CTG Italcementi Group

Direzione Laboratori
Laboratorio Materiali, Tecnologie e Additivi

Report n. 24

TUNNEL “UMBERTO I”, IN ROME
Monitoring program results

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Bergamo, 22 April 2008

Summary

This report deals with the results of an environmental monitoring campaign entailing the analysis of NO_x levels registered before and after the renovation work of the tunnel “Umberto I” in Rome, Italy.
The renovation of the tunnel (350 m long), was completed in late August 2007.
Environmental monitoring was accomplished through two campaigns (lasting two weeks each), in July 2007 (before the renovation) and September-October 2007 (after the renovation).
Results of monitoring campaigns highlighted efficient abatement of pollutants by the photocatalytic treatment of the tunnel vault, as evidenced by the lower concentrations fount after the renovation, even considering higher pollution level in Rome, in autumn 2007.
A NO_x reduction of about 20% was calculated in the centre of the tunnel (as an absolute comparison between the two periods) and a NO_x reduction of over 50%, considering the reference data registered in the official stations of the city of Rome (Official Environmental Agency – ARPA).
The duration of the monitoring campaigns performed seems to be considered significant from the statistical point of view, unlike all previous experiments which were carried out on the photocatalytic materials.
This work is the result of a sponsoring action by Italcementi and C.I.M. (Calci Idrate Marcellina), accepted by the Municipality of Rome, for the re-qualification of the most significant (and Historical) tunnel in the city. It represents the first example of en “environmentally friendly” private initiative, for the improvement of quality life, in an Italian city.

INTRODUCTION

Photocatalysis has been applied for over a decade to various materials - among which cementitious binders - to obtain a “self cleaning” and, more recently, “depolluting” effects. In particular, on-going research shows that cement-based materials containing TiO_2 have a good potential in urban pollution control. Examples of pollutants which can be eliminated by the photocatalytic cementitious products are NO_x, SO_x, NH_3, CO, volatile organic carbons (VOCs) such as benzene and toluene, organic chlorides, aldehydes, and polycondensated aromatics.

This technique is particularly effective when wide surfaces (horizontal or vertical) are applied. In this sense, the construction of pavements for busy streets, roads, parking lots, intersections, gas stations and toll gates seems to be the best solution in order to optimize the photocatalytic depollution.

Significant experiences have been recently carried out in Japan, Italy, France, Belgium and the Netherlands (concrete roads and pavements built by means of paving blocks, mainly).

At this point, several possible solutions can be adopted, for a wider use of this environmentally friendly technology which can make in a significant contribution to a healthier life.

Indeed, several cementitious materials and related products are by now widely validated in laboratory. However, the crucial point still seems to be the demonstration of their photocatalytic properties in real conditions. For this reason, some pilot projects, including a monitoring programme for demonstrating the degree of depolluting action (referred to NO_x) by means of photocatalytic cement-based materials, have already been carried out. Due to the high investments for equipment or costs related to the monitoring program management, this activity is still limited to relevant projects or to short duration of measurement, which sometimes means limited quantities of data for an acceptable statistical evaluation.

Furthermore, the variation of local weather conditions must be also considered, so that the complexity of the approach results to be higher.

Two pioneering experiences were carried out in Italy, and relevant NO_x abatement levels were registered in Segrate (a concrete road) and in Calusco (paving blocks).

Another relevant experience has been performed in Bergamo (via Borgo Palazzo, renovation of a main road using paving blocks). In this case, a broader monitoring approach was adopted in order to collect high quantities of data, both before and after the renovation work.

This report describes the first example of a monitoring approach adopted for an indoor application of photocatalytic product in a tunnel.

Indeed, in this case pollution and weather conditions are less variable than in any outdoor, so that it is possible to evaluate the photocatalytic depolluting action with a reduced number of parameters and the interpretation of collected data results to be less complex.

Furthermore, for this special project, the level of lighting can be considered constant, due to the complete substitution of the lighting system – by means of dedicated lamps, having a high amount of UV-A light, as well as the tunnel geometry, of course.

For the above mentioned reasons, the most relevant parameters considered in our evaluation will be:

- Level of pollution (strictly connected to the traffic pollution);
- Wind speed.

This report deals with the results of an environmental monitoring campaign entailing the analysis of NO_x levels registered before and after the renovation work of the tunnel "Umberto I" in Rome, Italy. Before presenting the results, a description of the tunnel and the renovation works will be given.

DESCRIPTION OF THE TUNNEL

The tunnel is located in the centre of Rome (Figure 1) and represents the most famous tunnel in the Capital, very relevant from the road system of the whole city centre. It is situated under the Quirinale Hill, near the Italian Republic President's Building (Quirinale).

The tunnel was built for these (main) reasons:

- To facilitate the road circulation in the centre of Rome;
- To build a direct connection between Via Nazionale and Piazza di Spagna/Via del Tritone, Figures 2 and 3;
- To improve the circulation between the Esquilino district and the Flaminio district;
- To make the circulation more efficient between the Central Railway Station (Termini Station) and the historical centre of Rome.

Its construction started in June 1900 (Figure 4) and the official opening was October 20, 1902.

Its dimensions are: length 347.70 m, width: 17 m, height: 8.5 m.

Its renovation was absolutely necessary, due to the need of substituting the lighting system (lamps) and the electrical lines (according to the current regulations and safety rules), and to the dirtiness of the vaults, coated by an oily thickness of smog, Figure 5.

An official decision concerning the tunnel renovation was taken in May 2007.

After which, a monitoring program to evaluate the current pollution condition, was immediately defined before the starting of the works (programmed in the summer period, in order to minimize the traffic problem in that very congested zone of Rome). According to the plan, works lasted one month (the whole month of August 2007).

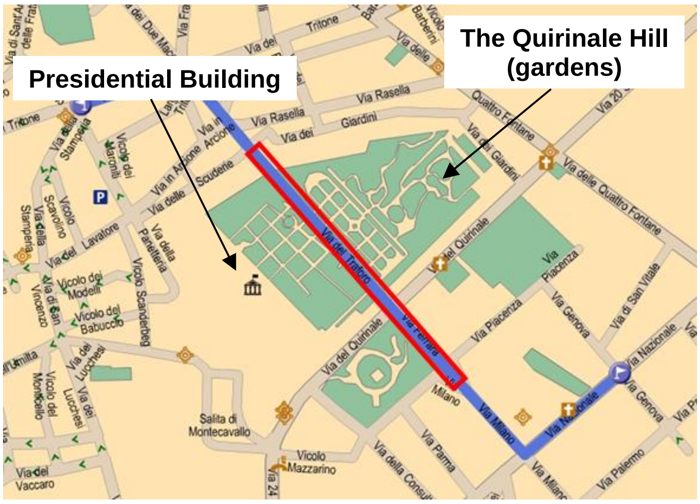


Figure 1 – Tunnel “Umberto I” in Rome – Position

Figure 2 – Entrance – Via Nazionale

Figure 3 – Entrance – Via del Tritone

Figure 4 – Construction of the tunnel (1900-1902)

The first step of the work included the removal of the existing lighting system, Figure 6. Then, an accurate washing/cleaning of the vault was carried out before the installation of the electrical line and of the new lighting system, Figure 7. Afterwards, the new photocatalytic paint was applied by airless spraying technique, in two layers (primer + paint), Figure 8. All these steps were completed in four weeks.

The tunnel was officially opened in September 8th, 2007, at 6.00 p.m. with the participation of the Mayor of Rome, Figure 9.

Figure 5 – Lighting conditions of the tunnel, before the renovation

Figure 6 – Removal of existing lighting system

Figure 7 – Washing and cleaning of the vault

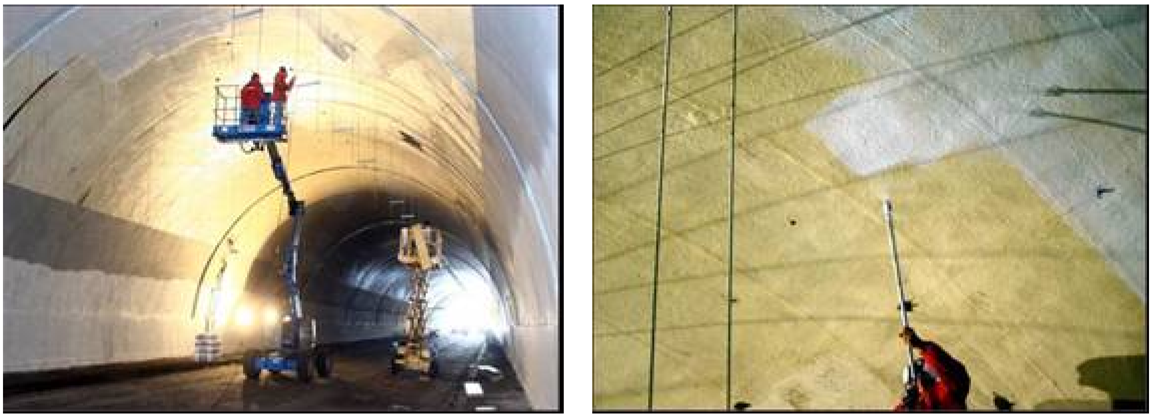


Figure 8 – Painting of the tunnel

Figure 9 – Inauguration of the tunnel (September 9, 2007)

For the tunnel renovation, a photocatalytic paint was applied on the vault (a grey paint up to 1.8 m of height and a white paint for the remaining surface), for a total of 9000 m^2, Figure 10.
The lighting system was designed by a partner Company of Italcementi and C.I.M. (Disano Group) and required the use of experimental data provided by CTG Laboratories, Figure 11, in order to determine the adequate level of UV lighting, necessary for the activation of the photocatalytic reactions along the tunnel, Figure 12.

