Norwegian Public
Roads Administration

15.5.2013

Statens vegvesen

NO$_2$/NOx volume ratio in three tunnels in Norway

Observations 2007 - 2013

NORWEGIAN PUBLIC ROADS ADMINISTRATION

No. 173

Statens vegvesen

Statens vegvesens rapportar

Tittel

Registrering av volumandel NO_2/NOx i tre norske tunnelar

Undertittel

2007 - 2013

Forfattar

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Avdeling

Ressursavdelinga

Seksjon

Prosjekteringsseksjonen

Rapportnummer

Nr. 173

Godkjent av

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Emneord
Tunnel, ventilasjon, luftkvalitet, bileksos, emisjonsfaktor, diesel, bensin, NO_2, NO, NOx, PM, PM10

Samandrag

Formålet med denne rapporten er å studere utviklinga av giftige gassar i bileksosen dei siste åra. Dette er nyttig kunnskap ved planlegging av ventilasjon i nye tunnelar og ved vurdering av konsekvensar for miljøet rundt tunnelportalane.

Rapporten inneheld målingar av NO og NO_2 i tre tunnelar i Region vest frå 2007 til 2013. Registreringane viser at utsleppet av støv og NO_2 frå tunge køyretøy har gått ned etter innføring av partikkelfilter som oppfyller Euro 5-krava. Men det har vore ei negativ utvikling i NO_2-utslepp frå personbilar på grunn av den sterke auken i talet på bilar med dieselmotor. I tunnelar med stor utfartstrafikk medfører dette høgt NO_2-nivå fredag ettermiddag og søndag kveld. I bytunnelar kan det ventast høgst NO_2-nivå i morgon- og ettermiddagsrushet.

Tal sider 67

Dato 15.5.2013

NPRA reports
Norwegian Public Roads Administration

Title

Observations of NO_2/NOx volume ratio in three tunnels in Norway

Subtitle

2007 - 2013

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Section

Detailed Design Section

Report number

No. 173

Approved by

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Key words
Tunnel, ventilation, air quality, car exhaust, emission factor, diesel, petrol, gasoline, NO_2, NO, NOx, PM, PM10

Summary

The purpose of this report is to study the development of toxic gases in car exhaust in recent years. This is useful knowledge when planning ventilation in new tunnels and for the assessment of environmental impact around the tunnel portals.

The report contains observations of NO and NO_2 in three Norwegian tunnels from 2007 to 2013. Emission of dust and NO_2 from heavy duty vehicles have been reduced after introduction of particulate filters that meet the Euro 5 requirements. However, there has been a negative trend in NO_2 emissions from passenger cars because of the significant increase in the number of diesel-powered cars in Norway. In tunnels with large weekend-traffic, this results in high NO_2 concentrations on Friday afternoon and Sunday evening. The highest NO_2 levels in urban tunnels can be expected during rush hours.

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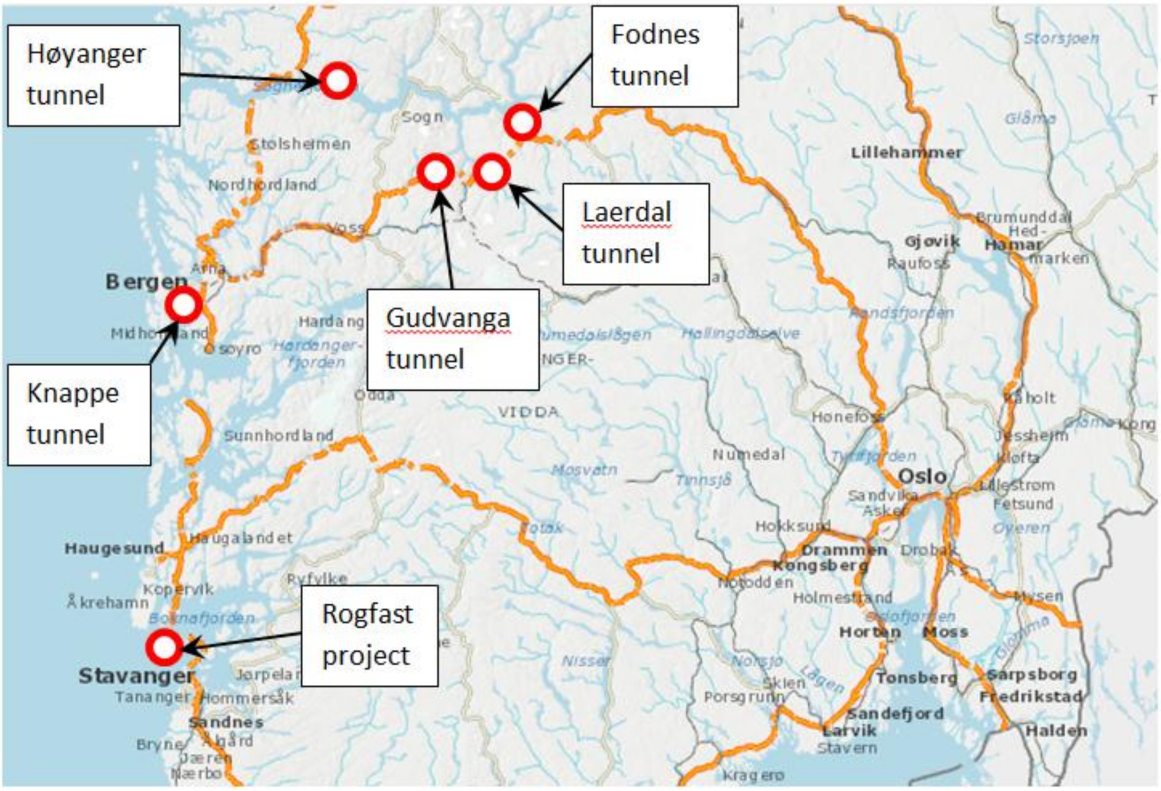
Introduction

The purpose of this report is to provide a sound basis for detailed planning of the ventilation system for the new Rogfast tunnel and other long road tunnels in Norway. The Rogfast tunnel which is being planned on the coastal road between Stavanger and Bergen, is a 25 km long subsea road tunnel with two tubes. The tunnel will be divided into four ventilation sections by three double ventilation shafts. Each section will have a longitudinal ventilation system with jet-fans.

The report is referring to observations of NO and NO_2 and in three Norwegian tunnels:

	Length	Daily traffic in 2012	% heavy duty vehicles
Laerdal tunnel	24.5 km	1 896	26 %
Fodnes tunnel	6.6 km	1 959	18 %
Knappe tunnel	2.5 km	19 153	5 %

Gas measurements in multiple tunnels in Norway have given new knowledge about the changes in NOx emissions from heavy duty vehicles and passenger cars since 2007. The introduction of particulate filters that meet the Euro 5 requirements, have reduced the emission of dust and NO_2 from buses and trucks. However, there has been an opposite trend in NO_2 emissions from passenger cars because of higher numbers of new passenger cars with diesel engines over the last years. In tunnels with large excursion traffic, the emissions from diesel powered cars are giving the highest NO_2 levels on Friday afternoon and Sunday evening. The highest NO_2 levels in urban tunnels have been observed during rush hours from Monday to Friday when there is a low share of heavy duty vehicles.



1. Nitrogen oxides (NOx), ozone (O_3) and particulate matters

1.1 Air quality guidelines for NO_2 and Particulate matters (PM)

The first standards for NO_2 were set by the US Environmental Protection Agency (EPA) in 1971. The EPA set both a primary standard (to protect health) and a secondary standard (to protect the public welfare) at 0.053 parts per million, averaged annually. The Agency has reviewed the standards twice since that time, but chose not to revise the standards at the conclusion of each review. 0.053 PPM is equal to 100 µg/m^3 at 11 °C (at standard air pressure). A new 1-hour standard at a level of 100 ppb[1] was introduced by EPA in 2010 to supplement the existing annual standard.

The EU air quality Directive 2008/50/EC sets concentration limits for nitrogen dioxide (NO_2) and particulate matter (PM_{10}):

Nitrogen dioxide (NO_2)	Hourly limit value for the protection of human health	Annual limit value for the protection of human health	Annual critical level for the protection of vegetation and natural ecosystems
Upper assessment threshold	70 % of limit value (140 µg/m^3, not to be exceeded more than 18 times in any calendar year)	80 % of limit value (32 µg/m^3)	80 % of critical level (24 µg/m^3)
Lower assessment threshold	50 % of limit value (100 µg/m^3, not to be exceeded more than 18 times in any calendar year)	65 % of limit value (26 µg/m^3)	65 % of critical level (19.5 µg/m^3)

Particulate matters (PM_{10} and $PM_{2.5}$)	24-hour average PM_{10}	Annual average PM_{10}	Annual average $PM_{2.5}$
Upper assessment threshold	70 % of limit value (35 µg/m^3, not to be exceeded more than 35 times in any calendar year)	70 % of limit value (28 µg/m^3)	70 % of limit value (17 µg/m^3)
Lower assessment threshold	50 % of limit value (25 µg/m^3, not to be exceeded more than 35 times in any calendar year)	50 % of limit value (20 µg/m^3)	50 % of limit value (12 µg/m^3)

The current WHO guideline value of 40 µg/m^3 (annual mean) was set to protect the public from the health effects of gaseous NO_2. Epidemiological studies have shown that symptoms of bronchitis in asthmatic children increase in association with long-term exposure to NO_2. Reduced lung function growth is also linked to NO_2 at concentrations currently measured (or observed) in cities of Europe and North America[2]. Continued exposure to high NO_2 levels can contribute to the development of acute or chronic bronchitis. The current WHO guideline for 1-hour mean is 200 µg/m^3 which is equal to 0.1 ppm at 21 °C (at standard air pressure).

The Norwegian government has given national targets and limit values for NO_2 and PM_{10}:

Nitrogen dioxide and particulate matters

Hour average limit value (NO_2)	Annual average limit value (NO_2)	24 hour average limit value (PM_{10})	Annual average limit value (PM_{10})
150 µg/m^3, not to be exceeded more than 8 hours in any calendar year	40 µg/m^3, not to be exceeded	50 µg/m^3, not to be exceeded more than 7 days in any calendar year	40 µg/m^3, not to be exceeded

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[1] 100 ppb = 0,10 ppm

[2] WHO: Air quality guidelines, Global update 2005

Upper threshold values for NO_2 in tunnels shorter than 10 km are given in the Norwegian design guide for tunnels. A tunnel with longitudinal ventilation shall be closed if the NO_2-concentration in the middle exceeds 0.75 ppm (equal to 1500 µg/m^3 at 15 ^oC) for more than 15 minutes. The threshold value in the middle of the tunnel is regarded as an average value for the NO_2-concentration in long tunnels with longitudinal ventilation. The upper threshold value in a 10 km long tunnel is set 10 times higher than the national hourly limit value for NO_2. This has been accepted because of the limited exposure time in the majority of Norwegian tunnels.

The limit values and gas-concentrations in Norwegian tunnels are given as *Parts Per Million* (ppm) which is a dimensionless value. Ppm is useful for presentation of gas measurements because of the independency of temperature and pressure for ideal gases. To convert ppm to a metric expression like μg/m^3, the density of the concerning gas is needed. Since gas density varies with temperature and pressure, both these parameters must be known in order to convert ppm to μg/m^3. The conversion of one ppm at different temperatures at standard pressure (1 bar) is given in the following table:

Air temperature ^oC	Air density, kg/m^3	1 ppm NO_2 in µg/m^3	1 ppm NO in µg/m^3
21	1,20	1 953	1 242
0	1,29	2 103	1 338
-12	1,35	2 200	1 399

1.2 Main sources for nitrogen oxides (NOx) in road tunnels

Heavy duty vehicles with diesel engines have been the main source of nitrogen oxides for many years. The total emission from road traffic in Norway is illustrated in figure 1. There has been a significant decline in the emission from heavy duty vehicles after 2007 because of stricter emission standards for new vehicles and improvement in motor technology since the first Euro-norm for NOx-emission was implemented in 1988 [3]. The upper limit for NOx emission from new heavy duty vehicles was gradually reduced from 16 g/kWh in 1988 to maximum 2.0 g/kWh when Euro 5 came into force in 2009. A further decline in the emission from heavy duty vehicles can be expected as the oldest trucks and buses are replaced with new vehicles.

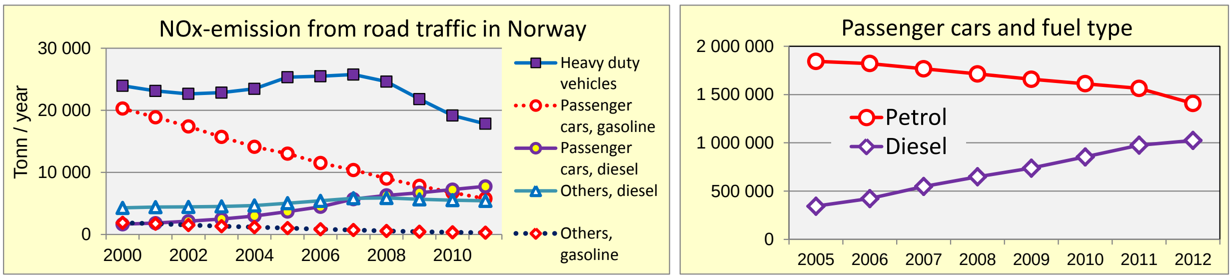

Figure 1: Trends in emission of nitrogen oxides from road traffic in Norway [4]

New cars in Norway are generally driven more than older cars, and diesel-powered passenger cars are driven more than cars with petrol fuel. Passenger cars less than five years old, were driven an average of 16 000 kilometres in 2011. The average mileage was 16 600 km for passenger cars with diesel engine and 10 700 km for petrol cars. The total share of diesel-powered passenger cars on Norwegian roads was 49.1 % in 2011.

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[3] Euro 1: 9 g NOx/kWh in 1992, Euro 2: 7 g/kWh in 1996: Euro 3: 5 g/kWh in 2000: Euro 4: 3.5 g/kWh in 2005

[4] Sources: www.klif.no and www.ssb.no

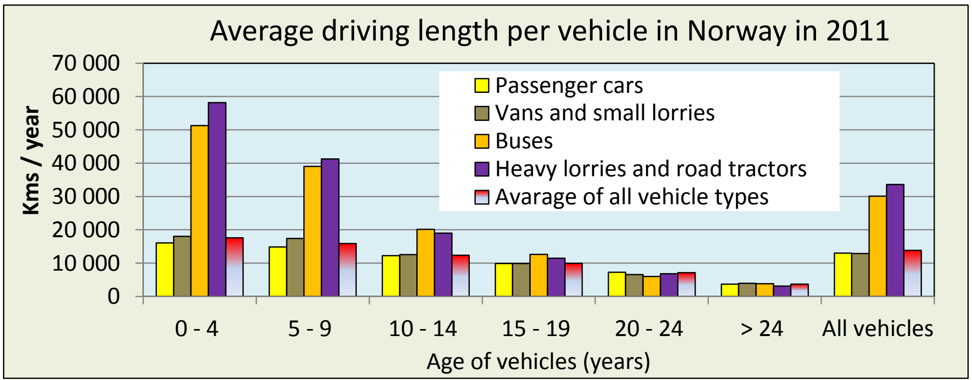

Figure 2: Average driving length for vehicles in Norway (www.ssb.no)

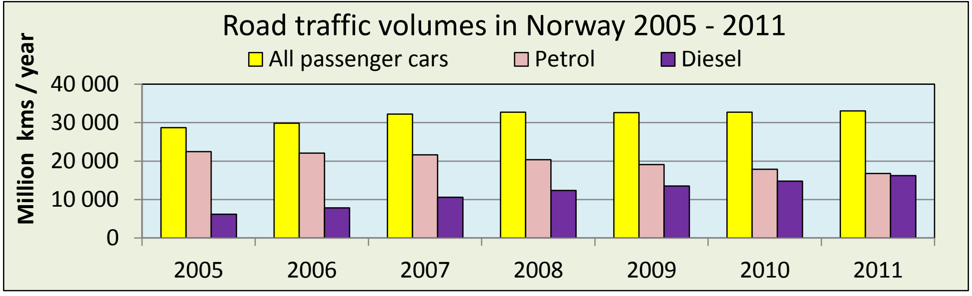

Figure 3: Road traffic volumes in Norway (www.ssb.no)

The decline in pollution emission from cars with gasoline fuel started when the first generation of catalytic converters was introduced in 1975. The two-way-converter reduced the emission level of carbon monoxide (CO) and unburned hydrocarbons (HC). The next generation of catalytic converters use a ceramic or metallic substrate with an active coating incorporating alumina, ceria and other oxides and combinations of the precious metals platinum, palladium and rhodium.

Three-way catalysts operate in a closed-loop system including a lambda or oxygen sensor to regulate the air:fuel ratio on petrol engines. The catalyst can then simultaneously oxidise CO and HC to CO_2 and water while reducing NOx to nitrogen (N_2).

The effective three-way catalyst has been mandatory on new cars with gasoline fuel in Europe since Euro 1 entered into force in 1992. The emissions of CO and NOx have been gradually reduced by introduction of new motor technology and improvement of the exhaust control systems. The emission of lead has been eliminated as a side effect of the catalyst, because lead fuel additive would have destroyed the catalyst.[5]

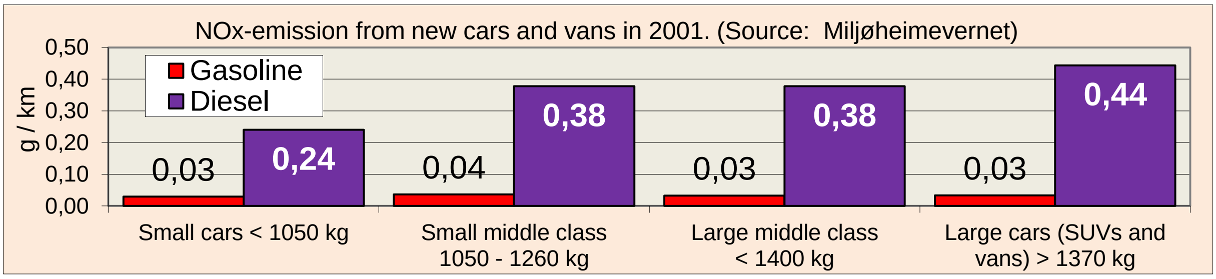

Figure 4: Diesel cars had 10 times higher NOx-emission than gasoline cars in 2001

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[5] Lead was used as an additive in petrol from the 1920s to the beginning of 2000 when European legislation stopped normal sale and distribution of leaded gasoline

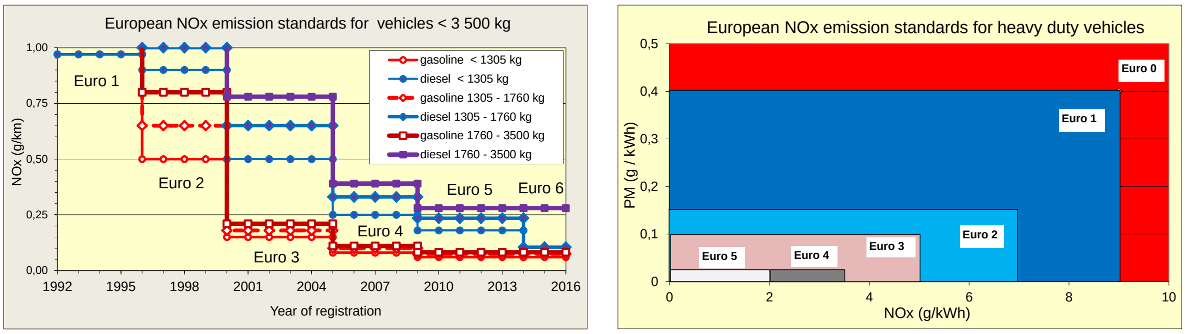

Figure 5: European emission limits varies with fuel type and weight of vehicles

Since 2002 there have been an increasing number of passenger cars, SUVs and vans with diesel engine in Norway. The sale of big diesel-powered cars was accelerated when the Norwegian government changed the tax structure for new cars in favour of diesel from January 2007. The diesel share increased from 16 % in 2005 to 42 % in 2011. 64 % of new passenger cars in Norway had diesel engine in 2012. The upward trend is continuing in 2013 with more than 50 % diesel share from January to April.[6] From figures 1 - 5 it can be assumed that the effect of replacement of old gasoline cars, will be balanced by the higher NO_2-emission from new cars with diesel-engine until 2014. Euro 6 is expected to give stricter emission standards for diesel-powered cars with total weight under 1760 kg. However, after 2014 new vans and other heavy diesel powered vehicles will still have higher NO_2-emission than cars with gasoline engines.

1.3 Some observations of NO_2 in long Norwegian tunnels

The first exact measurements of NO_2 in tunnels were performed in the 7.5 km long Høyanger tunnel in 1994 and 1995[7]. This tunnel was opened in 1982 in a longitudinal ventilation system and automatic regulation of 28 impulse fans according to the CO-concentration at five different points. There were no permanent detectors for NO or NO_2 before the NOx-measurements started in 1994. NO_2-concentrations above 5 ppm were observed several times before the ventilation started at 50 ppm CO. The 50 ppm start parameter for CO had not been changed since the tunnel was opened in 1982. 50 % NO_2/NOx-volume ratios were observed due to oxidation of NO when the longitudinal air speed was low.

The 11.5 km long Gudvanga tunnel which was completed in 1992, had five NO-sensors to control the ventilation level during the first years. A sensor for NO_2 was installed in the middle of the tunnel for observation of the NO_2/NOx-ratio. The lower detection limit for NO_2 was about 0.5 ppm and the accuracy was assumed to be low compared with the NO-sensors. Therefore the NO_2-values were not used as parameters in the ventilation program during the first ten years of operation.

In 1992 it was assumed that the NO_2/NOx volume ratio would be approximately 10 % and the air quality should therefore be acceptable as long as the NO-level was kept below 10 ppm at the end of the tunnel. When the ventilation was running at constant speed, an average value of 5 ppm NO and about 0.5 ppm NO_2 should be expected in the middle of the tunnel.

However, alarms from the NO_2-sensor in the middle of the tunnel became more frequent every year. NO_2-values higher than 0.75 ppm were often observed early in the morning when

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[6] www.ofv.no.

[7] HSF-rapport 6/97: Luftkvalitet i Høyangertunnelen

there had been low traffic during the night and the levels of CO and NO were below the start parameters for the ventilation system. Sometimes the natural ventilation direction changed during the night, and a dense plug of NO_2-gas could appear in the middle of the tunnel before the fans started. About ten years ago when new NO_2-sensors with better accuracy and lower detection limit had been developed, all NO-sensors in the Gudvanga tunnel were exchanged with NO_2-sensors.

In the 24.5 km long Laerdal tunnel which was opened in 2000, NO and NO_2 are used as parameters for ventilation control. Oxidation of NO is giving a considerable growth in the NO_2-concentration in this tunnel, and the NO-limits have been set much lower than in any other tunnel in Norway in order to delay the oxidation process. Figure 6 and 7 illustrate the observed growth of NO_2 from a start-concentration of 8 ppm NO in December 2012.

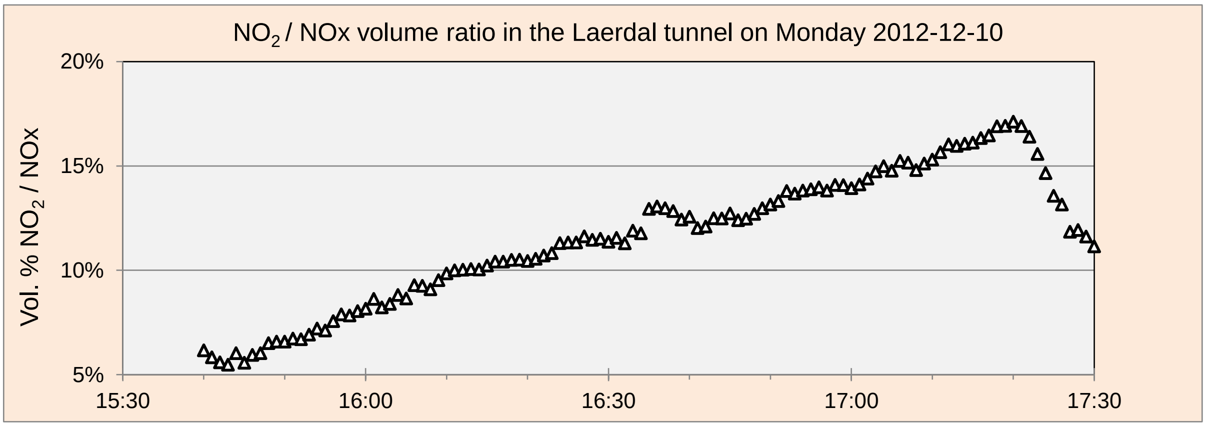

Figure 6: Observed NO_2 / NOx-ratio in the Laerdal tunnel in December 2012

Oxidation of NO was the main reason for the increase of NO_2/NOx volume ratio from 5 % at 15:45 to over 17 % one and a half hour later. Calculation of the NO_2-level from a start-concentration of 8 ppm NO is illustrated in figure 7. There is good compliance between the observed NO_2-values at three different points and the calculated values from NO-oxidation. The differences between observed and calculated NO_2-values were caused by variations in the air speed and new emissions from vehicles. More details from this incident are given in chapter 2.4.

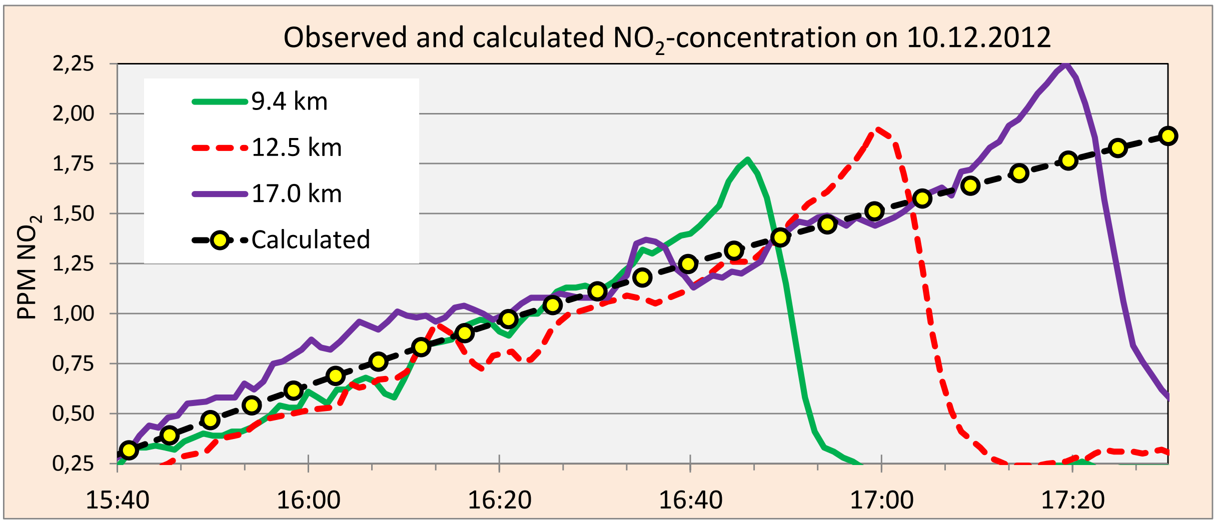

Figure 7: Observed and calculated NO-oxidation in the Laerdal tunnel

1.4 Nitrogen oxides (NOx)

Nitrogen dioxide (NO_2) is one of a group of highly reactive gasses known as oxides of nitrogen, or nitrogen oxides (NOx). Other nitrogen oxides include nitrous acid and nitric acid. The reddish-brown toxic NO_2-gas has a characteristic sharp, biting odor and is a prominent air pollutant from road traffic.

At temperatures above 21 ^{o}C ozone is produced directly by photolysis of NO_2 in bright sunlight (*hv*) where the NO_2-molecule is split and the excess energy is used to build an oxygen molecule with three atoms:

$$NO_2 + hv \rightarrow NO + O$$

$$O + O_2 \rightarrow O_3$$

Nitrous acid (HNO_2) is a weak and monobasic acid known only in solution and in the form of nitrite salts. In anything other than very dilute, cold solutions, nitrous acid rapidly decomposes into nitrogen dioxide, nitric oxide, and water:

$$2\ HNO_2 \rightarrow NO_2 + NO + H_2O$$

Nitric acid (HNO_3) is a highly corrosive and toxic strong acid. NO_2 decompose into nitric acid and nitrous acid in aqueous solution[8]:

$$2\ NO_2 + H_2O \rightarrow HNO_3 + HNO_2$$

Nitric oxide (NO) is the most common form of nitrogen oxides. Nitric oxide reacts with oxygen (O_2 and O_3) to form nitrogen dioxide (NO_2). The time required varies with the start concentration of NO in air as shown in figure 8:

NO concentration in air	**Time required for half NO to be oxidized to NO_2**	
(ppm)	(min)	(h)
10 000	0,35	0,006
1 000	3,5	0,06
100	35	0,58
10	350	5,8
1	3500	58
0.1	35000	25 days

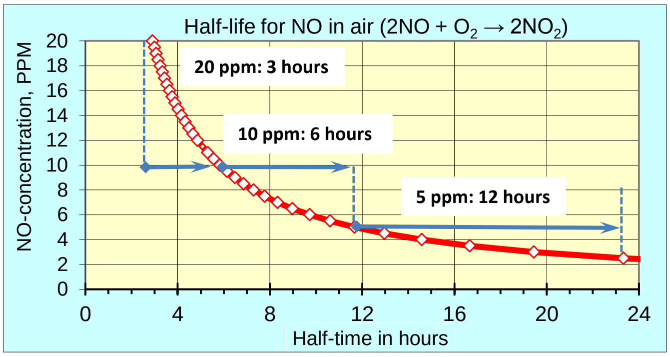

Figure 8: Time required for half NO in air

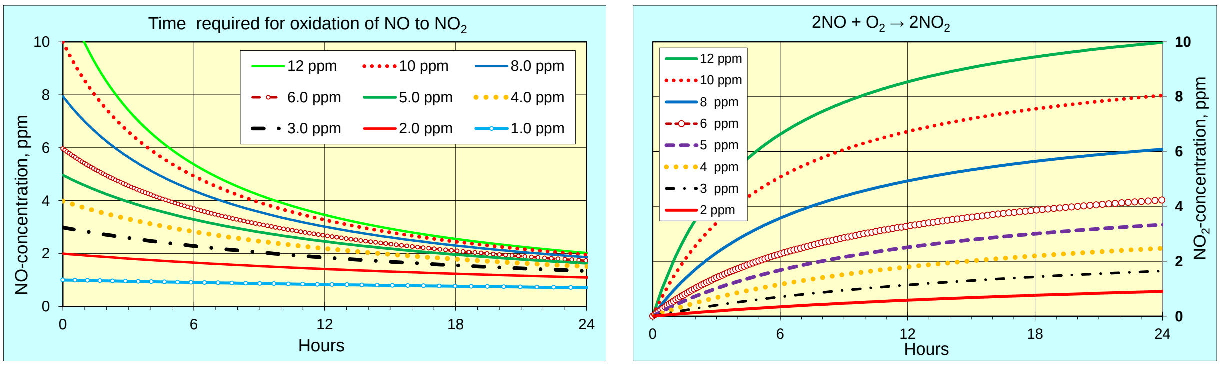

Figure 9: Calculated NO_2-production from oxidation of NO during 24 hours

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[8] Kameoka, Yohji; Pigford, Robert (February 1977): Absorption of Nitrogen Dioxide into Water, Sulfuric Acid, Sodium Hydroxide, and Alkaline Sodium Sulfite Aqueous.

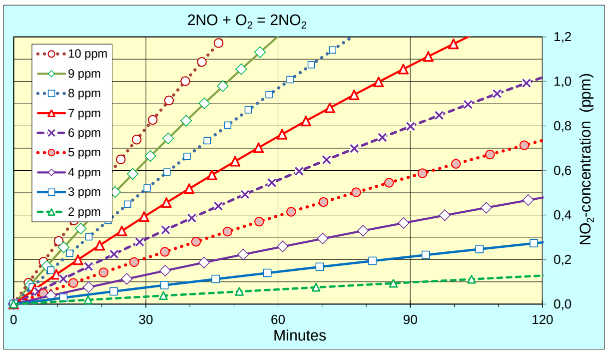

Figure 10: Calculated production of NO_2 from 2 – 10 ppm NO

Nitric oxide, NO	
Molecular weight (M)	30.006 g/mol[9]
Specific volume (V)	24.15483 l/mol
(1.013 bar and 21 °C)	0.805 m^3/kg
Nitrogen dioxide, NO_2	
Molecular weight (M)	46.05 g/mol
Specific volume (V)	23.5776 l/mol
(1.013 bar and 21 °C)	0.512 m^3/kg

The 16 gram difference in molecular weight between NO and NO_2 correspond with the extra oxygen atom in the NO_2 molecule. O_2 has a molecular weight of 31.9988 g/mol (~2 x 16).

Avogadro's law for ideal gases says that equal volumes of gases contain the same number of molecules at Standard Temperature and Pressure (STP). STP is defined as a condition of 100 kPa (1 bar) and 273.15 K (0 °C). For other temperatures and pressures than STP, the molar volume of ideal gases can be calculated by the ideal gas equation:

$pV = nRT$ where:

p = pressure (Pa)

V = molar volume (m^3)

n = the chemical amount of gas (mol)

R = Universal gas constant [8.3144621 $JK^{-1}mol^{-1}$]

T = Temperature (Kelvin)

The molar volume of an ideal gas at STP is 0.02271 m^3/mol (22.71 l/mol). The molar volume expands to 24.5 litres when the gas is heated to 21 °C. Nitrogen dioxide (NO_2) is far from an ideal gas at normal air temperatures in Norwegian tunnels. NO_2 is a liquid at all temperatures between the boiling point (21 °C) and the melting point (-11.2 °C).

The normal air temperature in Norwegian tunnels is below the condensation point (21 °C), and NO_2 is compressed 424 times a short distance from the exhaust pipe. Despite this fact, NO_2 is often regarded as an ideal gas for actual air temperatures in tunnels and the expression "NO_2/NOx volume ratio" is used in this report without any comments about liquid- or gas-phases. At low temperatures the NO_2-molecules in solid or liquid state must of course be heated to the boiling point in order to measure the gas-concentration as volume ratio NO_2/air in parts per million (ppm). Since oxygen and nitrogen also can be regarded as ideal gases at temperatures between -11°C and 21 °C, the calculated volume ratio NO_2/air will not change with variations in pressure or temperature.

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[9] www.encyclopedia.airliquide.com

1.5 Ozone (O_3) and oxides of nitrogen (NOx)

Ozone is a colourless and invisible gas, but often occurs along with oxides of nitrogen and particulate matters in urban areas where ozone is the primary ingredient of photochemical smog. Ozone is associated with extensive health effects, most notably associated with the respiratory system.

Under normal conditions the gas is unstable and thus very reactive and a powerful oxidant. Nitrogen dioxide is produced by a reaction between nitric oxide (NO) and ozone (O_3):

$$NO + O_3 \rightarrow NO_2 + O_2$$

The molecular weight of ozone is 46.05 g/mol which give the same gas density as nitrogen dioxide above 21.1 ^{o}C. At 1.013 bar and 21 ^{o}C the specific volume of O_3 is 0.519 m^3/kg. If there is a start-concentration of 50 µg/m_3 O_3 at the tunnel entrance and available NO-gas inside the tunnel, the equation above may produce 50 µg/m_3 NO_2 in addition to the NO_2-gas emitted from vehicles inside the tunnel.

