been measured. Some of these are shown in section 9.3.

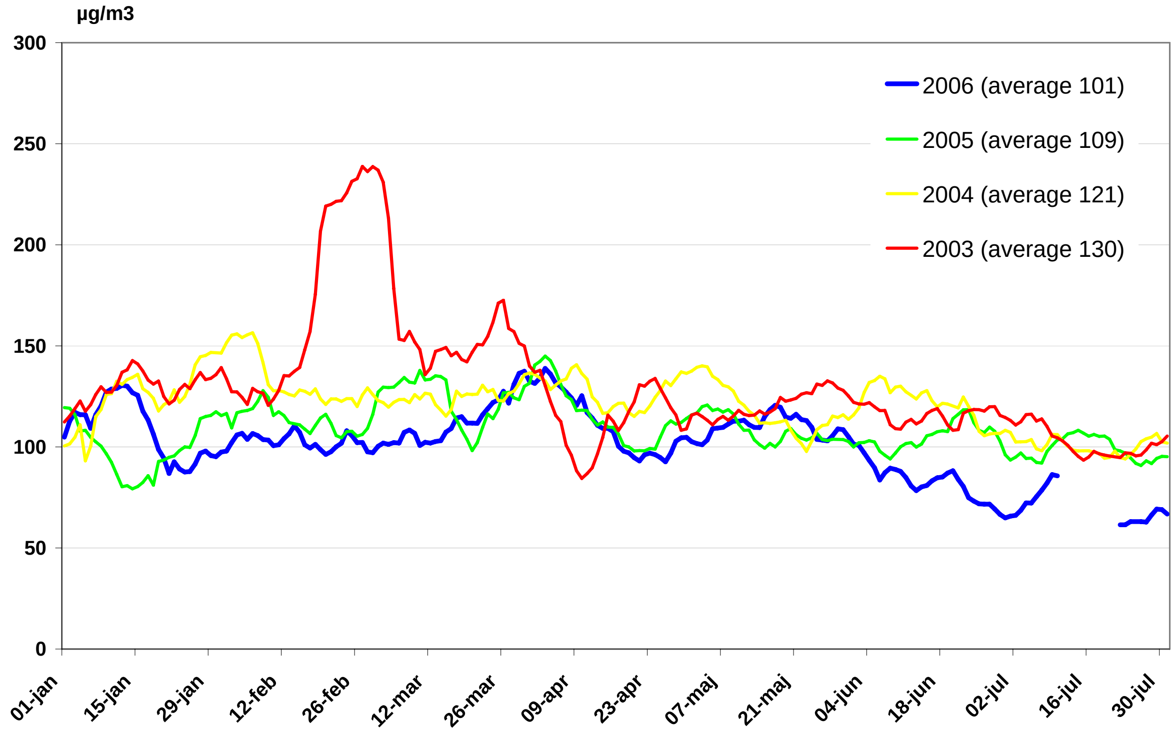


Figure 20. Levels of nitrogen dioxide, NOx, at street level on Hornsgatan in central Stockholm. Levels during the Stockholm Trial in 2006, compared with the same period the previous years.

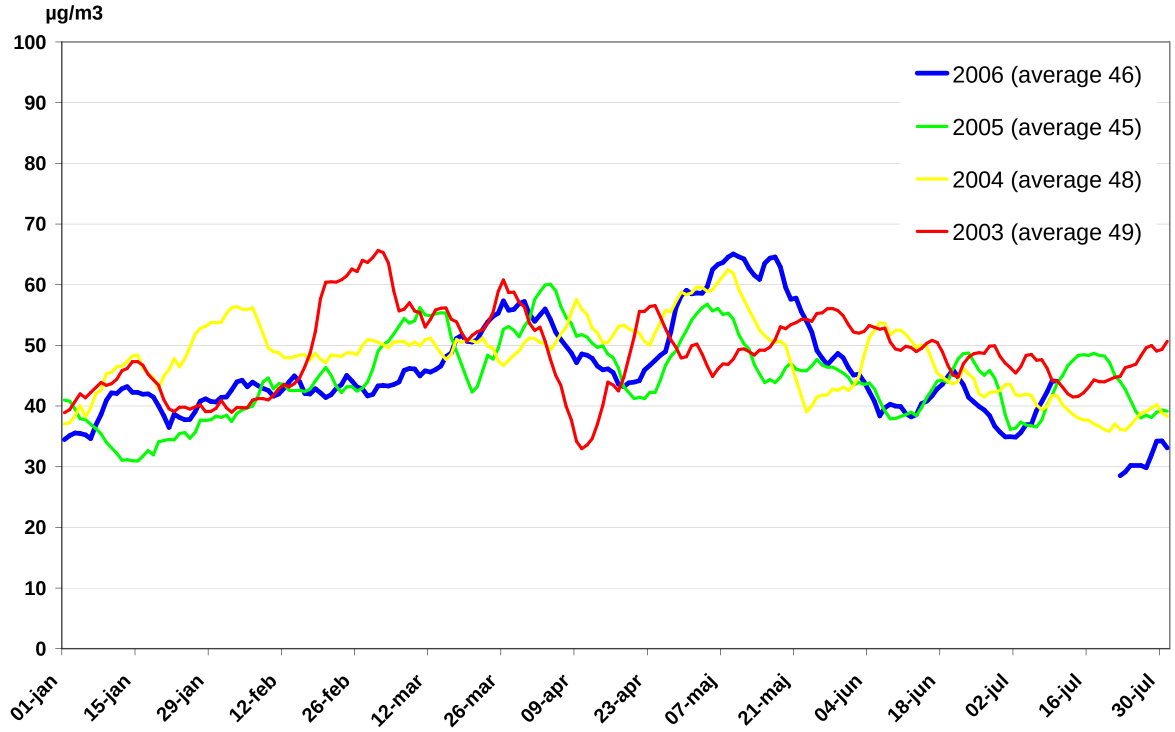


Figure 21. Levels of nitrogen dioxide, NO_2, at street level on Hornsgatan in central Stockholm. Levels during the Stockholm Trial in 2006, compared with the same period the previous years.

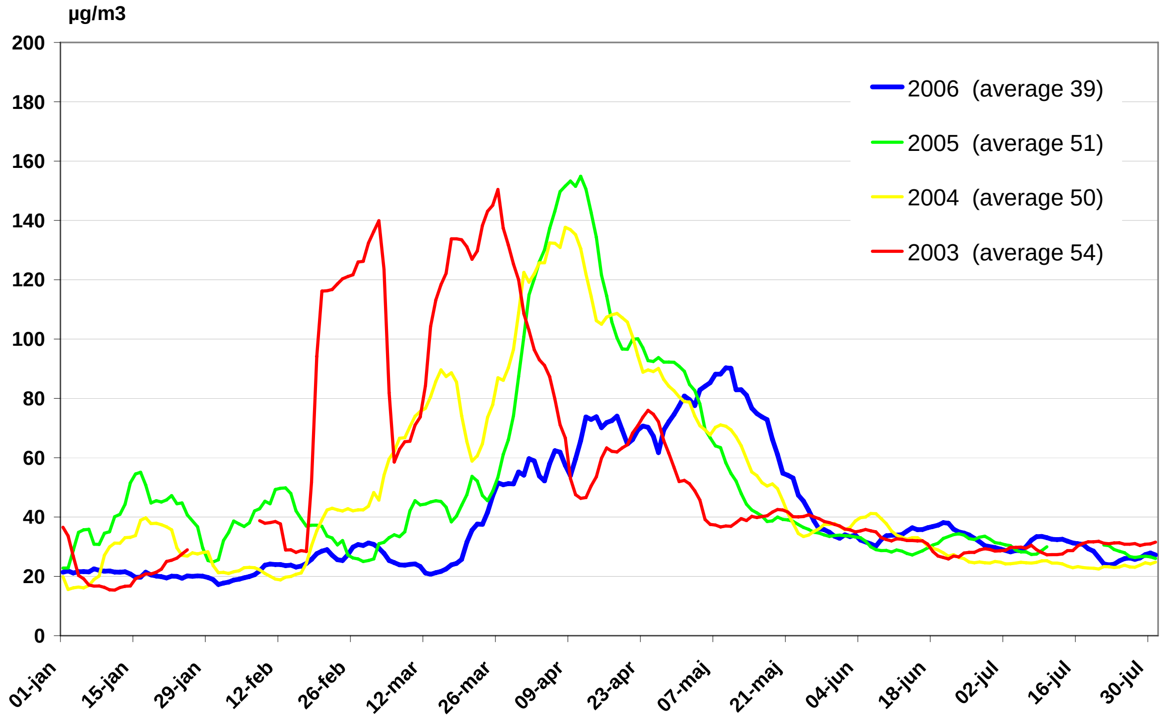


Figure 22. Levels of particles, PM_{10}, at street level on Hornsgatan in central Stockholm. Levels during the Stockholm Trial in 2006 compared with the same period in previous years.