For this purpose, two types of lamp were chosen and installed in the tunnel, optimizing the position even considering the safety aspects related to the height of pedestrians walking through the tunnel, Figures 13 and 14.

It is important to point out that the choice of the lighting system and the equipment to be used for is strictly connected to the tunnel geometry, to the depollution degree which is to be obtained and to the management costs from the energy (power consumption) point of view. Some specific considerations on this point can be received from Disano Group.

Figure 10 – The tunnel before re-opening

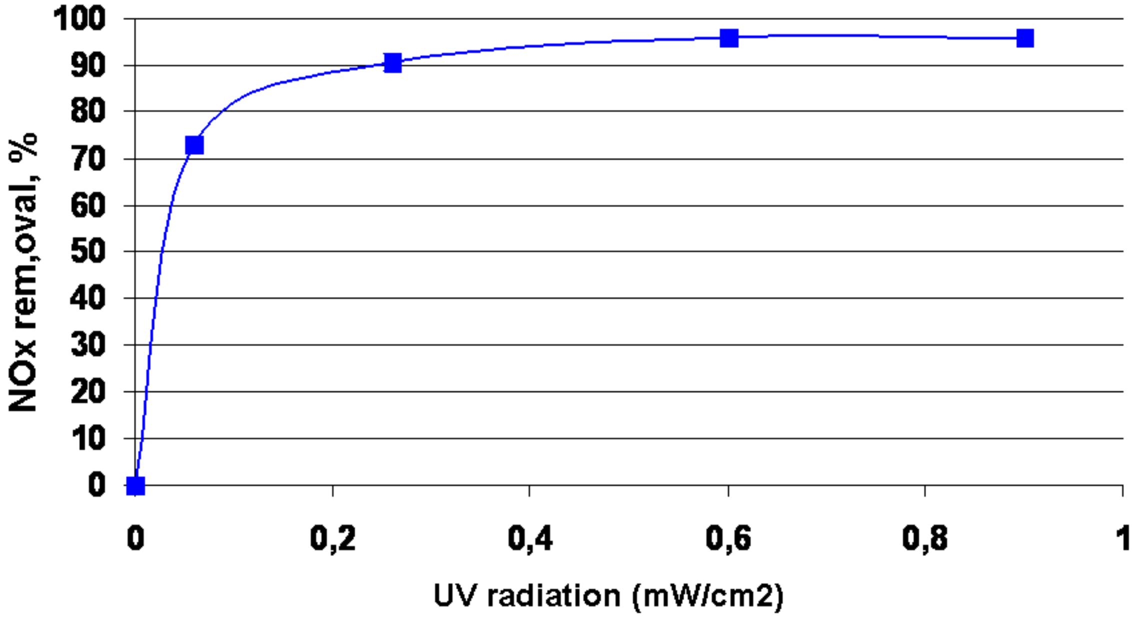


Figure 11 – Reference curve for NO_x abatement (CTG data)

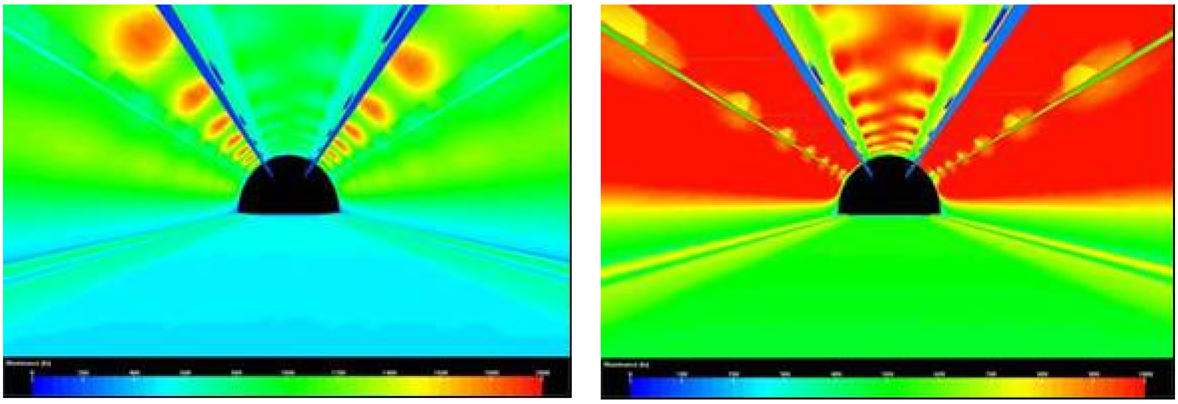


Figure 12 – Simulation design of lighting system: visible light irradiation (left) and UV-light irradiation (right)

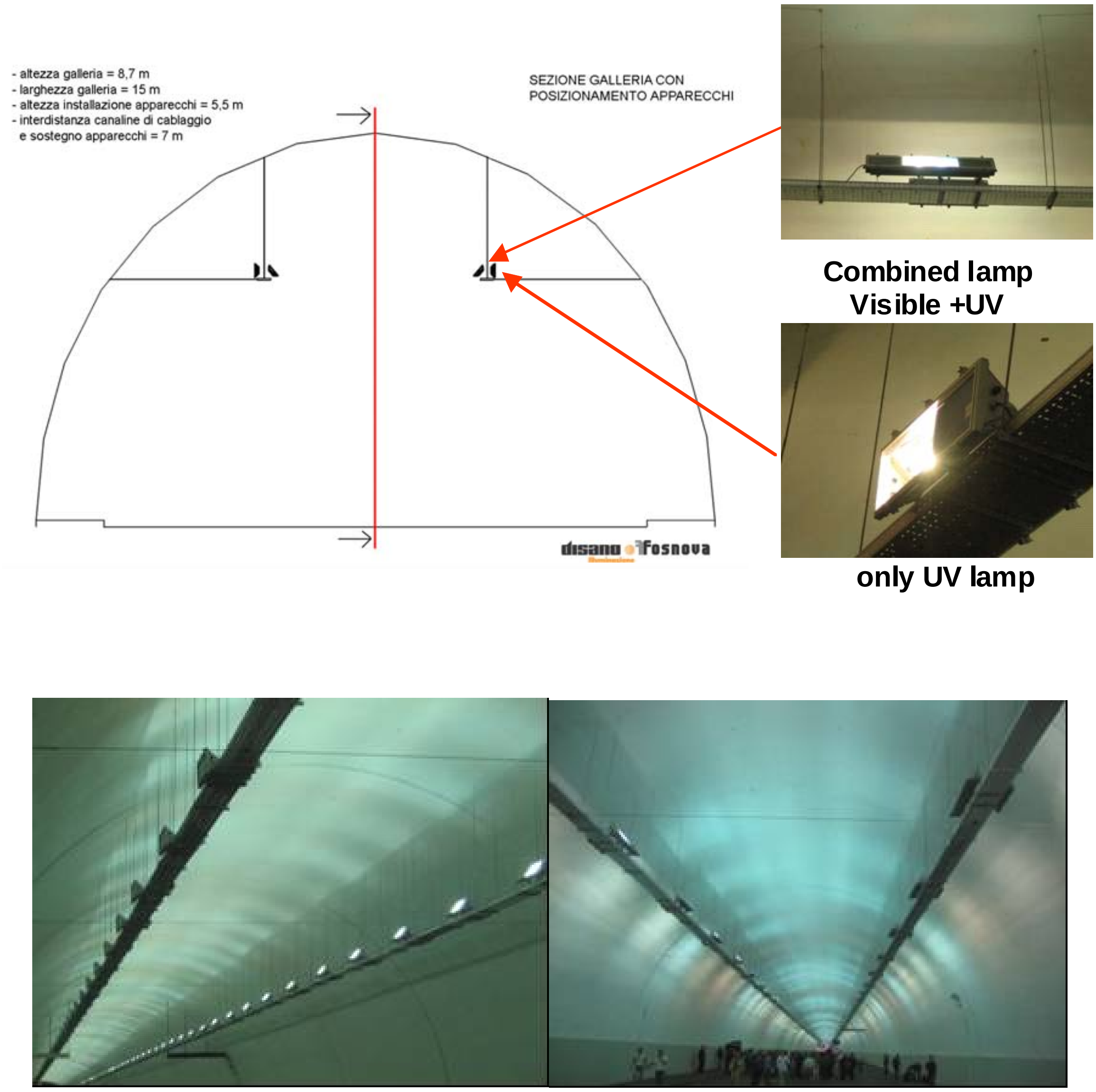
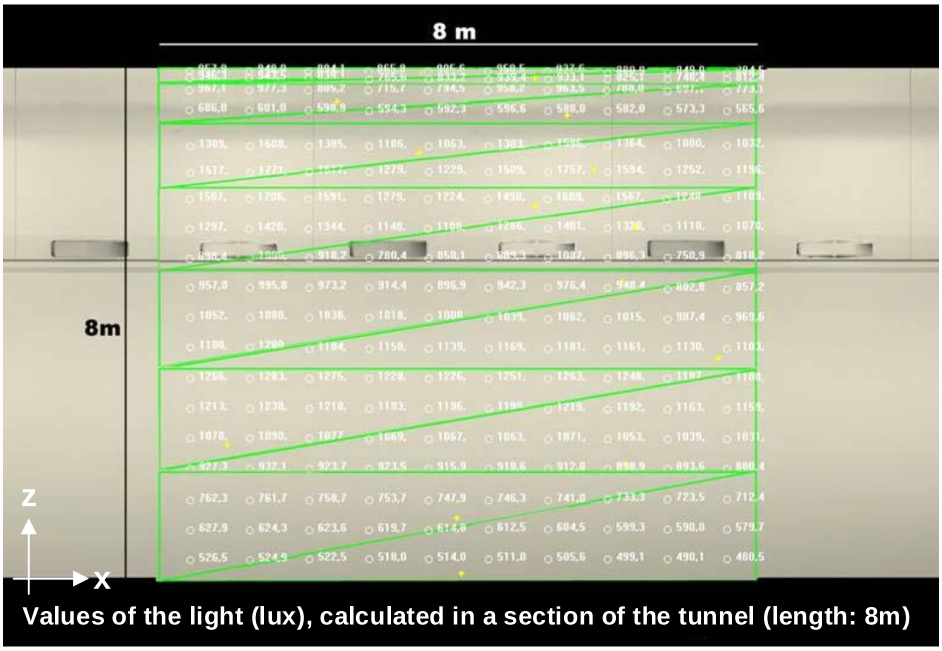