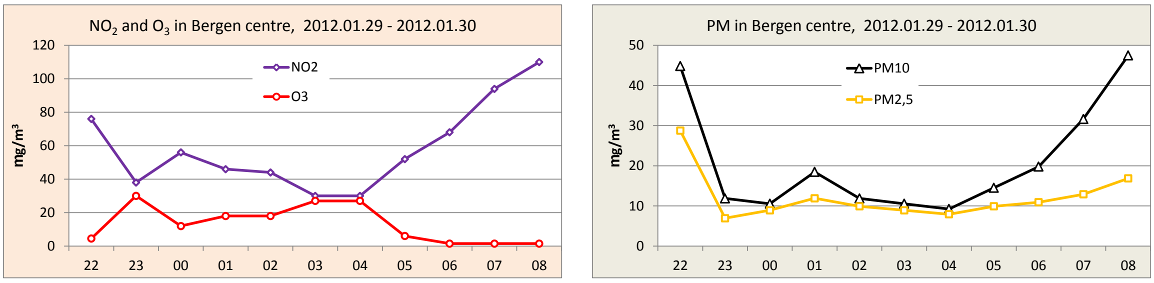

Figure 11: Nitrogen dioxide (NO_2), ozone (O_3) and particulate matters (PM) in January 2012

A normal drop in the NO_2-level in the Bergen area because of low traffic during the night, is illustrated in the left diagram in figure 13. The pollution of particulate matters was also low during night time on 29. January 2012. However, the ozone level rose quickly in the evening from near zero to 30 µg/m^3, and the relationship between the levels of ozone and nitrogen dioxide can be seen in the diagram. Nitric oxide from the first traffic in the morning gave a sudden drop in the ozone concentration.

At night time there is no ozone formation, and loss of ozone through NOx titration becomes the dominant process. The concentration of O_3 at night in urban centres is often lower than in the surrounding rural area for this reason[10]. The concentration of ozone is low in Norway during the winter months. High ozone levels are very rare when temperatures are below 20 ^{o}C. However, there are some exceptions caused by long transported air pollution.

The concentration of nitrogen dioxide, ozone and particulate matters with diameter less than 10 µm and 2.5 µm in the Bergen area at the end of January 2012 is illustrated in figure 12 on the next page. NO_2 produced from the reaction between NO and ozone is often referred to as background concentration of NO_2 at the tunnel entrance.

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[10] Sillman, S., The relation between ozone, NOx and hydrocarbons in urban and polluted rural environments. Millenial Review series, Atmos. Environ., 33, 12, 1821-1845, 1999.

Komponent: NO2 — Intervall: 72 timer

Komponent: NO2 — Intervall: 24 timer

Komponent: O3 — Intervall: 72 timer

Komponent: O3 — Intervall: 24 timer

Komponent: PM10 — Intervall: 72 timer

Komponent: PM10 — Intervall: 24 timer

Komponent: PM2.5 — Intervall: 72 timer

Komponent: PM2.5 — Intervall: 24 timer

Figure 12: Air quality in Bergen in January 2012 (www.luftkvalitet.info/)

1.6 Particulate matters (PM) and relative humidity (Rh)

There have been a gradually reduction of smoke particles in tunnels since the first Euro emission standards were entered into force. Since year 2000 visibility meters and dust detectors have been removed from several tunnels because NO_2 has become the dominant pollution factor to be used in the regulation of ventilation systems. The amount of particulate matters in tunnels varies with cleaning procedures in addition to traffic volume and speed. However, the most important factor is the amount of water vapour in the air which is expressed in terms of relative humidity (Rh). When it's raining or snowing outside, the cars are transporting water into the tunnel, and most of the road dust will stick to surfaces as long as the humidity inside the tunnel is high. In the winter season a gradual increase of the dust level has been observed in many tunnels after a period with rainy weather when the drying particles start moving with wind and turbulence forces caused by the vehicles. When the relative humidity falls below 60 %, the amount of dust particles (PM) is often 3 – 5 times higher than in rainy weather when the smallest dust particles from brakes, tyres and asphalt-wear may be stored inside the tunnel for several days.

In the afternoon of 31 January the PM_{10}-concentration near the city hall in Bergen reached 200 µg/m^3 which was the highest observed value in January 2012. Dry weather and road dust were the main contributors to the reduced city air quality that was observed several days this week at two different locations in Bergen city. The observed dust level in the Knappe tunnel was 4 – 5 times higher than the maximum level in the city centre.

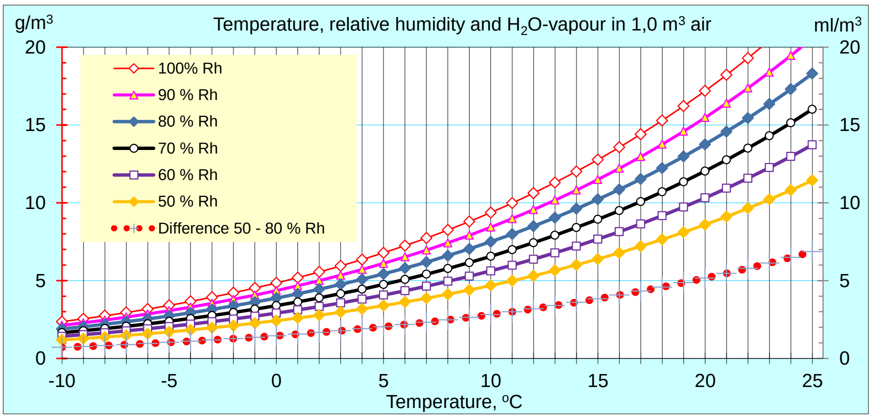

Figure 13: Relationship between relative humidity and temperature

The relationship between temperature and relative humidity is plotted in figure 13. The geothermal heat is lifting the temperature inside Norwegian tunnels during the winter. The airstream in the north direction of the Knappe tunnel is also heated by the natural compression caused by the downward gradient from Dolvik. The 600 Pa pressure difference between the tunnel entrance and the deepest point in this tunnel is giving about 0.6 % compression and 0.3 °C natural temperature difference between Dolvik and the deepest point in the tunnel.

When there is no rain or snow outside, the moisture in the exhaust is too low to compensate for the drying effect from higher temperatures, and the relative humidity in the tunnel will change according to the curves in figure 13.

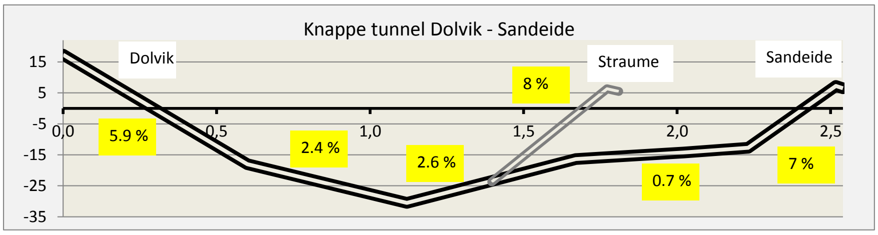

Figure 14: Length profile of the Knappe tunnel in Bergen

(Dolvik – Sandeide = "north direction")

1.7 Diesel Particulate Filters (DPF) and NO_2/NOx-ratio

Diesel particulate filter is a generic terms used to describe systems which reduce particulate matter in diesel engine exhaust emissions. There are several categories of DPFs known as Particulate trap (RT), continuously regenerated traps (CRTs), catalyzed continuously regenerated traps (CCRTs) or catalysed DPFs (CDPF). The first generation of DPFs were passive filters where all visible smoke and soot particles with a diameter above 2.5 µm (PM10) were collected. These filters have no effect on the smallest and most harmful particles to human health which have been linked to lung ailments, cancer and heart disease. The smallest particles are often referred to as $PM_{2.5}$ which means particulate matters smaller than 2.5 µm[11].

From 1997 to 2003 there was a statistically significant downward trend in NOx, averaged across a network of 36 sites in London. In the same period the NO_2/NOx volume ratio increased from 5 – 6 % to about 17 %. 8000 buses in London were fitted with DPFs from 1999 to 2006[12]. A higher share of diesel-powered cars in the same period has also been regarded as an explanation for the high NO_2/NOx-ratio in London compared with other cities in Europe.

The DPF has to be regularly cleaned or regenerated by driving at high rpm in order to rise the temperature above the ignition temperature for soot and burn off the collected particles. About ten minutes is needed for a complete regeneration in ordinary cross-country driving. The burning of particles will create CO_2 and a small amount of ash which will remain inside the filter. The regeneration of passive filters without a catalyst has no effect on nitric oxides (NO) or nitrogen dioxides (NO_2).

The automatic regeneration of the filter will be interrupted if the motor is stopped or if the exhaust temperature should fall under the ignition temperature for the collected soot particles (> 500 ^oC). The exhaust temperature varies with driving conditions and will fall during long down-hill descents (mountain roads and sub-sea tunnels), frequent driving in the low-load range (congested traffic, idling at traffic lights and also in ordinary low speed city traffic).

Regeneration of active filters is started automatically by the system's control unit when the pressure loss through the filter has reached a certain limit. Specific measures are taken to rise the filter temperature above 550 – 600 ^oC for 5 – 10 minutes. If the regeneration process is interrupted by the driver, the control unit will start the process again on the next tour.

The new generation of DPFs are removing more of the smallest and most dangerous particles from the exhaust. Ceramic wall-flow filters remove almost completely the carbon particulates, including fine particulates less than 100 nanometre[13] diameter with an efficiency of 95 % in mass and 99 % in number of particles over a wide range of engine operating conditions. The soot trapped in the filter must be regularly burnt to clean or regenerate the filter. Almost all active filter regeneration techniques operate by raising the temperature of the filter to around 600 °C. An exhaust gas temperature of approximately 550 °C is needed to start the combustion.

The catalytic converters, which following the EURO 2 standard, became mandatory in 1996 on light duty diesel vehicles, are using NO_2 to regenerate the filter. Unfortunately, this has led to significant increase in NO_2 emissions from new diesel-powered cars during the last years.

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[11] 1 µm = 1/1000 mm = 1000 nm (nanometer)

[12] David C. Carslaw: Evidence of an increasing NO_2/NOx emission ratio from road traffic emissions (Atmospheric Environment, vol, 39, 2005)

[13] 100 nanometer (nm) = 0,1 mikrometer (µm), 1 µm = 1/1000 mm

Regeneration of filter with oxygen:	$C + O_2 \rightarrow CO_2$
Production of NO_2 by catalyst:	$2NO + O_2 \rightarrow 2NO_2$
Regeneration with NO_2:	$2C + 2NO_2 \rightarrow N_2 + 2CO_2$

The amount of available oxygen varies with driving condition and motor load. The regeneration process becomes more effective with nitrogen dioxide because NO_2 is a more effective oxidizer than oxygen. If the exhaust gases have an ideal balance between particles and NOx, no harmful nitrous gases should be emitted. However, this is only possible in the laboratory. At normal driving conditions there is a surplus of NO_2-gas emitted to the outside air. Therefore a higher NO_2/NOx-ratio should be expected from diesel-powered cars with catalysed DPFs because of the surplus NO_2 from the catalyst and the reduced volume of NO-gas.

Selective Catalytic Reduction (SCR) is now fitted to new heavy-duty diesel engines in Europe[14]. The efficiency of SCR for NOx reduction also offers a benefit for fuel consumption. It allows diesel engine developers to take advantage of the trade-off between NOx, PM and fuel consumption and calibrate the engine in a lower area of fuel consumption than if they had to reduce NOx by engine measures alone. Particulate emissions are also lowered, and SCR catalytic converters can be used alone or in combination with a particulate filter.

In the SCR system, ammonia is used as a selective reductant, in the presence of excess oxygen, to convert over 70 % (up to 95 %) of NO and NO_2 to nitrogen over a special catalyst system. Different precursors of ammonia can be used; one of the most common options is a solution of urea in water (e.g. AdBlue®[15]) carefully metered from a separate tank and sprayed into the exhaust system where it hydrolyses into ammonia ahead of the SCR catalyst. The consumption of AdBlue® is typically 3 - 4 % of the fuel consumption for an Euro IV engine, and 5 - 7 % for an Euro V engine, depending on driving, load and road conditions.

1.8 NO_2-sensors, measurement principles and detection limits

When the 24.5 km long Laerdal tunnel was opened in 2000, the air quality was monitored by means of nine electrochemical diffusion NO-sensors and two NO_2-sensors from Dräger.

Product data for new sensors for Polytron 7000 (at 20 °C, 50 % RH and 1013 mb)	NO_2	NO
Standard measuring range:	10 ppm	50 ppm
Lower detection limit:	0.3 ppm	3 ppm
Uncertainty of measured value uncertainty minimum	± 5 % ± 0.1 ppm.	± 4 % ± 1.0 ppm.
Calibration interval:	6 months	6 months

The NO- and NO_2-sensors were tested in the Laerdal tunnel together with a precision instrument during four days in September 2007. This test gave new knowledge about the accuracy and the real measuring range of the Dräger sensors.

The API M200A NOx analyzer used in the test, is designed to measure the concentration of nitric oxide (NO), total oxides of nitrogen (NOx) and, by calculation, nitrogen dioxide (NO_2).

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[14] http://www.aecc.be/en/Technology/Catalysts.html

[15] AdBlue® is a solution of 32.5 % Urea in deionized water. Urea, chemical formula (NH2)2CO, is also known as a fertilizer

The instrument measures the light intensity of the cheminiluminiscent gas phase reaction of nitric oxide and ozone (O_3) as follows:

$$NO + O3 \rightarrow NO_2^* + O_2$$

$$NO_2^* \rightarrow NO_2 + hv$$

The reaction of NO with ozone results in electronically excited NO_2 molecules as shown in the first equation above. The excited NO_2 molecules release their excess energy by emitting a photon and dropping to a lower energy level as shown in the second equation. It has been shown that the light intensity produced is directly proportional to the NO concentration present. The analyzer samples the gas stream and measures the NO concentration by digitizing the signal from the analyzer's photomultiplier tube. A valve then routes the sample stream through a converter containing heated molybdenum to reduce any NO_2 present to NO. The analyzer now measures the total NOx concentration. The NO_2 concentration is found by subtracting the NO and NOx values from each other. The instrument has a lower detectable limit of 0.4 ppb (0.0004 ppm) and a precision of 0.5 % of reading. The instrument was calibrated for a maximum value of 1000 ppb (1 ppm) NO_2 before the test started.

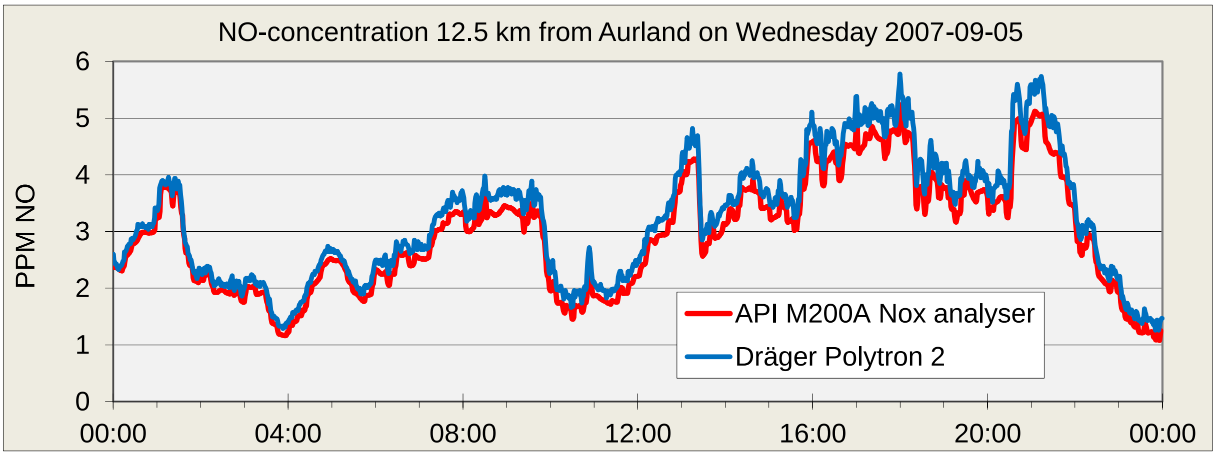

Figure 15: Comparison of NO-values from a Dräger sensor with values from a precision instrument

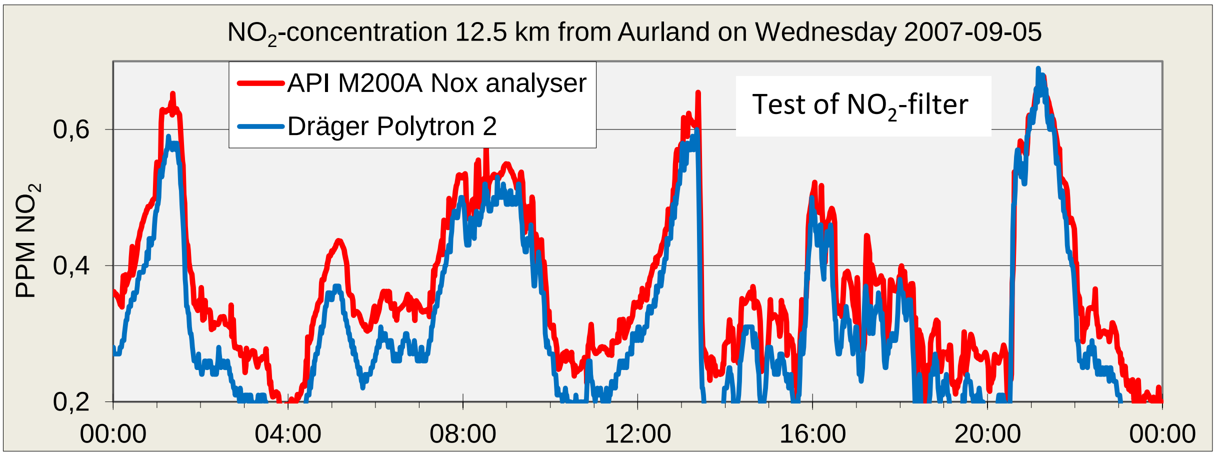

Figure 16: Comparison of NO_2 values from a Dräger sensor and a precision instrument

One sample per minute is plotted in figures 15 and 16. The average NO-values during 24 hours were 0.26 ppm higher from the Dräeger sensor than the calculated NO-values from the API-analyzer. The 24 hour average NO_2–level from the Dräeger sensor was 0.08 ppm lower than the API-values during the same period.

Calculated values for NO_2/NOx volume ratio for Wednesday and Thursday are plotted in figure 17. NO_2-values below 0.25 ppm from the Dräeger sensor were excludes from the calculation. The average difference between the two curves is 2.0 %.

It looks like the major part of this difference between the two instruments was caused by an inaccurate zero-point-calibration of the Dräeger-sensors. All sensors are calibrated with new gas every year, and it is assumed that the accuracy has been improved after 2007.

The NO-curves in figure 15 have a sudden drop from 5 ppm to 3 ppm about 13:00. At the same time the NO_2-level was reduced from 0.65 to 0.25 ppm. This reduction was caused by activating the NO_2-filter which is located 9.4 km from Aurland. The filter gave about 5 % reduction of the NO_2/NOx volume ratio in the middle of the tunnel [16].

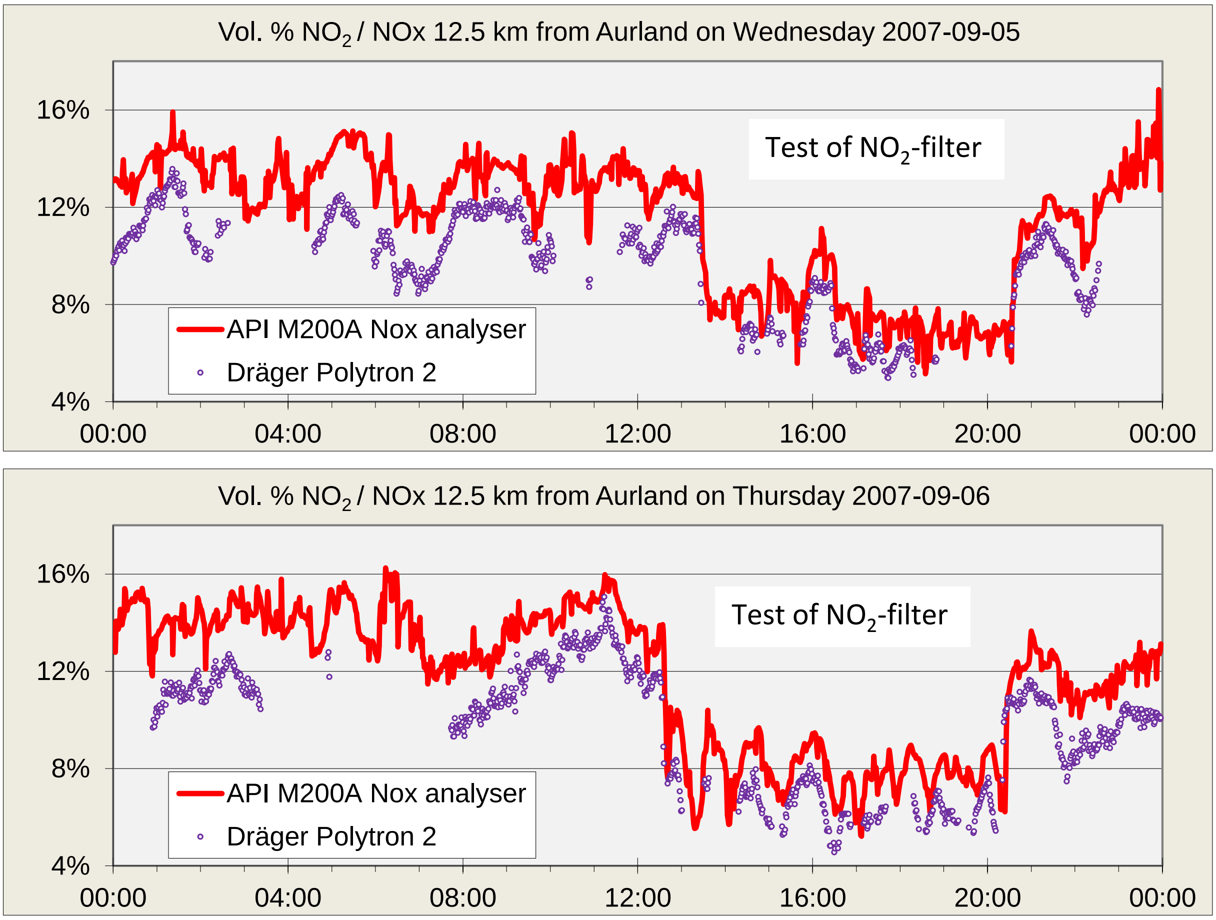

Figure 17: Calculated NO_2 / NOx volume ratios from two instruments

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[16] Statens vegvesen: E16 Lærdalstunnelen. Kontroll av luftkvalitet og energibruk (2007-10-24)

2 Observations of NO_2 / NOx volume ratio in the Laerdal tunnel

2.1 The ventilation system

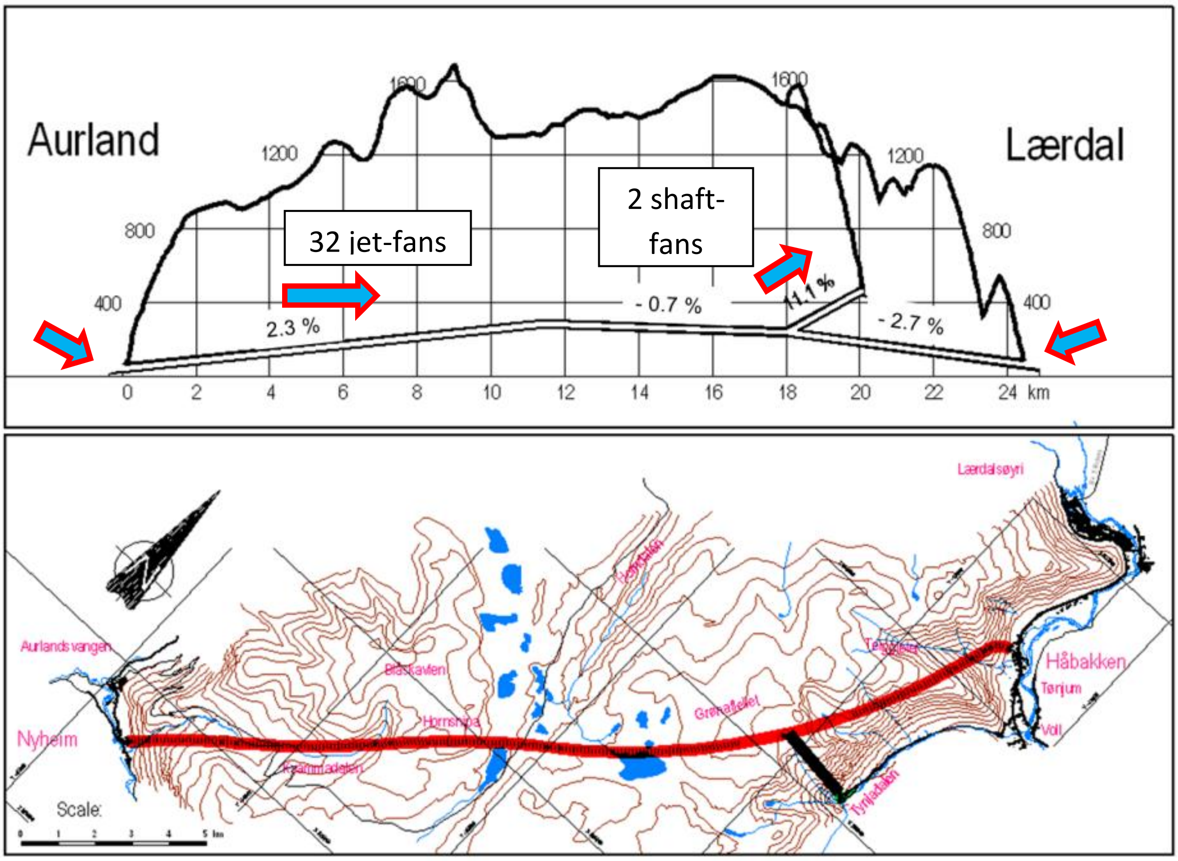

Figure 18: Ventilation principle in the Laerdal tunnel

The longitudinal ventilation system in the Laerdal tunnel is illustrated in figure 18. The 24.5 km long tunnel is divided into two ventilation sections by a ventilation tunnel 18 km from the Aurland portal. Two shaft fans with a total capacity of 500 m^3/sec are extracting polluted air through the ventilation tunnel.

The ventilation system is regulated in four levels. Values from nine NO-sensors and two NO_2-sensors were used in 2007:

Ventilation level	Start-parameter		Speed of shaft fans	Number of jet-fans	Air velocity from Aurland	Air velocity from Laerdal
	NO	NO_2				
1	4 ppm	0,7 ppm	350 rpm	0	1.0 m/s	2.5 m/s
2	6 ppm	0,9 ppm	550 rpm	6	2.0 m/s	3.5 m/s
3	9 ppm	1,2 ppm	750 rpm	16	3.0 m/s	4.5 m/s
4	15 ppm	1,5 ppm	990 rpm	32	4.5 m/s	5,5 m/s

The ventilation tunnel has a gradient of 11.1 % which is giving a considerable chimney-effect during the winter and in other periods when the outside air temperature is below 10 - 15 ^{o}C.

Fresh air from both portals is heated by the surrounding rock which has a constant temperature of 17 °C in the middle of the tunnel. The natural ventilation forces caused by the 400 m height difference between the tunnel portals and the outlet of the ventilation tunnel, are giving sufficient ventilation in periods with low traffic from September to May.

There are great variations in the air velocity from Aurland and Laerdal depending on the number of vehicles driving in each direction. A group of heavy duty vehicles driving in the south direction, will reduce the air velocity from Aurland, and the air may sometimes move in the opposite direction at low ventilation levels. Figure 19 show great variations in the natural ventilation on a Sunday in August 2007 before the fans started after 12:00. The negative parts of the velocity curve were caused by the piston-effect from vehicles. Negative air velocity was also observed a few minutes in the evening when the shaft fans were running at low speed.

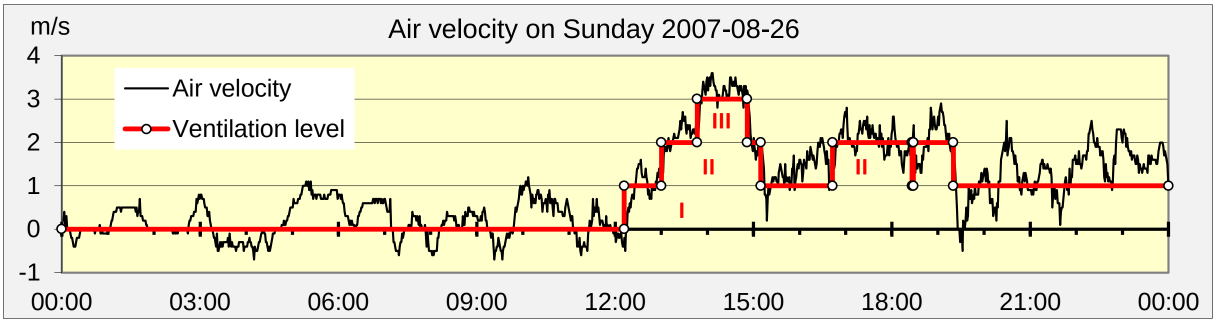

Figure 19: Example of natural ventilation during 12 hours before the fans started

2.2 Observations of NO and NO_2 in September 2007 and 2008

The concentration of NO and NO_2 was measured every minute in the Laerdal tunnel during five weeks in August – September 2007. The concentration of NO_2 was measured at two points in week no. 33 - 34 and at three points from week no. 35 - 37. NO_2/NOx volume ratios were calculated from the observations at 9.4 km, 12.5 km and 17 km from Aurland. The values from 08:00 to 20:00 were used in the calculation of a daily average concentration of NO, NO_2 and a daily average NO_2/NOx volume ratio. NO-values below 1.0 ppm and NO_2-values below 0.2 ppm were excluded from the calculation of NO_2/NOx-ratio because of the unknown accuracy of these values.

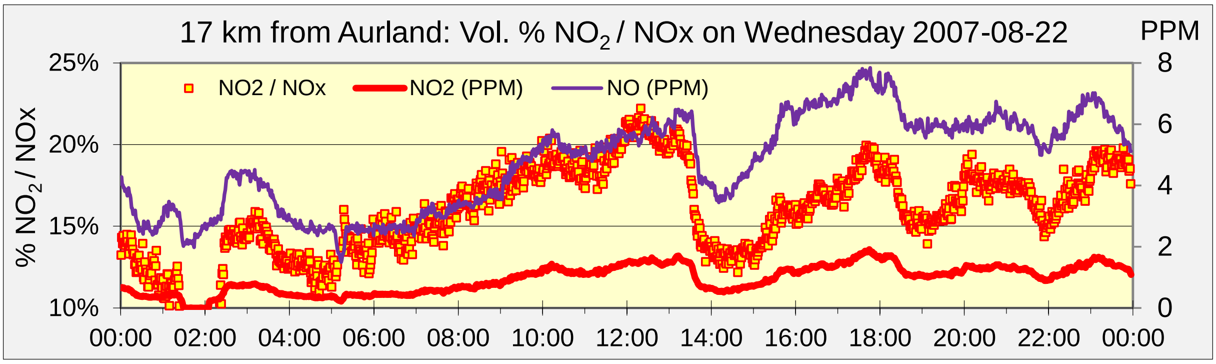

Figure 20: Example of growth of NO_2 / NOx volume ratio in the morning before the fans started

High NO_2-production should be expected in the Laerdal tunnel from figures 8 - 10 in chapter 1.4 because of the long ventilation section from Aurland and long periods with low air velocity. If the ventilation fans are turned off in the evening with 3 ppm NO in the air and 10 vol. % NO_2/NOx and it takes more than six hours to ventilate the tunnel, we can expect NO_2-concentrations above 1.0 ppm in the morning without any contribution from traffic during the night.

Start of ventilation during the night because of high NO_2-concentration was observed several times in 2007. An example of night ventilation because of NO-oxidation is given in figure 21. The fans started because of 0.75 ppm NO_2 at the sensor 17.5 km from Aurland when the night traffic was less than 20 vehicles/hour. Examples of high NO_2/NOx-ratios at low ventilation levels in the afternoon are given in figures 22 and 23 on the next page.