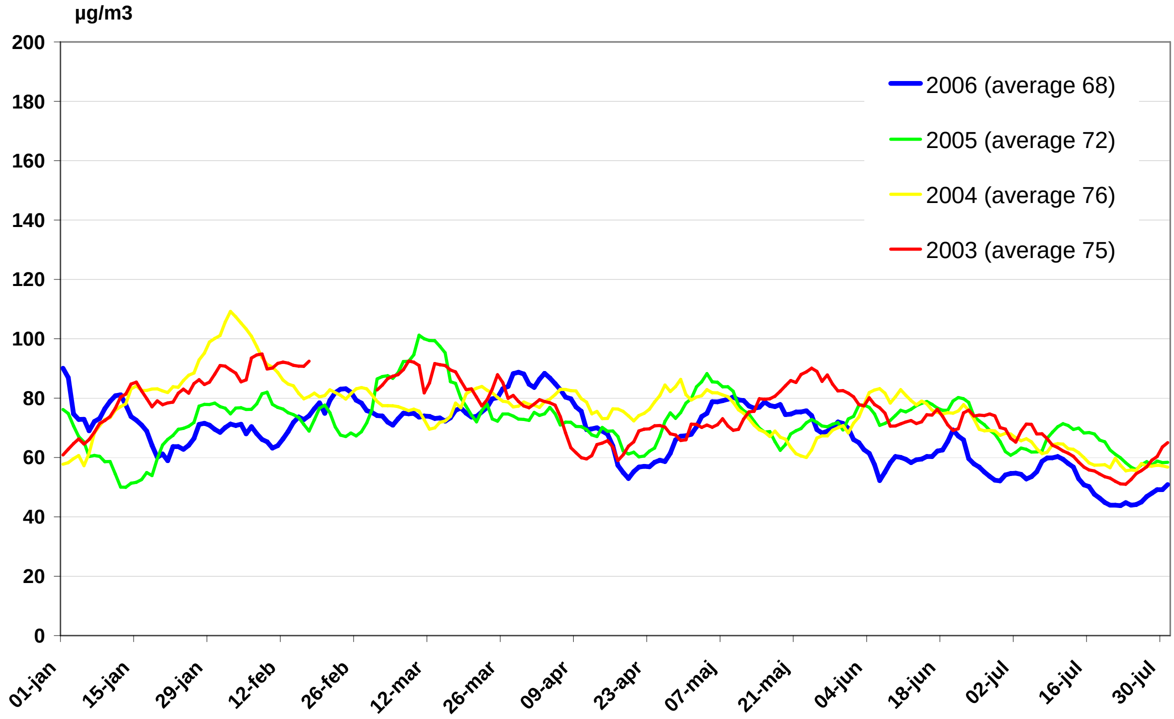


Figure 23. Levels of nitrogen oxides, NOx, at street level on Sveavägen in central Stockholm. Levels during the Stockholm Trial in 2006 compared with the same period in previous years.

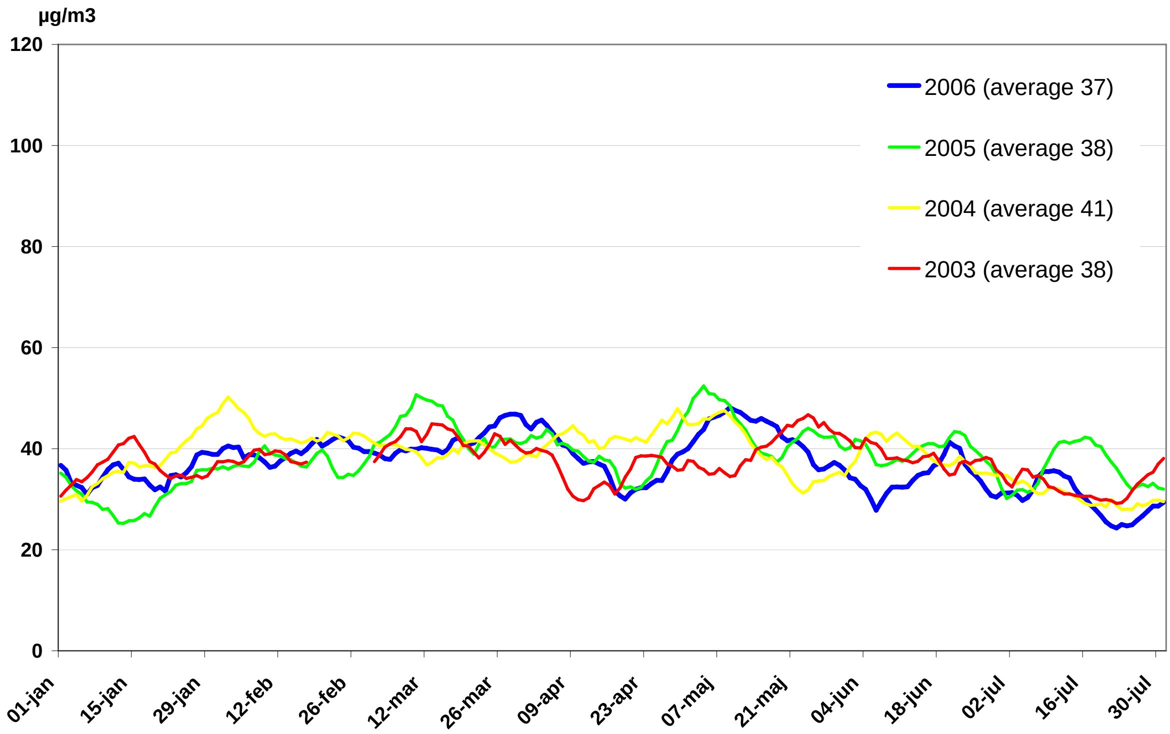


Figure 24. Levels of nitrogen dioxide, NO_2 at street level on Sveavägen in central Stockholm. Levels during the Stockholm Trial in 2006 compared with the same period in previous years.

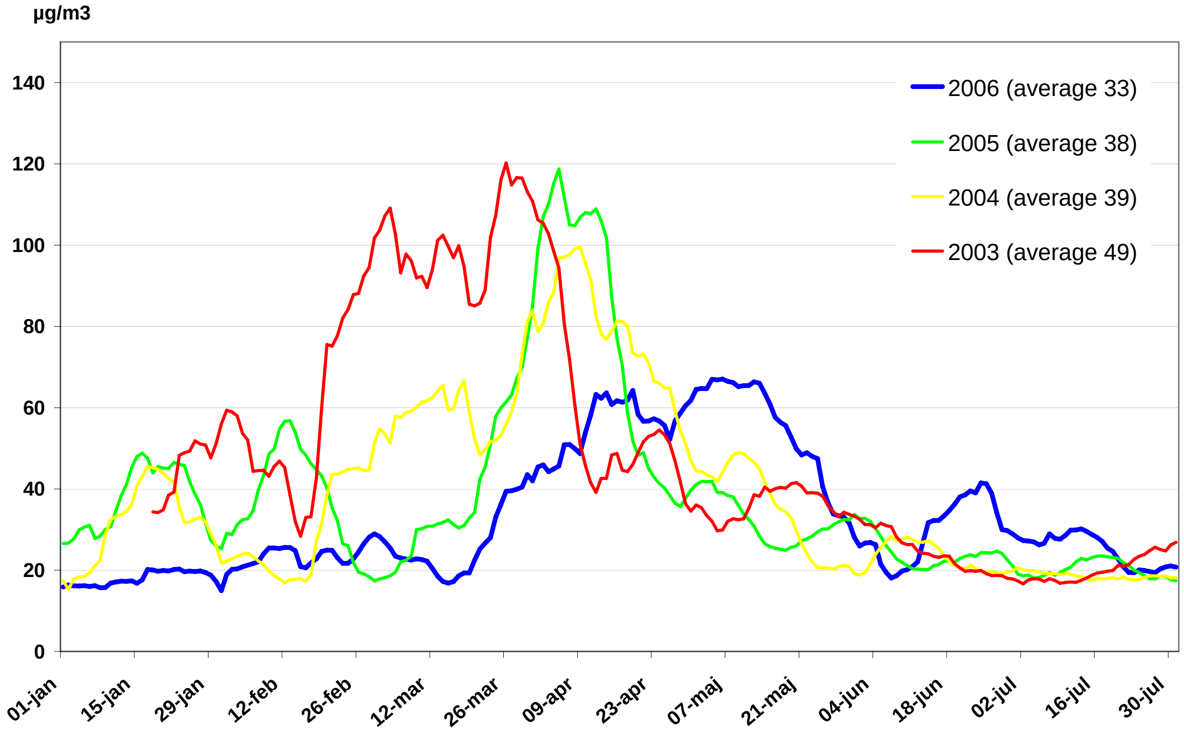


Figure 25. Levels of particles, PM_{10}, at street level on Sveavägen in central Stockholm. Levels during the Stockholm Congestion Charge Trial in 2006 compared with the same period in previous years.