Figure 13 – Position and types of lamp



Values of the light (lux), calculated in a section of the tunnel (length: 8m)

Figure 14 – Calculation of light irradiation, along the tunnel

PAINTS

In order to renovate the tunnel, using a photocatalytic cement-based material, a commercial paint produced by CIM was used.

In particular, a grey paint was used on both sides of the tunnel, until 1,80 m of height and a white paint for the remaining surface, Figure 10.

The photocatalytic property of both products was assessed according to the NOX gas recirculation method, adopted by CTG for the quality evaluation of TX Active products, Figures 15 and 16.

Several formulations of both white and grey paints were prepared by CIM and afterwards evaluated in the Italcementi Laboratory in Brindisi.

According to the cited testing methodology, the best formulations chosen for the tunnel renovation showed a **NOx abatement capacity of 88-90% after 60 minutes**, under UV light irradiation.

Some qualitative tests carried out according to the UNI standard 11259 (colorimetric - Rhodamine B test) gave an indication of the maintenance capacity of the white paints: the a* reduction after 26 hours was **over 70%**, with respect to the initial values of redness (minimum level of acceptance for standard mortars prepared with photocatalytic hydraulic binder: 50%).

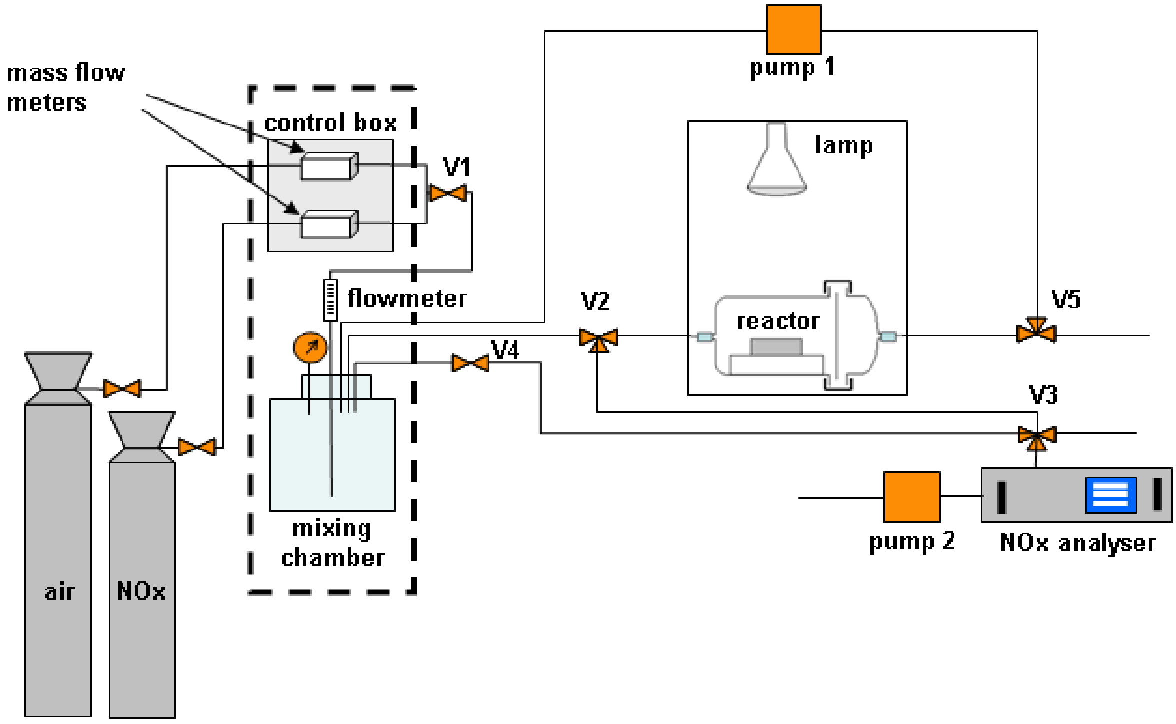


Figure 15- NOX gas recirculation test – A schematic view

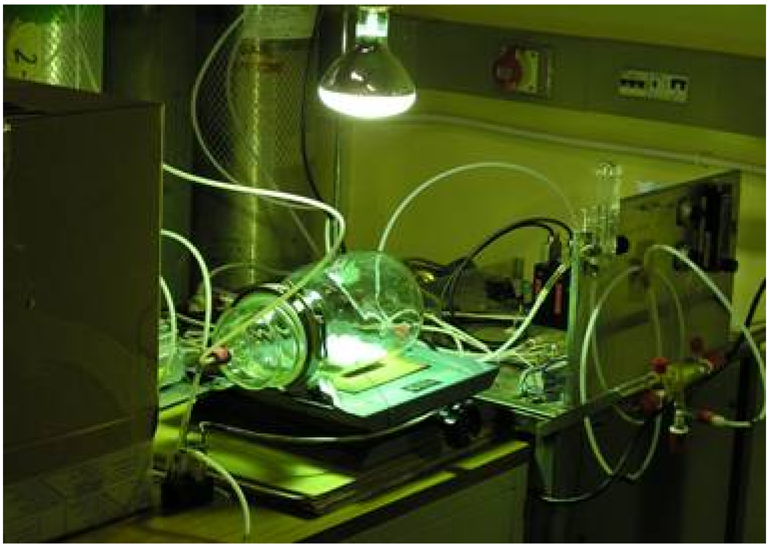


Figure 16 – NOx gas recirculation test – the light irradiation step

THE MONITORING PROGRAMME

The monitoring approach was defined by CTG in agreement with some managers of the Municipality of Rome (Department for the Environmental Activities).

Due to the particular situation in terms of both monitoring approach (use of NO_x meters along the day) and the need of collecting some relevant data in a manual way (traffic, light conditions, wind speed), this monitoring activity has required the presence of almost three resources/day. So, the following experts from CTG and CIM were involved:

CTG Laboratories – Bergamo

- Enrico Peccati
- Giovanni Cividini
- Maurizio Lamera
- Marco Plebani
- Valerio Spreafico
- Gian Luca Guerrini

C.I.M. – Rome

- Gianfranco Faro
- Davide Gerani
- Alessandra Broggi
- Massimo Bernardoni

The monitoring was generally carried out during the daytime (period 8.00-18.00), from Monday to Friday. One nocturnal monitoring was also carried out, per each campaign.

Environmental monitoring was accomplished through two successive campaigns, each of them lasting two weeks (10 working days):

Main equipment used for the monitoring campaigns, as follows:

- 4 chemiluminescence NO_x analyzers (ENVIRONNEMENT);
- 1 calibrating system (ENVIRONNEMENT);
- 1 Thermo-hygrometer (TESTO);
- 1 Luxmeter – TESTO;
- 1 UVA/UVB/RAD radiometer (Delta OHM);
- 1 Anemometer.