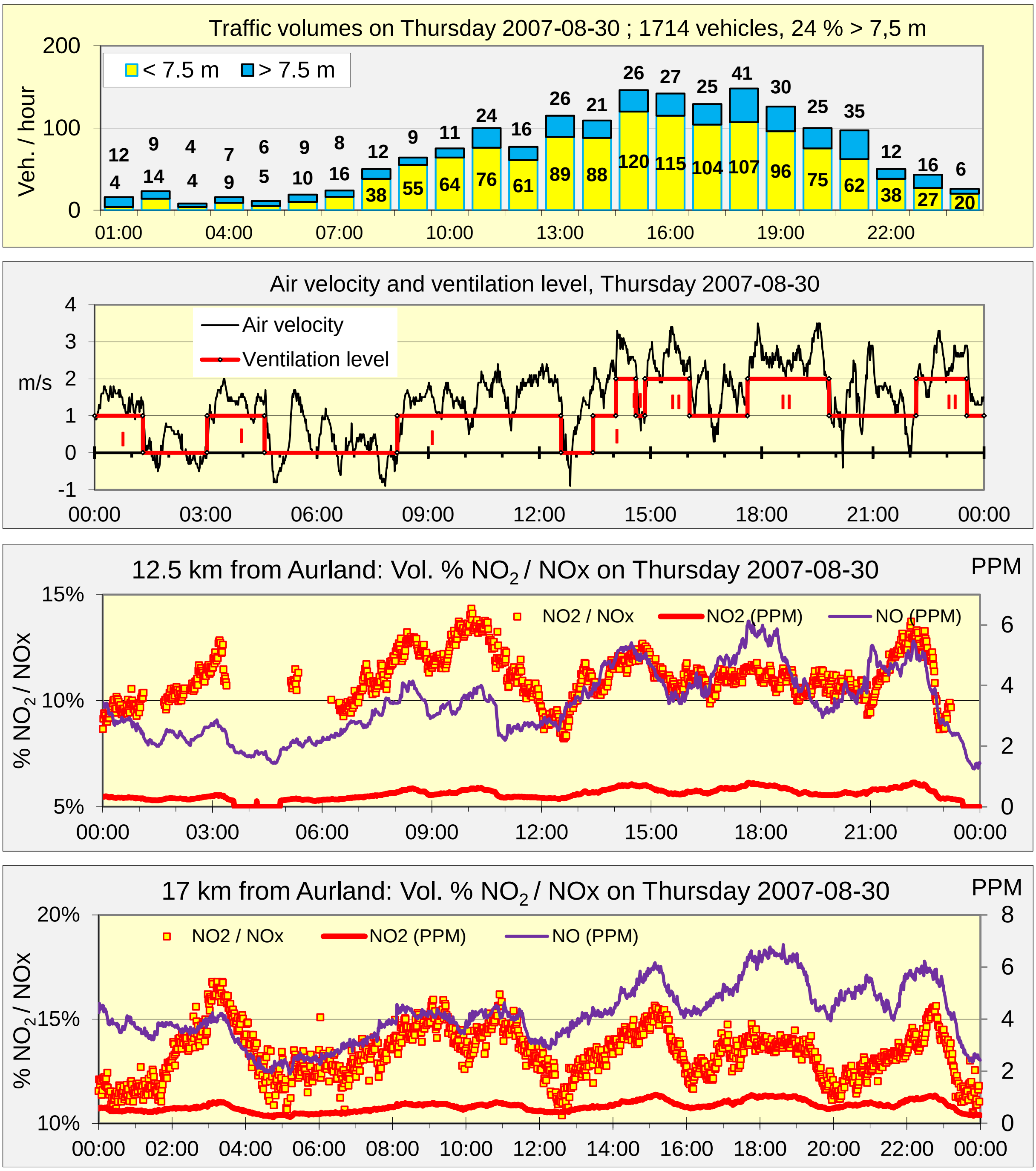

Figure 21: Example of low night traffic and start of ventilation at 03:00 because of NO-oxidation

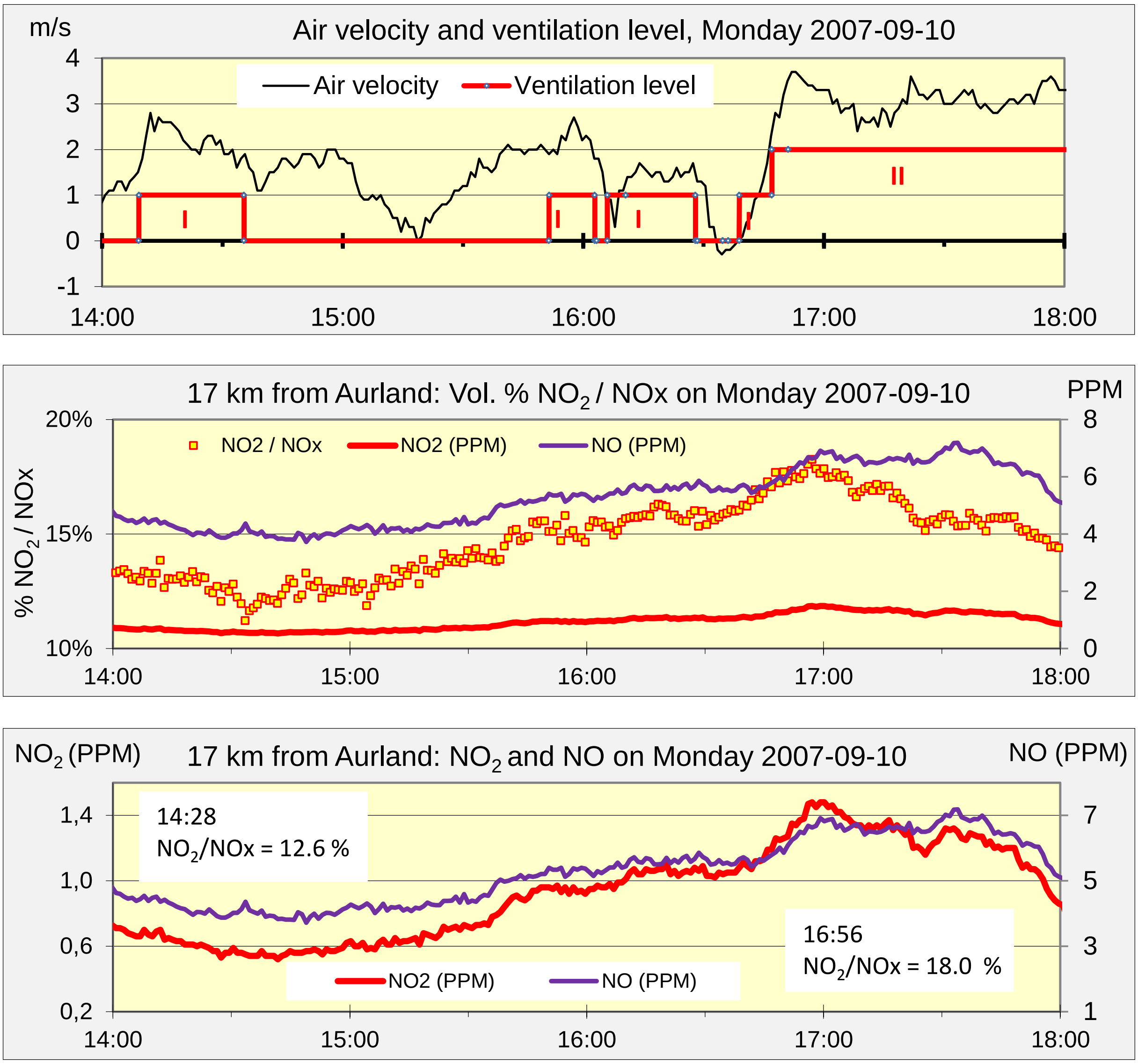

Figure 22: Example of low ventilation level and high NO_2 / NOx volume ratio on Monday afternoon

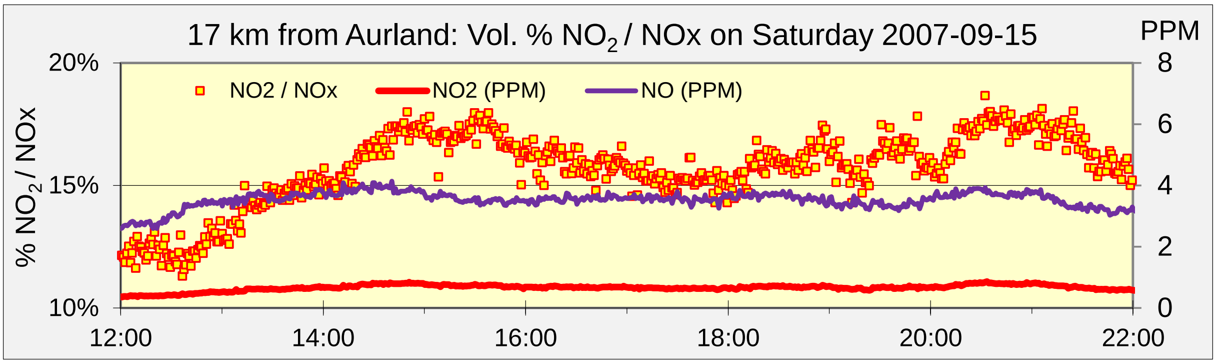

Figure 23: Example of high NO_2 / NOx volume ratio on Saturday afternoon

The NO-concentration on Saturdays is often low because of reduced traffic of heavy duty vehicles in the week-ends. A low ventilation level is giving a higher production of NO_2 from oxidation of NO. The average transport time for fresh air from Aurland to the shaft fans at 18 km was 2 hours and 40 minutes between 11:00 and 21:00 on Monday in week no. 37 (average air velocity: 1.9 m/s). The average air velocity was reduced to 0.9 m/s and the time for oxidation of NO was lengthened to more than five hours on Saturday.

Trend-curves for average NO- and NO_2-concentration from Monday to Thursday are plotted in figure 24. The gradient of the NO-curve is declining in the upper part, and the oxidation product is making a gradually steeper NO_2-curve.

The average values on Sundays in 2007 were different from the first five days in the week. The difference was explained by the high proportion of heavy duty vehicles from Monday to Friday. The measurements were repeated in three weeks with similar traffic conditions in August – September in 2008.

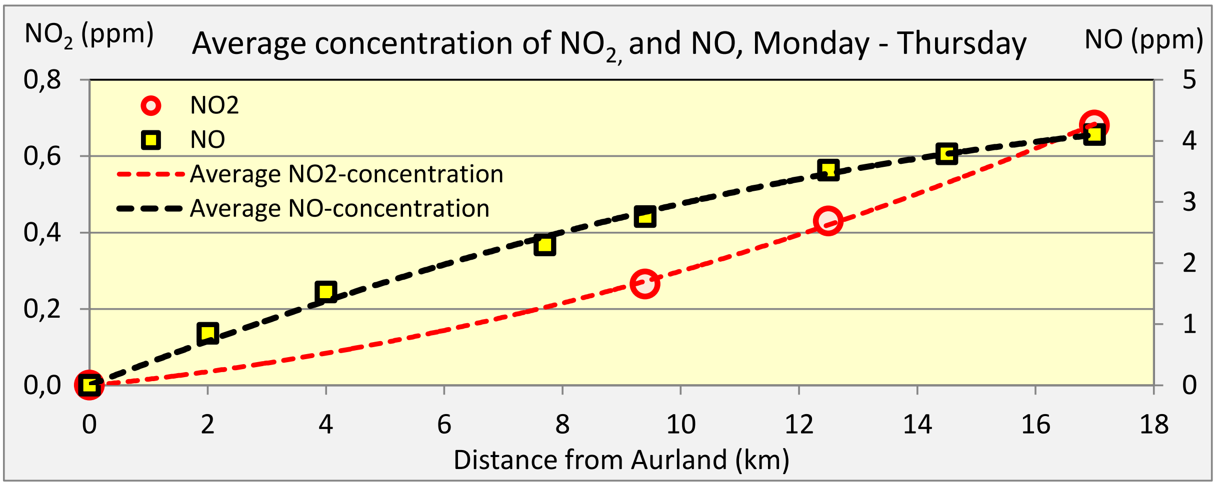

Figure 24: Average concentration of NO_2 and NO in week no. 37 in 2007

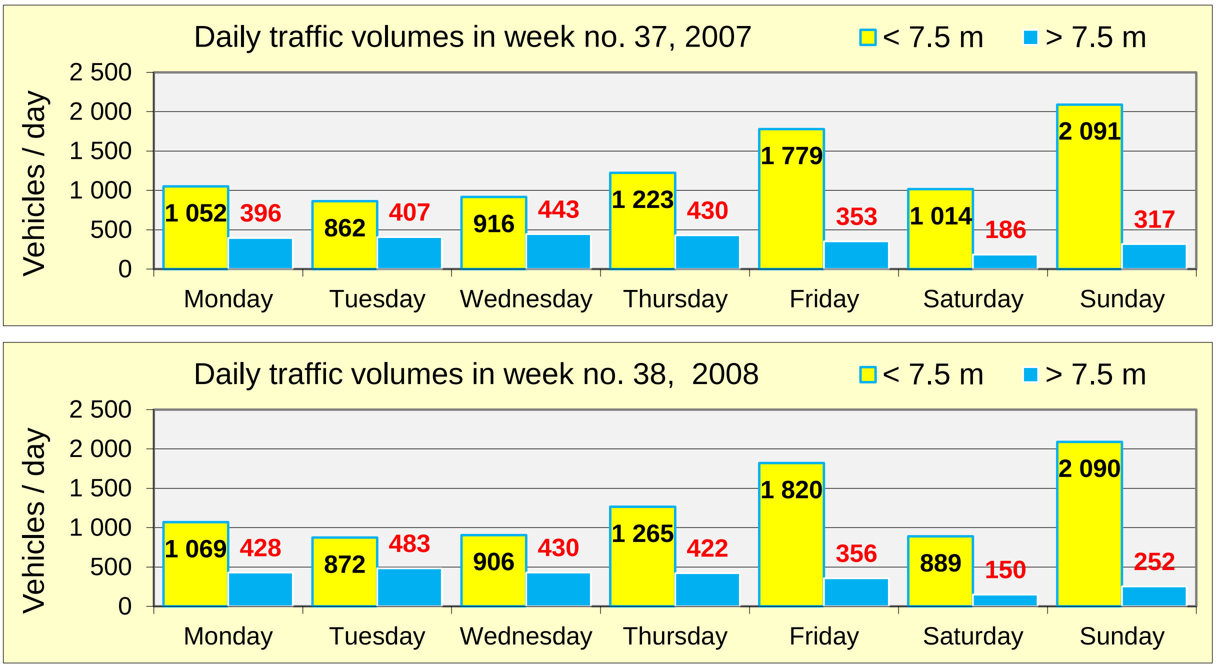

Figure 25: Daily traffic in week no. 37 in 2007 and week no. 38 in 2008

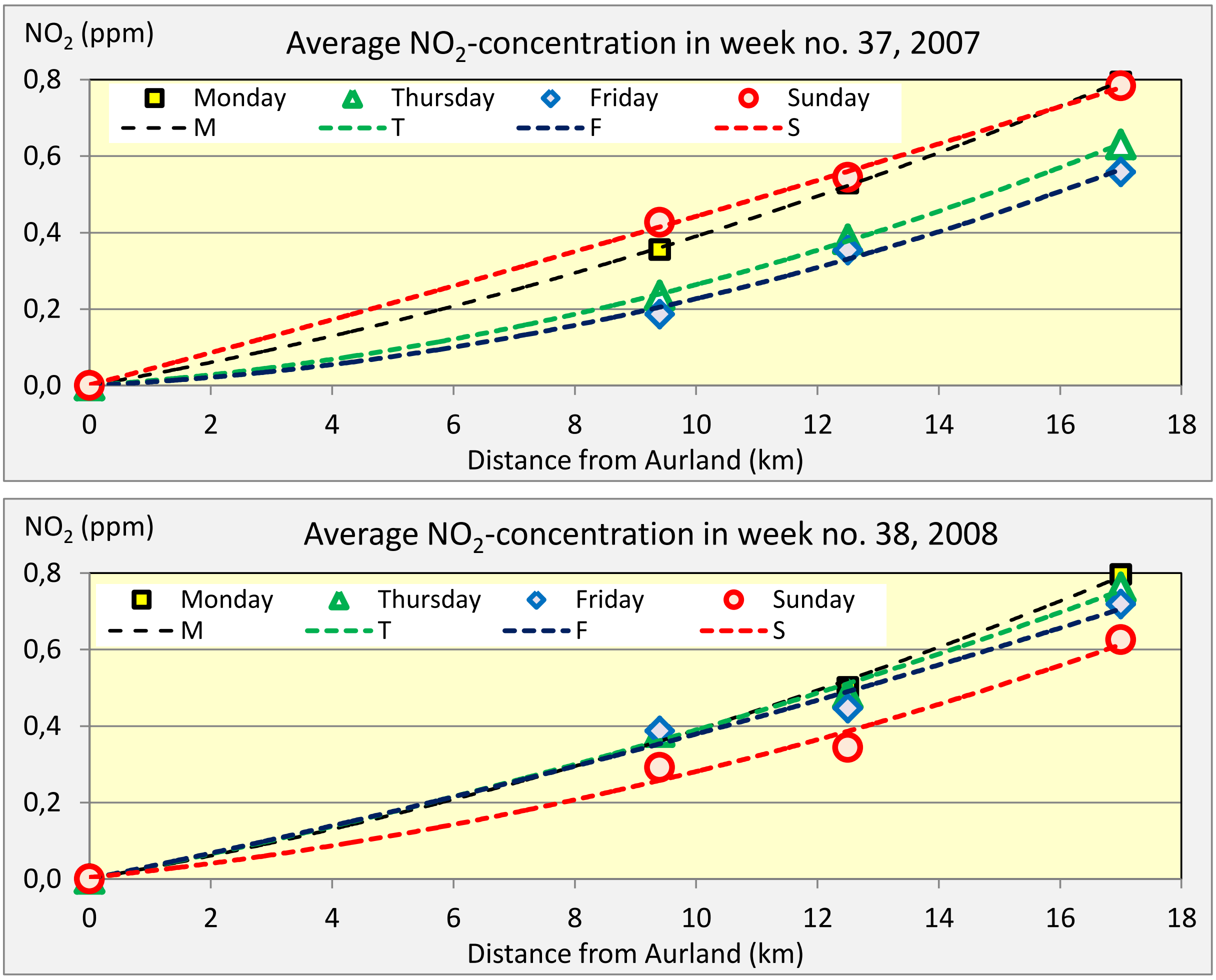

Figure 26: Average concentration of NO$_2$ in week no. 37 in 2007 and week no. 38 in 2008

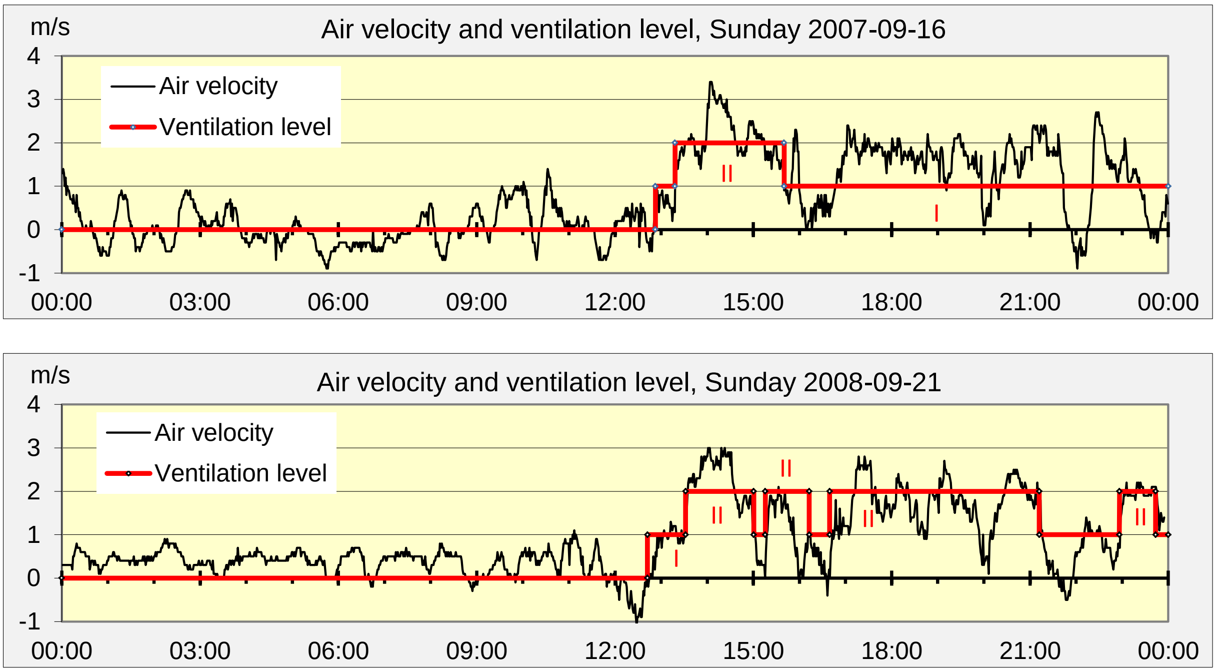

Figure 27: Ventilation level and air velocity from Aurland on a Sunday in September 2007 and 2008

Week-end traffic in the south direction on Sunday afternoon reduces the air velocity from Aurland. On some occasions in 2007 the NO_2-concentrations exceeded the upper threshold limit (0.75 ppm) in the middle of the tunnel. Therefore the start-parameter for NO_2 was reduced from 0.7 ppm to 0.4 ppm in 2008. Earlier start of ventilation gave only small changes in the average air quality from Monday to Friday. However, the average NO_2-concentration on Sunday was reduced by 0.2 ppm in week no. 38 in 2008 compared with the average level in week no. 37 in the previous year. There was also a significant reduction of the NO-concentration on Sundays in 2008 compared with days with similar traffic in 2007. The average NO-concentrations in week no 37 in 2007 and week no 38 in 2008 are plotted in figure 28.

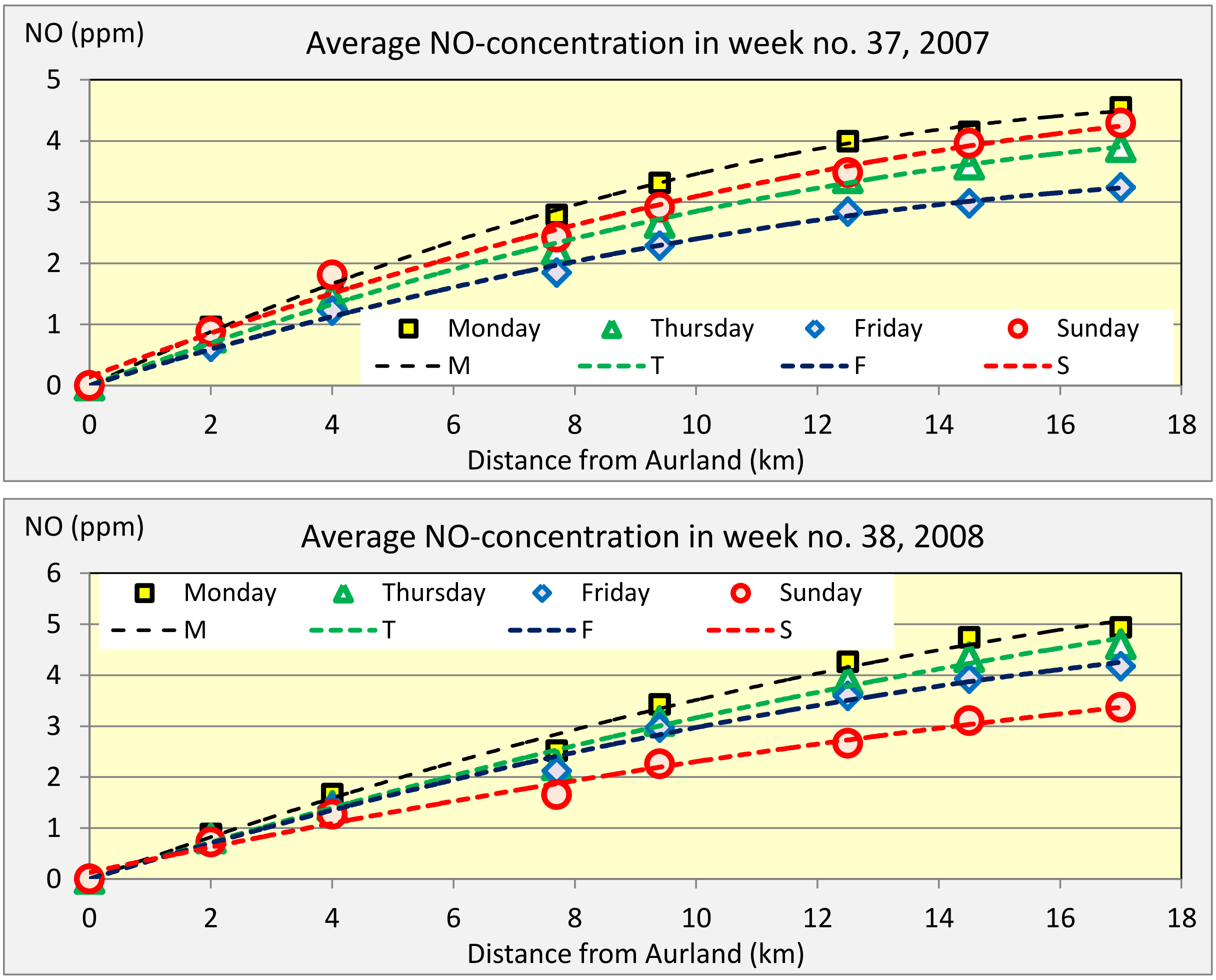

Figure 28: Average concentration of NO in week no. 37 in 2007 and week no. 38 in 2008

Calculated NO_2/NOx volume ratios 9.4 km and 17 km from Aurland are plotted in figures 29 and 30 on the next page. The highest values in both years were observed from Friday afternoon to Sunday, and it is obvious that there is a great difference in the chemical composition of the exhaust gases from passenger cars and heavy duty vehicles. From the lowest values at 9.4 km from Monday to Friday, we can conclude that some heavy duty vehicles were producing NOx with about 6 % NO_2 in 2007. The NO_2/NOx volume ratio increased to over 15 % in periods with weekend-traffic of passenger cars and low numbers of heavy duty vehicles. There were small changes of the average values from 2007 to 2008. However, there was a significant change of the highest values each day in the week. The most likely explanation for the higher values at 9.4 km in 2008 is the increased number of diesel-powered passenger cars.

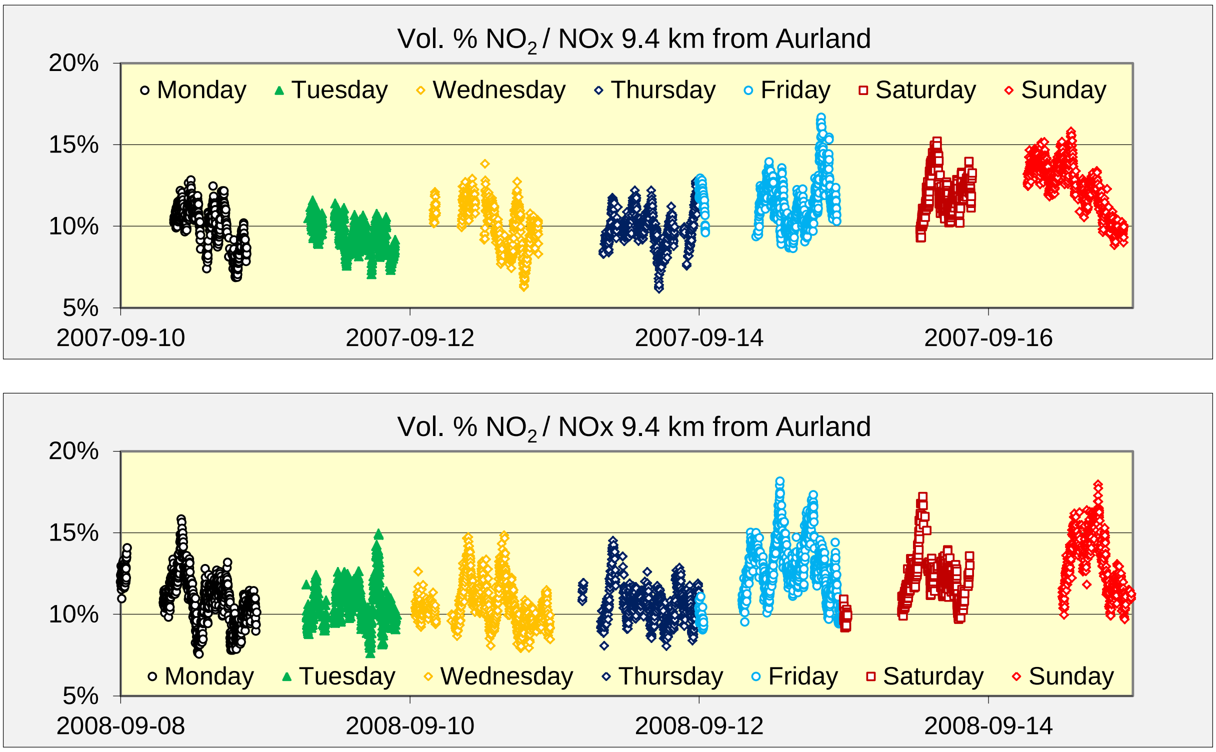

Figure 29: NO_2 / NOx volume ratio at 9.4 km in week no. 37 in 2007 and week no. 38 in 2008

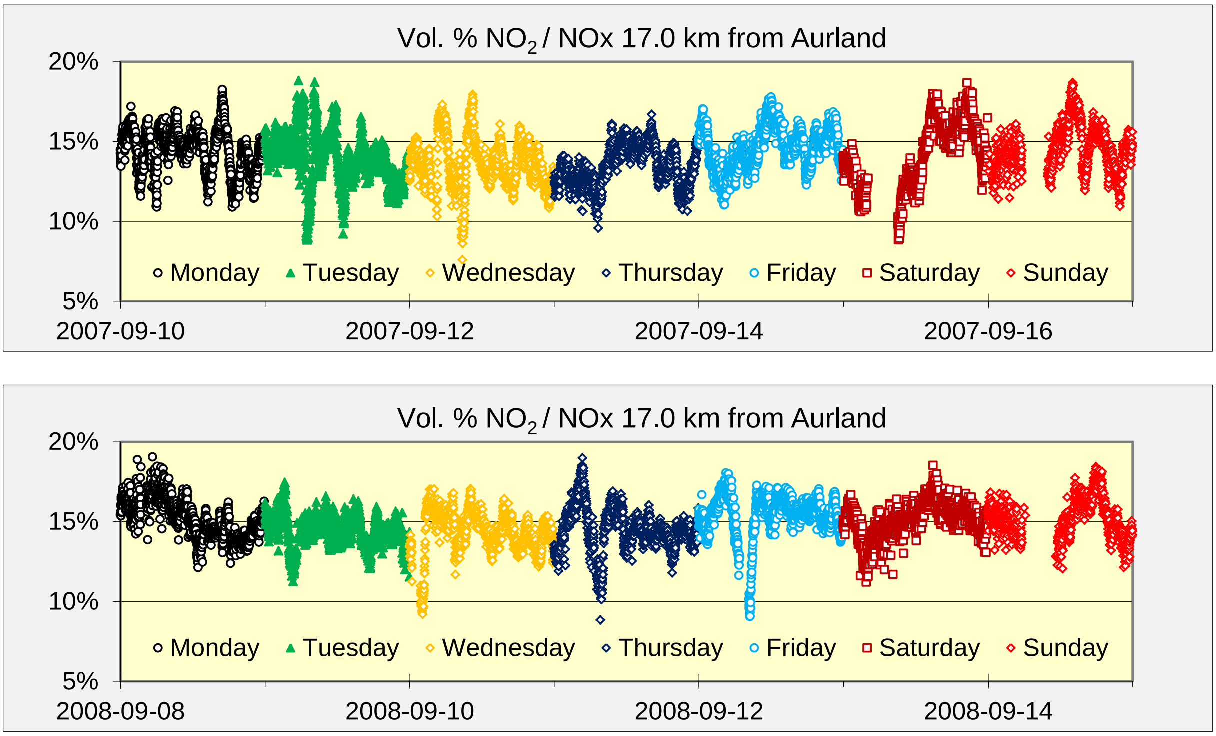

Figure 30: NO_2 / NOx volume ratio at 17 km in week no. 37 in 2007 and week no. 38 in 2008

Observations of NO and NO_2 on Monday and Sunday in week no. 37 in 2007 are plotted in figure 31 and 32 with ten times difference in the vertical scales. The NO- and NO_2-curves are close at 9.4 km with NO_2/NOx volume ratios between 8 % and 12 %. From 9.4 km to 17 km the NO_2-concentration is increasing much faster than NO. It has been assumed that oxidation of NO is the main reason. However, a higher NO_2-emission between 12.5 km and 17 km because of different vertical alignment before and after 12.5 km could be another possible explanation. Se comments about the observed effect of vertical alignment in the Laerdal tunnel in chapter 2.4.

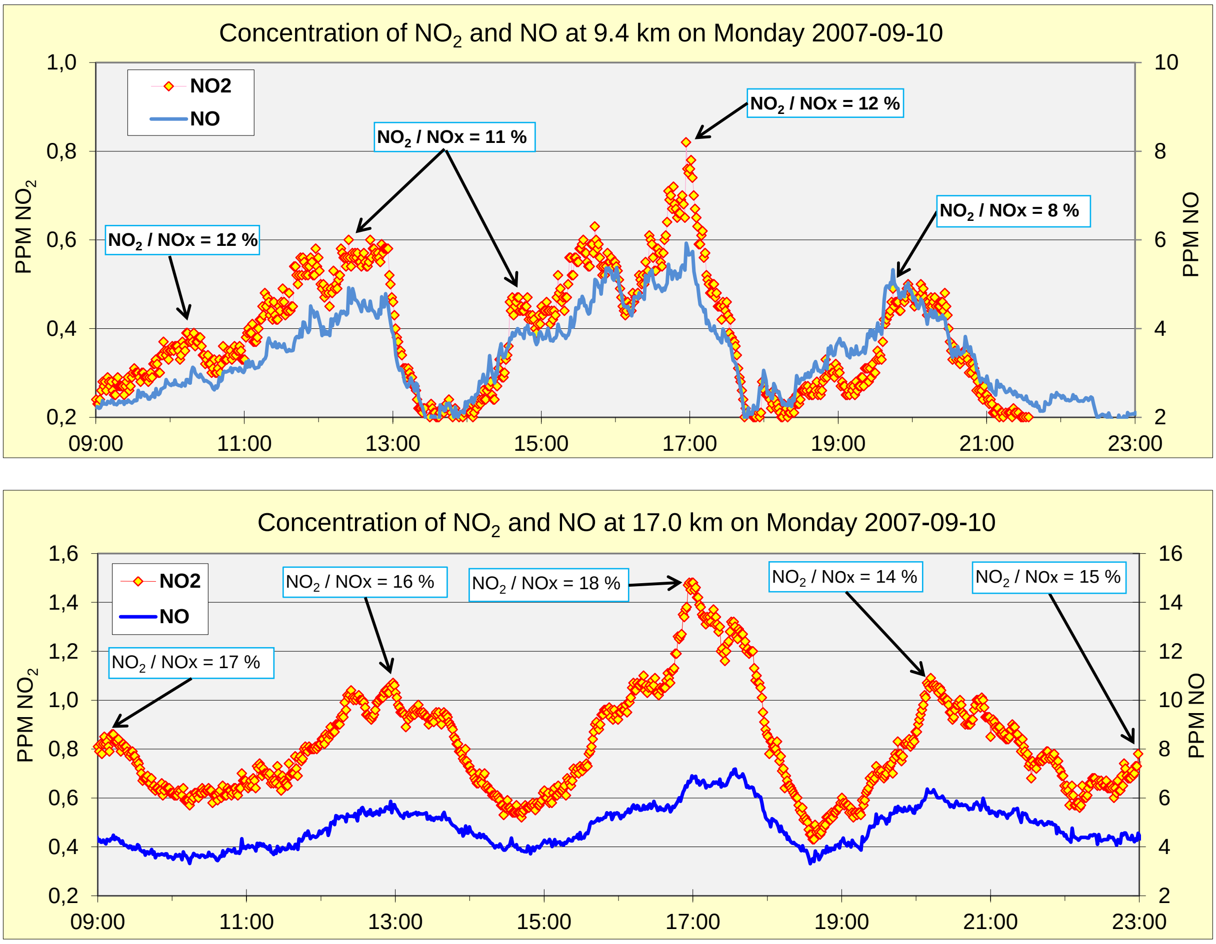

Figure 31: NO_2 and NO concentration 9.4 km and 17 km from Aurland on Monday 2007-09-10

The high NO_2/NOx volume ratio on Sunday morning at 9.4 km in figure 32, were caused by little traffic and low air velocity before the fans started at 12:00. A few hours later the Sunday values were reduced to near 12 % at 9.4 km and 15 % at 17 km.

The average values for each day in the week are plotted in figure 33 and 34. There were only small variations around 10 % from Monday to Thursday at the sensors located 9.4 km from Aurland. From Friday to Sunday the values were 2 – 4 % higher at the same point. 17 km from Aurland the average NO_2/NOx volume ratios were 4 - 5 % higher. However, at 17 km there was a falling tendency from week no. 33 to week no. 37 and greater variations.[17] Average NO_2/NOx volume ratios during three weeks in 2008 are plotted in figure 35 and 36. There was no significant change of the average NO_2/NOx-ratio from 2007 to 2008.