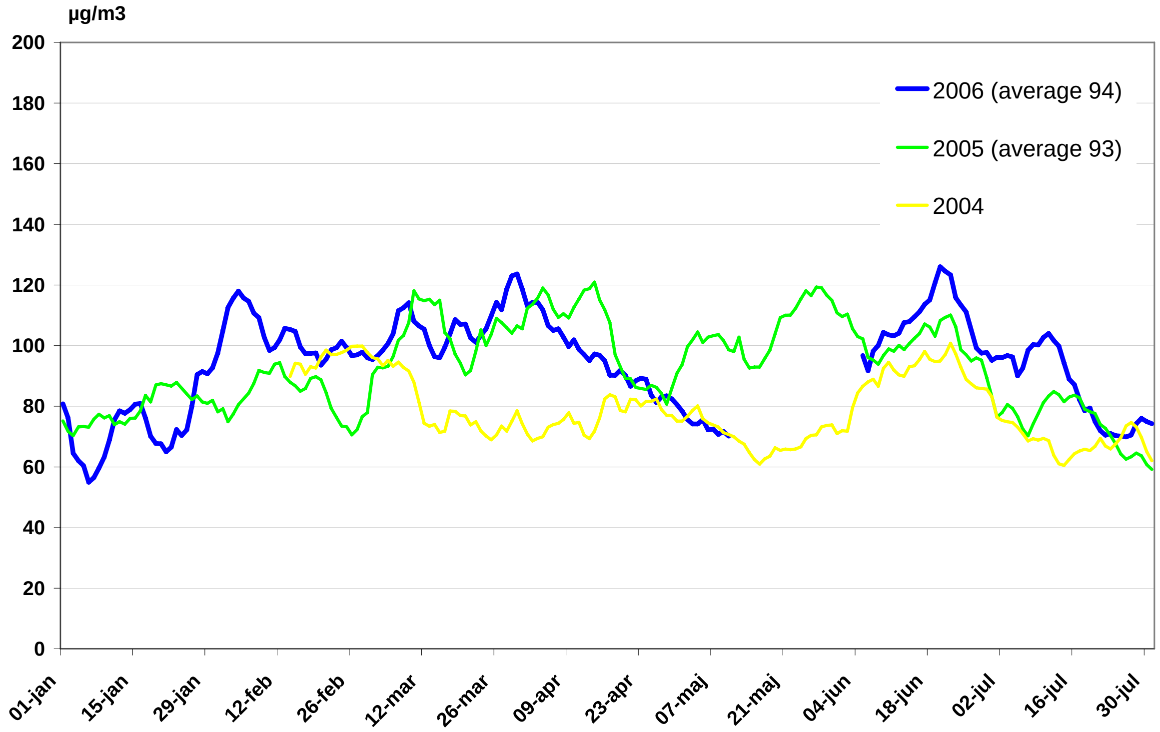


Figure 26. levels of nitrogen oxides, NOx, at street level on Norrlandsgatan in central Stockholm. Levels during the Stockholm Trial in 2006 compared with the same period in previous years.

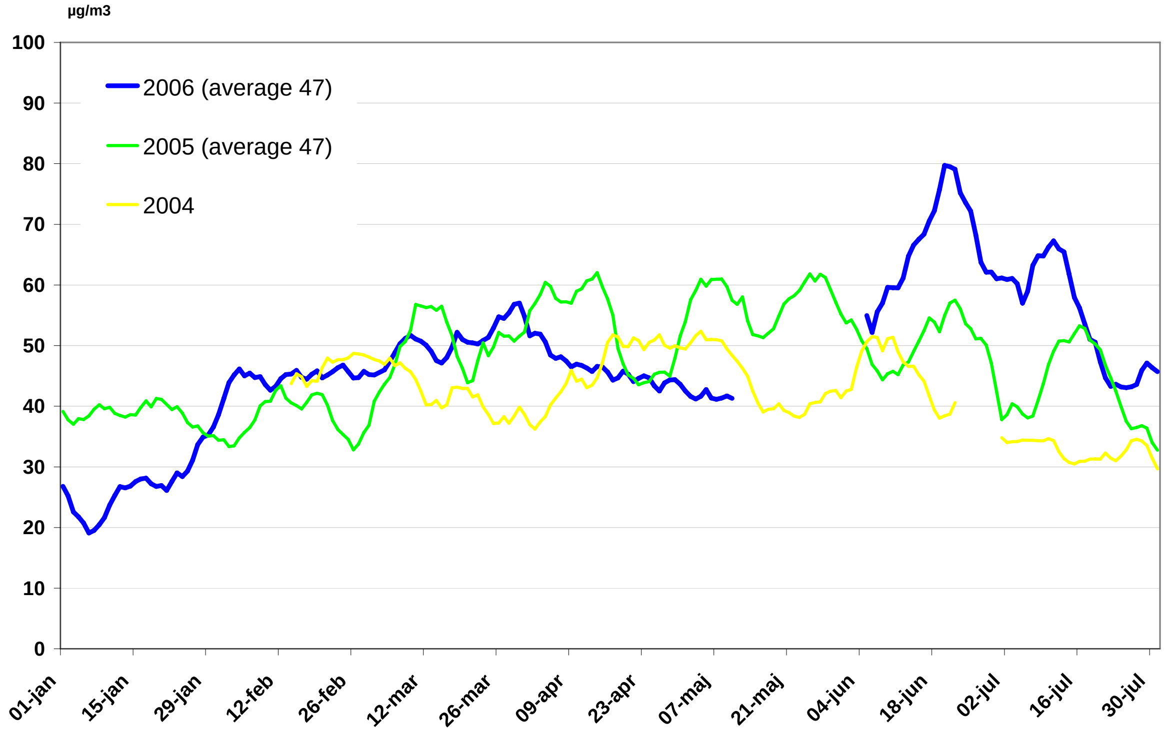


Figure 27. Levels of nitrogen dioxide, NO_2 at street level on Norrlandsgatan in central Stockholm. Levels during the Stockholm Trial in 2006 compared with the same period in previous years.

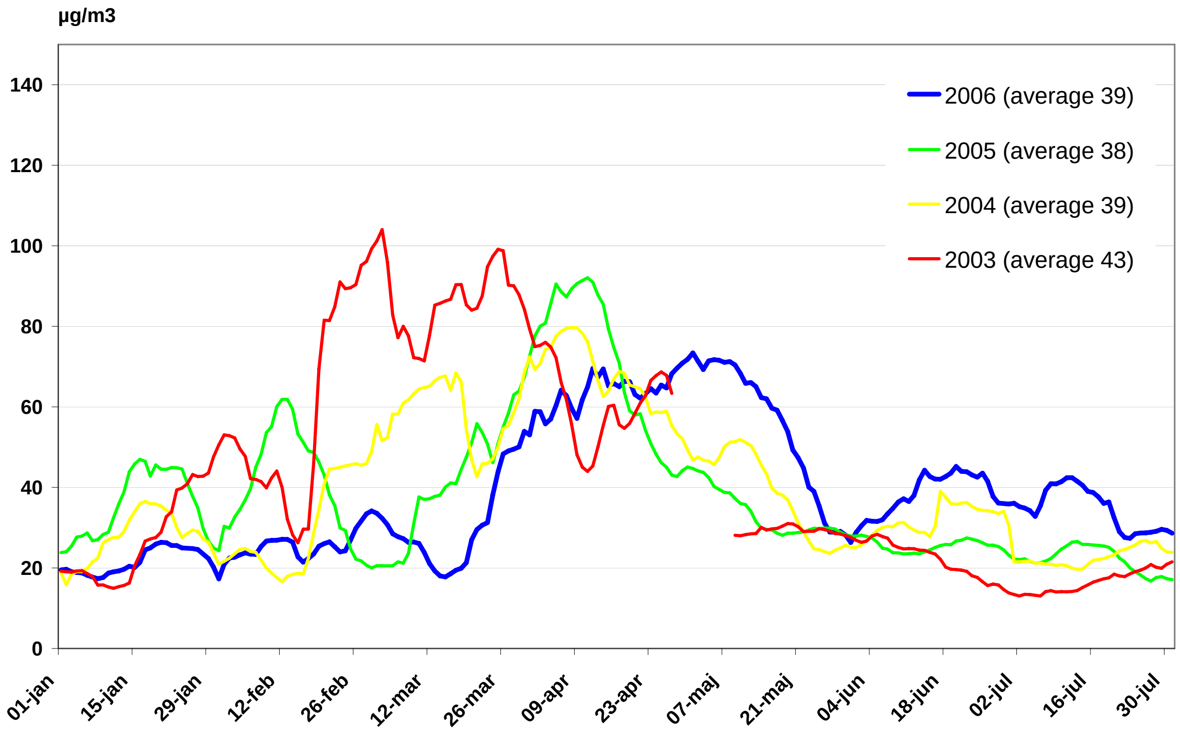


Figure 28. Levels of particles, PM_{10}, at street level on Norrlandsgatan in central Stockholm. Levels during the Stockholm Trial in 2006 compared with the same period in previous years.