The first campaign was carried out in the period: July 3, 2007 - July 20, 2007.

During the three weeks, the positions of the four NO_x analyzers in the tunnel (or next to the tunnel) are reported in Figure 17.

The numbers of the different analysers are summarized in Table 1.

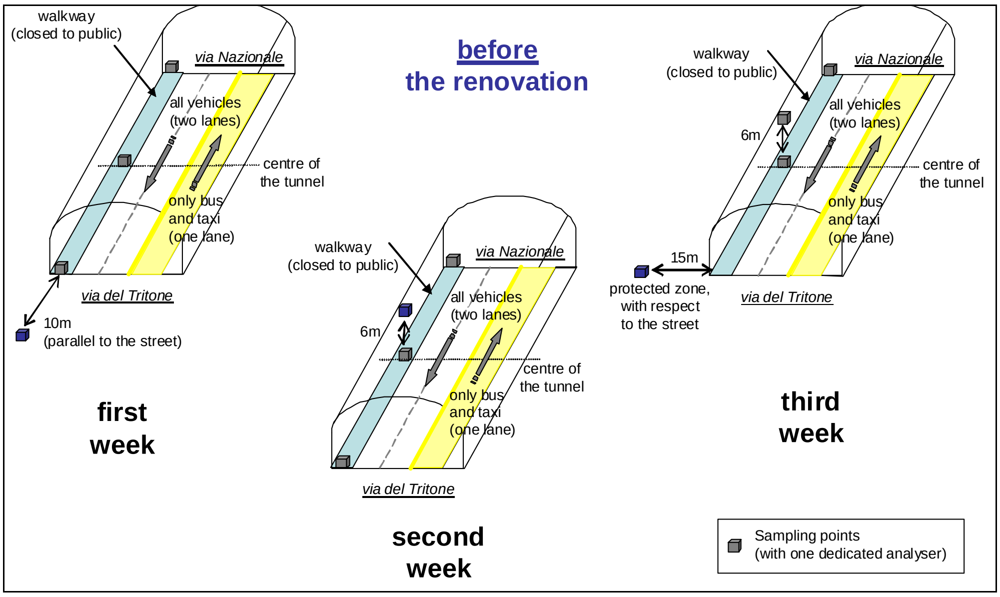
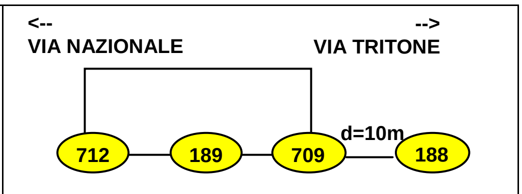
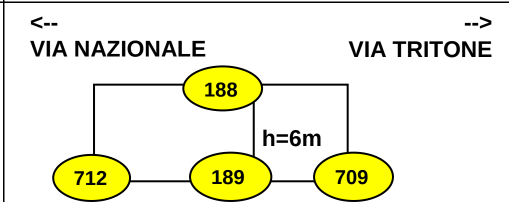
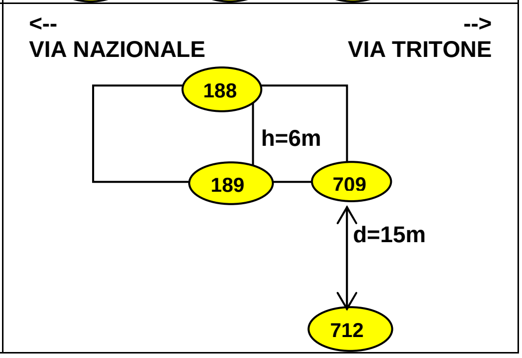


Figure 17 – Positions of NO_x analysers, during the first campaign

Table 1 – Number of NO_x analysers, during the first campaign

FIRST WEEK (3/7-9/7 2007) #712 – entrance “via Nazionale” #189 – in the centre of the tunnel, sampling: 1m #709 – entrance “via del Tritone” #188 - external, 10m about, from the entrance “via del Tritone”	
SECOND WEEK (10/7-13/7, 2007) #712, #189 and #709 – as in the first week #188 – in the centre of the tunnel, as #189 (sampling point: 6m about, from the ground)	
THIRD WEEK (16/7-20/7, 2007) #188, #189 and #709 – as in the second week #712 – external position (protected zone, 15m about from the street)	

Height of sampling points: 1m from the ground (exception: #188: 6m)

The second campaign was carried out in the period: September 25, 2007 - October 12, 2007.
During the three weeks, the positions of the four NO_x analyzers in the tunnel (or next to the tunnel) are reported in Figure 18.

The numbers of the different analysers are summarized in Table 2.
The height of gas sampling was approximately 1 m, except for the analyzer referred to the 6m of height, in the centre of the tunnel.

The analyzers were set to measure air concentration values, in ppbVol, of NO_x, NO and NO_2 (measuring frequency: one measurement/minute).

In addition to NO_x measurements, the most significant weather data (humidity, temperature, wind parameters, cloudiness, pressure and atmospheric precipitations) were also recorded.

The number of vehicles travelling at daytime was also recorded, with an hourly frequency.

A nocturnal data collection was decided, along the two periods:

- From 8.00 of July 11, 2007 to 18.00 of July 12, 2007 (before the renovation)
- From 8.00 of October 10, 2008 to 18.00 of October 11, 2007 (after the renovation)

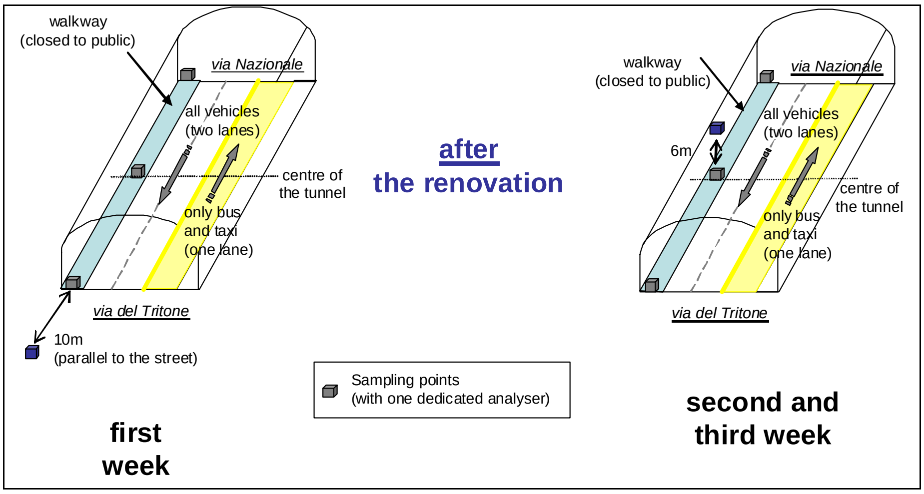
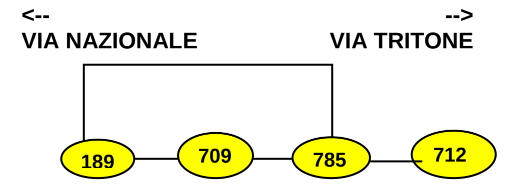
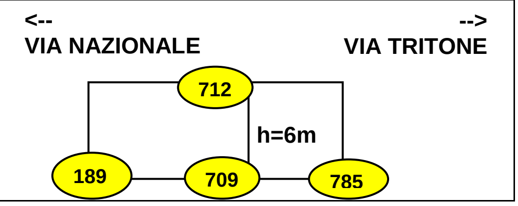


Figure 18 – Positions of NO_x analysers, during the second campaign

Table 2 – Number of NO_x analysers, during the second campaign

FIRST WEEK (25/9-28/9, 2007) #189 – entrance “via Nazionale” #709 – in the centre of the tunnel, sampling: 1m #785 – entrance “via del Tritone” #712 - external, 10m about, from the entrance “via del Tritone”	
SECOND AND THIRD WEEK (1/10-12/10, 2007) #189 #709 and #785 – as in the first week #712 – in the centre of the tunnel, as #709 (sampling point: 6m about, from the ground)	

Height of sampling points: 1m from the ground (exception: #712: 6m)

Figures 19-24 show some phases of the two monitoring campaigns.

Figure 19 – CTG working site, next to the tunnel (via del Tritone)

Figure 20 – Position of one analyser (via del Tritone)

Figure 21 – Measurement of wind speed

Figure 22 – Position of one analyser (via Nazionale)

Figure 23 – Positions of two analysers, in the centre of the tunnel (before the renovation)

Figure 24 – Positions of analysers, in the centre of the tunnel (left) and in the entrance Via Tritone (right), after the renovation

During the monitoring campaign after the renovation works, some measurements of lighting parameters were also carried out in different points of the tunnel, both at 1.8 m and 6 m of height, Figures 25-26. These measurements confirmed the mean light values, previewed in the design phase.