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[17] Test of the NO_2-filter in week no. 36 reduced the average NO_2/NOx-ratio from Monday to Friday

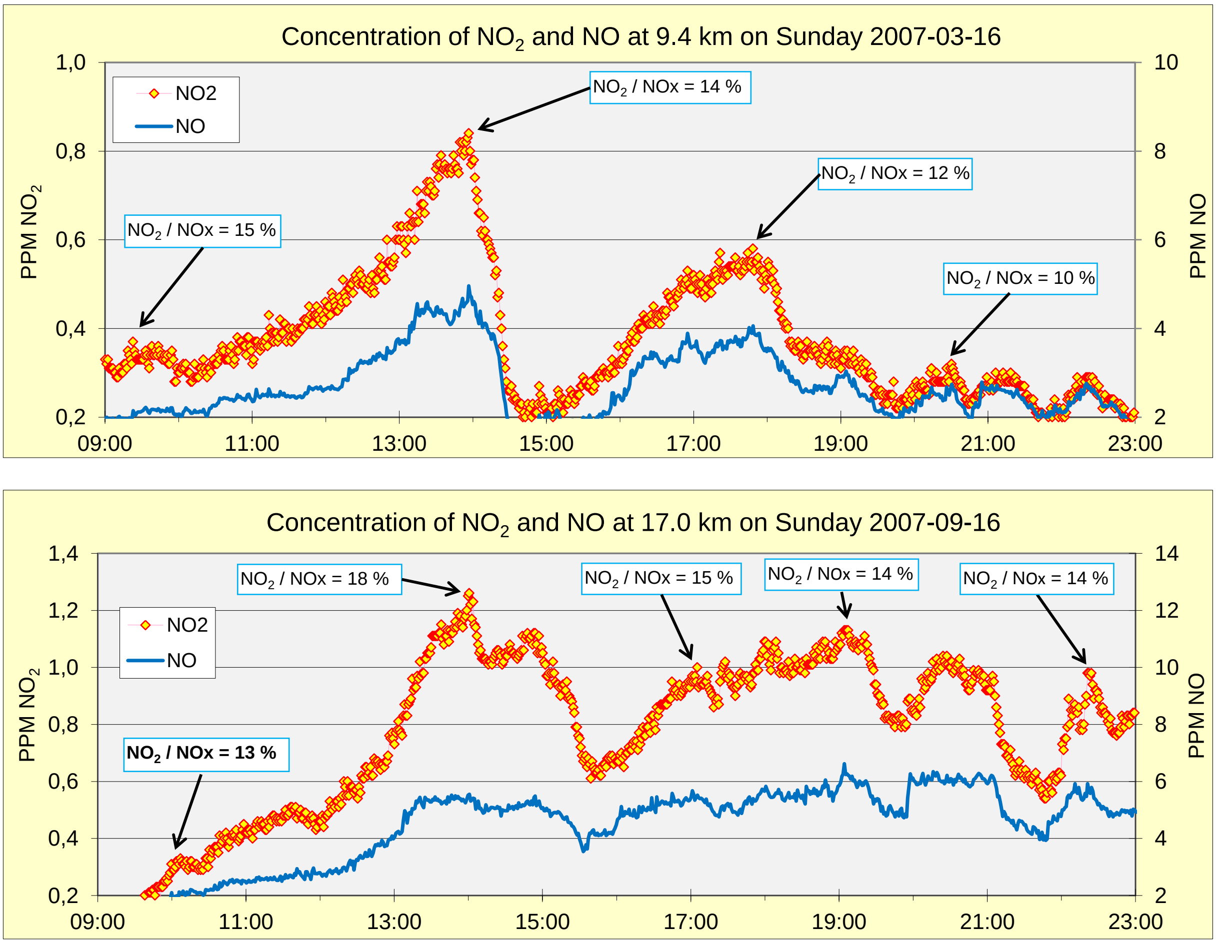


Figure 32: NO$_2$ and NO concentration 9.4 and 17 km from Aurland on Sunday 2007-09-16

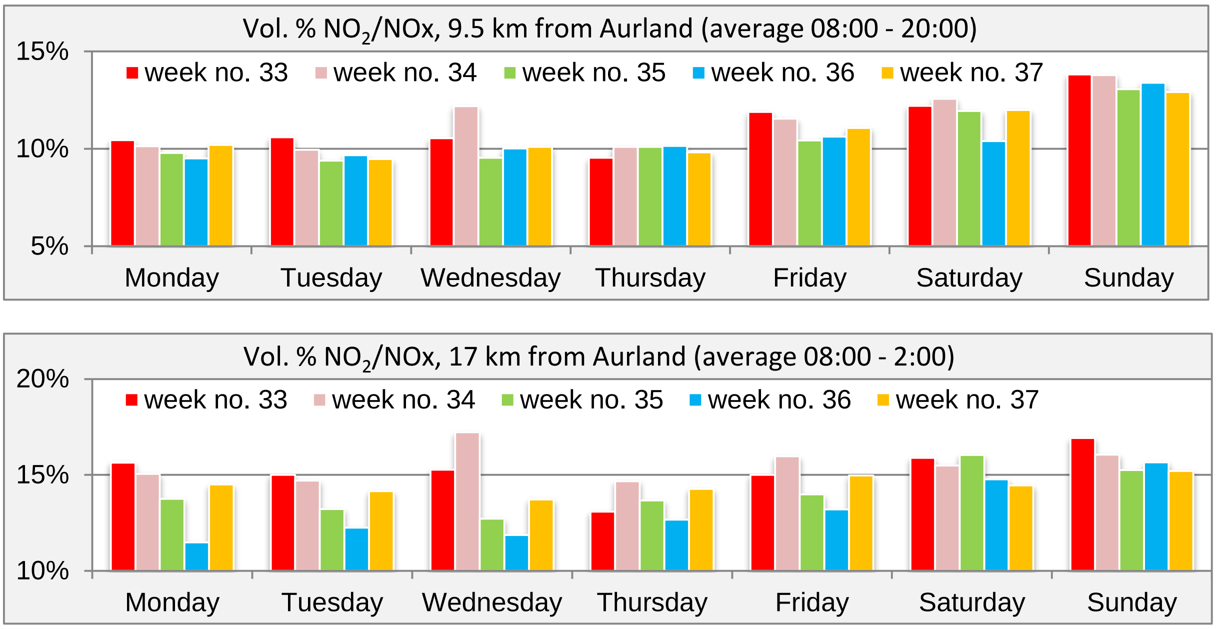


Figure 33: NO$_2$ / NOx volume ratio at 9.4 km and 17 km from 13 August to 16 September 2007

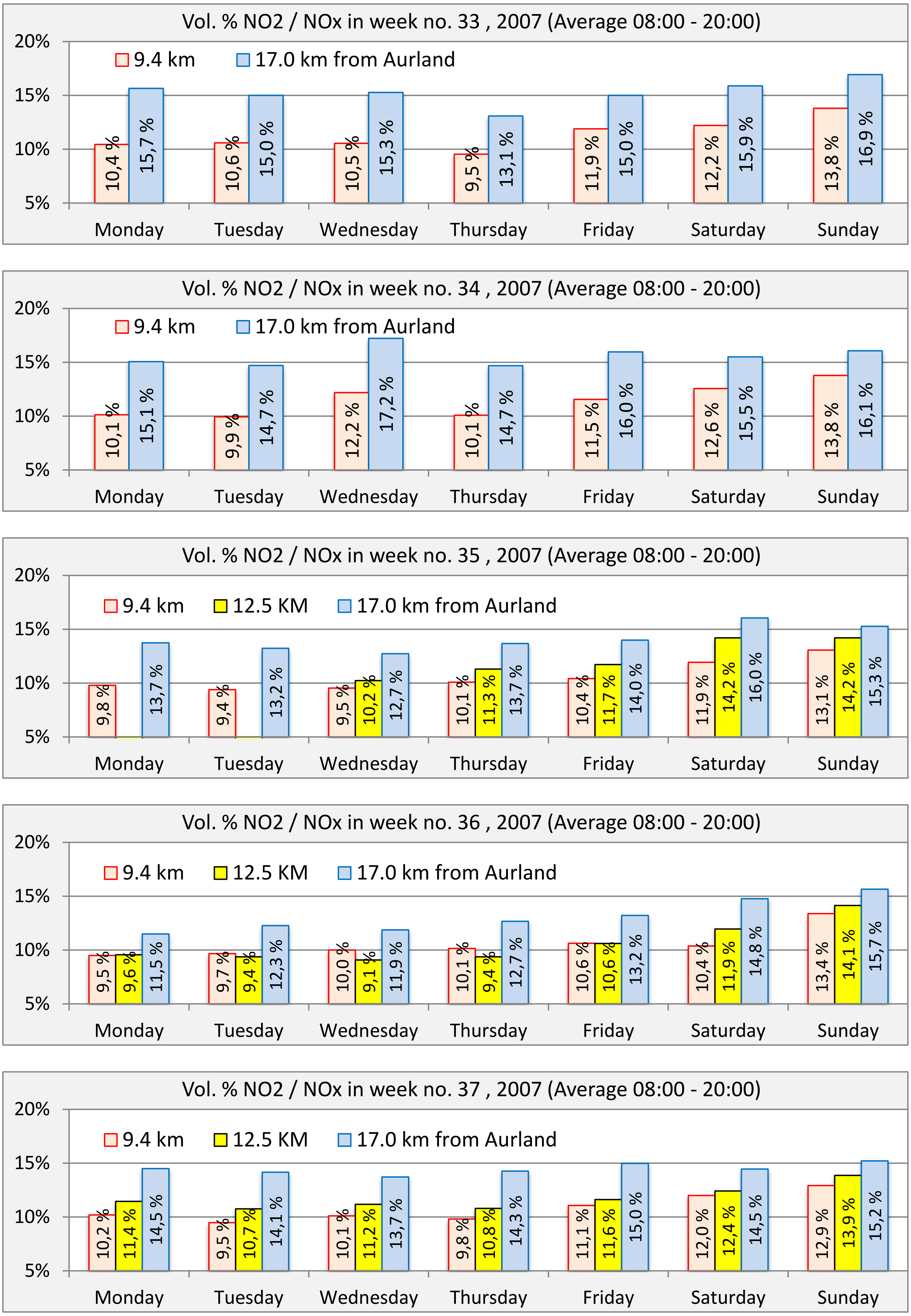


Figure 34: Average NO_2 / NOx volume ratio in week no. 33 – 37 in 2007

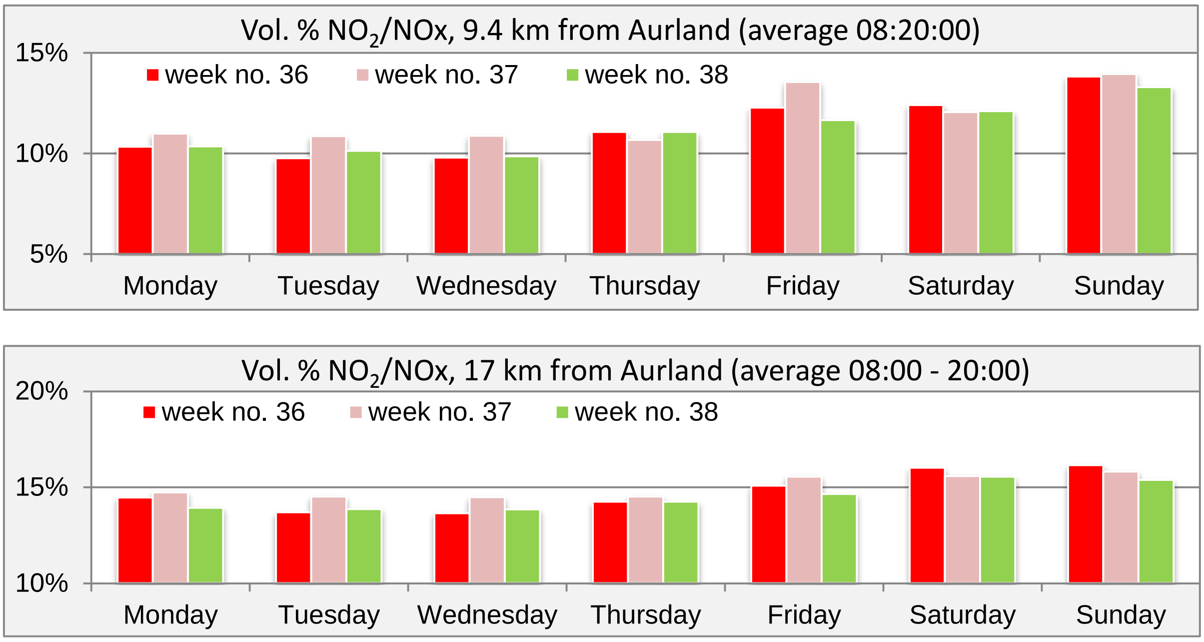


Figure 35: NO_2 / NOx volume ratio at 9.4 km and 17 km 1 – 21 September 2008

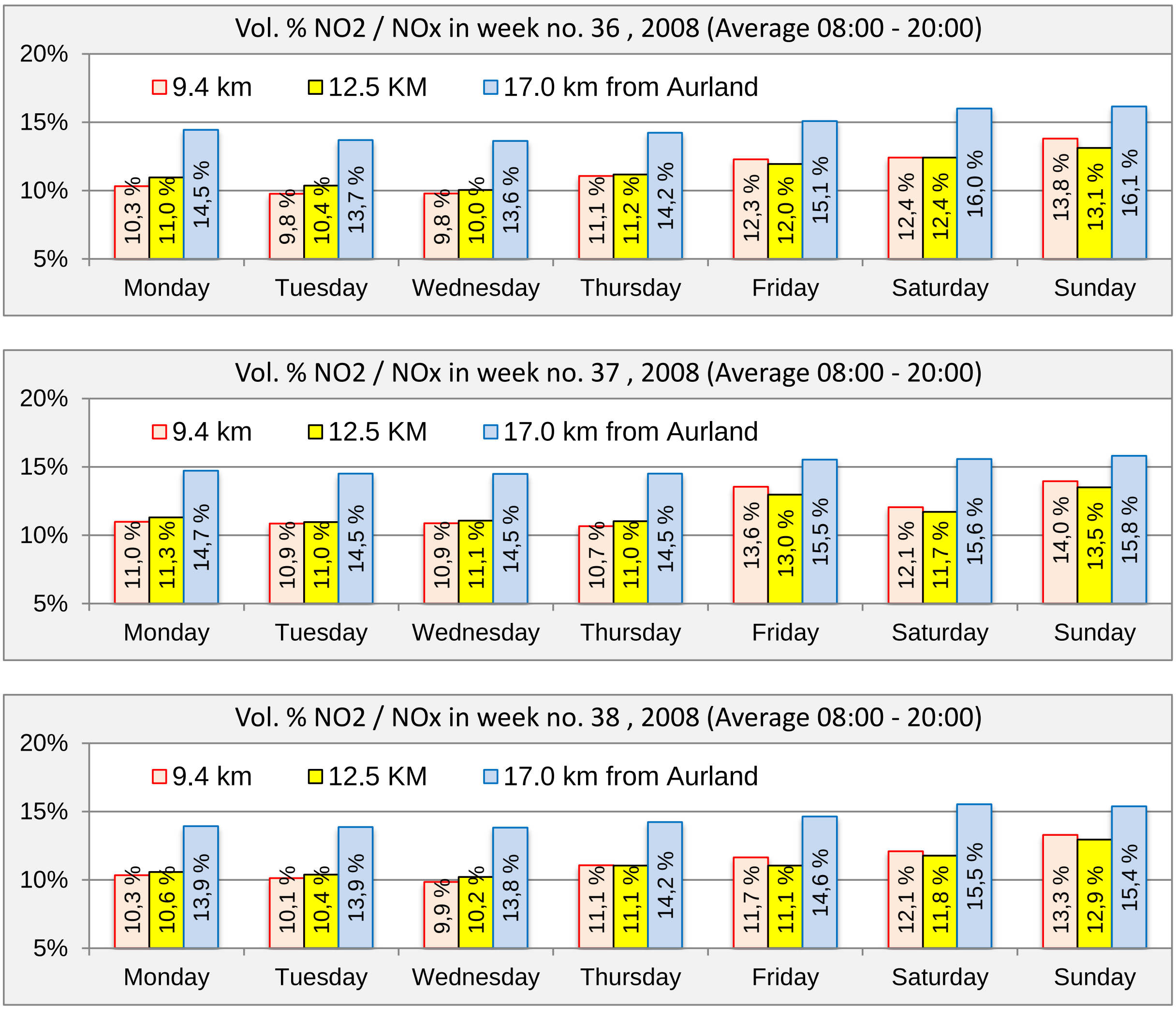


Figure 36: Average NO_2 / NOx volume ratio 1 – 21 September 2008

2.3 Observations of NO and NO_2 in July - September 2011

The concentration of NO and NO_2 was measured every five minutes during nine weeks in order to observe the changes in NOx-emission from passenger cars and heavy duty vehicles. The traffic growth in week no. 37 was about 20 %. from 2007 to 2011. The average NO_2/NOx volume ratios for three weeks are plotted in figure 37. There was less difference between the values on Monday and Sunday in 2011 than in 2008.

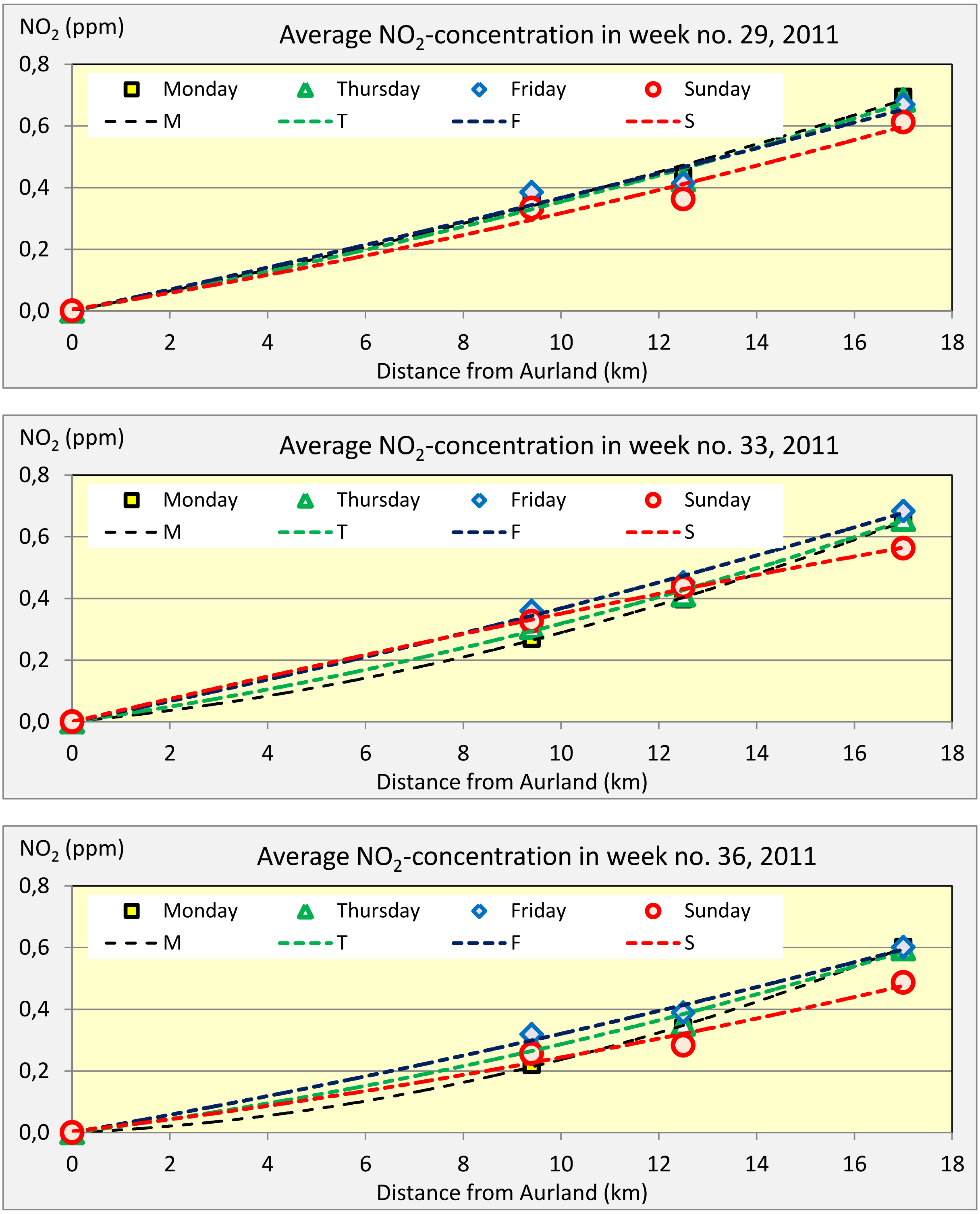


Figure 37: Average concentration of NO_2 in week no. 29, 33 and 36 in 2011

The average NO-concentrations at 17 km in figure 38 were reduced by one ppm compared with the values for 2008 (in figure 28 on page 25). NO_2-emission from new diesel-powered passenger cars gave a higher ventilation level in 2011 and lower average NO-values on Sundays. Higher air velocity in 2011 reduced the effect of NO-oxidation between the gas-sensors at 9.4 km and 17 km.

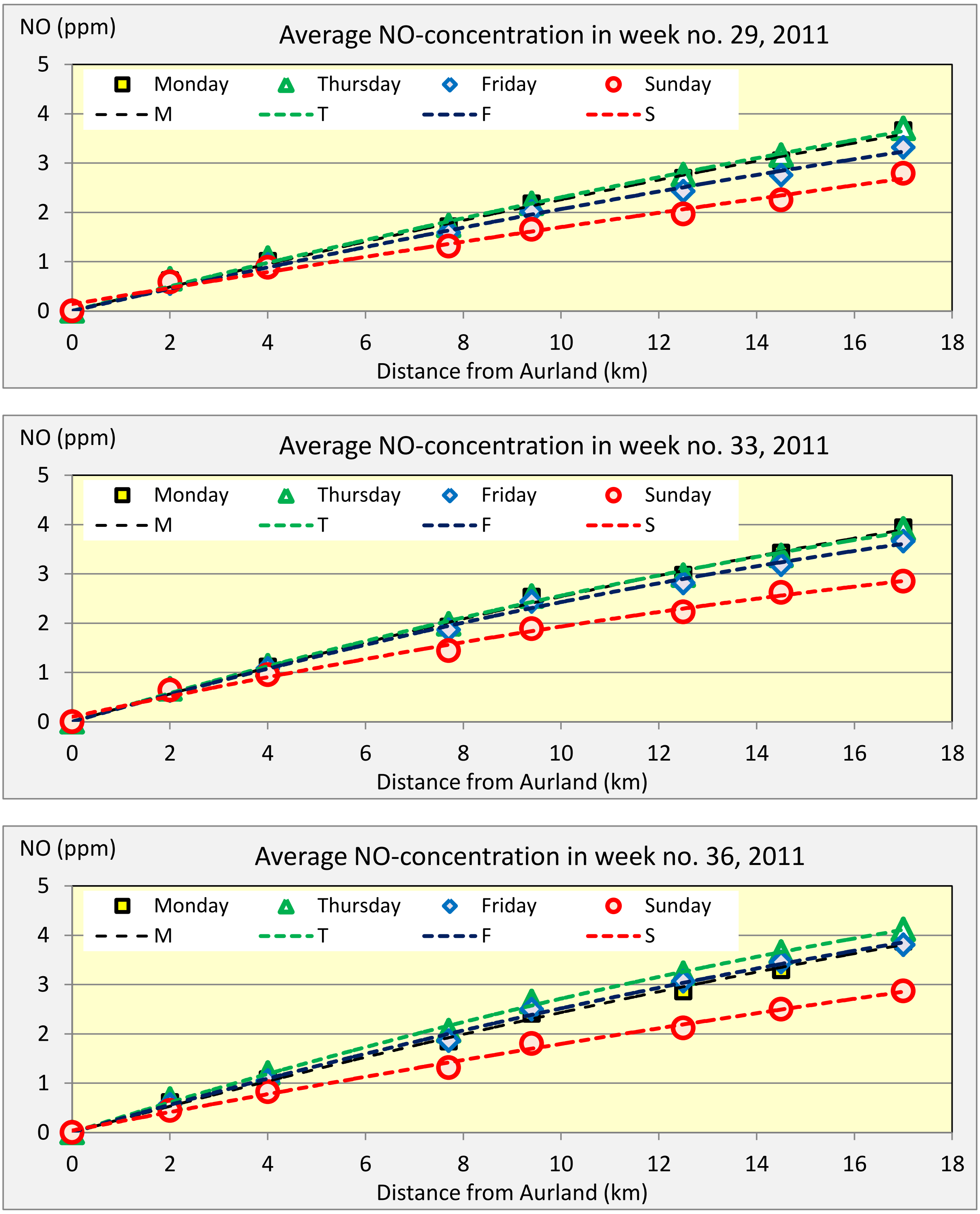


Figure 38: Average concentration of NO in week no. 29, 33 and 36 in 2011

The gradual reduction of average NO_2/NOx volume ratio from July to September is illustrated in figure 39. In the same period there was a good correlation between reduction of NO_2/NOx and reduced traffic of passenger cars from Monday to Thursday. From Monday to Thursday in week no. 36, the average NO_2/NOx volume ratio at 9.4 km was near 10 % which means that there had been no significant change in the exhaust from heavy duty vehicles since week no. 33 – 37 in 2007 (Figure 33 on page 28).

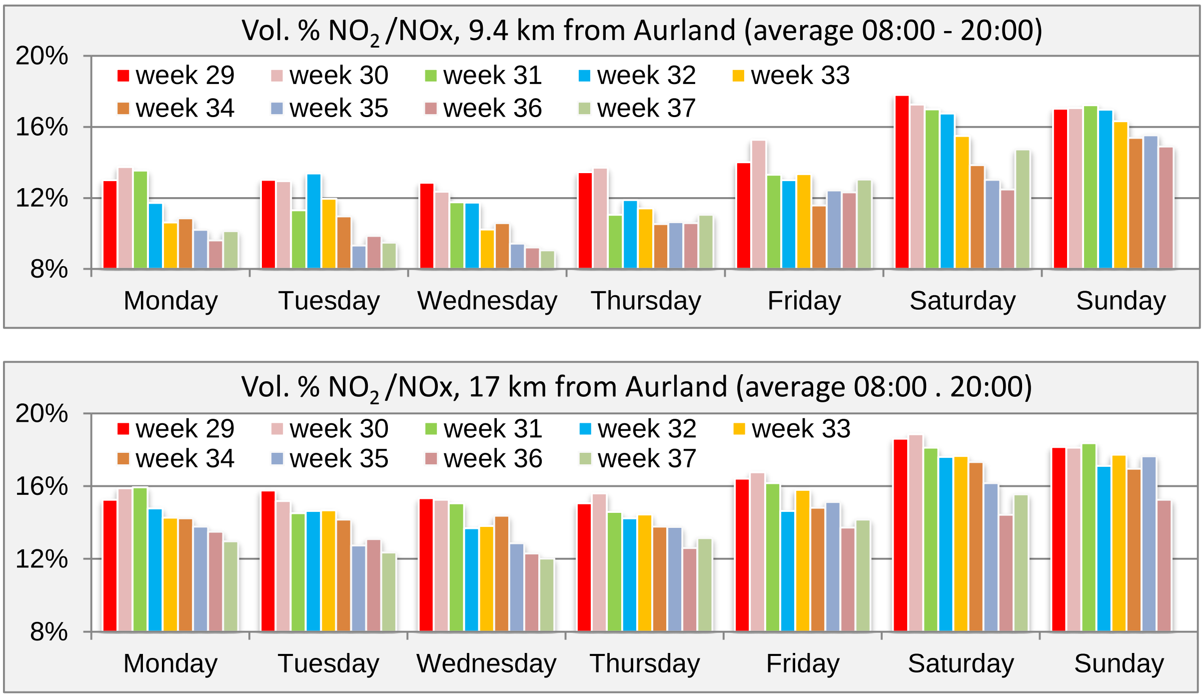


Figure 39: Average NO_2 / NOx volume ratio at 9.4 km and 17 km in week no. 29 - 36 in 2011

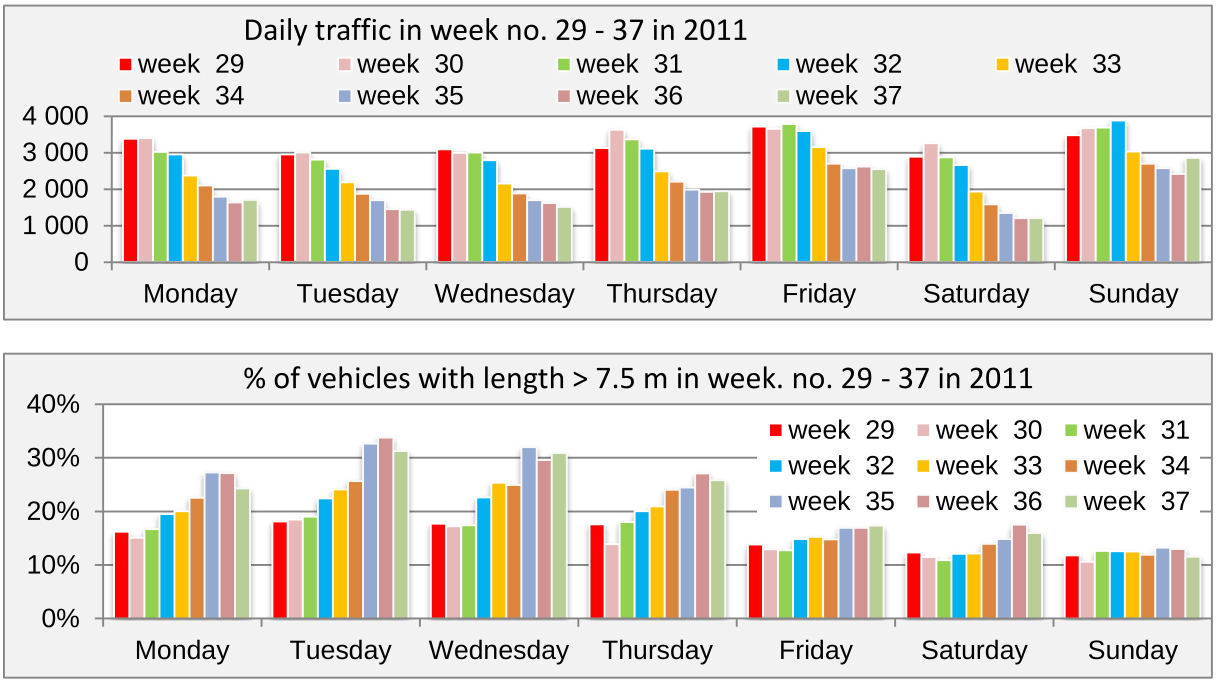


Figure 40: Daily traffic and ratio of heavy duty vehicles in week no. 29 - 37 in 2011

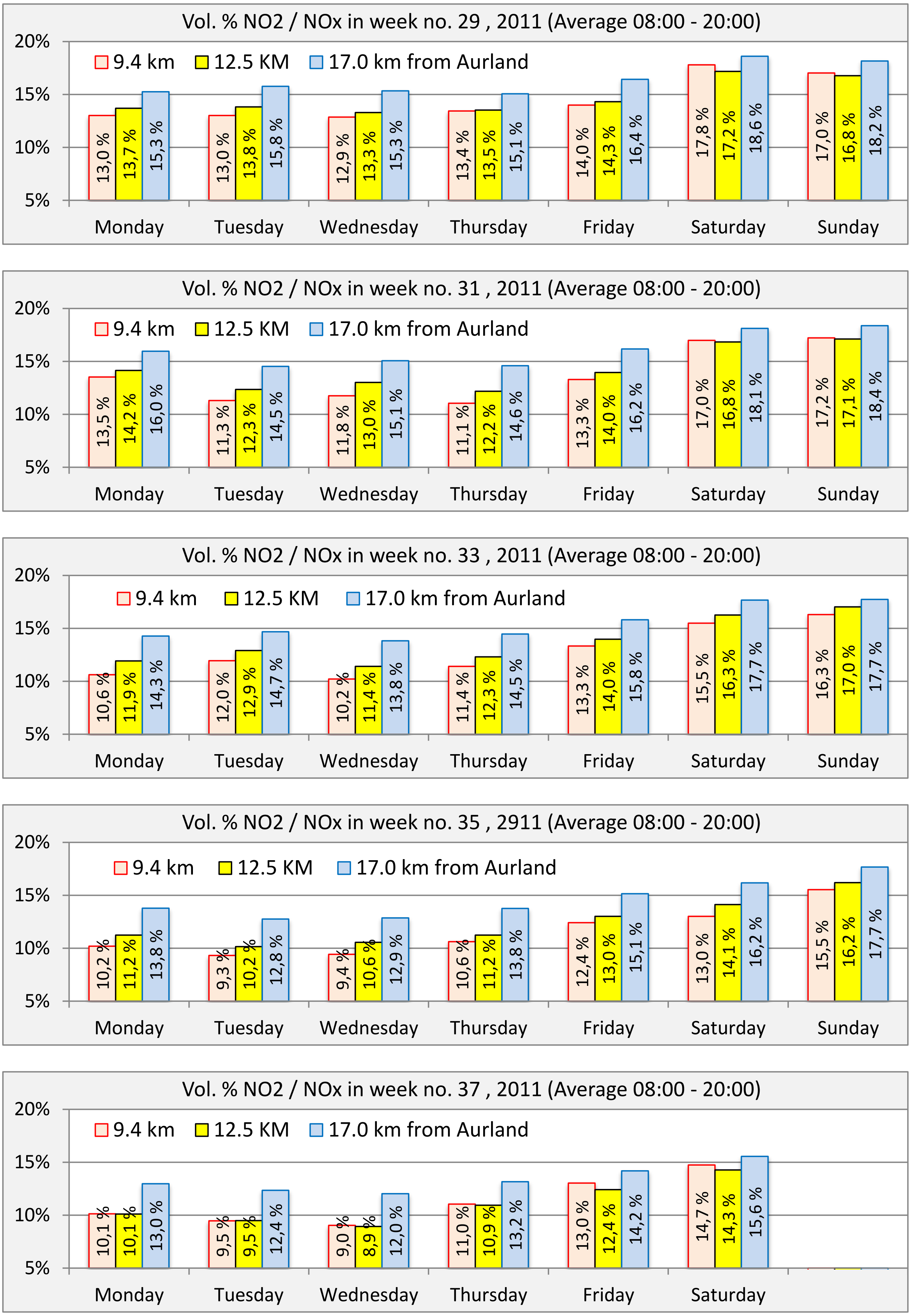


Figure 41: Average NO_2 / NOx volume ratio from 2011-07-18 to 2011-09-17

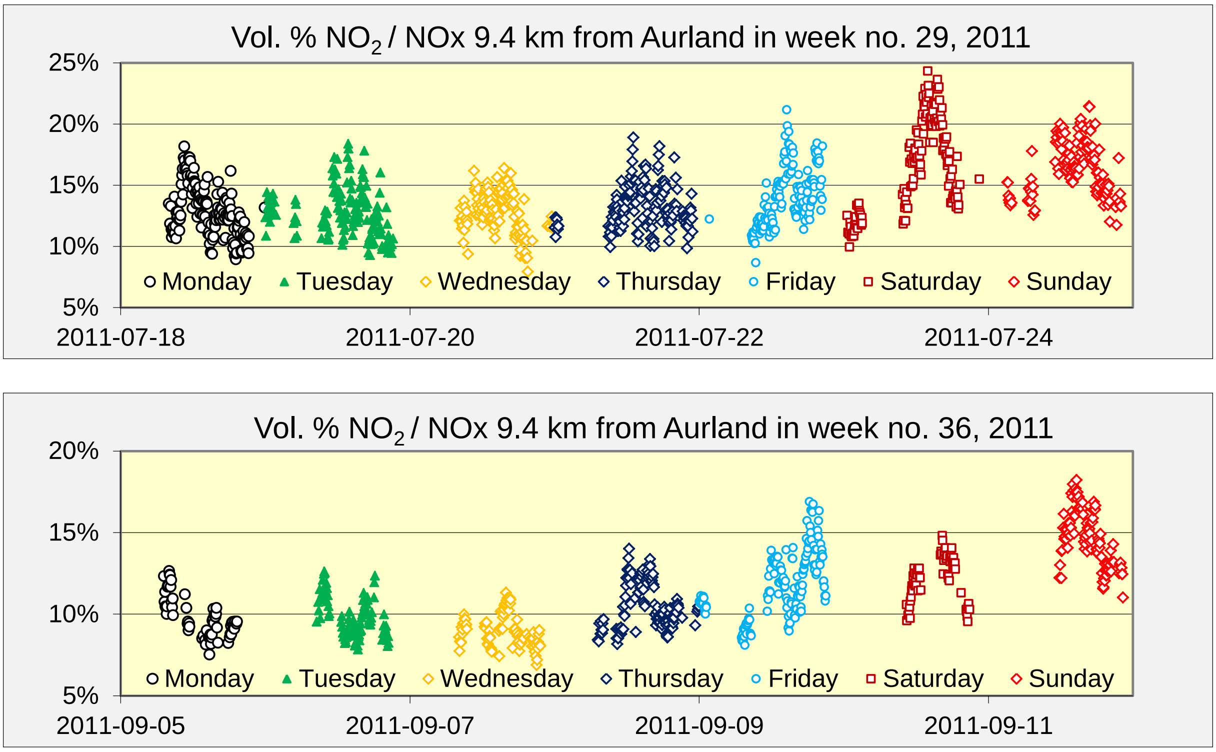


Figure 42: NO_2 / NOx volume ratio 9.4 km from Aurland in week no. 29 and 36 in 2011

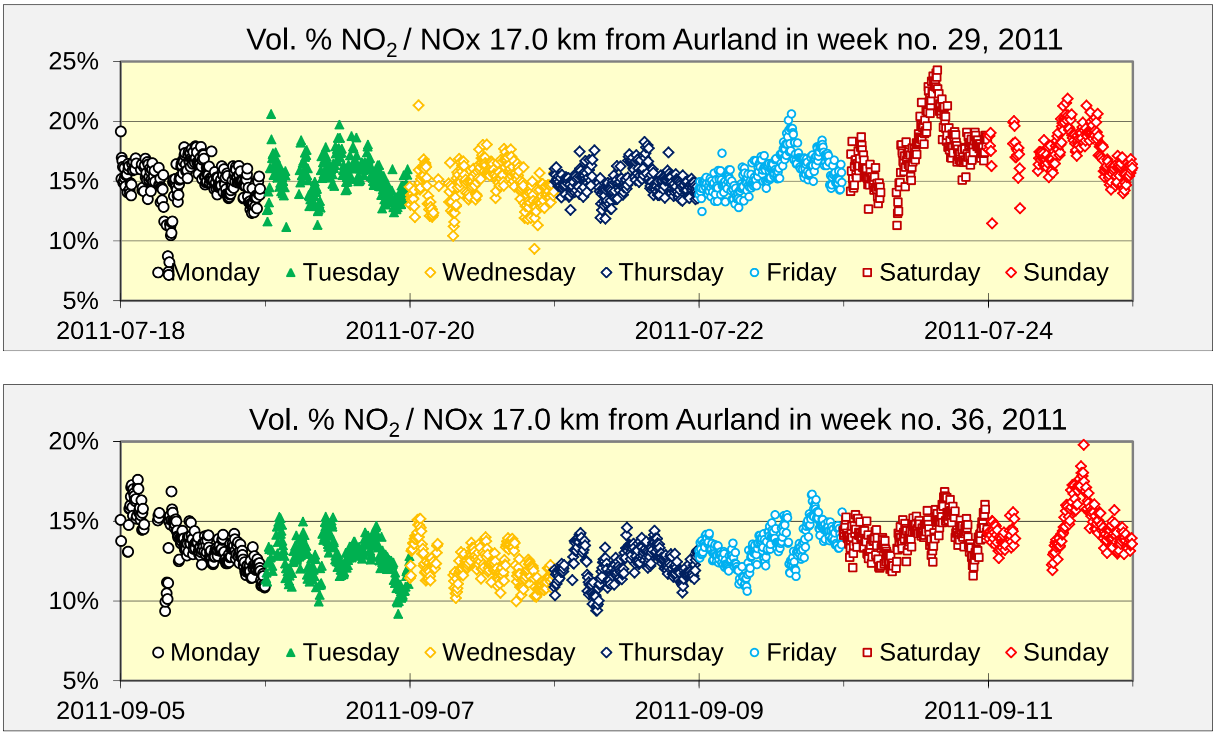


Figure 43: NO_2 / NOx volume ratio 17 km from Aurland in week no. 29 and 36 in 2011

2.4 NOx-emission from heavy duty vehicles in December 2012

When the Laerdal tunnel was opened at 15:22 on Monday 2012.12.10 after a traffic accident on Sunday evening, there were 100 heavy duty vehicles and 50 passenger cars waiting near the portals. 30 minutes later the NO-concentration had increased to 8 ppm near the Aurland portal and 13 ppm near Laerdal. The fast growth of NO-concentrations in the tunnel section from 2 – 17 km from Aurland is plotted in figure 44. The highest values at the Aurland side were observed at the NO-sensor located 2.0 km from the portal. The NO-emission five minutes after start was 10 - 15 % higher than the average emission-values in the middle of the tunnel. This cold-start-effect was gradually reduced during the first ten minutes and was negligible after 9.4 km.