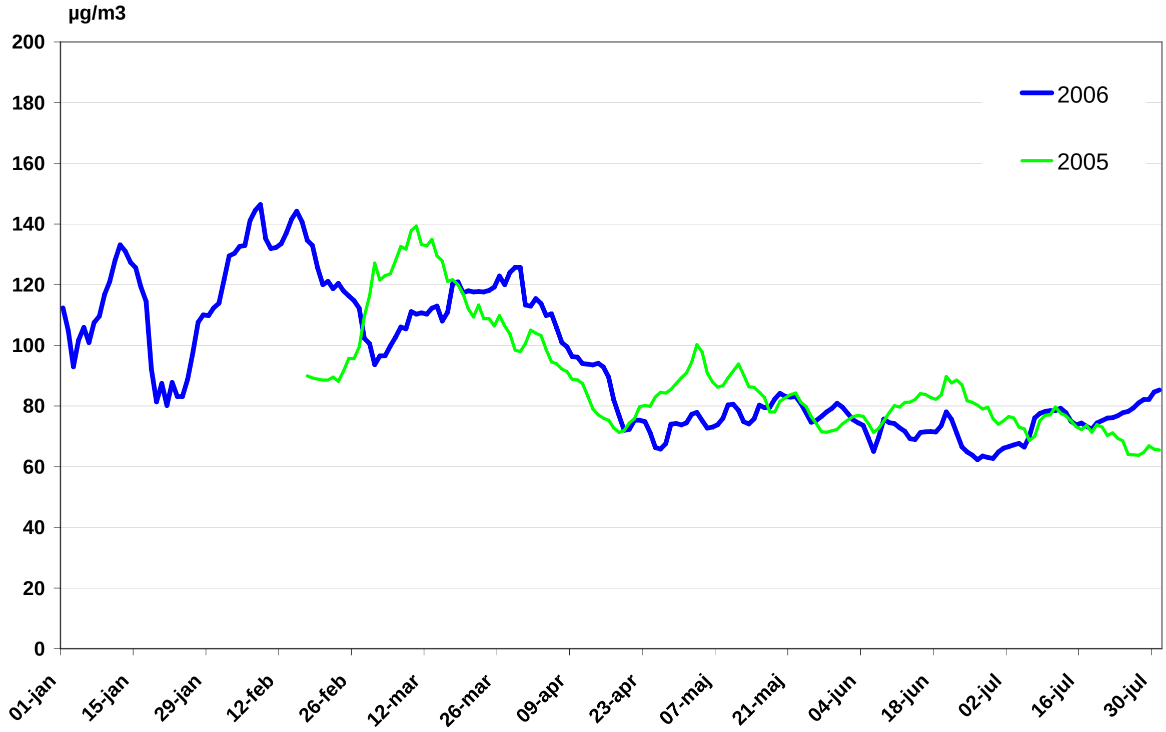


Figure 29. Levels of nitrogen oxides, NOx, at the curb of the E4 highway on Lilla Essingen in Stockholm. Levels during the Stockholm Trial in 2006 compared with the same period in previous years.

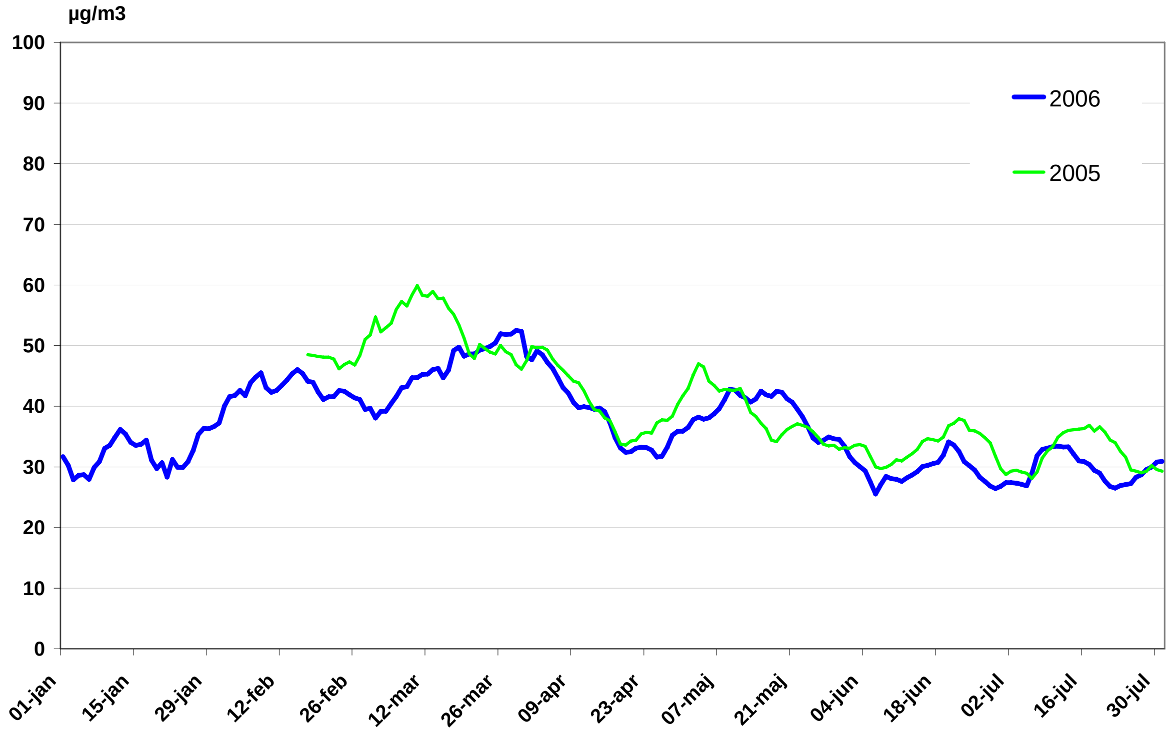


Figure 30. Levels of nitrogen dioxide, NO_2, at the curb of the E4 highway on Lilla Essingen in Stockholm. Levels during the Stockholm Trial in 2006 compared with the same period in previous years.

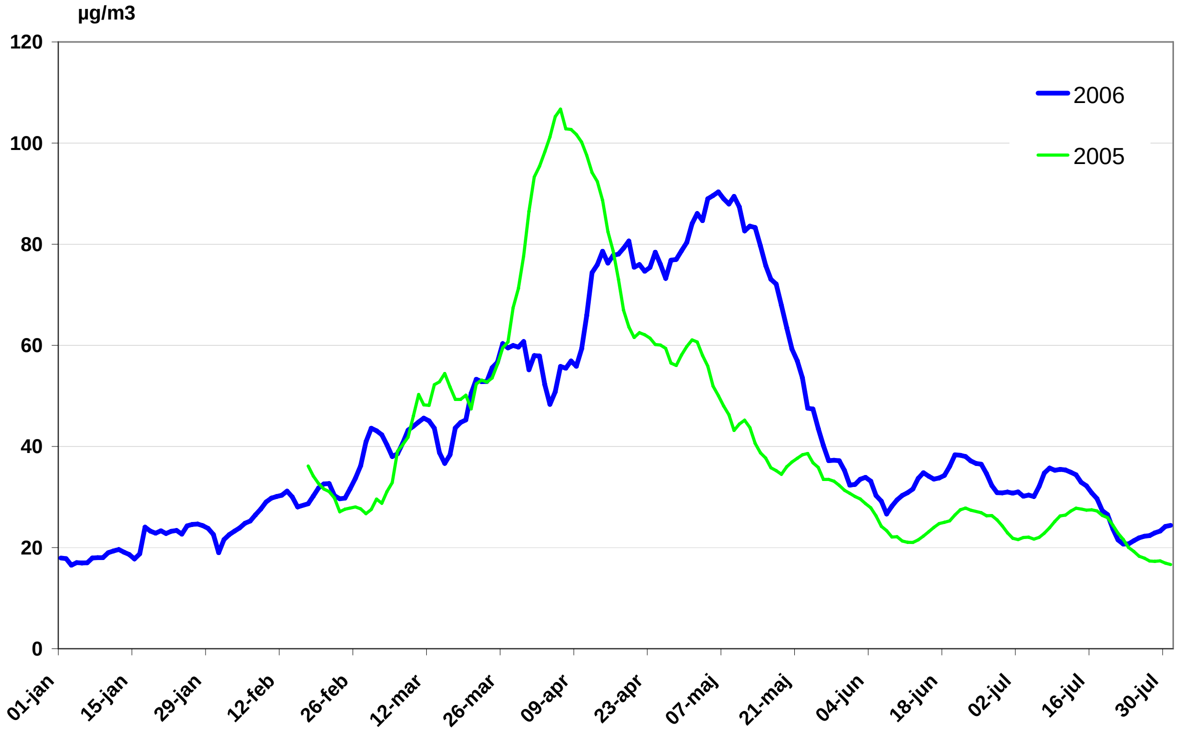


Figure 31. Levels of particles, PM_{10}, at the curb of the E4 highway on Lilla Essingen in Stockholm. Levels during the Stockholm Congestion Charge Trial in 2006 compared with the same period in previous years.