Figure 25 – Measurement of the light intensity, in the tunnel

Figure 26 – Measurement in the tunnel, using the photo-radiometer

RESULTS AND DISCUSSION

The following data were collected:

- NOx values (NO, NO2 and NOx);
- Weather conditions (T, RH, P, wind speed) and sometimes, light conditions inside and outside the tunnel (UVA, UVB, RAD, Lux);
- Traffic situation, vehicles/hour.

In order to make a comparison among different calculated mean values of NOx in different positions of the tunnel, the official data from ARPA Lazio (Official Environmental Protection Agency in Rome) were processed in advance.

Official pollution data, from ARPA Lazio

Some data which will be included in this report, were collected by some official weather stations (ARPA Lazio). ARPA Lazio, the regional environmental agency operates several air quality monitoring sites in the Region including Rome. The Rome monitoring network consists of 13 monitoring stations classified as four different types: A, B, C and D. Type A are usually located in areas not directly affected by traffic sources such as parks or green areas. They monitor pollutants such as CO, SO_2, NO_x, NO, BTX, PM10 and O_3. Types B are located in areas with heavy traffic conditions. They monitor CO, NO_x, BTX, PM10 and O_3. Types C are located in residential areas. They monitor CO, NO_x and BTX. Types D are located outside the urban area, almost in the countryside. They monitor O_3 and NO_x, and are devoted to the control of photochemical pollution. The monitoring network receives concentration data every hour. Data are sent to the Regional Environmental Protection Agency (ARPA) for validation and delivered to the Environmental Department of the Municipality of Rome that is responsible for data collecting, storing and delivering.

In the full list of monitoring stations, three of them were chosen for reference, with the agreement of the Technical Managers of the Environmental Department of the Municipality of Rome, Figure 27:

- Villa Ada (“background” station) – A Type (gardens);
- Largo Arenula (“traffic” station) – B Type (avenue);
- Fermi (“traffic” station) – B Type (avenue).

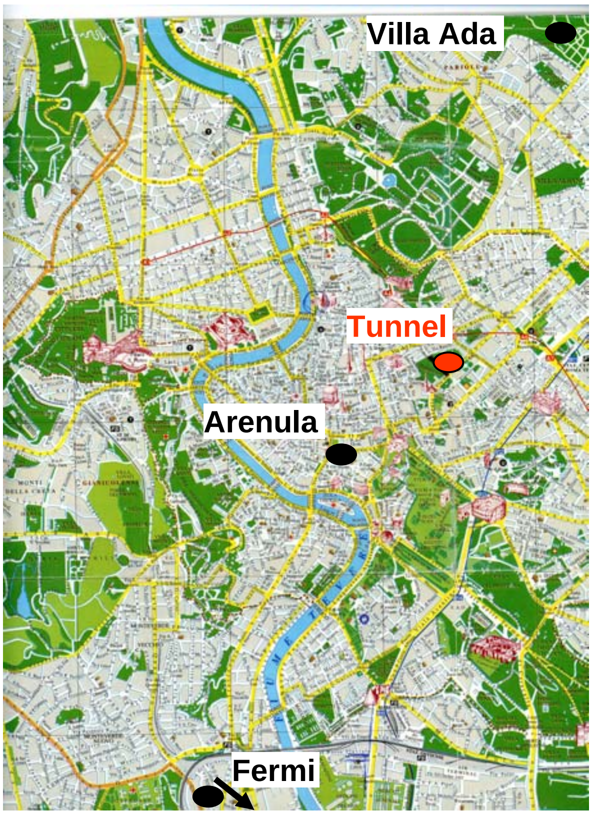


Figure 27 – Positions of official stations chosen (ARPA Lazio)

A general remark concerning pollution in Rome, for the two reference periods is that **the daily values registered by means of official (fixed) stations were higher in the period of three-week monitoring campaign (September-October 2007), in comparison with the three-week period of July 2007.**

This is clearly confirmed in Figures 28-35 and Table 3, referred to Largo Arenula and Villa Ada stations.
Data are referred to NOx and NO_2 as mean daily values, between 8.00 a.m. and 6.00 p.m. hours and are expressed as micrograms/m^3.

Table 3 – A comparison of mean daily values – NO_x and NO_2

Values in g/m^3	**NO_x**		**NO_2**	
	July 2007	**Sept-Oct 2007**	**July 2007**	**Sept-Oct 2007**
Largo Arenula	114	252	65	73
Via Fermi	161	185	95	102
Villa Ada	57	92	38	49