6 ppm is equal to a NO-volume of 336 l/km since the average tunnel profile is 56 m^2. The observed NO-concentration at 2 km corresponds to an average NO-emission of 7.5 l/km from heavy duty vehicles in the south section where the uphill gradient is 2.3 %. The average downhill NO-emission from heavy duty vehicles was less than 1.0 l/km in this section.

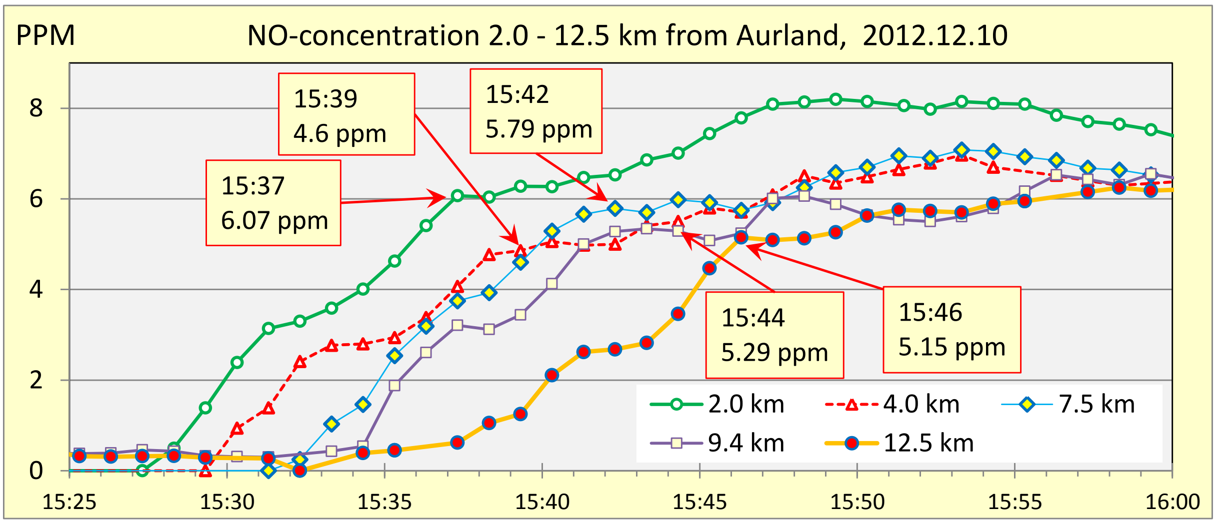


Figure 44: Observed NO-concentration at five points in the south half of the tunnel

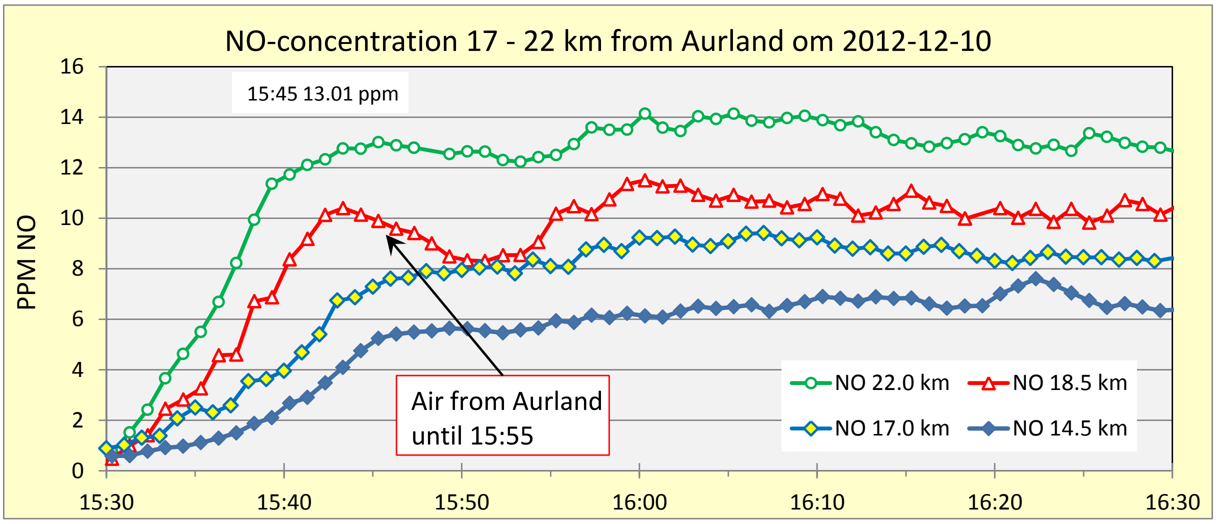


Figure 45: Observed NO-concentration in the north half of the tunnel during 60 minutes

The lowest NO-values in figure 44 and 45 were observed 14.5 km from Aurland. The average NO-emission factor for heavy duty vehicles was near 3.7 l/km in this section.

The average NO-emission factors from heavy duty vehicles from the Laerdal side were 10 l/km at 22 km and 8.7 l/km at 18.5 km. There was no detectable NO-emission from heavy duty vehicles driving downhill towards Laerdal from 18.5 to 24.5 km.

Distance from Aurland (km)	0 - 7.5	7.5 - 11.5	12.5 - 14.5	14.5 - 17	18.5 - 22	22 - 24.5
Gradient	2.3 %	2.3 %	-0.7 %	-0.7 %	-2.7 %	-2.7 %
NO-emission, north direction	7.4 l/km	7.0 l/km	2.8 l/km	2.8 l/km	0	0
NO-emission, south direction	1.0 l/km	1.0 l/km	4.7 l/km	5.8 l/km	8.7 l/km	10.1 l/km
Average NO-emission-factor	4.2 l/km	4.0 l/km	3.7 l/km	4.3 l/km	4.3 l/km	5.0 l/km
Effect of cold-start and load	13 %	6 %	0 %	16 %	16 %	36 % (?)

Higher emission rates were expected in the south direction near Laerdal because of 2.7 % uphill gradient and heavier loaded vehicles driving from Oslo to Bergen. The effect of cold-start during the first ten minutes is uncertain. Heavy loaded trucks may be another likely explanation for the high NO-emission in the uphill section from the Laerdal portal.

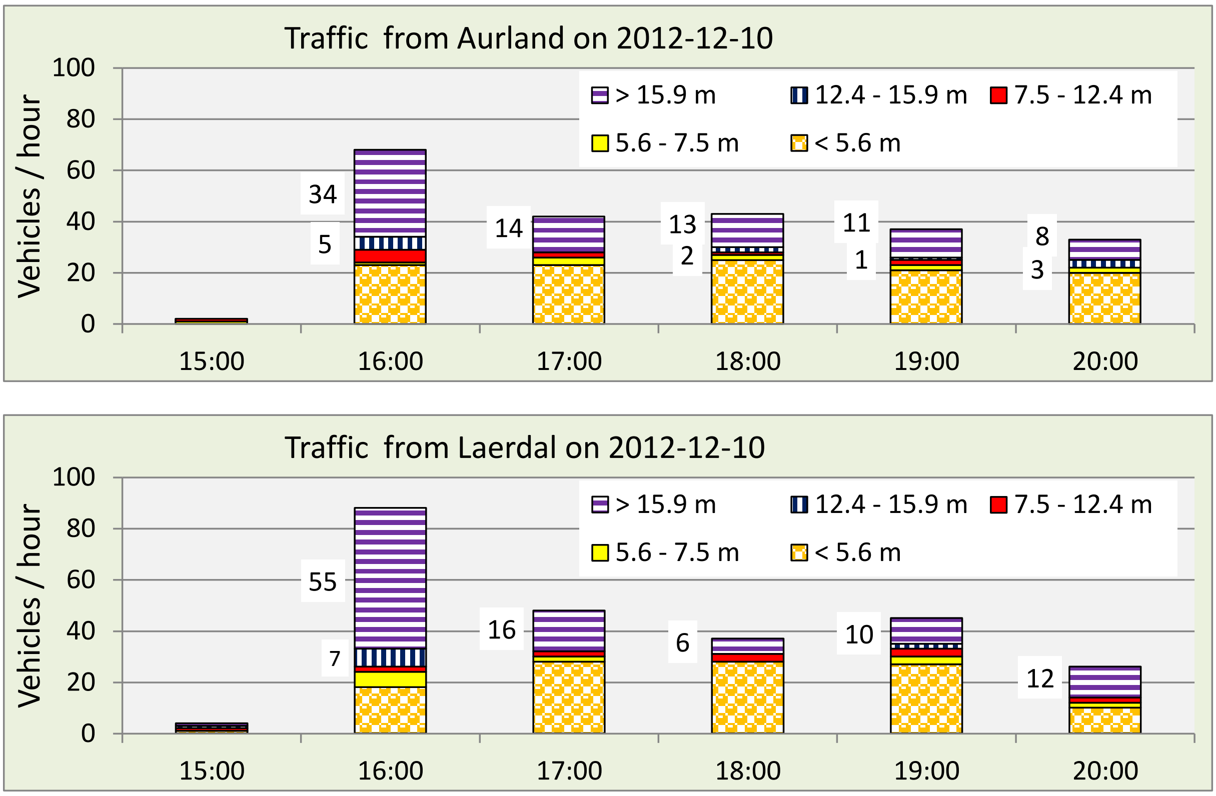


Figure 46: Traffic in the Laerdal tunnel on Monday 2012-12-10

The NO-concentration was almost constant during the first hour after the two vehicle columns had driven through the tunnel. There were few vehicles the next hour. However, the growth of NO_2-concentration continued. The extreme values are plotted in figure 48 together with normal NO_2-values from Saturday to Tuesday.

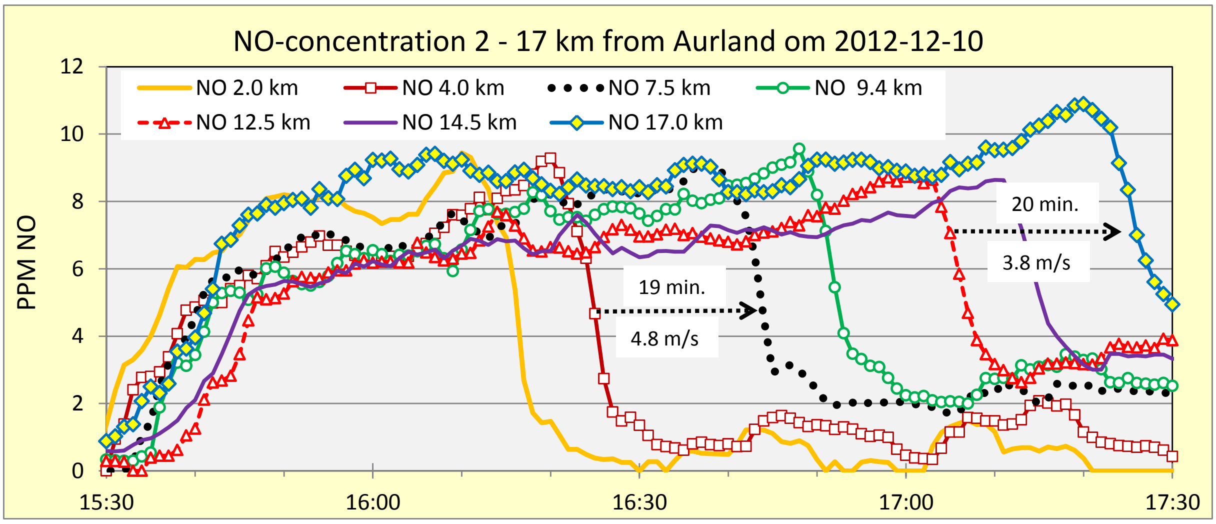


Figure 47: Observed NO-concentrations from Aurland during two hours

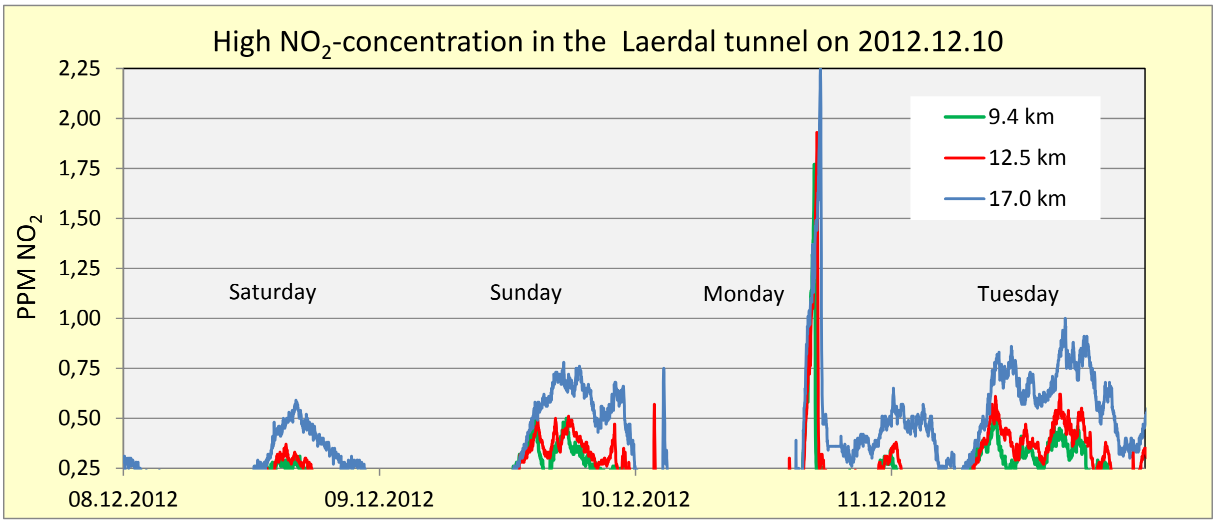


Figure 48: High NO_2-concentration on Monday 2012-12-10

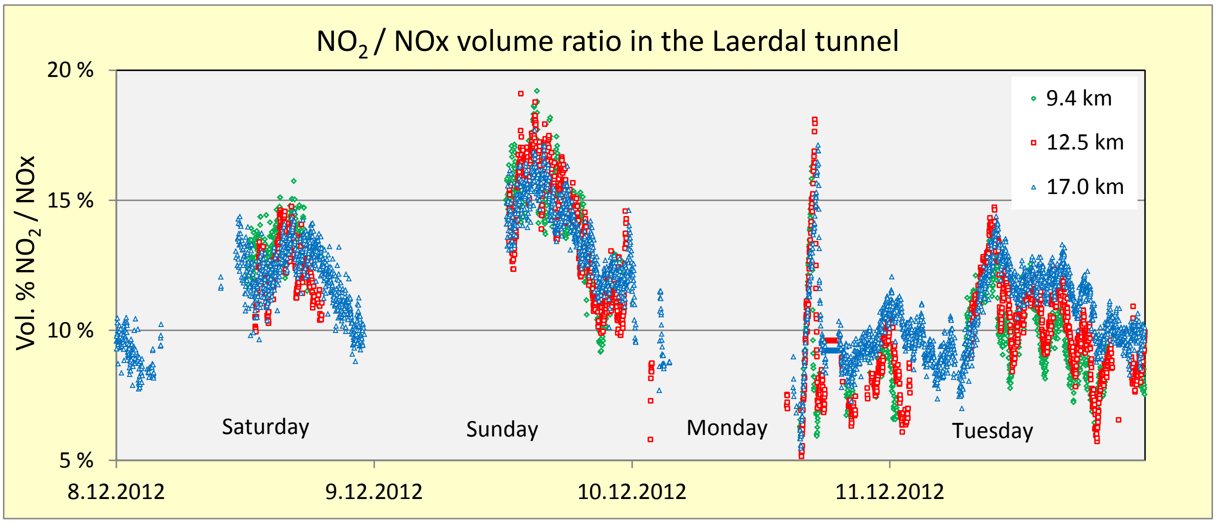


Figure 49: Variations in NO_2 / NOx volume ratio from Saturday to Tuesday

Observed NO_2-concetrations every minute at 9.4 km, 12.5 km and 17.0 km from Aurland, are plotted in figure 50. The average NO_2-emission from heavy duty vehicles driving in the north direction at 9.4 km and 12.5 km was 0.35 l/km. The average NO_2-emission rate for both directions from 12.5 km to 17 km was 0.25 l/km which give a total NOx-emission value near 4.0 l/km for vehicles with length over 7.5 m. (3.75 l NO + 0.25 l NO_2)/km.

There was no significant change of the NO_2/NOx-ratio caused by the variations in vertical alignment. Change of vertical alignment after 11.5 km and 60 % of the heavy duty vehicles driving in the south direction, gave higher NO_2-values at 17 km than at 9.4 km and 12.5 km. However, the NO-emission was also higher from vehicles driving in the south direction in the middle of the tunnel.

The three control points in figure 51 had almost identical increase of NO_2/NOx volume ratio caused by oxidation of NO during the first hour after the tunnel was opened. The average NO_2/NOx volume ratio from the first 40 heavy duty vehicles from Aurland varied between 5 % and 6 %.

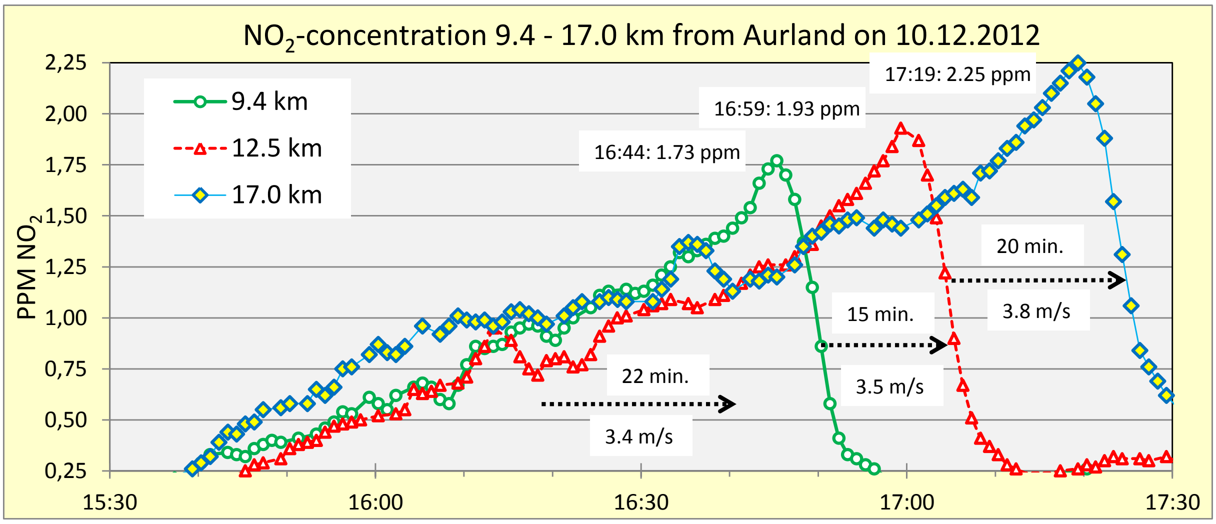


Figure 50: Growth of NO_2-concentration from oxidation of NO

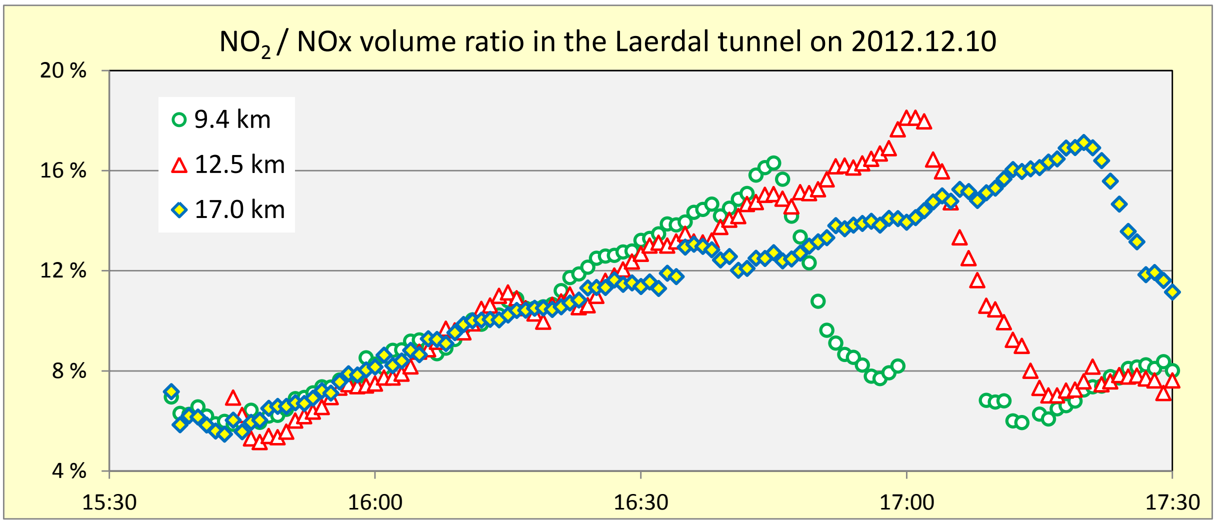
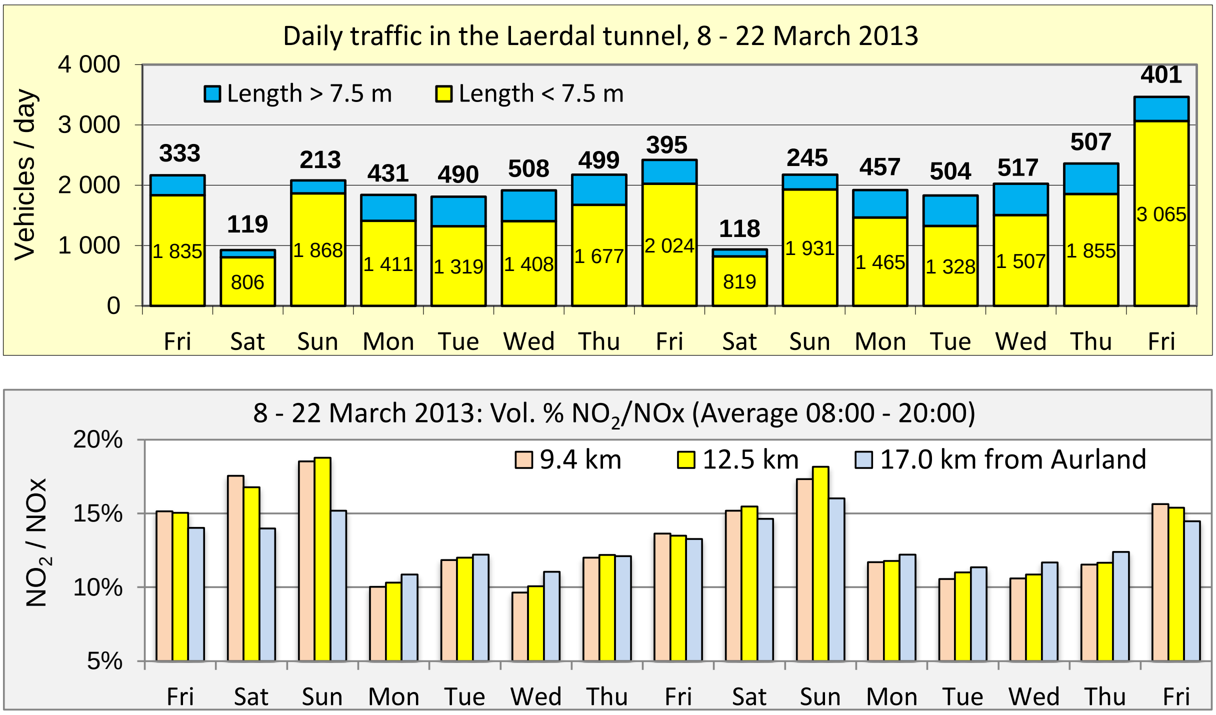


Figure 51: Variations of NO_2 / NOx volume ratio during two hours

2.5 NOx-emission from passenger cars in March 2013

The natural ventilation forces in the Laerdal tunnel are strongest in cold periods. High natural air velocity is reducing the available time for oxidation of NO in periods with little traffic. Small differences between NO_2/NOx volume ratios were observed between the sensors at 9.4 km and 17 km during two weeks in March 2013. The values from Monday to Thursday in figure 52 were similar to the values in week no. 35 – 37 in 2011. (Figure 41 on page 34). However, the 2013-values from Friday to Sunday at 9.4 km were higher than the observed values in 2011. Reduction of the NO_2/NOx volume ratio at 17 km from 2011 to 2013 was caused by higher ventilation levels because of increased traffic and shorter periods with high NO-oxidation. Low ventilation levels and traffic of passenger cars gave NO_2/NOx volume ratios above 25 % on Friday afternoon in figure 53.


Daily traffic in the Laerdal tunnel, 8 - 22 March 2013

8 - 22 March 2013: Vol. % NO_2/NOx (Average 08:00 - 20:00)

Figure 52: Daily traffic and average NO_2 / NOx volume ratio 2 weeks in March 2013

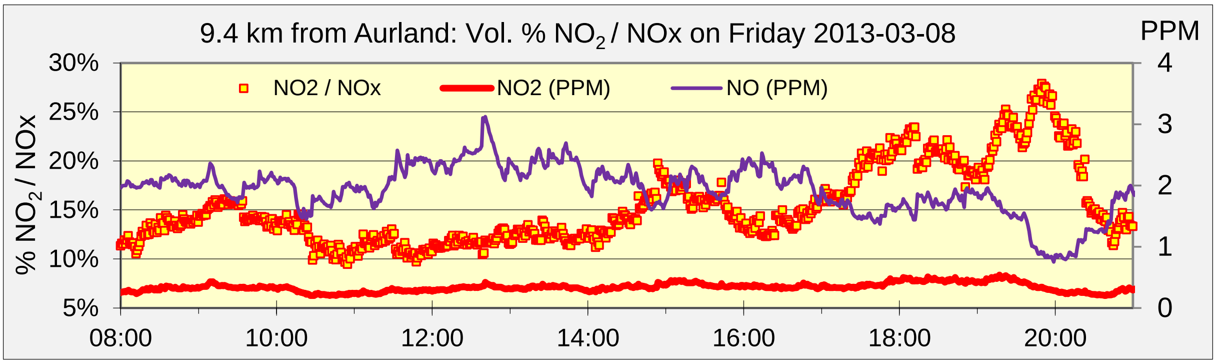

9.4 km from Aurland: Vol. % NO_2 / NOx on Friday 2013-03-08

Figure 53: Normal growth of NO_2 / NOx volume ratio from weekend-traffic on Friday afternoon

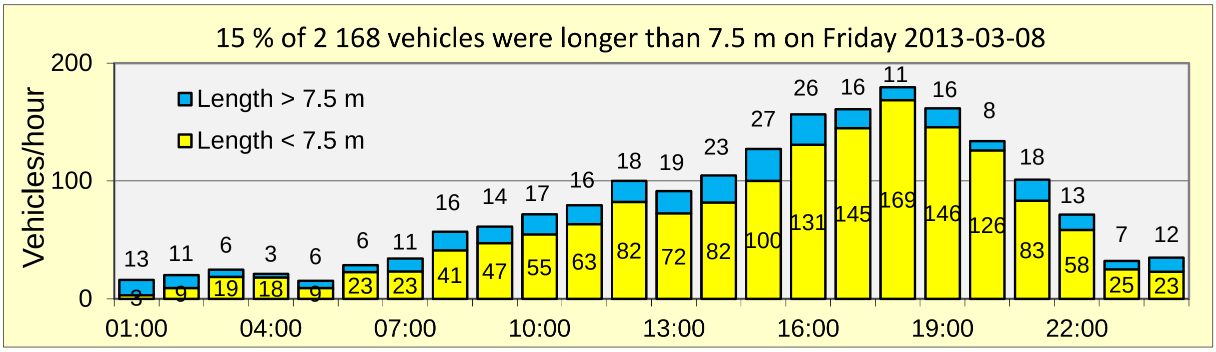


Figure 54: Traffic variations on Friday 2013-03-08

Typical traffic variations on Friday are illustrated in figure 54. 15 % NO_2/NOx-volume ratio in the morning in figure 53 was caused by NO-oxidation because of low air velocity before the fans started. The growth of NO_2/NOx volume ratio after 17:00 was caused by reduced traffic of heavy duty vehicles and higher NO_2-emission from passenger cars.

Reduced traffic of heavy duty vehicles gave higher NO_2/NOx volume ratios during the Easter week in 2013 except for Monday and Tuesday. Detailed observations are given in figures 55 – 58. Cold weather gave high natural ventilation and average air velocity near 2 m/s during the night and no sign of NO_2 from oxidation in the morning. The NO_2/NOx volume ratio at 17 km was lower than at 9.4 and 12.5 km for all days in figure 55 except Monday and Tuesday. The most likely explanation is that passenger cars are producing less NO_2 at the low gradient section from 11.5 to 17 km compared with the first tunnel section from Aurland. The 30 % NO_2/NOx-ratio at 9.4 km on Easter Sunday was probably a combination of NO-oxidation and NO_2-emission from diesel-powered passenger cars. The ratio varied between 20 % and 25 % after start of ventilation.