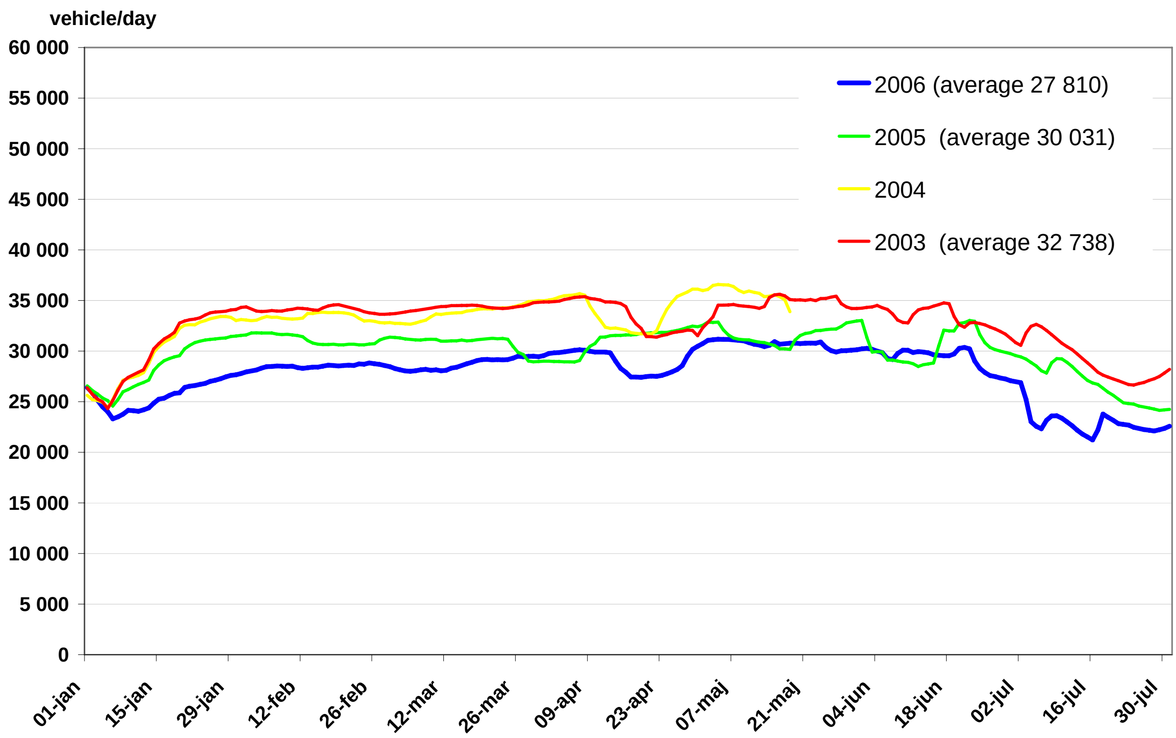
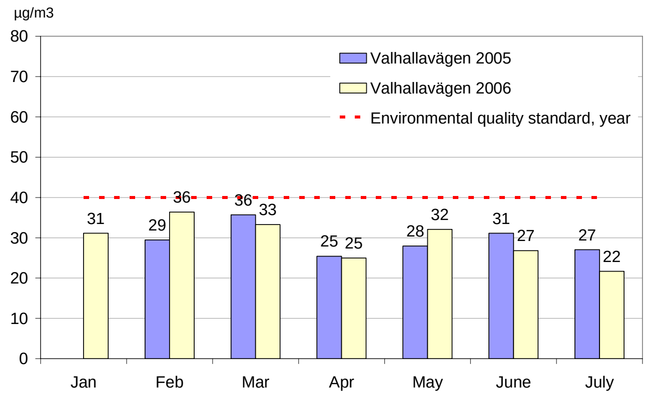


Figure 32. Traffic flow on Hornsgatan in central Stockholm. Levels during the Stockholm Trial in 2006, compared with the same period the previous years.

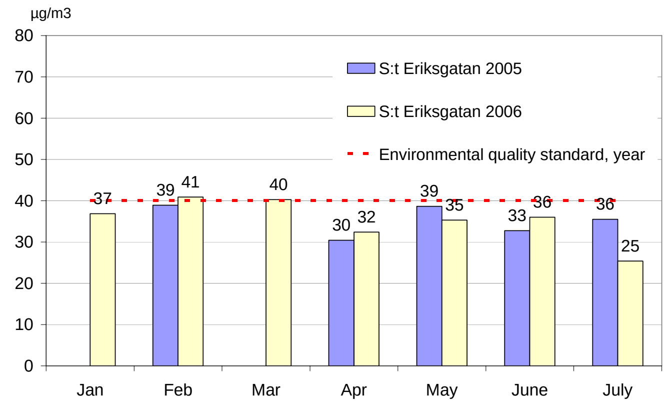
9.1 Other measurements of nitrogen dioxide

Mean monthly values for nitrogen dioxide, NO_2 are given below for the period February to July 2005 and January to July 2006 (that is during the Stockholm Trial). The measurements were carried out with a diffusion sampler ('passive monitoring'). IVL Swedish Environmental Research Institute has provided the analysis results. A comparison has been made with the environmental quality standard for the mean annual value, which in Stockholm is normally easier to meet than the environmental quality standard for the mean daily value.

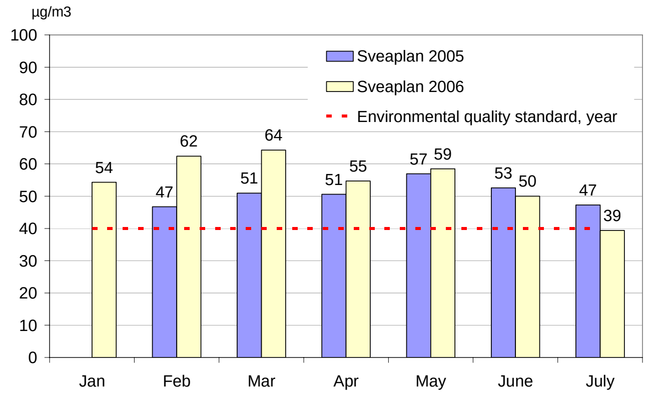
Valhallavägen (5)



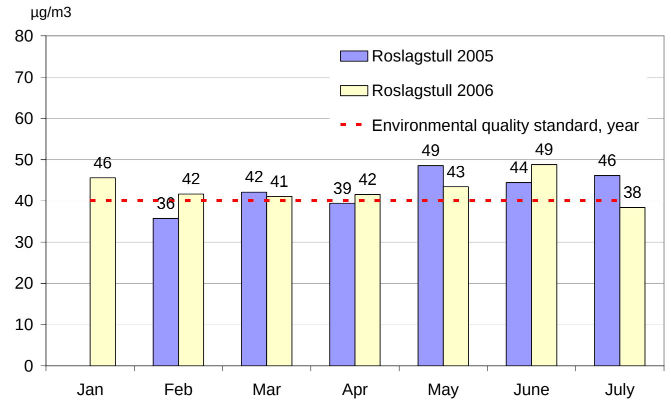
S:t Eriksgatan (4)



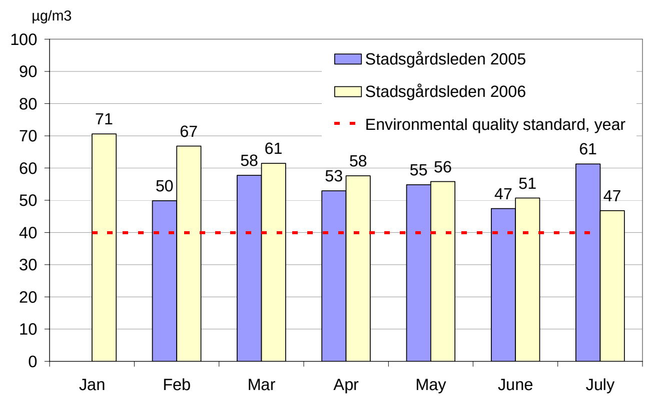
Sveaplan (7)



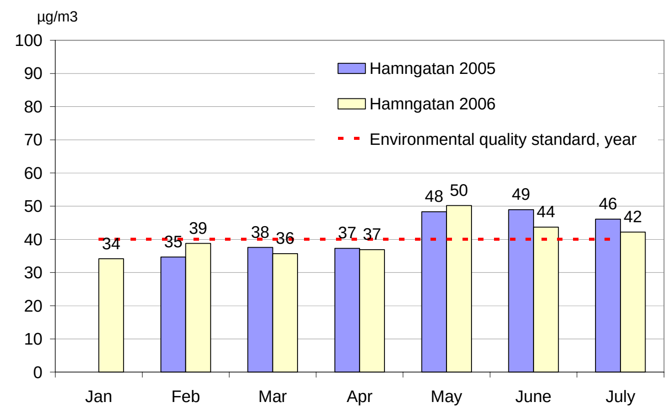
Roslagstull (6)



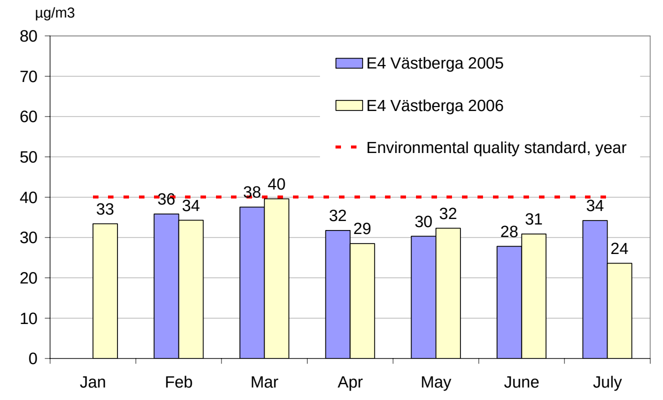
Stadsgårdsleden (8)



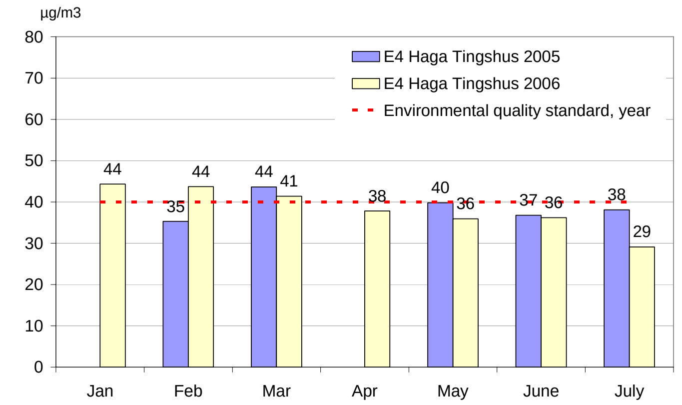
Hamngatan (9)