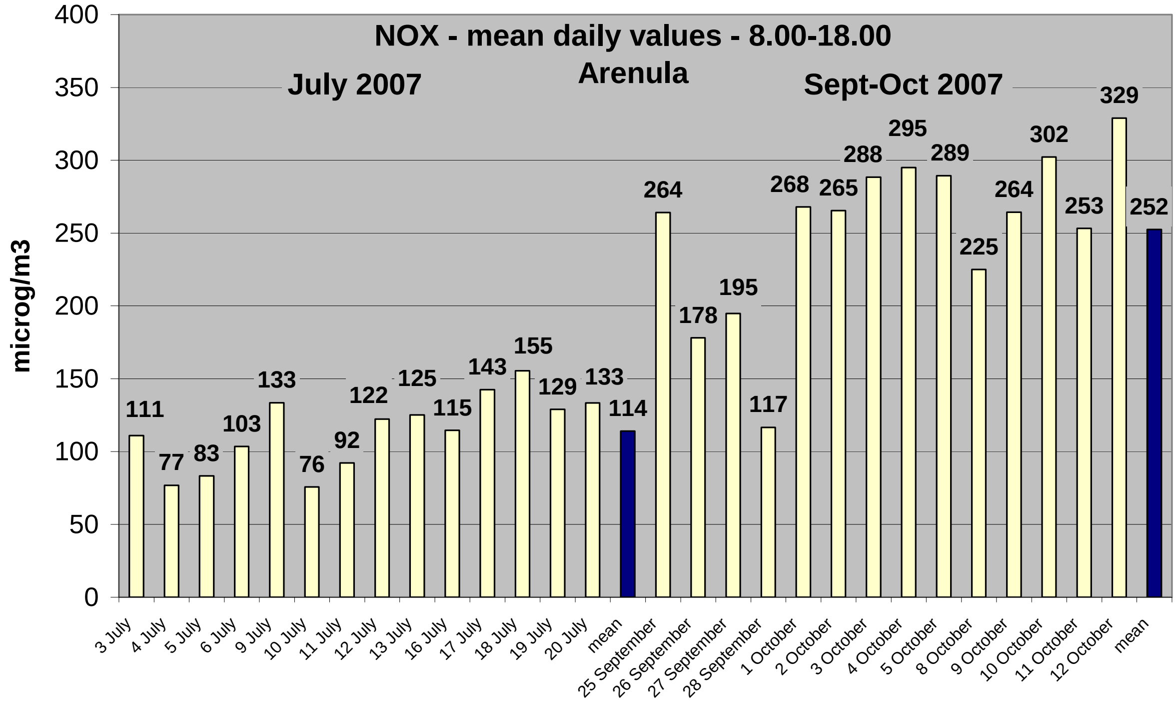


Figure 28 – Largo Arenula: NO_x mean daily values

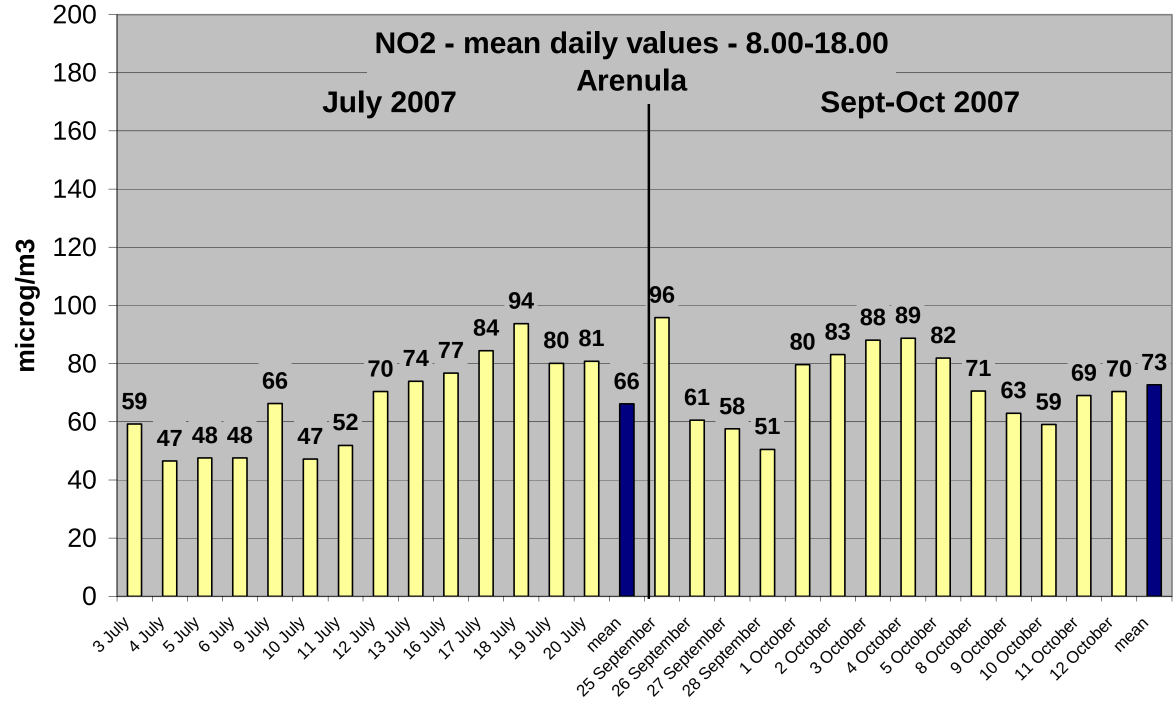


Figure 29 – Largo Arenula: NO_2 mean daily values

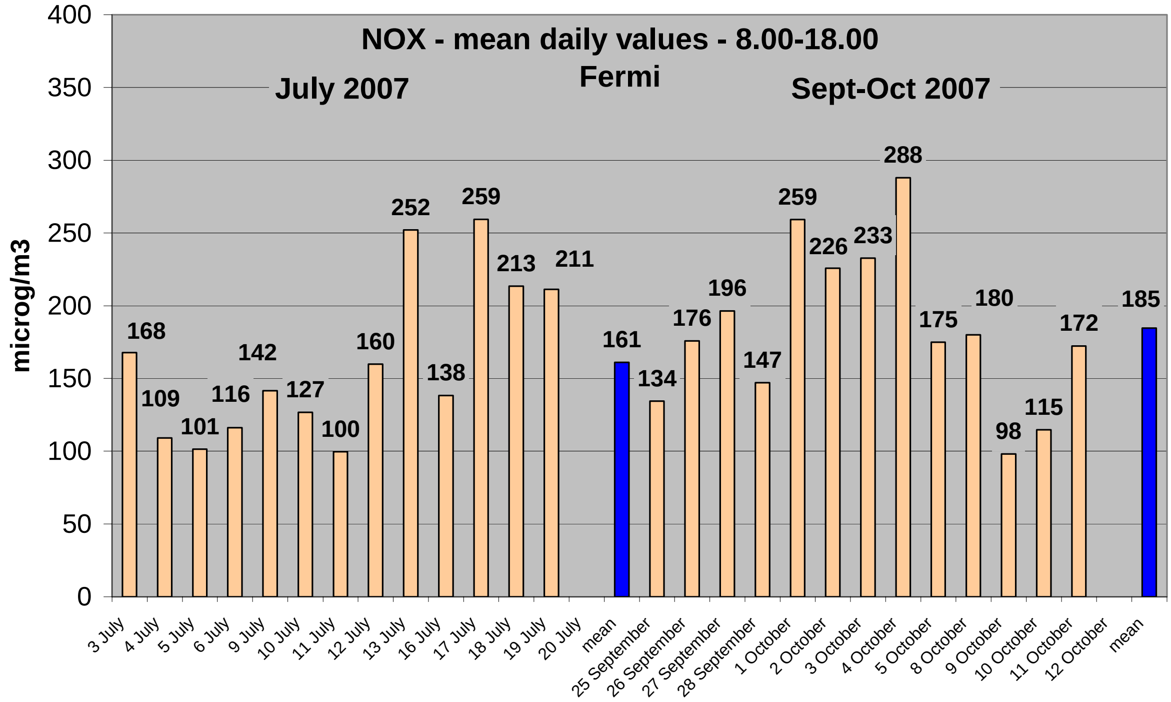


Figure 30 –Via Fermi: NO_x mean daily values

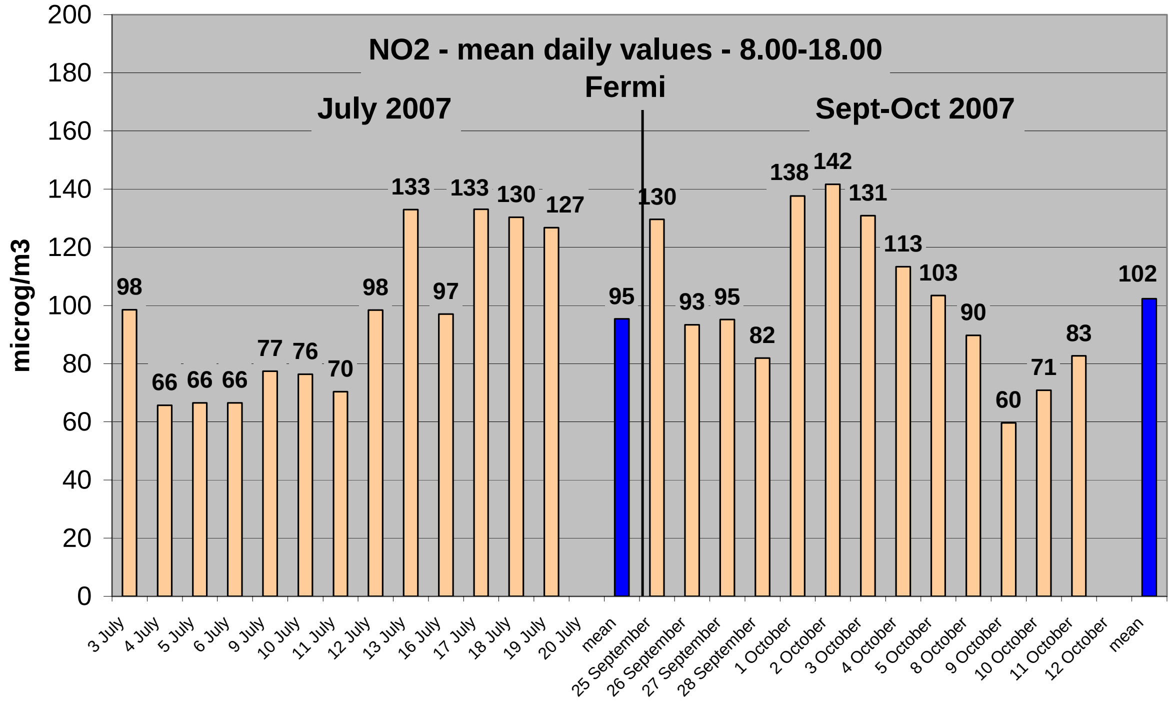


Figure 31 – Via Fermi: NO_2 mean daily values

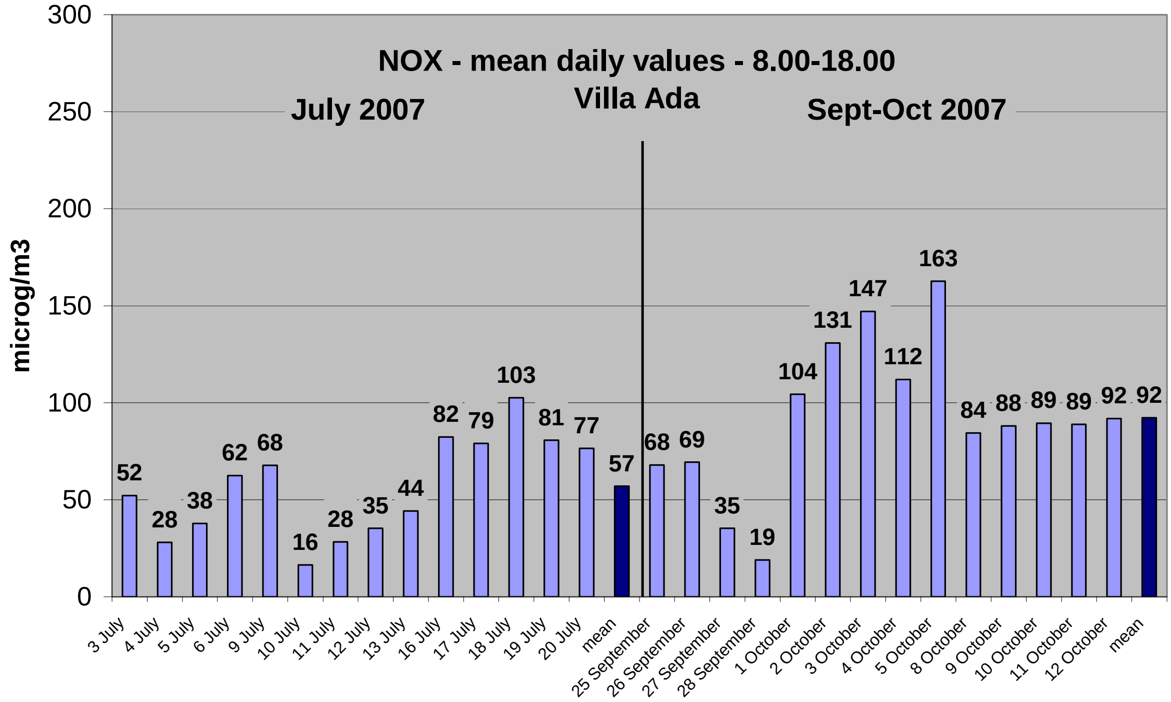


Figure 32 – Villa Ada: NO_x mean daily values

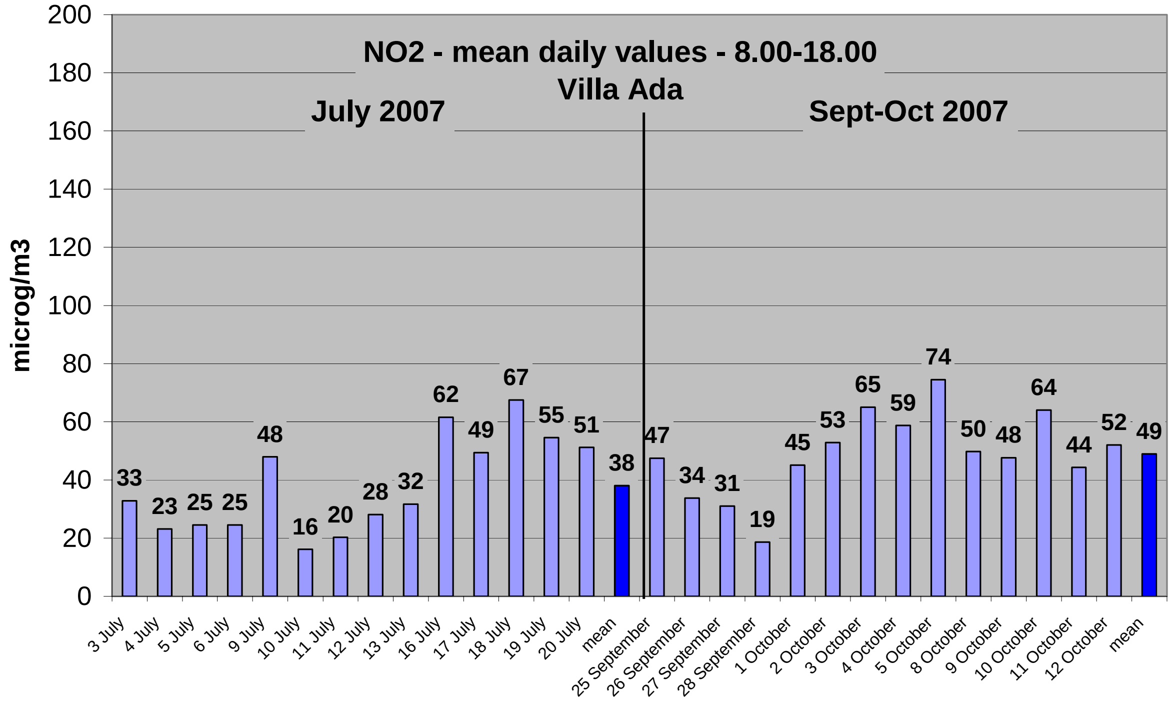