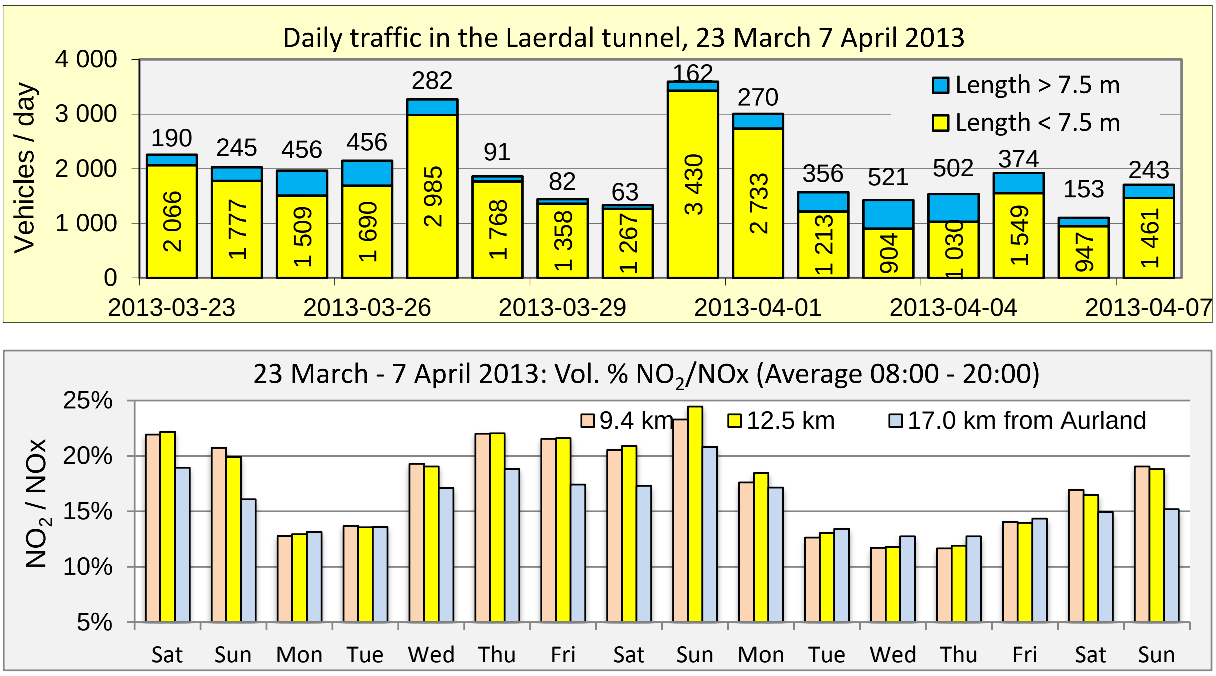


Figure 55: Traffic and NO_2 / NOx volume ratio, March - April 2013

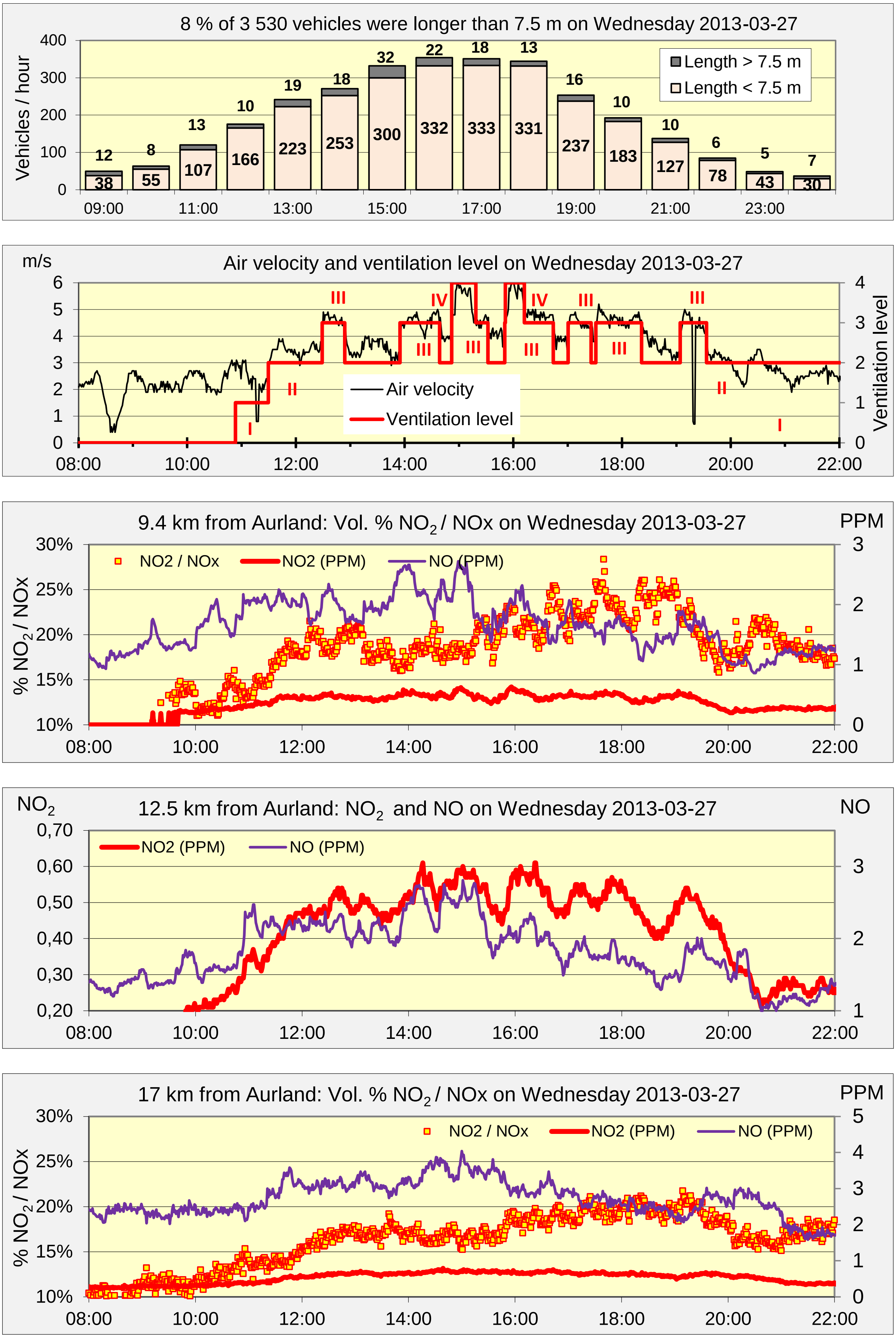


Figure 56: Traffic and NOx at the start of Easter holidays in 2013

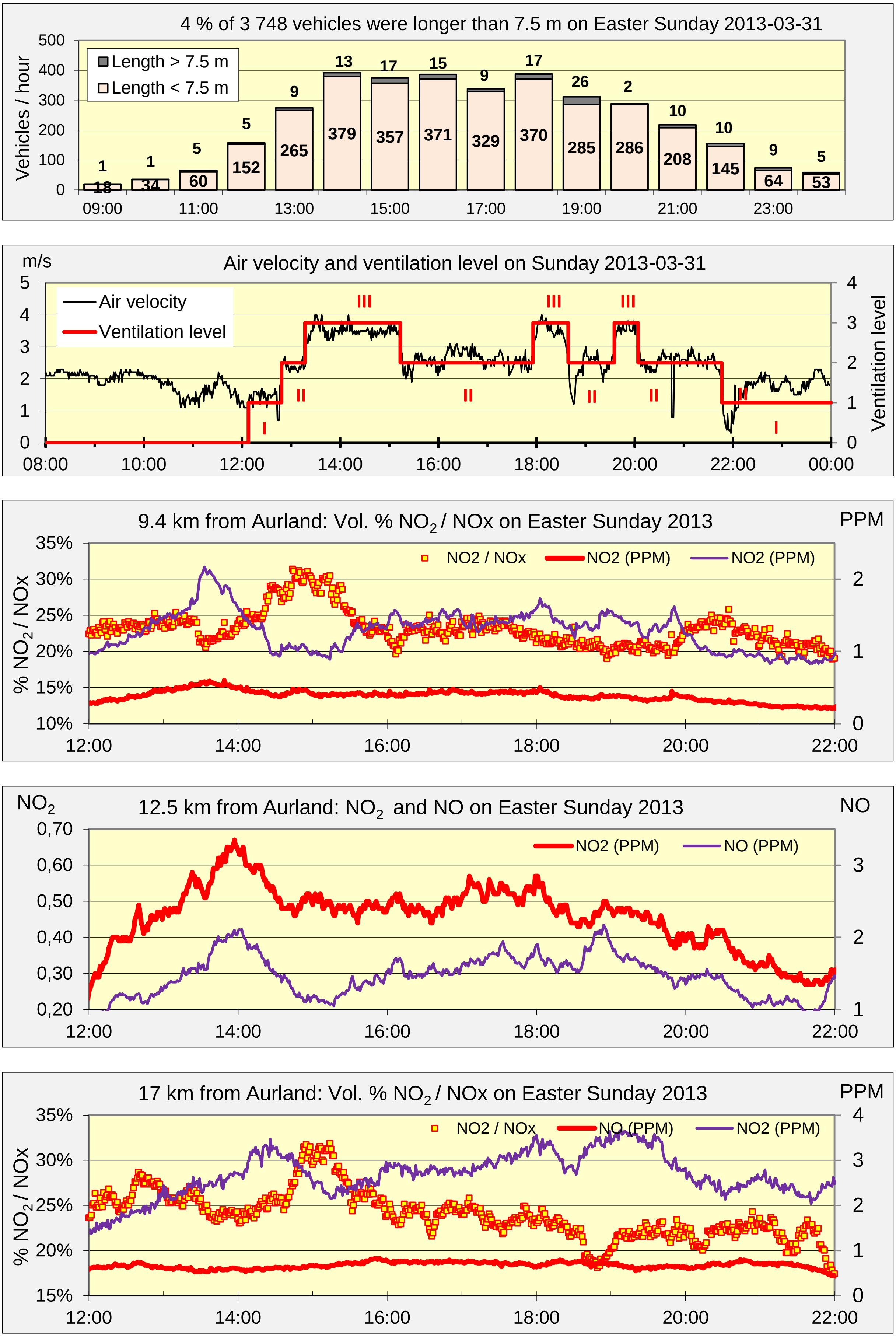


Figure 57: Traffic and NOx on Easter Sunday in 2013

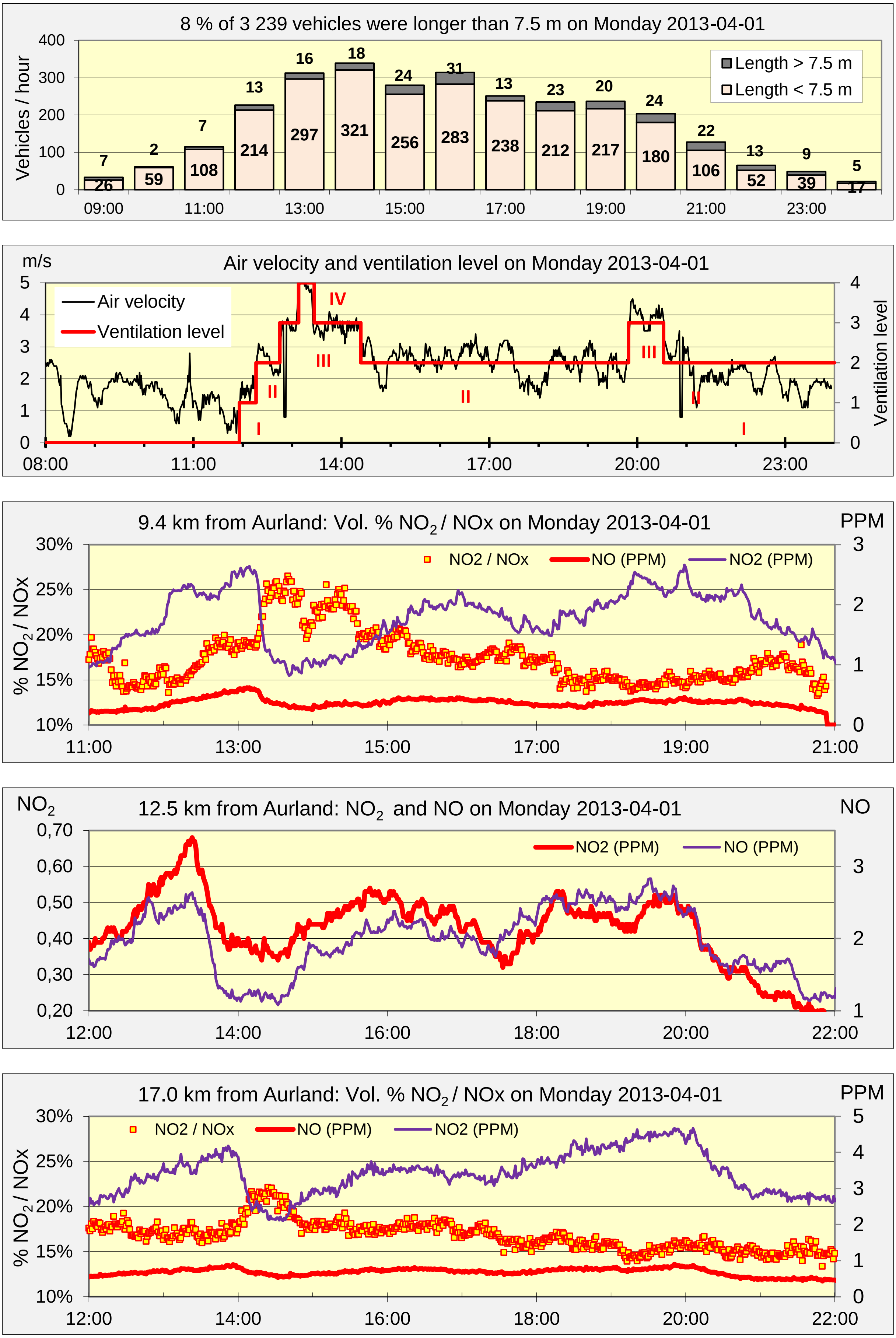


Figure 58: Traffic and NOx on Monday 2013-04-01

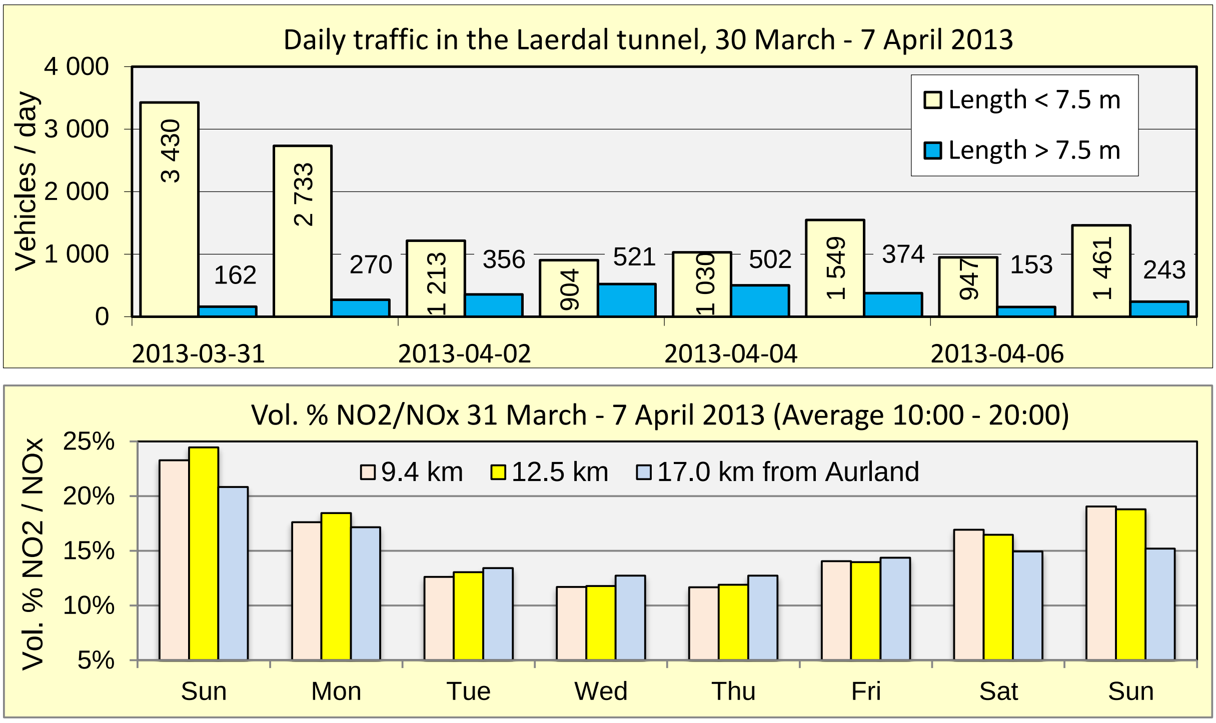


Figure 59: Traffic and NO_2 / NOx volume ratio one week after Easter 2013

The low number of heavy duty vehicles during the Easter week made it possible to calculate an average NOx-emission factor for passenger cars. Emission factors from December 2012 were used in the calculation of total NOx-emission from heavy duty vehicles in the table below. Observations from Monday and Tuesday were not included in the table because more than 70 % of the total NOx-volume came from heavy duty vehicles these days. The average NOx-emission factor in the table is 0.29 l/km for vehicles with length under 7.5 m. The same factor was found at 9.4 and 17 km on Easter Sunday when only 4 % of the vehicles were longer than 7.5 m.

Date	Sensor location	NOx-volume m^3/(10:00 – 20:00)			Vehicles > 7.5 m	Emission factor l / km / vehicle
		Total (m^3)	L > 7.5 m	L < 7.5 m		
2013-03-23	9.4 km	10.15	4.09	6.07	8 %	0.30
	17.0 km	16.05	7.31	8.74		0.24
2013-03-24	9.4 km	9.02	4.09	4.92	11 %	0.31
	17.0 km	16.02	8.18	7.85		0.28
2013-03-27	9.4 km	16.28	7.36	8.92	8 %	0.31
	17.0 km	25.18	12.42	12.77		0.25
2013-03-28	9.4 km	6.68	1.44	4.74	5 %	0.31
	17.0 km	10.25	3.64	6.61		0.24
2013-03-29	9.4 km	4.96	1.62	3.35	6 %	0.32
	17.0 km	8.34	3.20	5.14		0.27
2013-03-30	9.4 km	4.28	1.04	3.24	5 %	0.35
	17.0 km	7.45	2.28	5.17		0.31
2013-03-31	9.4 km	7.62	1.87	5.75	4 %	0.29
	17.0 km	14.82	4.59	10.22		0.29
2013-04-01	9.4 km	9.41	4.07	5.34	8 %	0.30
	17.0 km	17.81	8.61	9.20		0.29
Average NOx-emission-factor for vehicles shorter than 7.5 m:						**0.29**

3 Observations of NO and NO_2 in the Fodnes tunnel

The Fodnes tunnel is 6.6 km long with a vertical gradient about 1.0 % from Laerdal towards Fodnes. The north end is located 2.0 km from the ferry connection between Fodnes and Mannheller. The average traffic volume varies between 1500 vehicles/day in November - March to over 3000 vehicles/day in July. 18 % of the vehicles (346 vehicles/day) were longer than 7.5 m in 2012 compared with 26 % (493 vehicles/day) in the Laerdal tunnel. Therefore a higher NO_2/NOx-ratio could be expected in the Fodnes tunnel.

The tunnel has gas-sensors installed at three points located 1.1 km, 3.5 km and 5.5 km from Laerdal. The average NO_2/NOx volume ratio has been calculated for NO_2-concentrations above 0.25 ppm and NO-values over 1.0 ppm.

3.1 Observations of NO_2/NOx volume ratio in 2010

Observed NO_2/NOx-volume ratios in two 6-day-periods in March 2010 are plotted in figure 60 and 61. In figure 60 the tunnel was ventilated towards Fodnes from Tuesday to Thursday. Low air velocity and oxidation of NO gave 3 - 5 % higher NO_2/NOx ratio near Fodnes than at the sensors located 1.1 km from the Laerdal portal. When the direction of ventilation changed towards Laerdal from Friday to Sunday, the highest ratio was found near Laerdal. In figure 61 there is 5 % increase in the NO_2/NOx ratio from 1.1 km to 5.5 km on Wednesday when the tunnel was ventilated towards Fodnes. The ventilation direction changed several times the next days, and the lowest values were observed in the middle of the tunnel. No extra NO_2-emission was observed during the first minutes after cold-start on the ferry. The average NO_2/NOx ratio near Fodnes was not higher than in the Laerdal end of the tunnel.

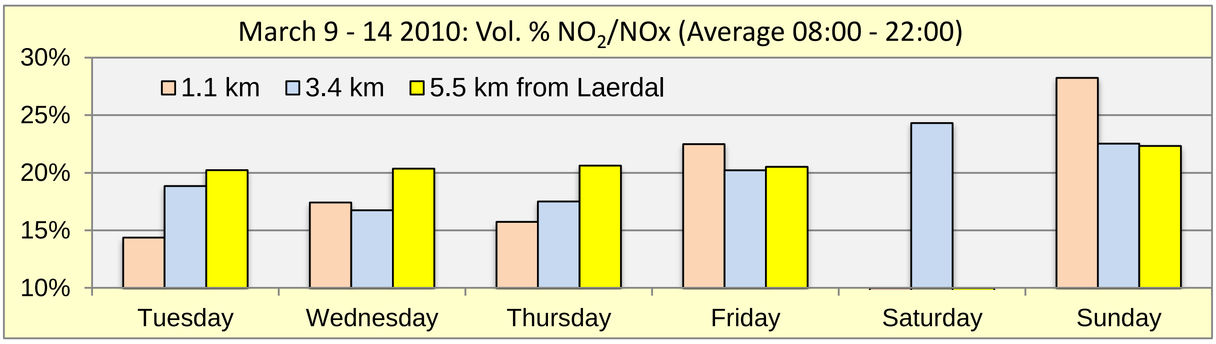


Figure 60: Average NO_2 / NOx volume ratio in the Fodnes tunnel 9 - 14 March 2010

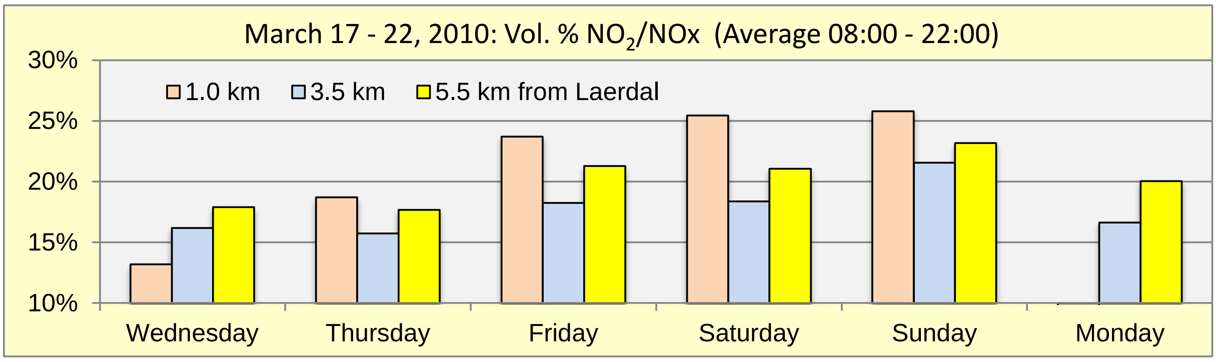


Figure 61: Average NO_2 / NOx volume ratio in the Fodnes tunnel 17 - 22 March 2010

The start direction for the longitudinal ventilation system varies with wind, temperature and traffic. Natural air velocity over 1.0 m/s is often sufficient for ventilation of this tunnel without start of jet-fans. The ferry frequency is one tour per 20 minutes, and the traffic column of 50 – 100 vehicles from the ferry often turns the airflow in the tunnel for 5 – 10 minutes. Sometimes fresh air is blown up to the gas-sensors located 1.1 km from the tunnel portals. In the diagrams on the next pages this effect can be seen as a short drop in the concentration of nitrous gases at 1.1 and 5.5 km.

The highest NO_2/NOx volume ratios were observed in periods with low natural ventilation when the NO-level was below the start-parameter for ventilation. Examples are given in figures 62 and 63. The natural ventilation was towards Laerdal in figure 62. However, the NO-values 5.5 km from Laerdal show that the direction of ventilation has been unstable. The low air velocity in the tunnel gave high NO-oxidation in the afternoon and 5 – 10 % increase of the NO_2/NOx volume ratio from 3.4 km to 1.1 km.

The NO_2/NOx ratio was also high on Sunday in the same week until the traffic of heavy goods vehicles gave increased NO-concentration after 17:00 in figure 63 on the next page.

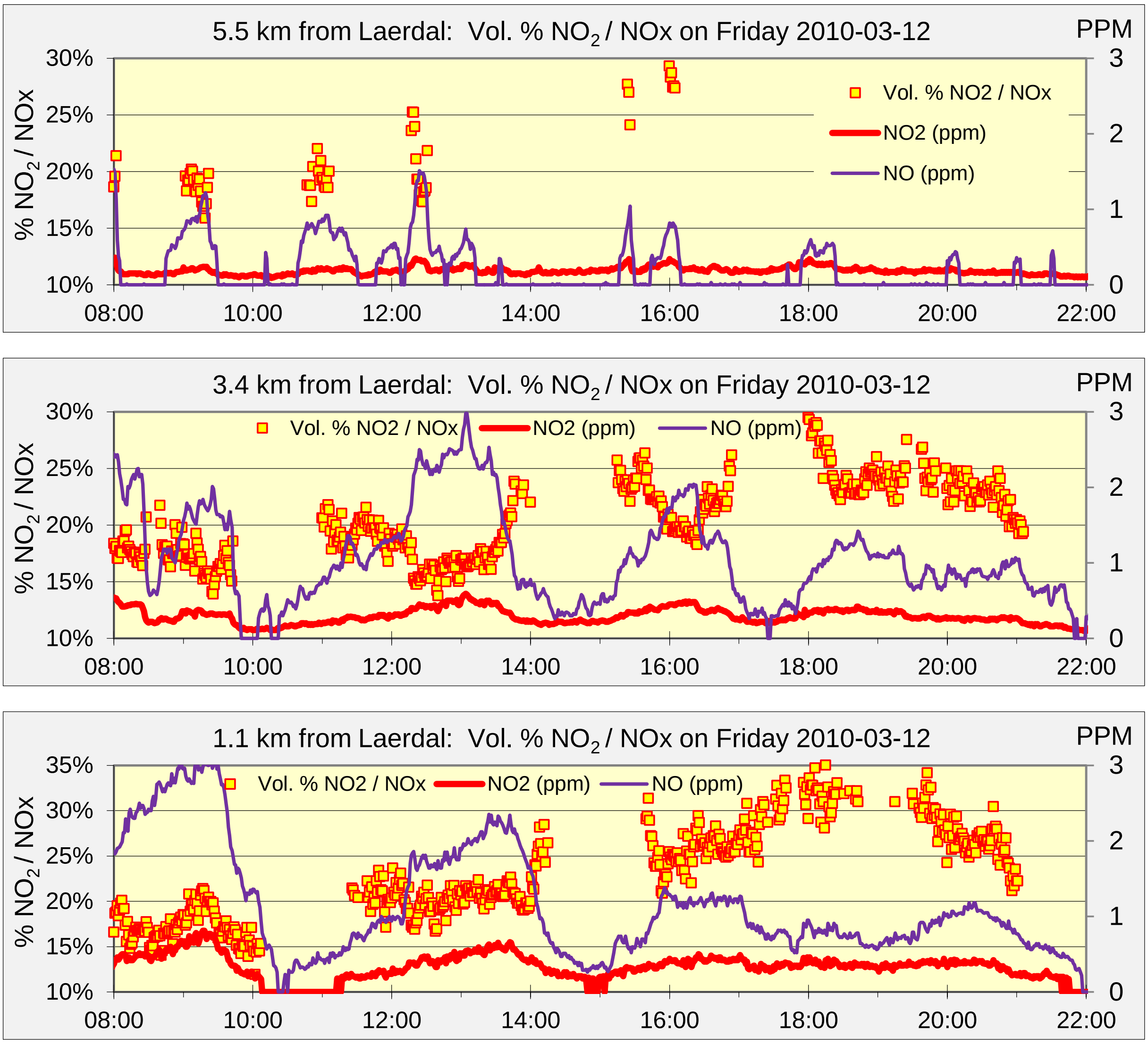


Figure 62: Natural ventilation and average NO_2 / NOx volume ratio on Friday 2010-03-12

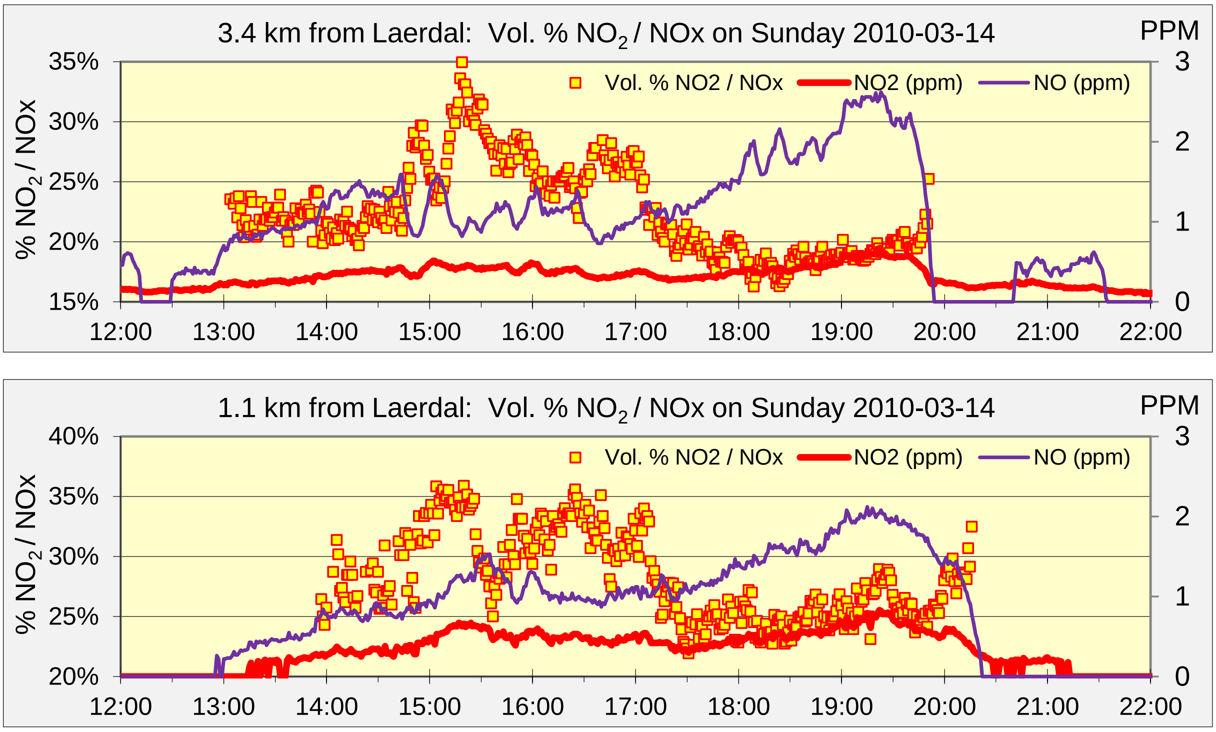


Figure 63: Ventilation level and average NO_2 / NOx volume ratio on Sunday 2010-03-14

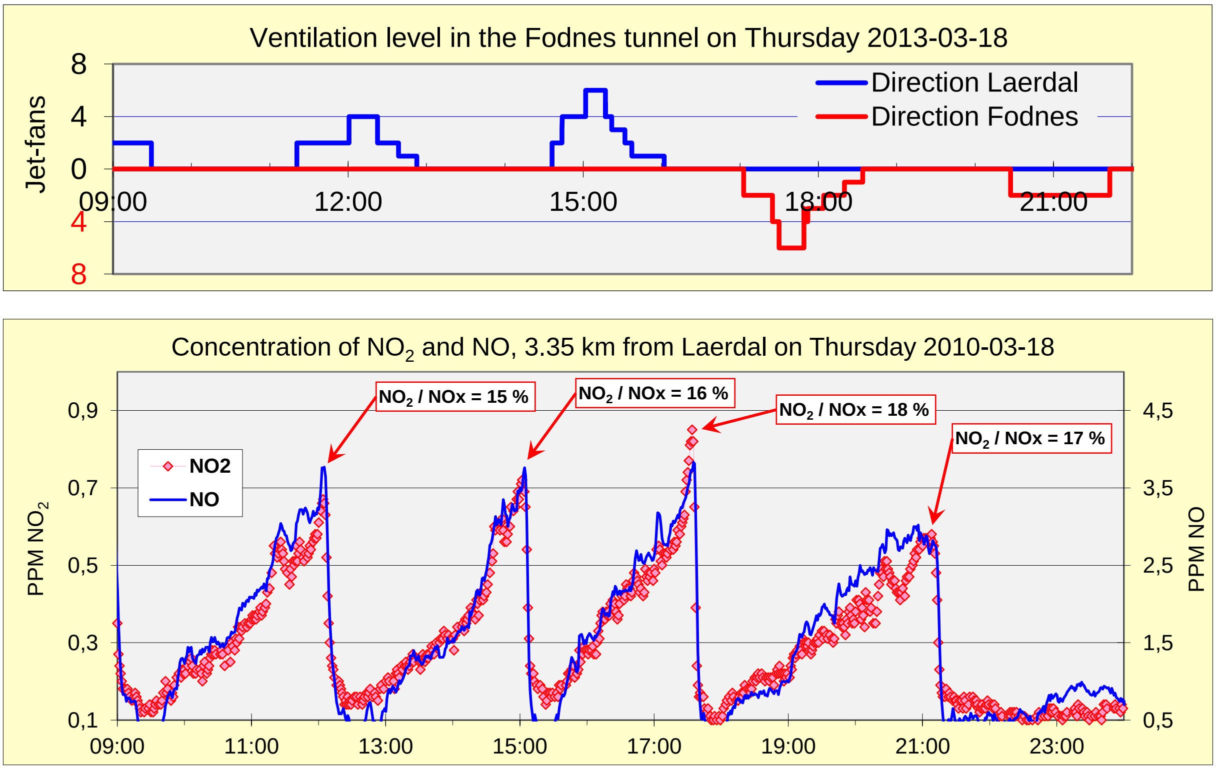


Figure 64: Ventilation level and average NO_2- and NO-concentration on Thursday 2010-03-18

The start parameters for the ventilation system are adjusted to keep the NO_2-concentration below the upper threshold limit. Values above 0.75 ppm in the middle of the tunnel are accepted for maximum 15 minutes before the tunnel is closed. High values are often observed when the ventilation direction is changed during the day. The fans started towards Laerdal at 11:20 and 14:36 in figures 64 and 65. Then the natural ventilation changed before the next start at 17:02 and backflow of air increased the NO_2-concentration in the middle of the tunnel from 0.6 ppm to 0.85 ppm after a few minutes. This triggered start of 100 % ventilation with an average air velocity of 3 m/s towards Fodnes. The highest gas concentration reached the NO_2-sensor at 5.5 km about 12 minutes later.