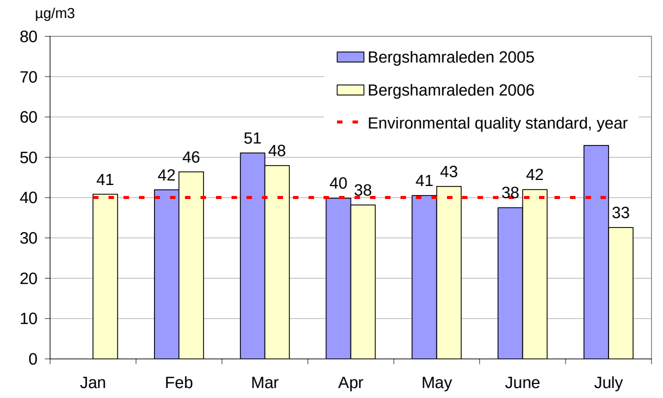
E4 – Västberga (12)



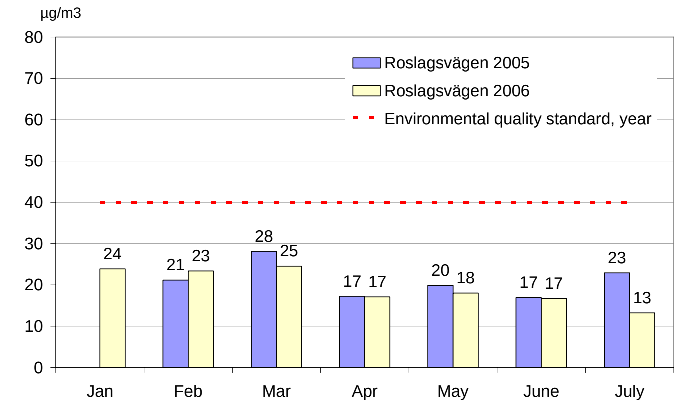
E4 Haga Tingshus (19)



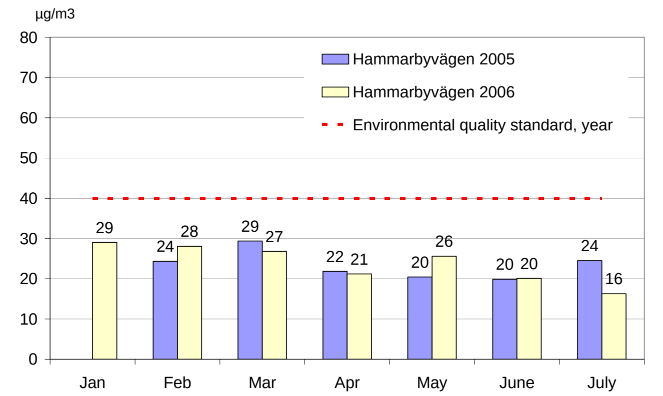
Bergshamravägen (13)



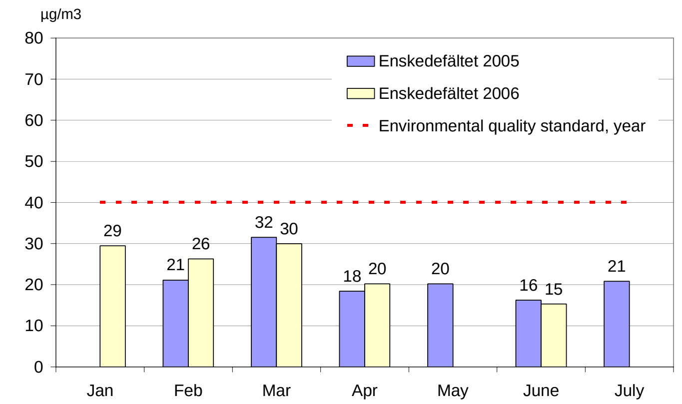
Roslagsvägen (14)



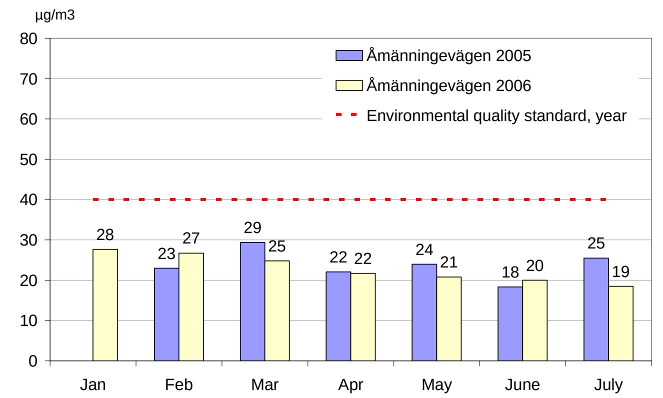
Hammarbyvägen (15)



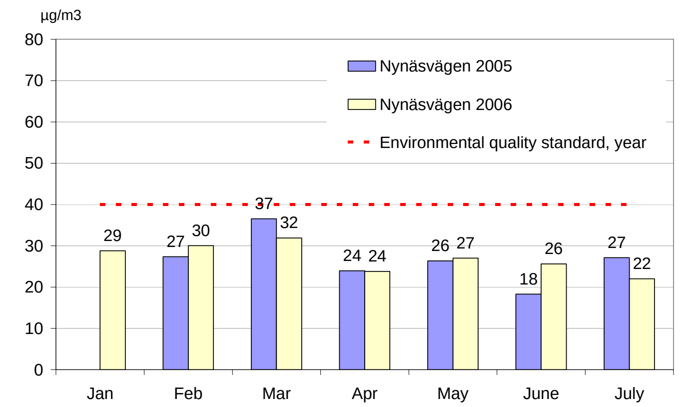
Enskedefältet (16)



Åmänningevägen (17)

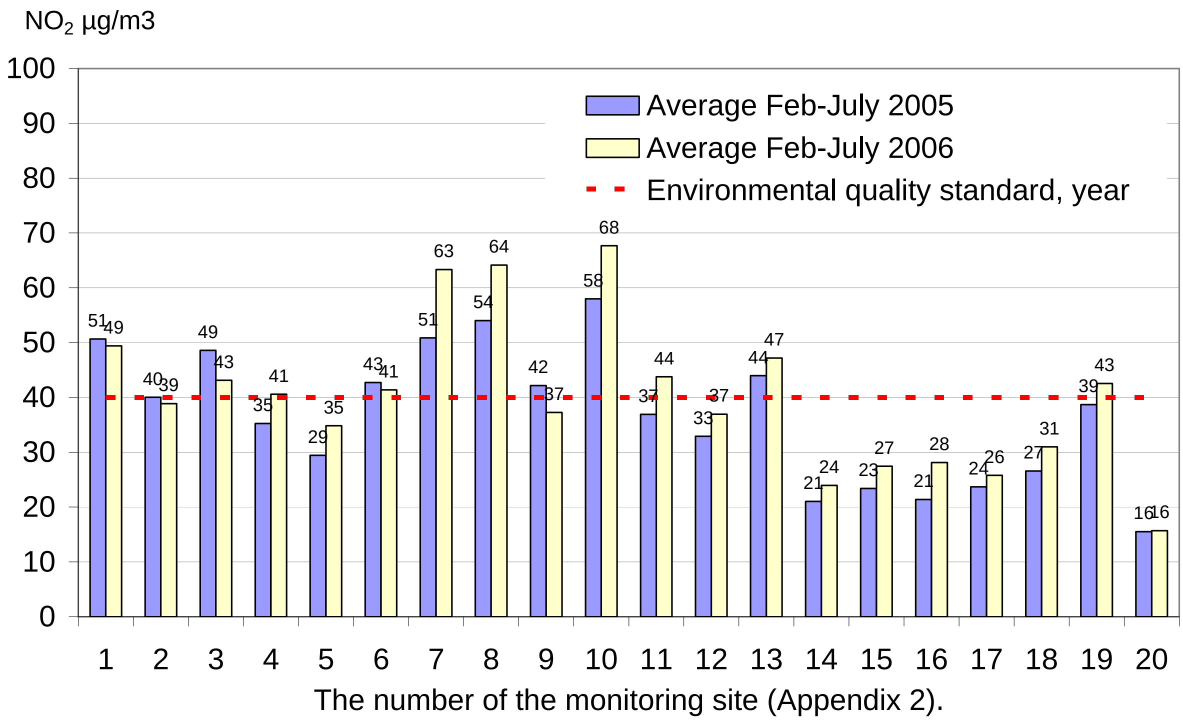


Nynäsvägen (18)



Period averages for all NO_2 monitoring sites (Feb-July)

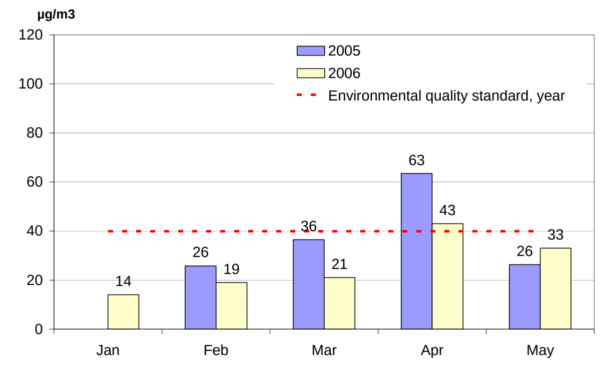
The description of the monitoring sites appears in Appendix 2.