Figure 33 – Villa Ada: NO_2 mean daily values

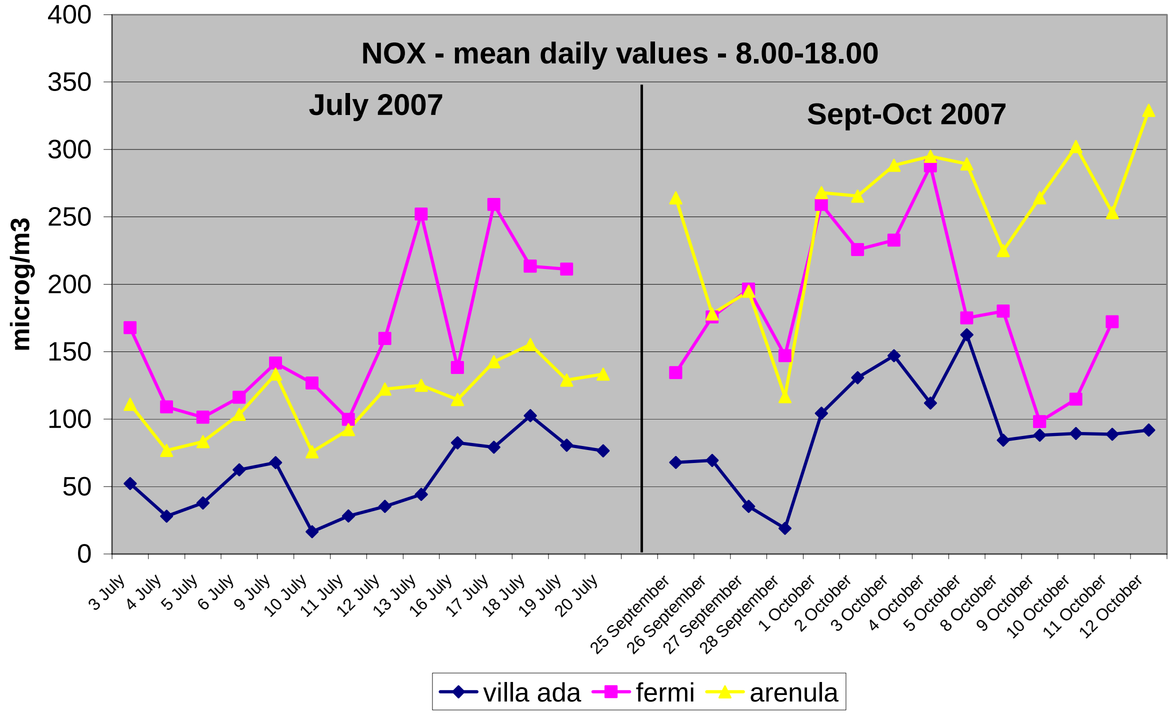


Figure 34 –Trend of NO_x mean daily values, for official (fixed) stations

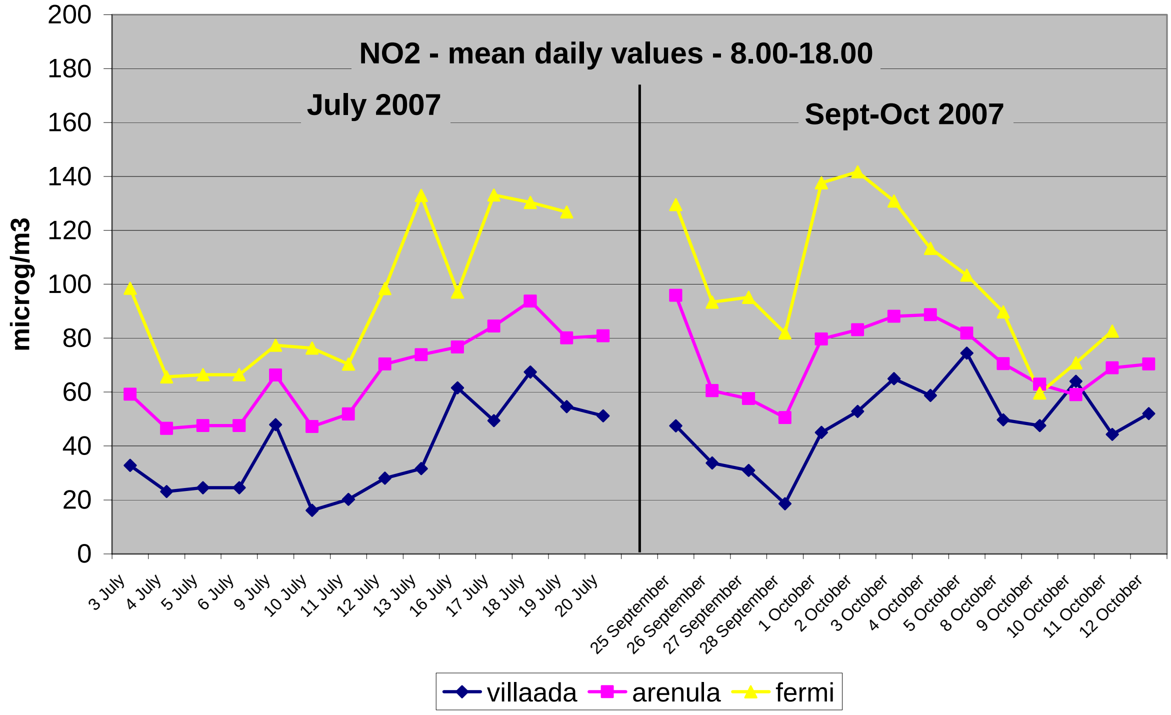


Figure 35 –Trend of NO_2 mean daily values, for official (fixed) stations

Crossing the tunnel from via Nazionale to via del Tritone, the mean daily NO_x values increase, probably due to the already mentioned windy conditions and to the pollution effects derived from the other entrance (“via del Tritone”).