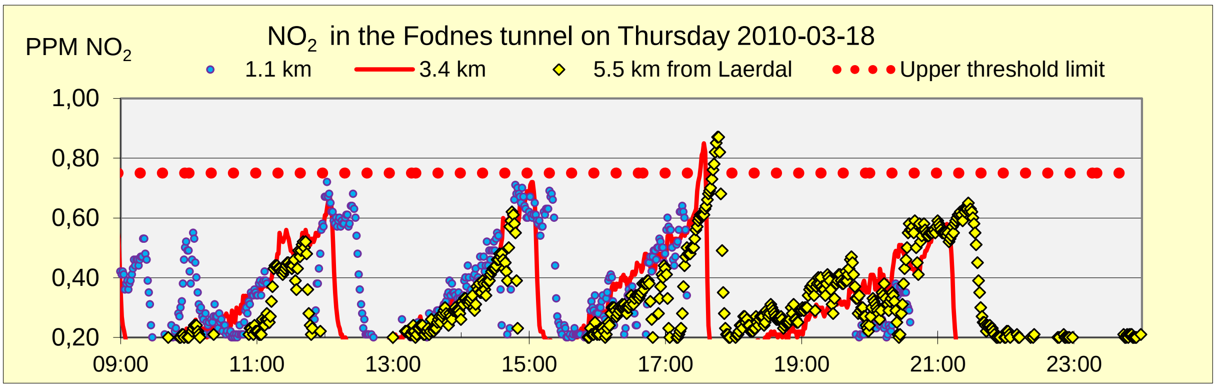


Figure 65: NO_2- concentration on Thursday 2010-03-18

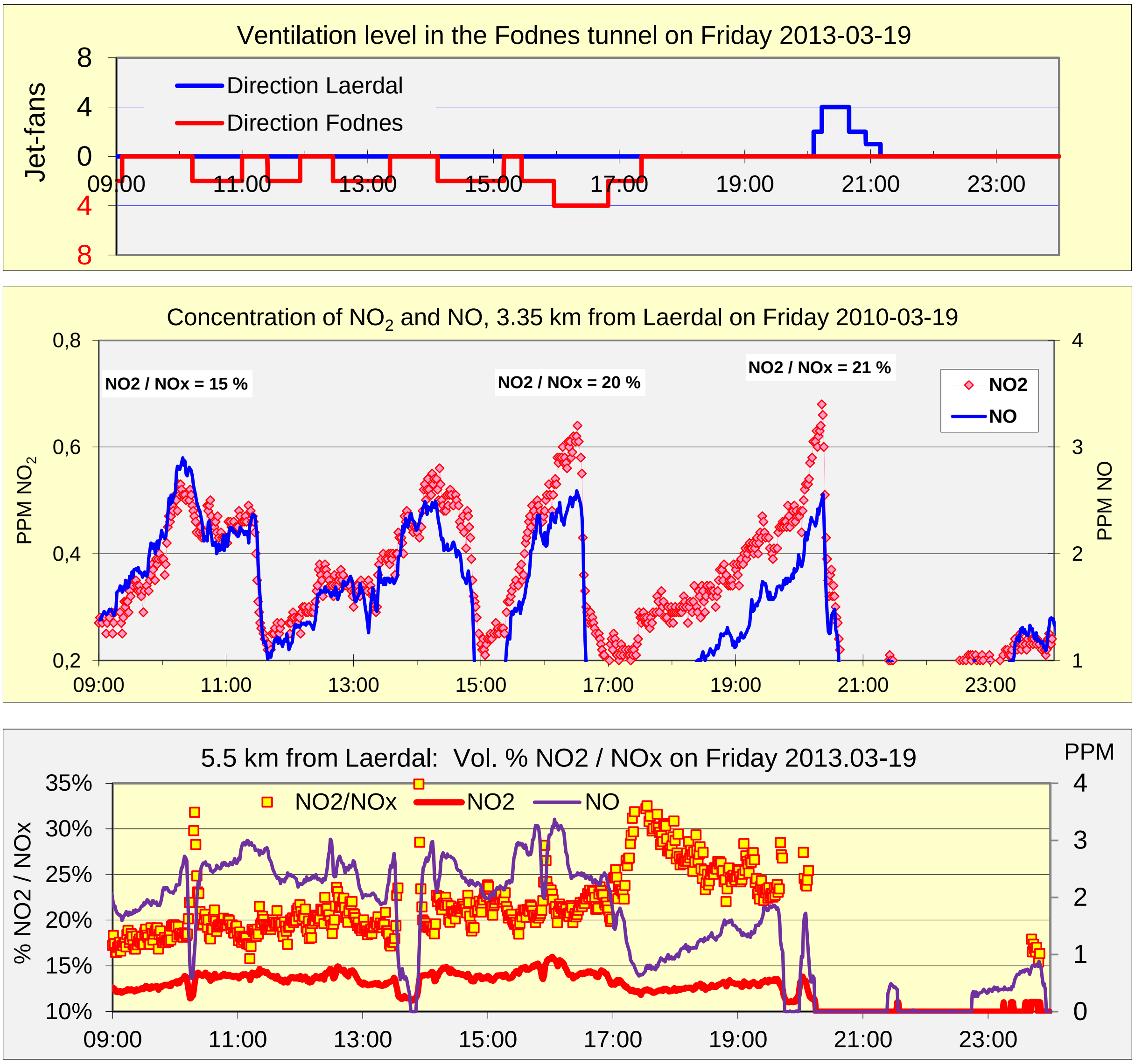


Figure 66: Ventilation level and average NO_2- and NO-concentration on Friday 2010-03-19

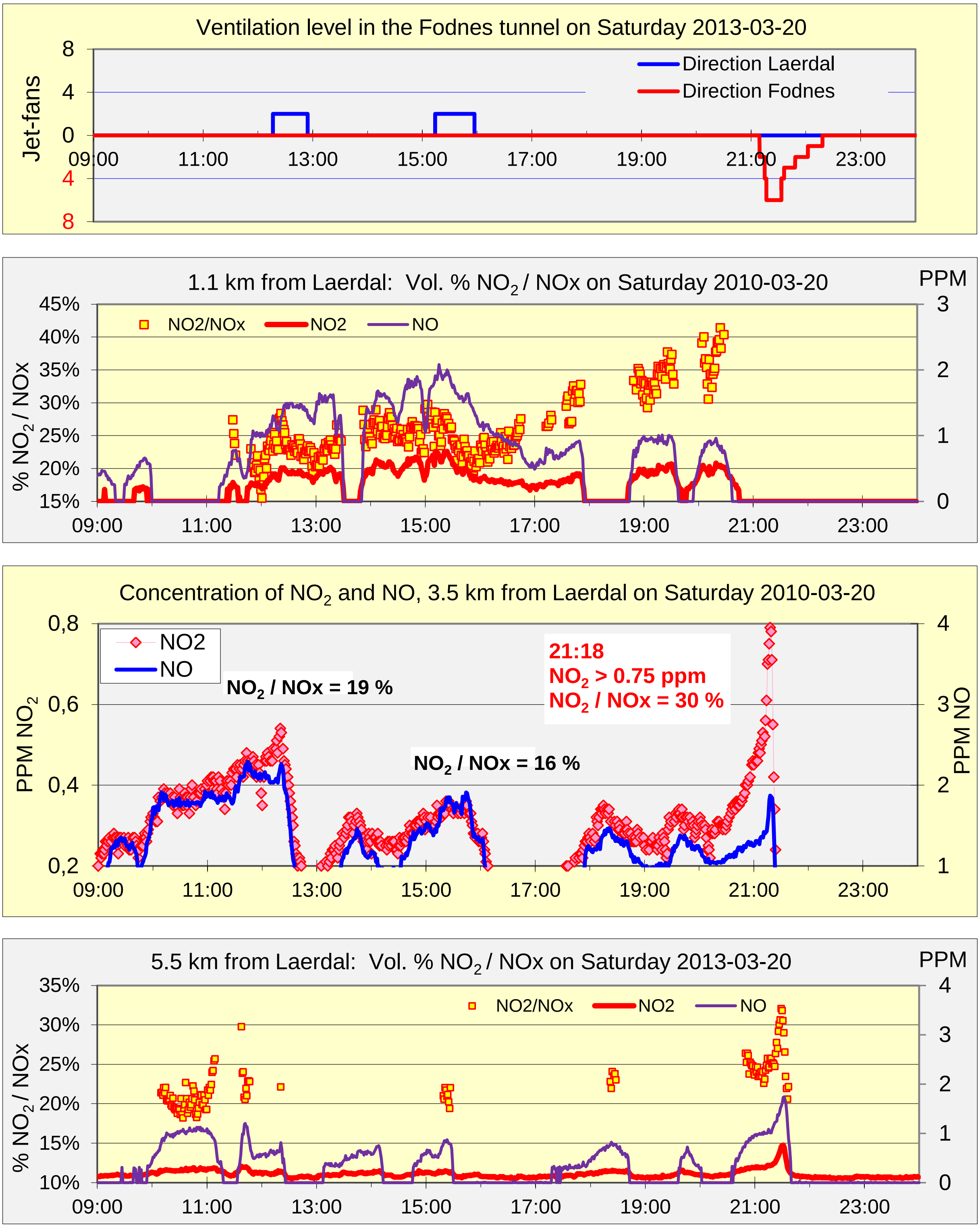


Figure 67: NO_2- and NO-concentration on Saturday 2010-03-20

NO_2/NOx volume ratio over 40 % was observed on Saturday 2013-03-20. Low air velocity and change of natural ventilation direction several times after 17:00 gave almost no replacement of air in the tunnel from 17:00 to 21:00 in figure 67. All the fans started at 21:15 when the NO_2-concentration in the middle of the tunnel reached 0.75 ppm. The NO_2-concentration at 5.5 km increased to 0.76 ppm 16 minutes later and fell below the detection limit at 21:42.

3.2 Observations of NO_2/NOx volume ratio in 2011

Calculations of the average NO_2/NOx-ratio at two points in the Fodnes tunnel for nine weeks from July to September in 2011 are plotted in figure 71. Unfortunately the NO-sensor near Fodnes was not in working order these weeks. The correlation between NO_2/NOx-ratio and the reduced traffic volume of passenger cars from July to September is similar to the observed values in the Laerdal tunnel in figures 39 – 40 on page 33. Traffic of heavy duty vehicles was almost constant from Monday to Friday and low on Saturday and until noon on Sunday. The weekend traffic of passenger cars started on Friday afternoon and gave the highest NO_2/NOx volume ratio in this period. The lowest average NO_2/NOx-values from Monday to Thursday were about 5 % higher than in the Laerdal tunnel (figure 52 on page 40).

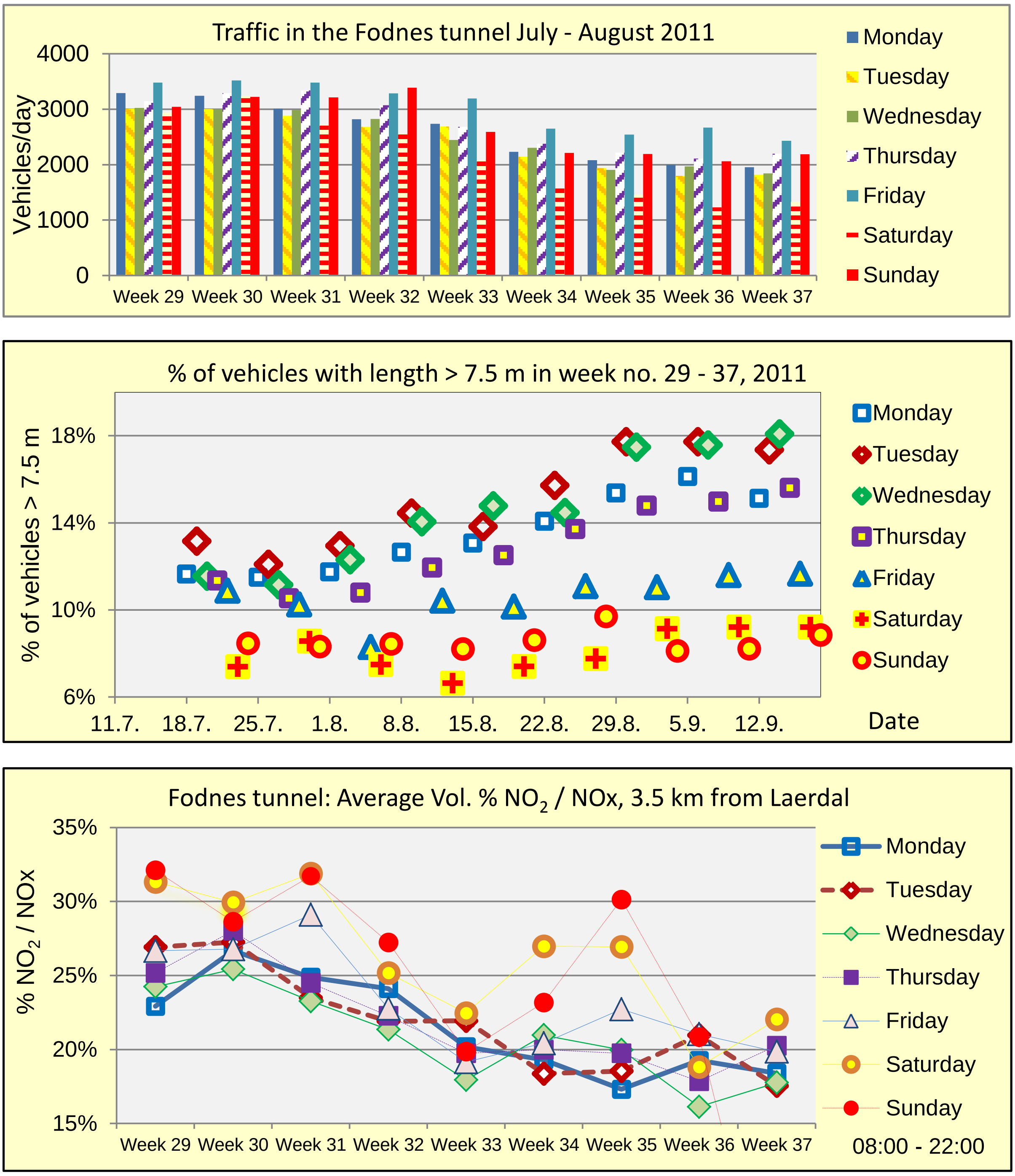


Figure 68: Variations in traffic and NO_2 / NOx volume ratio from week no. 29 to week no 37 in 2011

3.3 Observations of NO_2/NOx volume ratio in 2013

Normal heavy duty traffic around 15 – 20 % in March 2013 gave NO_2/NOx volume ratios near 15 %. Few heavy duty vehicles in the weekends and during the Easter holidays gave 10 – 20 % higher values. Cold weather and high natural air velocity gave low average NO-oxidation from the middle of the tunnel to the sensors near Fodnes in March – April this year.

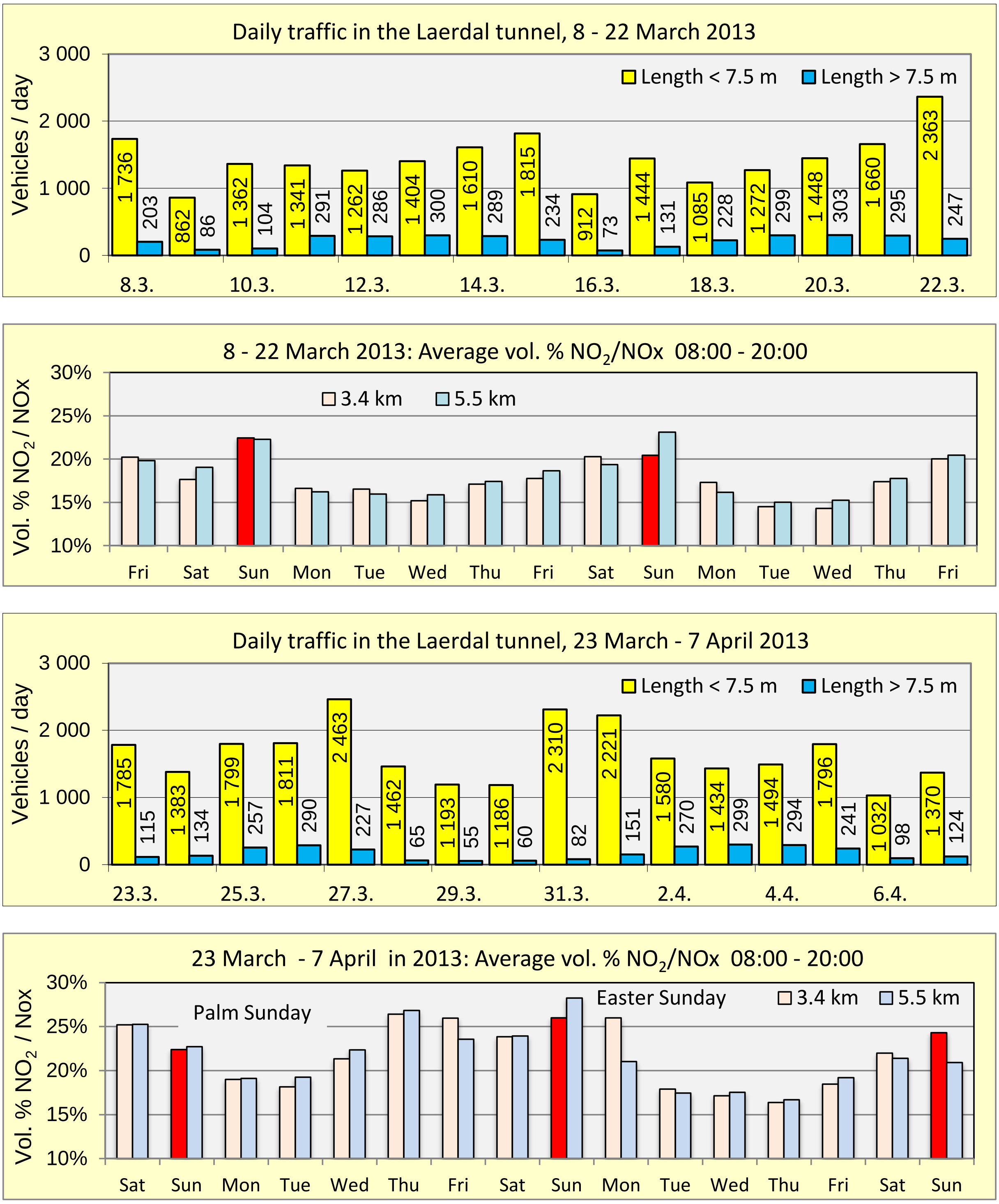


Figure 69: Variations in traffic and NO_2 / NOx volume ratio in March – April 2013

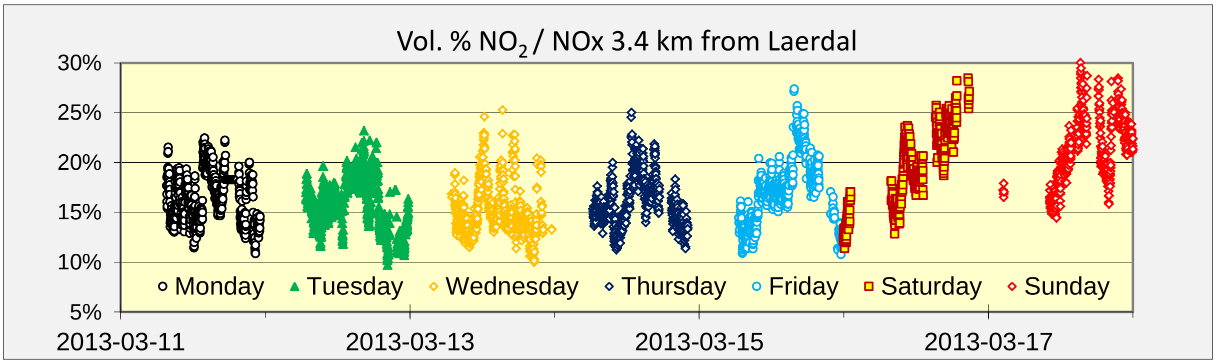


Figure 70: Daily variations of the NO_2 / NOx volume ratio during week no. 11 in 2013

Normal variations of the NO_2/NOx volume ratio in the middle of the Fodnes tunnel during one week are plotted in figure 70. Values below 10 % were observed when the traffic was dominated by heavy duty vehicles. Detailed observations during six days in March are given on the next pages.

Figure 71 and 72: Wednesday 2013-03-13 and 2913-03-27

15 % heavy duty vehicles gave NO_2/NOx ratio variations around 15 % on Wednesday 13 March. Similar values were observed in the morning of Wednesday two weeks later. Doubled traffic of passenger cars in the afternoon lifted the NO_2/NOx volume ratio to 25 – 30 %. 0.4 ppm NO_2 in the middle of the tunnel started two fans towards Fodnes 10:53 in figure 72. Average air velocity around 1.0 m/s was sufficient until the NO_2-level in the middle of the tunnel reached 0.6 ppm 14:43 and three new fans started.

Figure 73 and 74: Friday 2013-03-08 and 2913-03-15

Two jet-fans gave sufficient ventilation on Friday 2013-03-08. The fans started four times when the NO_2- concentration reached 0.40 ppm at 3.4 km. The last start at 18:00 was caused by 0.60 ppm NO_2 at 5.5 km. The NO_2/NOx volume ratio was near 15 % in the morning and increased to over 20 % from 11:00 to 13:00. Values near 30 % were observed several times in the afternoon when the number of heavy duty vehicles was low. The same tendency was observed on Friday in the following week in figure 74.

Figure 75: Saturday 2013-03-23

Low traffic of heavy duty vehicles gave the highest NO_2/NOx volume ratios this week. Values around 30 % were observed several times at 3.4 km and 5.5 km. The production of NO_2 from oxidation was negligible because the NO-concentration in the south half of the tunnel was below 1.0 ppm and the average air velocity was over 1.0 m/s.

Figure 76: Easter Sunday 2013-03-31

Easter Sunday had the lowest traffic of heavy duty vehicles in this period with only 3 % average. Variations of NO_2/NOx volume ratios between 30 and 35 % were observed from 13:00 to 18:30. The values are slightly higher than the values at 9.4 km in the Laerdal tunnel (figure 57 on page 43).

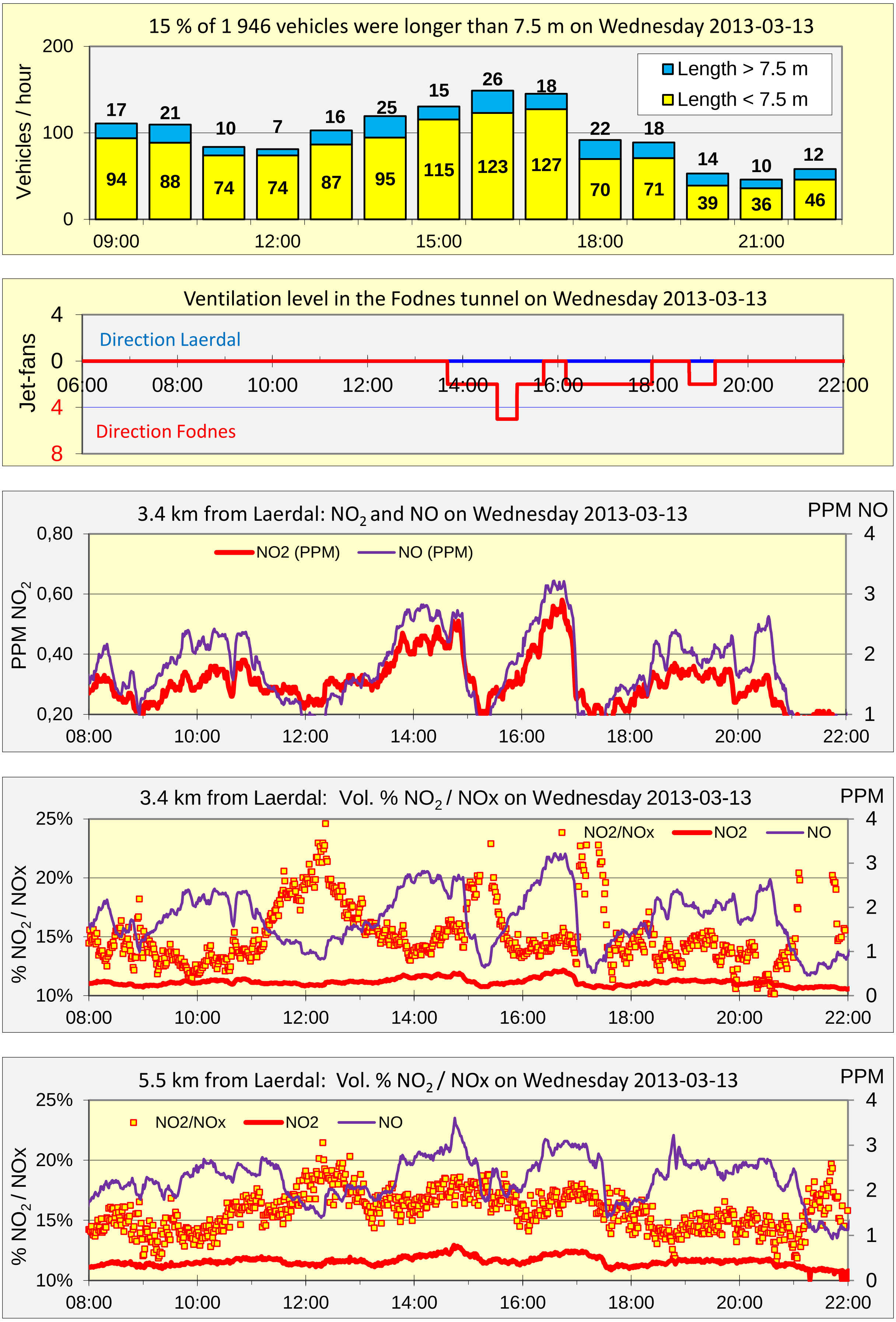


Figure 71: Ventilation and NO_2 / NOx volume ratio on Wednesday 2013-03-13

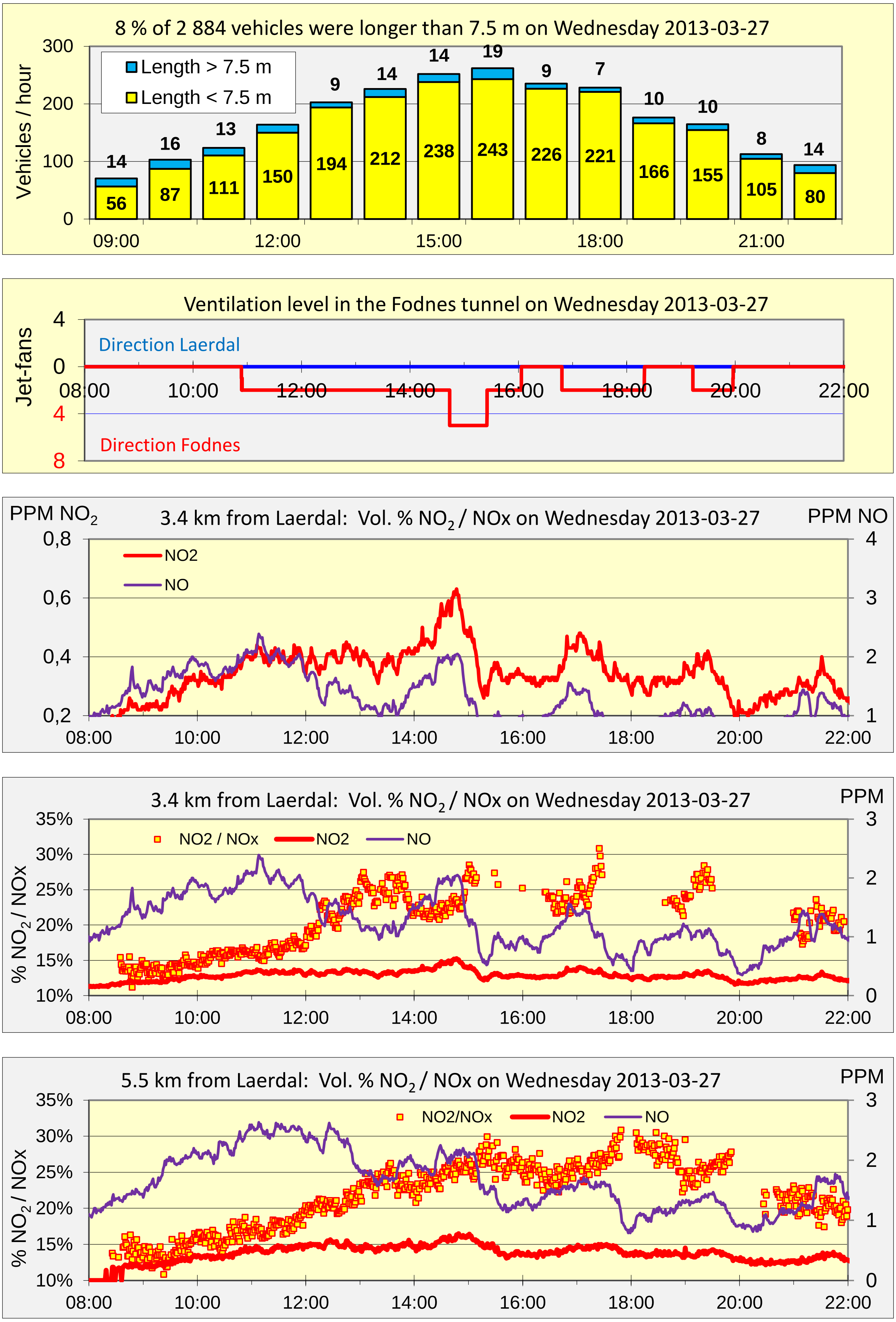


Figure 72: Ventilation level and NO_2 / NOx volume ratio on Wednesday 2013-03-27

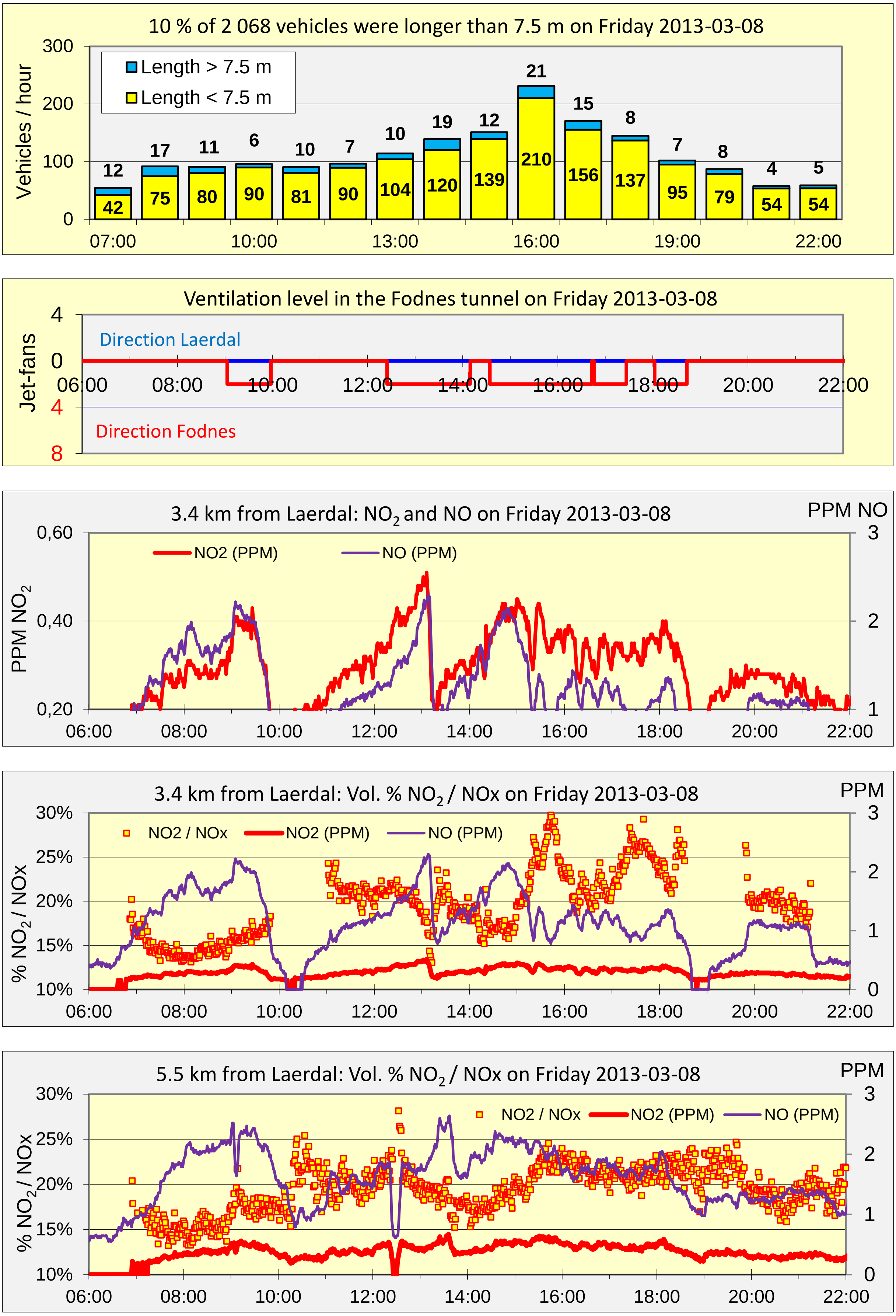


Figure 73: Traffic, ventilation and NO$_2$ / NOx volume ratio on Friday 2013-03-08

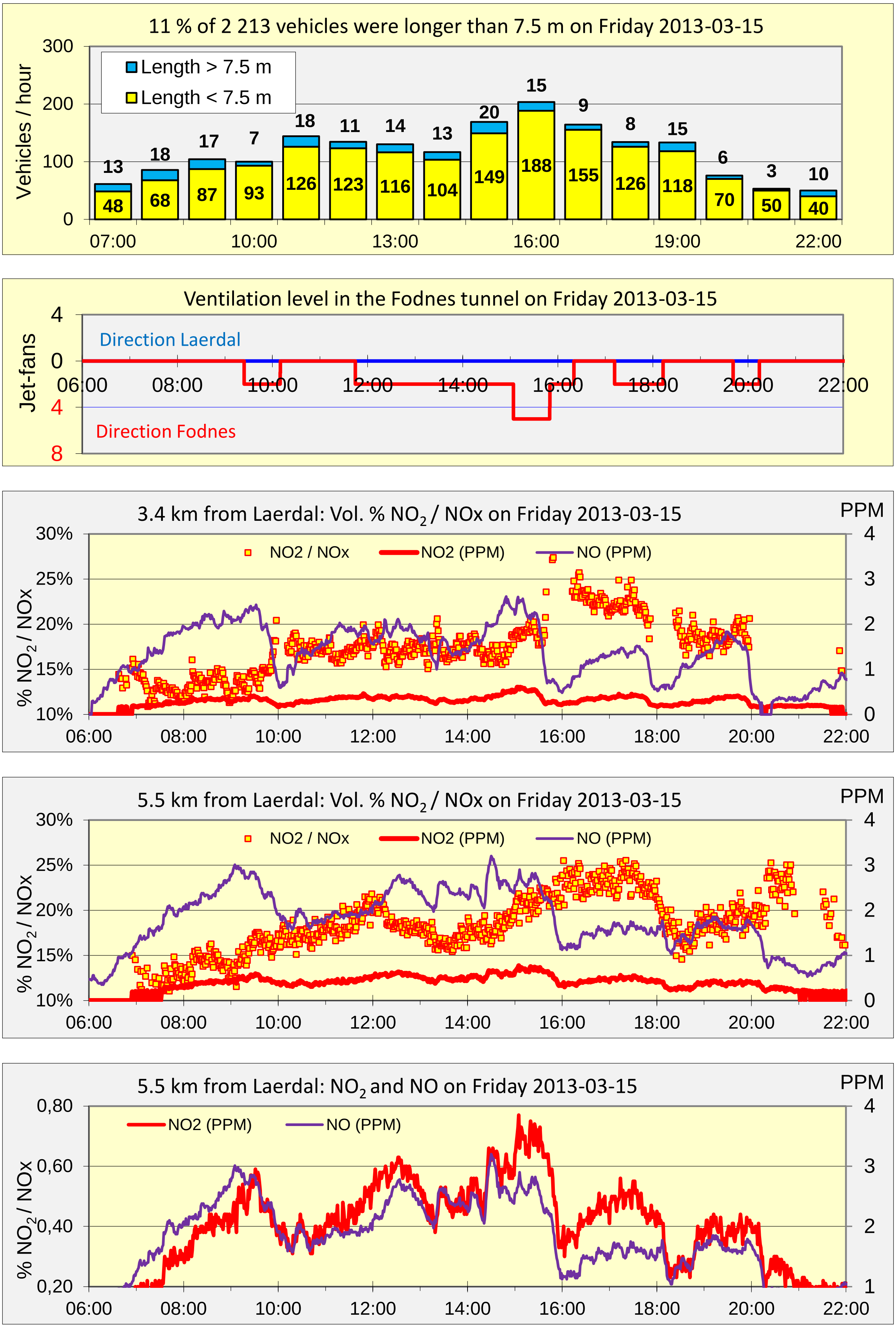
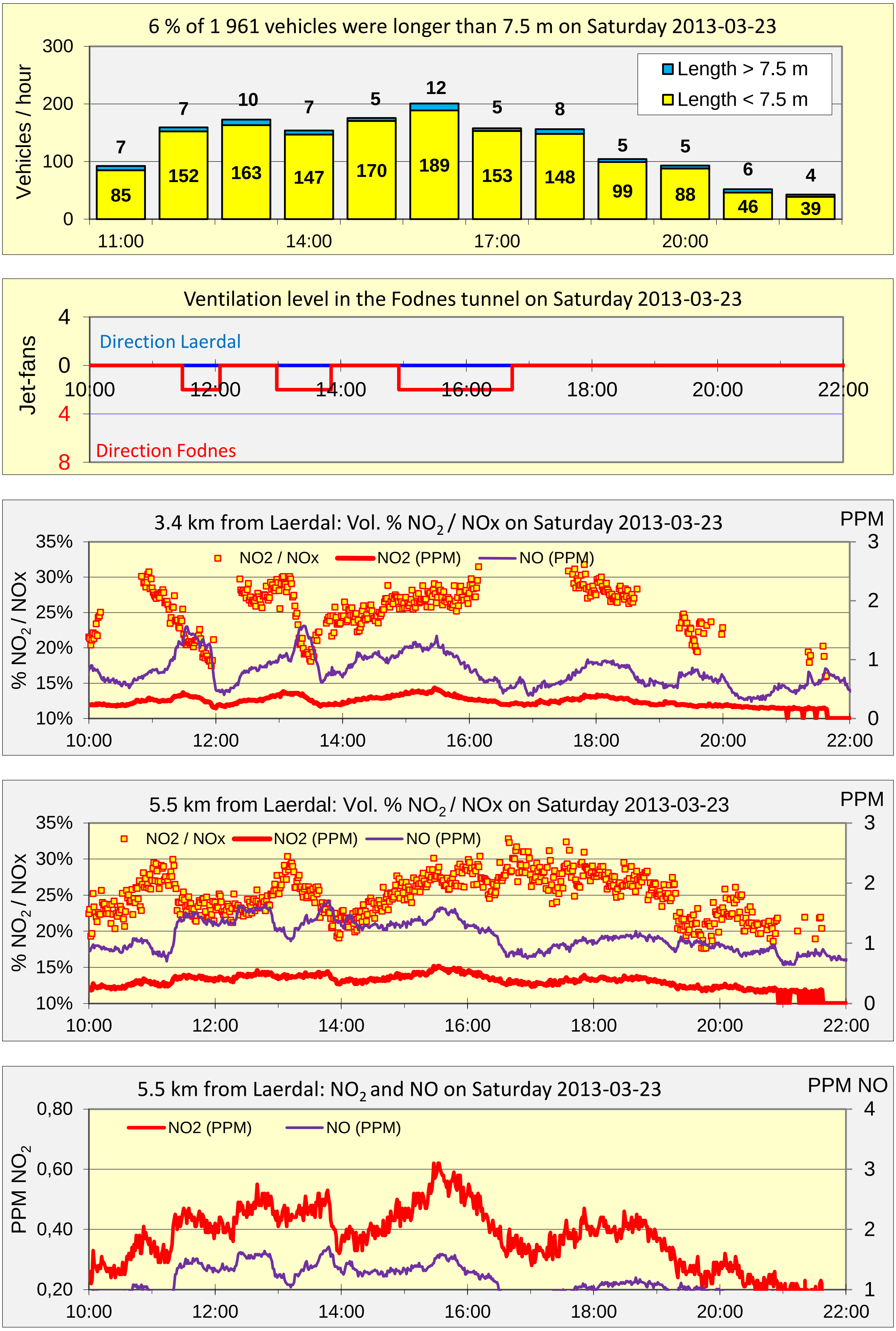