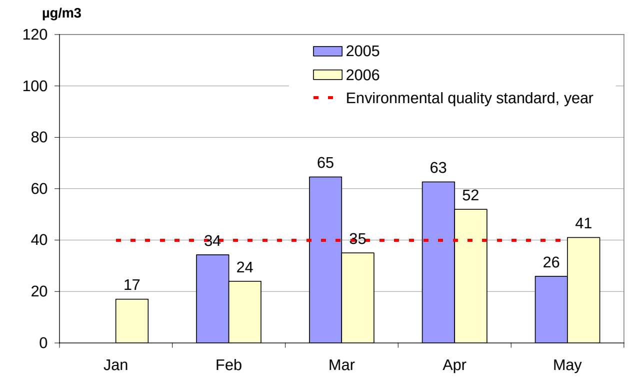
9.2 Other measurements of particles, PM10

The monthly mean values for particles, PM10, are shown below for the period February to May 2005 and January to May 2006. The measurements were made with daily resolution with 'filter samplers'. IVL Swedish Environmental Research Institute has provided the results of the analysis. A comparison has been made with the environmental quality standard for the mean annual value, which in Stockholm is normally easier to meet than the environmental quality standard for the mean daily value.

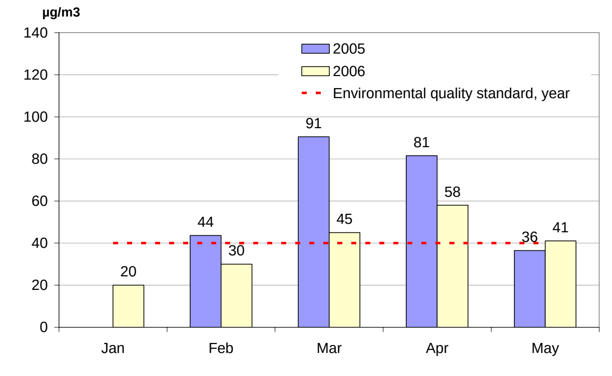
Valhallavägen (5)



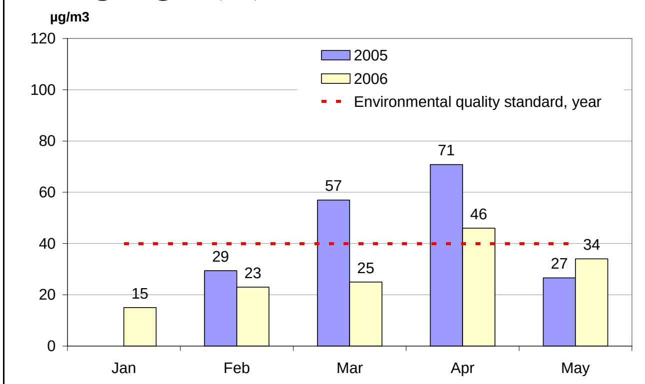
E4-Västberga (12)



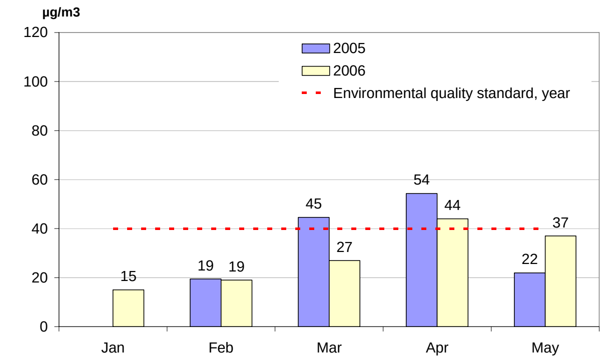
Bergshamravägen (13)



Roslagsvägen (14)

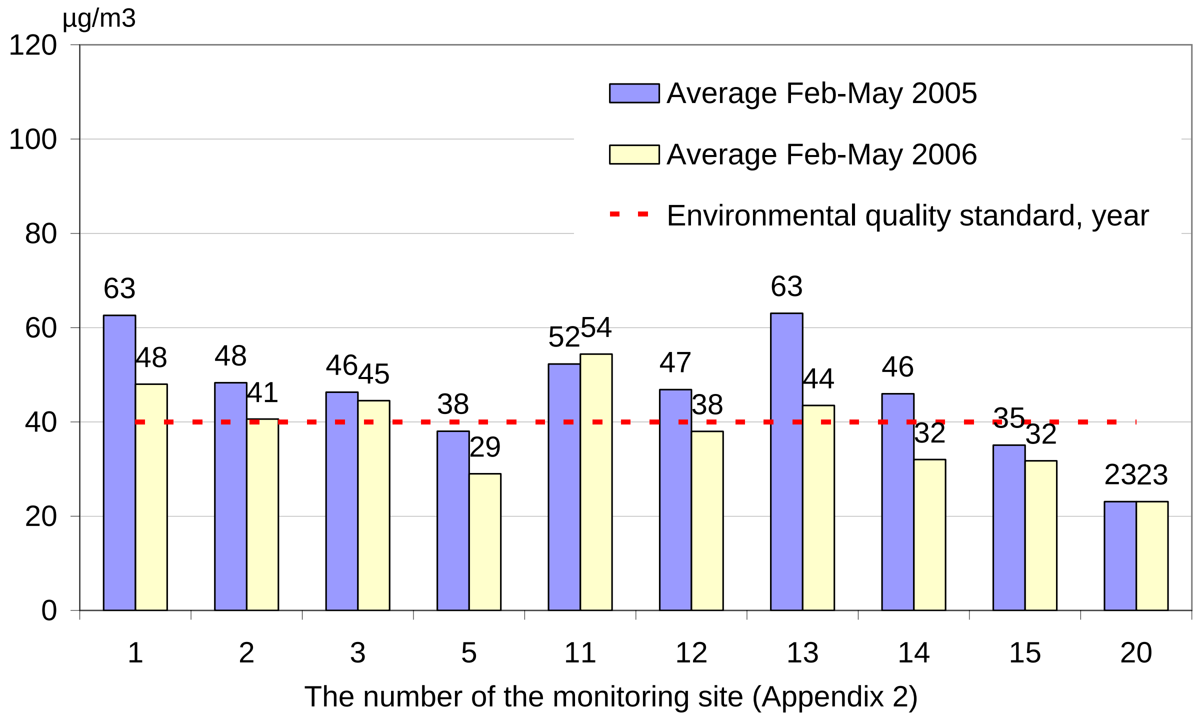


Hammarbyvägen (15)



Period averages for all PM10 monitoring sites (Feb -May)

The description of the monitoring sites appears in Appendix 2.