Figure 74: Traffic, ventilation and NO$_2$ / NOx volume ratio on Friday 2013-03-15



6 % of 1 961 vehicles were longer than 7.5 m on Saturday 2013-03-23

Ventilation level in the Fodnes tunnel on Saturday 2013-03-23

3.4 km from Laerdal: Vol. % NO_2 / NOx on Saturday 2013-03-23

5.5 km from Laerdal: Vol. % NO_2 / NOx on Saturday 2013-03-23

5.5 km from Laerdal: NO_2 and NO on Saturday 2013-03-23

Figure 75: Ventilation and NO_2 / NOx volume ratio on Saturday 2013-03-23

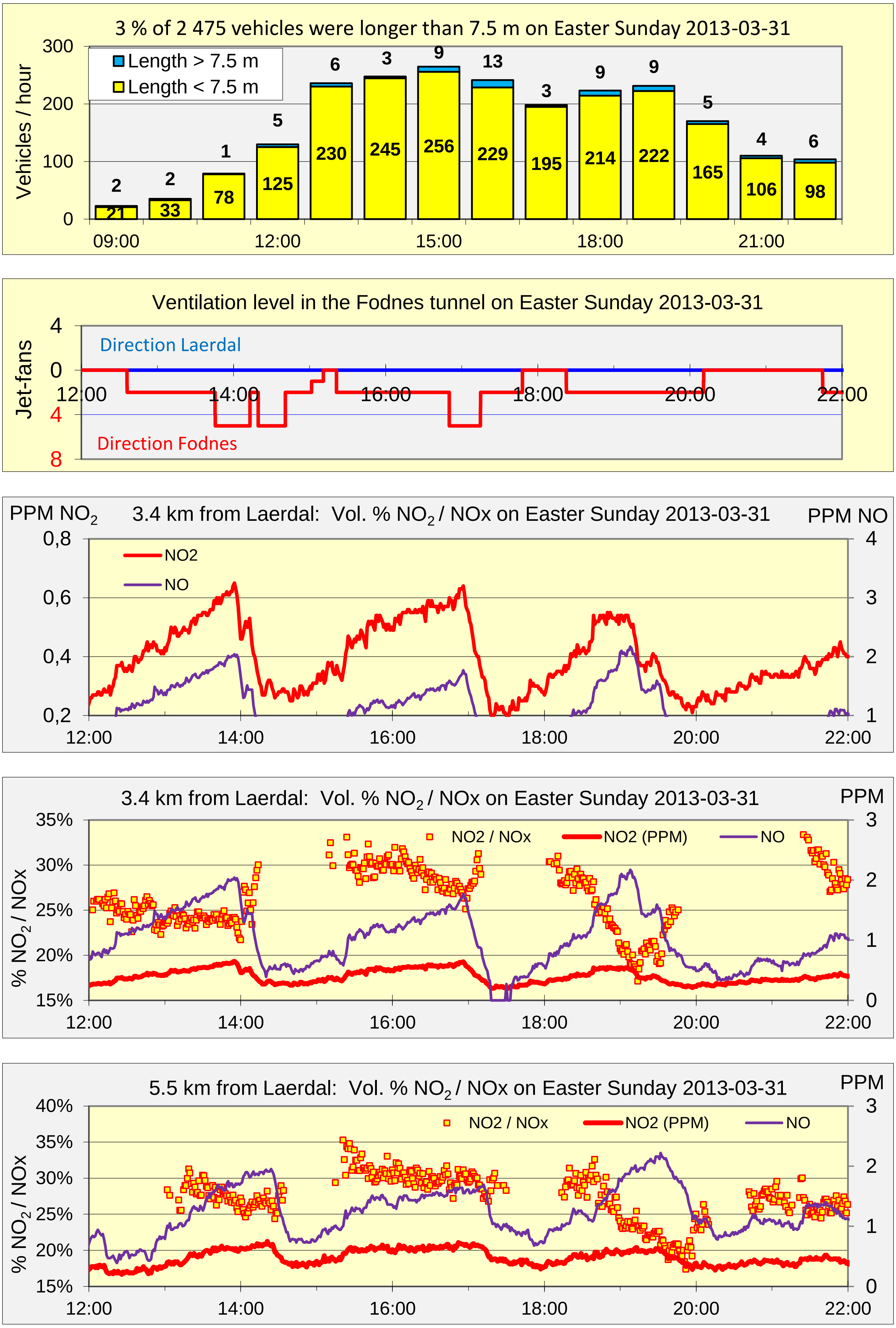


Figure 76: Ventilation level and NO$_2$ / NOx volume ratio on Easter Sunday 2013-03-31

4 Observations of PM_{10} and NOx in the Knappe tunnel in Bergen

4.1 Particulate matters (PM) and relative humidity (Rh)

The Knappe tunnel is a 2.5 km long city tunnel with two tubes on a ring road outside Bergen centre. The average daily traffic in 2012 was 9500 vehicles/day in each direction. Only 5 % of the vehicles are longer than 7.5 m. The piston-effect from vehicles is giving sufficient ventilation without start of jet-fans.

The tunnel has two PM-meters with 300 m distance in the north direction and with 950 m distance in the south direction. Typical PM_{10}-variations and air velocity in both tubes in January 2011 are plotted in figure 77. Observed values from a week with similar traffic density in September 2011 are plotted in figure 78 on the next page. The air velocity in the south part of the tunnel is about 2 m/s higher than the values in the diagram because of the on/off ramps in the middle of the tunnel. (See length profile at page 14).

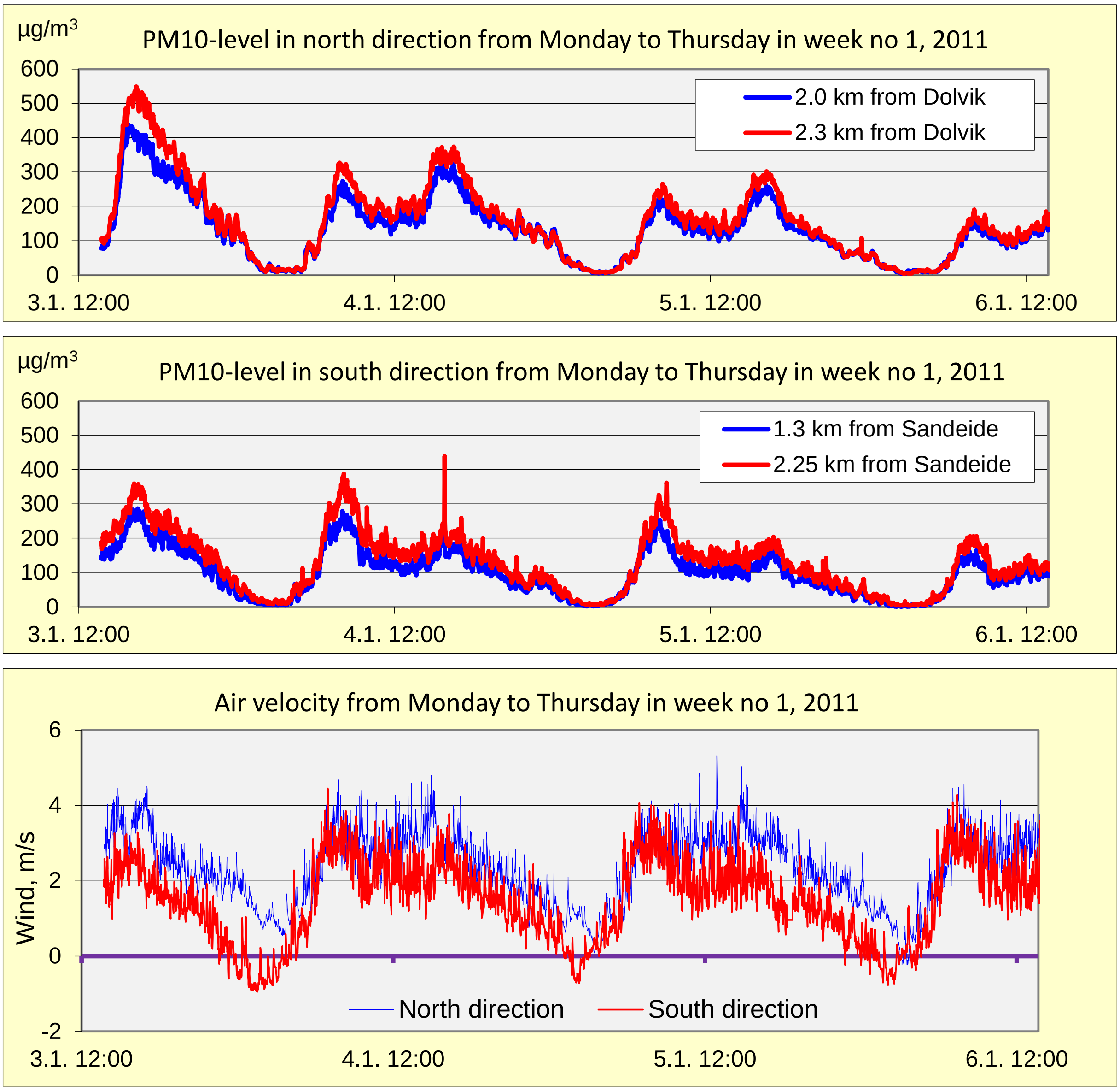


Figure 77: PM_{10}-values and air velocity in the Knappe tunnel in January 2011

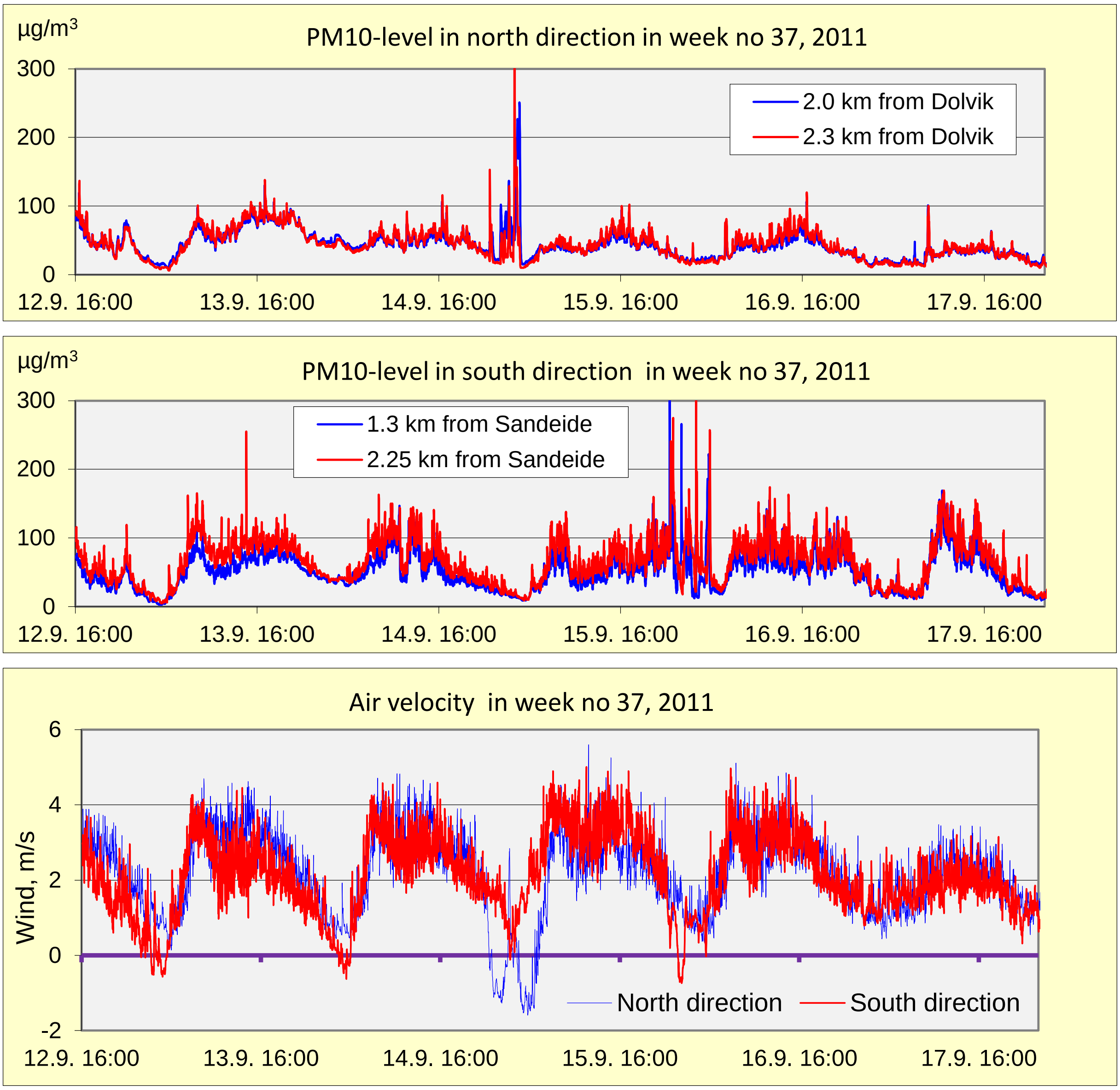


Figure 78: PM_{10}-values and air velocity in the Knappe tunnel in September 2011

From the great variations in PM10-values from one day to the next in week no 1 and 37, it is clear that the predominant portion of PM_{10} comes from road dust and not from car exhaust. The PM_{10}-level varies with air velocity and traffic density. However, the daily variations of the PM_{10}-level are not proportional to the amount of traffic and do not increase according to the driven distance from the tunnel entrance . For long periods there is almost no detectable change of dust-level between the two control-points in each tube.

Use of studded winter tyres in Norway is causing a great difference in PM10-values between summer and winter months. About 1/5 of the cars in Bergen are using studded tyres from November to March[18].

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[18] Statens vegvesen&Bergen kommune: Luftkvalitet i Bergen 2010 (March 2011)

The majority of cars have travelled at least five minutes before entering the Knappe tunnel. Therefore the influence of cold start has been assumed to be low. So far no evidence has been found for a higher smoke production from the average car engine at low temperatures.

Shifting weather conditions with periods of cold and dry air is giving the highest values of particulate matters in Norwegian tunnels. The lowest PM-values are often found at the end of a rainy period when the relative humidity in the tunnel air is over 90 %. An example of high PM10-values at the end of a cold and dry period in January 2012 is given in figure 79. Two weeks later the PM_{10}-level had fallen to the same low level as in September 2011.

At high relative humidity, H_2O-molecules are absorbed by small dust particles, and the weight of these particles will increase. Wet dust particles are deposited on all available surfaces in the tunnel. When the weather changes and the evaporation rate wins over condensation, the small particles will start flying again in the turbulence and wind from vehicles. In periods with high PM_{10}-concentrations, there is a significant reduction in the dust-level from morning to afternoon because the traffic is creating sufficient longitudinal wind speed to blow dry particles out of the tunnel during the middle of the day. Low traffic during the night is creating less turbulence and not enough wind speed to have any cleaning effect. In cold and dry weather, the evaporation will continue throughout the night, and the dried dust particles will give a higher PM_{10}-level the next morning when the traffic produces higher longitudinal air speed and enough turbulence to start moving of the particles.

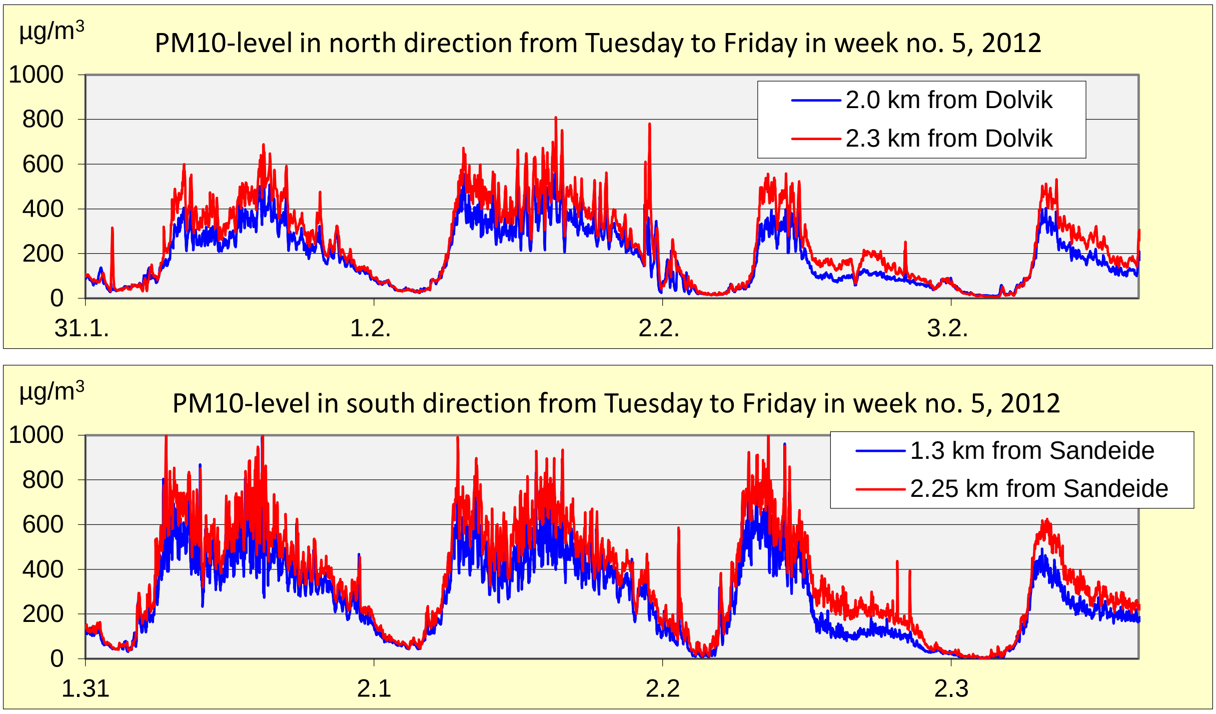

Figure 79: PM_{10}-values in the Knappe tunnel in January 2012

4.2 Observations of NO_2 and NO in January 2012

Sensors for NO and NO_2 in the northbound tube are located 2.2 km from the south entrance of the Knappe tunnel after a nearly horizontal section. The sensors in the southbound tube are located in the 5.9 % uphill section, 2.25 km from the north entrance. A high proportion of the cars are using the tunnel at the same time every day from Monday to Friday. The morning rush in the south direction is of same magnitude as the afternoon rush in the north direction.

Observations of NO_2 and NO in January 2012 are plotted in figure 80 - 82. NO_2-values below 0.20 ppm and NO-values below 0.50 ppm were excluded from the calculation of NO_2/NOx volume ratio because of the unknown accuracy for these values. However, the accuracy of these calculations is low compared with Laerdal and Fodnes tunnels because the observed gas values in the Knappe tunnel were below or near the lower detection limit for long periods.

The weekend NO_2-level in 2012 was too low to calculate any NO_2/NOx ratio with acceptable accuracy.

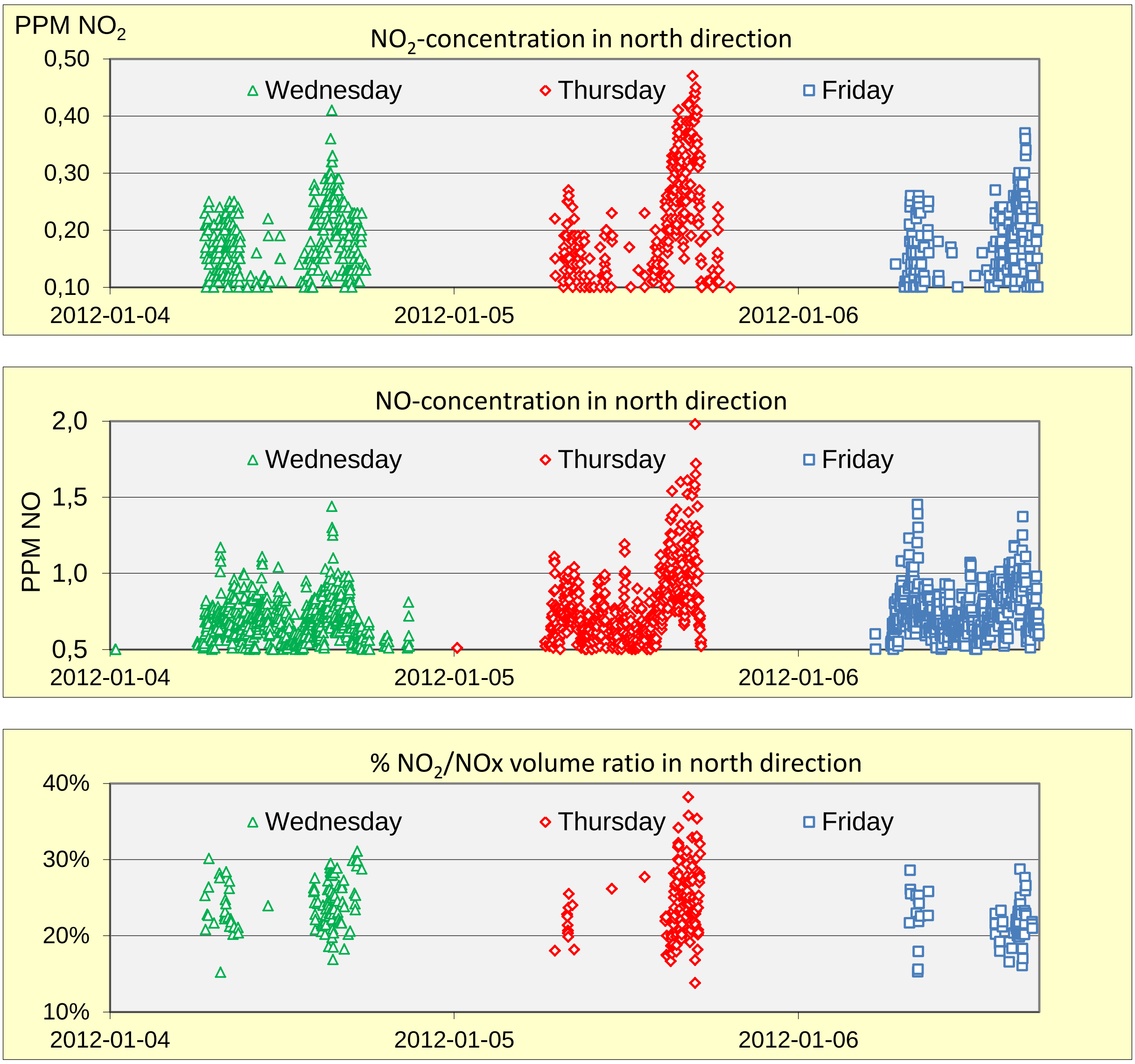

Figure 80: Daily variations of NO_2, NO and NO_2/NOx in the north direction in January 2012

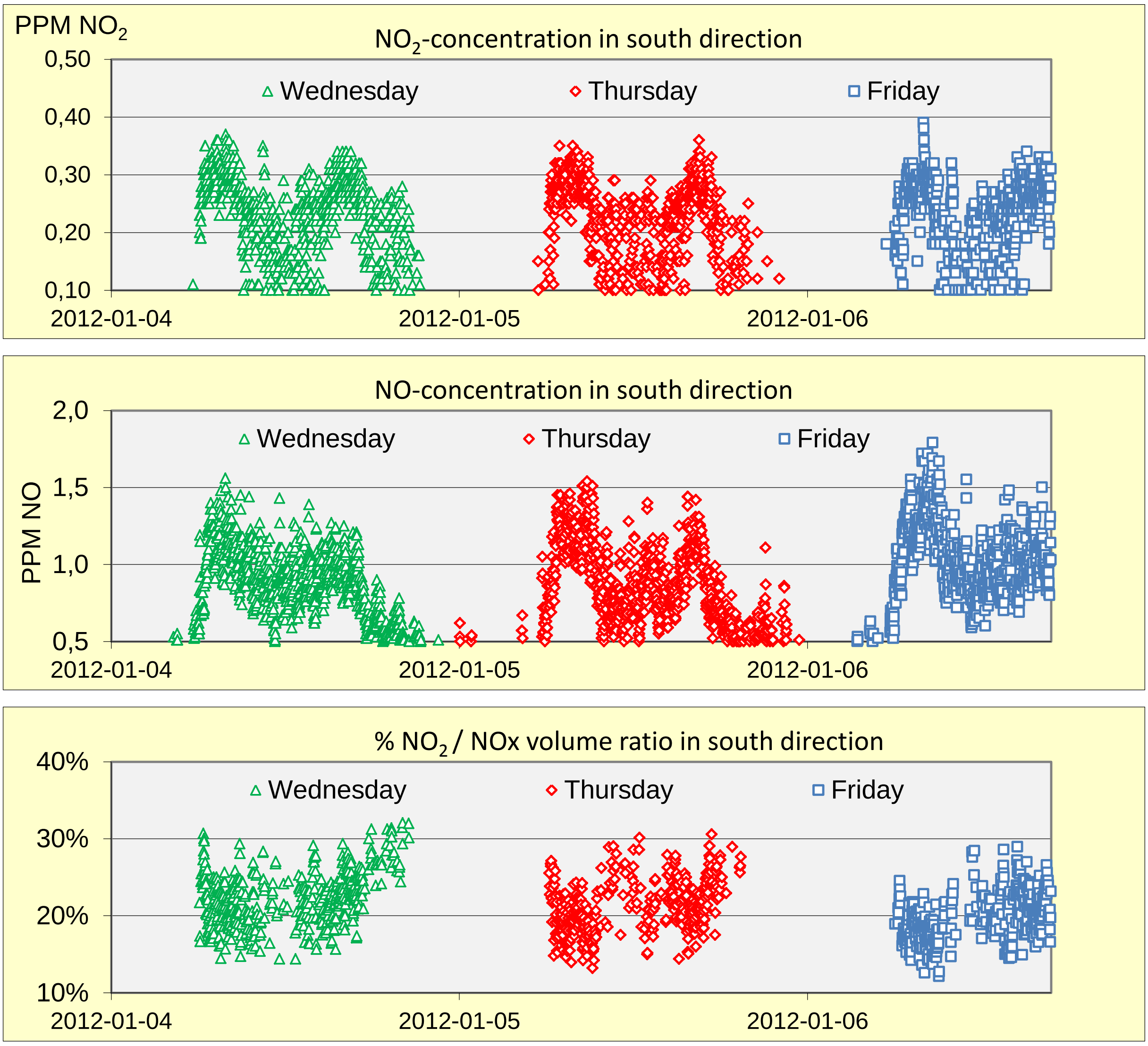

Figure 81: Daily variations of NO_2, NO and NO_2/NOx in the south direction in January 2012

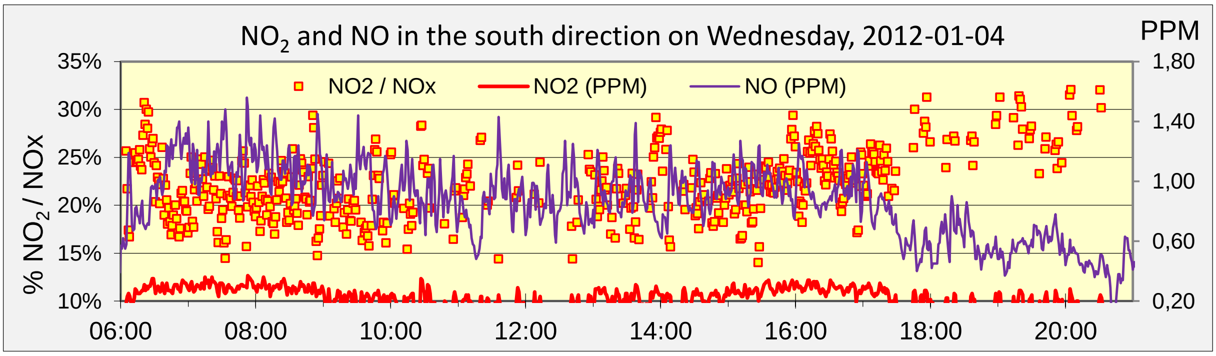

Figure 82: NO_2, NO and NO_2/NOx on Wednesday 2012-01-04

4.3 Observations of NO_2 and NO in March 2013

Variations in the average NO_2/NOx volume ratio from Monday to Friday around 16 to 18 % are near the observed values in the Fodnes tunnel in figure 70 on page 53. The NO-concentration was low on Sunday in figure 83 compared with the values from Monday to Friday because of very few heavy duty vehicles in the week-end.

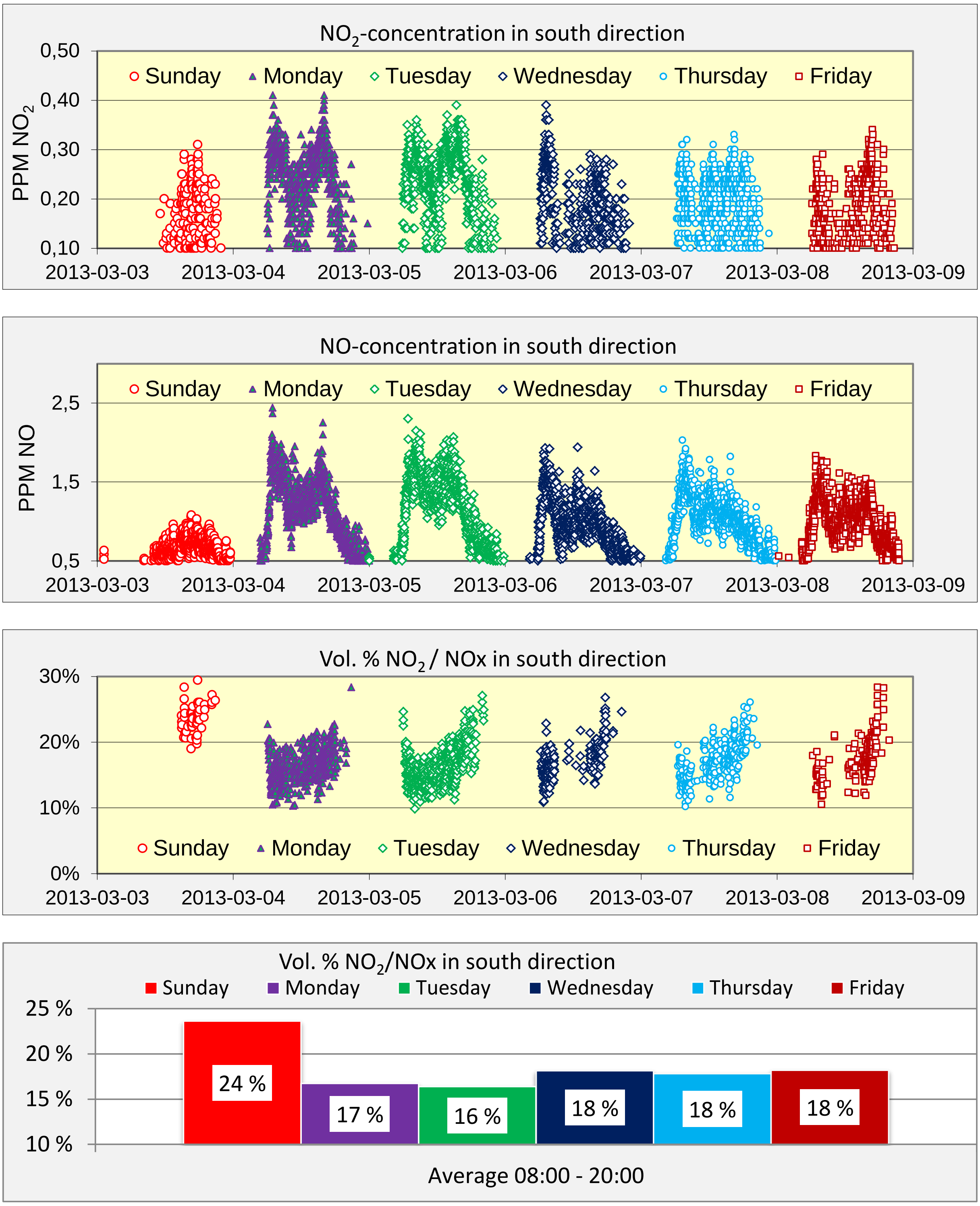

Figure 83: NO_2, NO and average NO_2/NOx in south direction in March 2013

5 Concluding remarks

Heavy duty vehicles (Vehicles > 7.5 m)

- The introduction of diesel particulate filters (DPFs) that meet the Euro 5 requirements for heavy duty vehicles, has given significant reductions of visible air pollution (PM_{10}) in Norwegian tunnels.
- Emission of visible smoke particles from new buses and trucks is negligible when they are driving at constant speed and with warm engines (hot DPFs).
- Road dust is the main contributor to PM_{10} in tunnels. The highest PM_{10}-levels were observed in periods with low air humidity.
- The average NOx-emission from heavy duty vehicles in the Laerdal tunnel is 4.0 l/km. This is 20 % below the emission-factor in the Norwegian design guide for tunnels.
- The average NO_2-emission from heavy duty vehicles is 0.25 l/km (≈ 0.50 g/km)
- The average NO_2/NOx-ratio in the exhaust gas from heavy duty vehicles is probably less than 6 % for vehicles produced after 2009 (Euro 5).

Passenger cars (Vehicles < 7.5 m)

- Diesel has been the dominant fuel type for new passenger cars since 2007. 42 % of the passenger cars in Norway had diesel engines in 2012. However, new cars are driven more than older cars, and the average percentage of diesel-powered passenger cars on Norwegian roads reached 60 % in 2012.
- The average NOx-emission is near 0.30 l/km (≈ 0.44 g/km). This is 100 % over the emission-factor in the Norwegian design guide for tunnels (March 2010).
- The average NO_2-emission from passenger cars is 0.10 l/km (≈ 0.20 g/km)
- The average NO_2/NOx volume ratio has increased from 10 % to over 30 % over the last ten years.
- The average age at the time of scrapping in 2012 was 18.1 years for private cars and 15.0 years for vans[19]. Scrapping of diesel-powered cars from the years 2006 - 2013 (Euro 4 and 5) will give a gradual reduction of the average NO_2-emission from passenger cars from 2020 to 2030.

Appropriate measures

- In order to provide safe control of air quality in long tunnels, the existing gas-sensors for NO must be replaced with new sensors for detection of NO_2.
- The maximum NO-concentration in long tunnels without NO_2-sensors should not be higher than 5 ppm from Friday to Sunday.
- The Draeger Polytron sensor for NO_2 (tunnel variant) has given acceptable accuracy for control of ventilation systems in tunnels.

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[19] www.ssb.no

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ISSN: 1893-1162

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