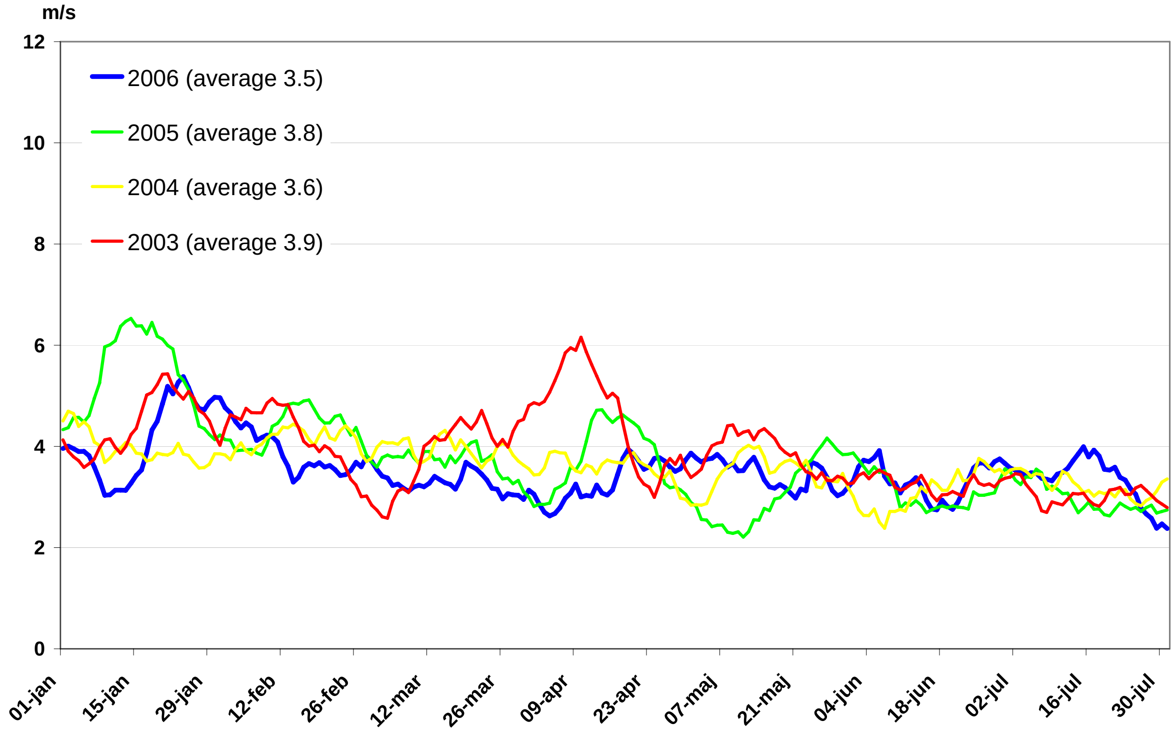


9.3 Measurements of meteorology

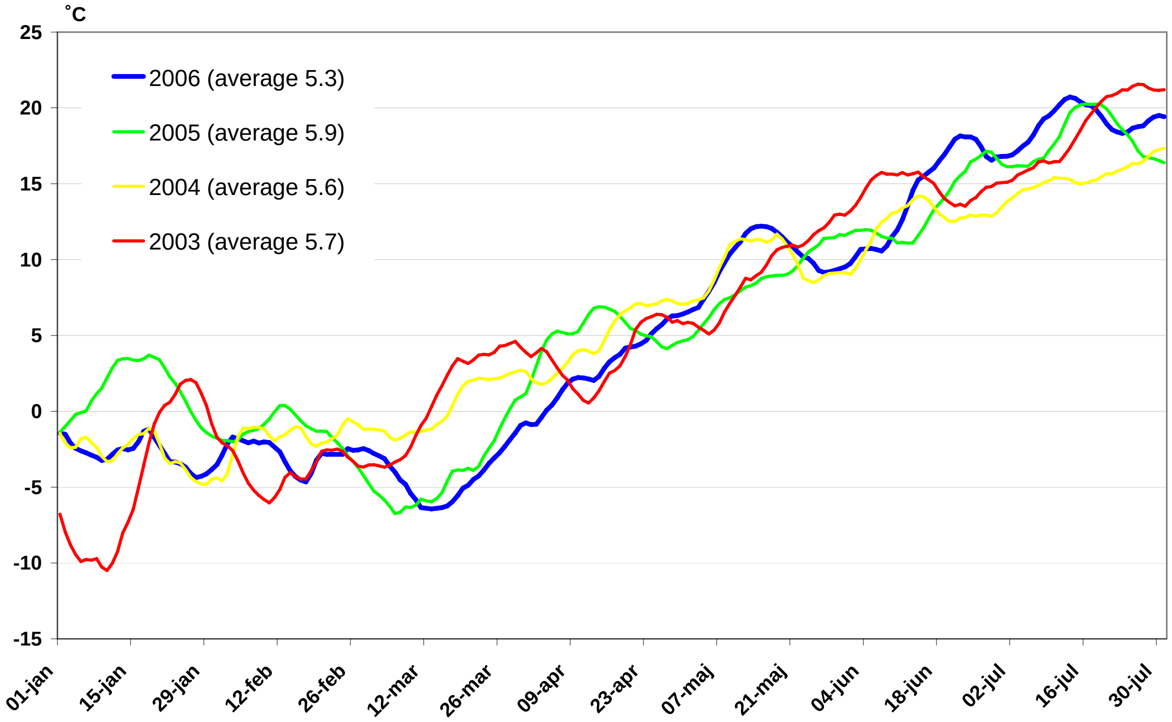
Meteorological factors such as e.g. wind speed, wind direction and temperature are of great significance for the measured air pollution levels in connection with the Stockholm Trial. Generally speaking, high wind speeds increase the dilution and dispersion of air pollutants, so that levels drop compared with low wind speeds. Wind direction is decisive for whether pollutant emissions blow towards monitoring sites or not. The temperature plays a general role both for emissions of air pollutants and dilution. At low temperatures car emissions increase through cold start effects.

Measurement data for meteorology in connection with the Stockholm Trial follow below. Wind, temperatures and precipitation have been registered at the City of Stockholm Environment and Health Administration's weather station at Högdalen in southern Stockholm.

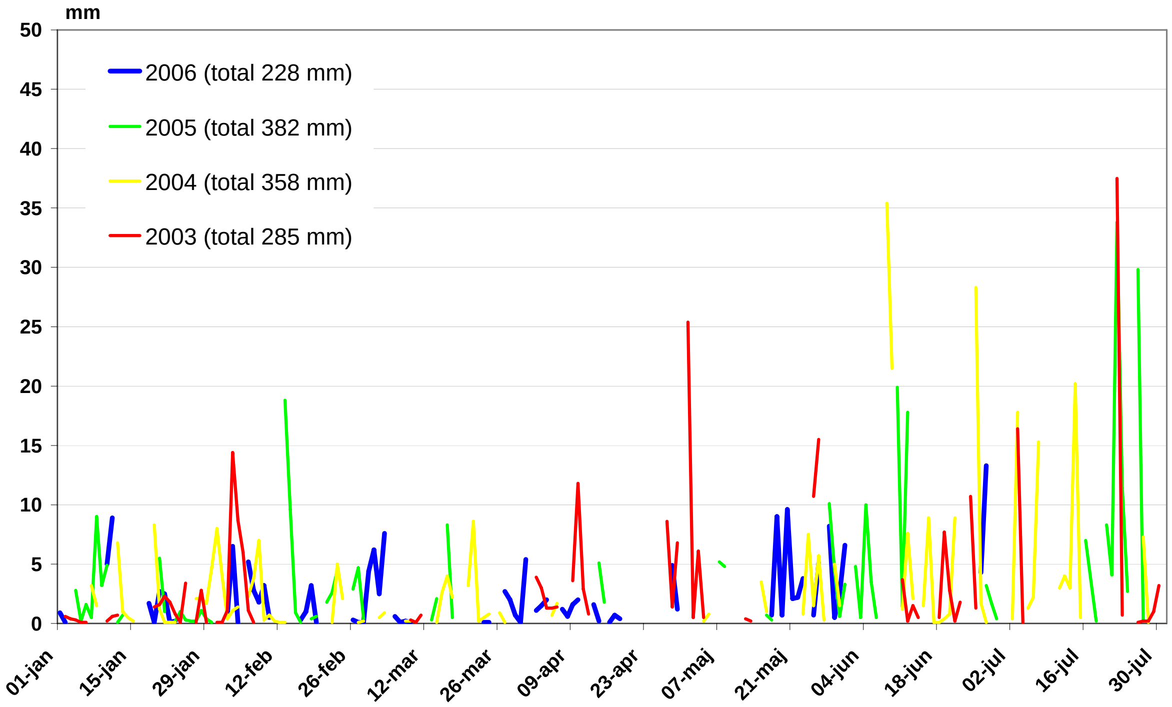
Wind speed



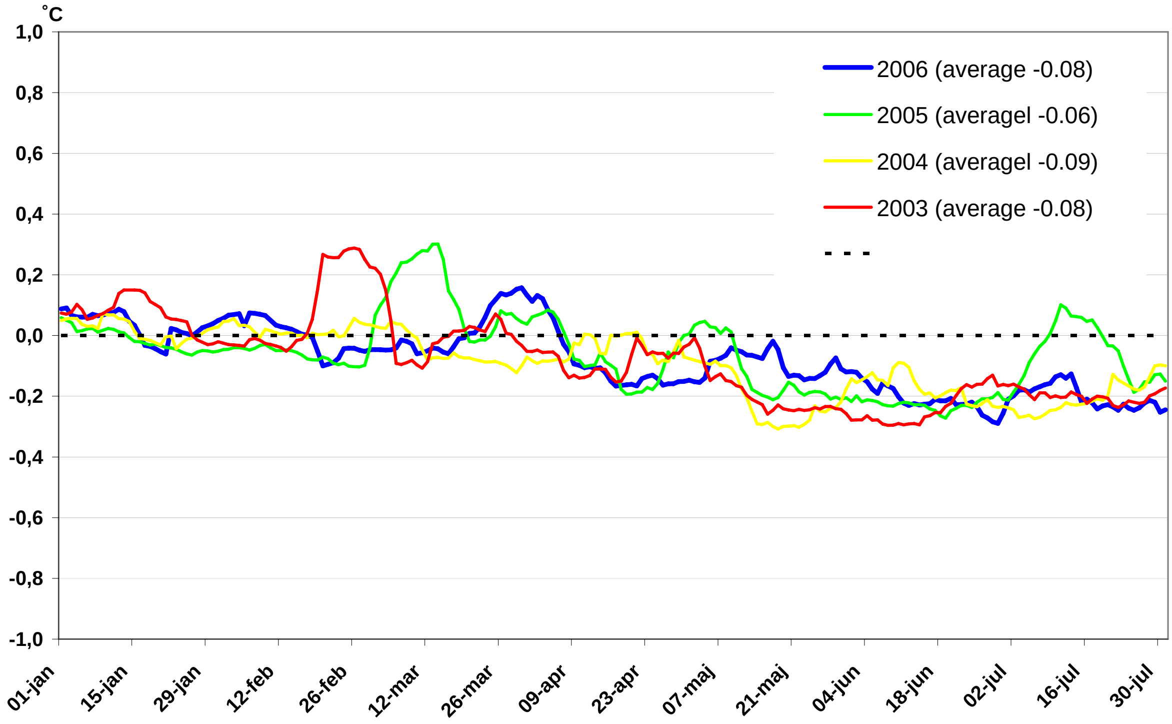
Temperature



Precipitation



Temperature difference



SLB·analys

is a unit of the City of Stockholm Environment and Health Administration which

- studies
- monitors
- estimates
- informs

on the quality of the air outdoors. SLB-analys also takes on external commissions regarding air quality.

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