The NO_x mean values are very high, but lower than the values registered in the previous, similar experience in Milan (via Porpora, 2004): daily values of 400-800 ppb (Rome) against 1200-1400 ppb (Milan).

An increase of NO_x values during the afternoon was almost regularly observed, due to the tourist traffic above described (especially for the positions next to the entrance “via del Tritone”) and very high pollution peaks were sometimes registered.

Traffic

The number of vehicles per hr (mean hourly value), which was manually registered in occasion of the two monitoring campaigns, was similar for both periods (July 2007 and September-October 2007): 1100 vehicle/hr, about.

During the two campaigns, the range was between 940 and 1240 vehicles/hr, from Monday to Friday, without any possibility to define a weekly trend for the traffic.

The location of the tunnel is in the historical centre of Rome, corresponds to the Restricted Access Zone (LTZ, Limited Traffic Zone, “Zona a Traffico Limitato”), where public traffic is stopped daily from 7.00 a.m. to 6.00 p.m. (from Monday to Friday). During evening and night hours and during week-ends, no restrictions are applied on public circulation (exception: Saturday afternoon).

During the LTZ period, the traffic is mainly consisting of public transport, tourist buses, taxies (more or less, 50%) and private transport or “blue cars”.

Indeed, a large number of tourist buses were observed along the day, mainly in the range: 10.00 a.m. - 4.00 p.m. (both in July and in Sept-Oct period).

Environmental conditions, in the tunnel

In relation to the semi-confined conditions, the values of temperature, relative humidity and pressure in the tunnel were almost constant, along the day and in the interested weeks.

During the first period (July), the average temperature measured in daylight period was in the range 28-40°C (entrance “via del Tritone”), around 30-32°C (in the tunnel).

In the second period, the average temperature was 20-28°C (outside) and 23-25°C (tunnel).

The average relative humidity was in the range 15-40% during the first campaign and in the range 40-70%, during the second campaign (a few days of rain which have not influenced the conditions in the tunnel).

The speed of the wind was influenced by the traffic variations along the two periods, because of the high speed of vehicles passing through the tunnel.

However, typical values registered in the entrance “via del Tritone” range between 0.10 and 1.70 m/sec, corresponding to an average value of 0.38 m/sec. Highest values along the tunnel were always detected in the centre. The direction of the wind was always the same: from the entrance “Via Nazionale” towards “Via del Tritone”.

NOx monitoring results: preliminary remarks

Before considering and discussing the numerical results, some preliminary remarks can be summarized, as follows:

a) In relation to the specific application (a tunnel, that is a semi-confined place, rather than a road or another open space), we can consider lighting conditions as steady. However, due to the large dimensions of the tunnel, a certain amount of sunlight could reinforce the photocatalytic action, in addition to the artificial light (in some hours of the day).

b) On this basis, the most relevant parameters which could influence the monitoring results are **traffic** (number of vehicles per hour) and **wind speed**.

c) In order to evaluate the trend of traffic along a day, a nocturnal data collection was carried out, along the two periods:
   - from 8.00 a.m. of July 11, 2007 to 6.00 p.m of July 12, 2007 (before the renovation), Figure 36;
   - from 8.00 a.m. of October 10, 2007 to 6.00 p.m. of October 11, 2007 (after the renovation).

d) The data collection of analysers positioned just outside the entrance “via del Tritone” was strongly influenced by local traffic, due to the temporary parking (few minutes) of tourist buses (the tunnel is a few hundred meters far from the famous “Fontana di Trevi”).
   This phenomenon is seasonal, from spring period to the end of summer period). It is particularly evident in the central part of the day (from 10.00-11.00 a.m. to 4.00-5.00 p.m., according to the days).

e) The tunnel is quite windy, due to its large size and, above all, due to the volume of traffic which is predominant in one direction (from via Nazionale to via del Tritone), as well as to its two lanes (in the opposite direction the circulation is allowed only to public vehicles (buses, taxi) service vehicles and “official cars” (no private vehicles).

f) The tunnel is slightly downhill, from via Nazionale to via del Tritone.

g) A large number of tourist buses was recorded along the day, mainly in the time range from 10.00 a.m. to 4.00 p.m. (both in July and in Sept-Oct period).

Monitoring data were collected as .txt files from the NO_x-meters and then evaluated by means of simple statistical methods.

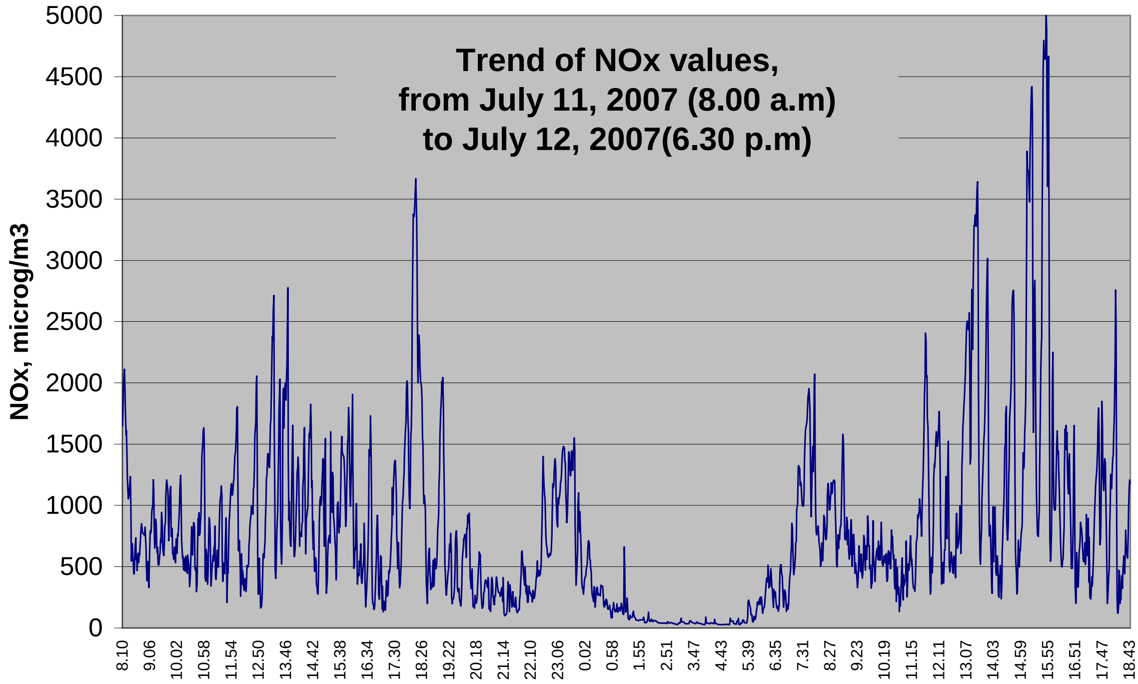


Figure 36 – Trend of NOx values, in the centre of the tunnel, including a nocturnal data collection

Collected NO_x data, in the tunnel

With reference to preliminary considerations concerning:

- Daily trends of NO_2 values (see previous graph);
- Geometry and local conditions of the tunnel;
- Possible origin of pollution in the tunnel (traffic + private buses).

In the following Tables 4-5 and Figures 37-41, the data referred to the centre of the tunnel (1m) will be taken as the most representative for this evaluation. However, all registered data were elaborated and included in this report.

Tables 4-6 show NO_x, NO and NO_2 average values for each day, for all NOx-meters used in the tunnel. Tables 7-8 show the average values for three main analysers in the tunnel, in comparison with official stations.

As expected, the values of polluting gases (NO_x) increase, from one side to the other side of the tunnel. This is the typical distribution of pollutants in a tunnel with a natural ventilation, due to a “plug effect”, Figure 37. Indeed, there is a homogenization of the gas concentration in the cross-section of the tunnel, which was confirmed by the direct comparison of NO_x concentrations at the centre of the tunnel, at two different heights (1 m and 6 m). A slight difference for these values was registered only in occasion of a very windy day (July 20, 2007), Figure 38.

As to the values registered in the centre of the tunnel, the reduction of pollution is clear (in absolute value), Figures 39-41.

The reduction of average daily values after the tunnel renovation is also clear, if compared with the corresponding values registered in the official stations, Figures 42-43.

In particular, values referred to the centre of the tunnel and to the entrance “via del Tritone” clearly decrease, but this reduction is even more significant for the entrance “via Nazionale” as it has the same order of magnitude referred to the “open space” official stations, both for NO_x and NO_2.

Besides, the values of NO_2 in the centre of the tunnel are within the reference limit value of 200 mg/m^3, defined for outdoor urban situations (and these values are certainly lower if referred to the 24 hr period, in relation to the lower volume of traffic during night hours).

Indeed, even if the tunnel situation is critical, as it is a semi-confined zone where an accumulation of pollution can be registered, after the tunnel renovation a better environment is definitively obtained.

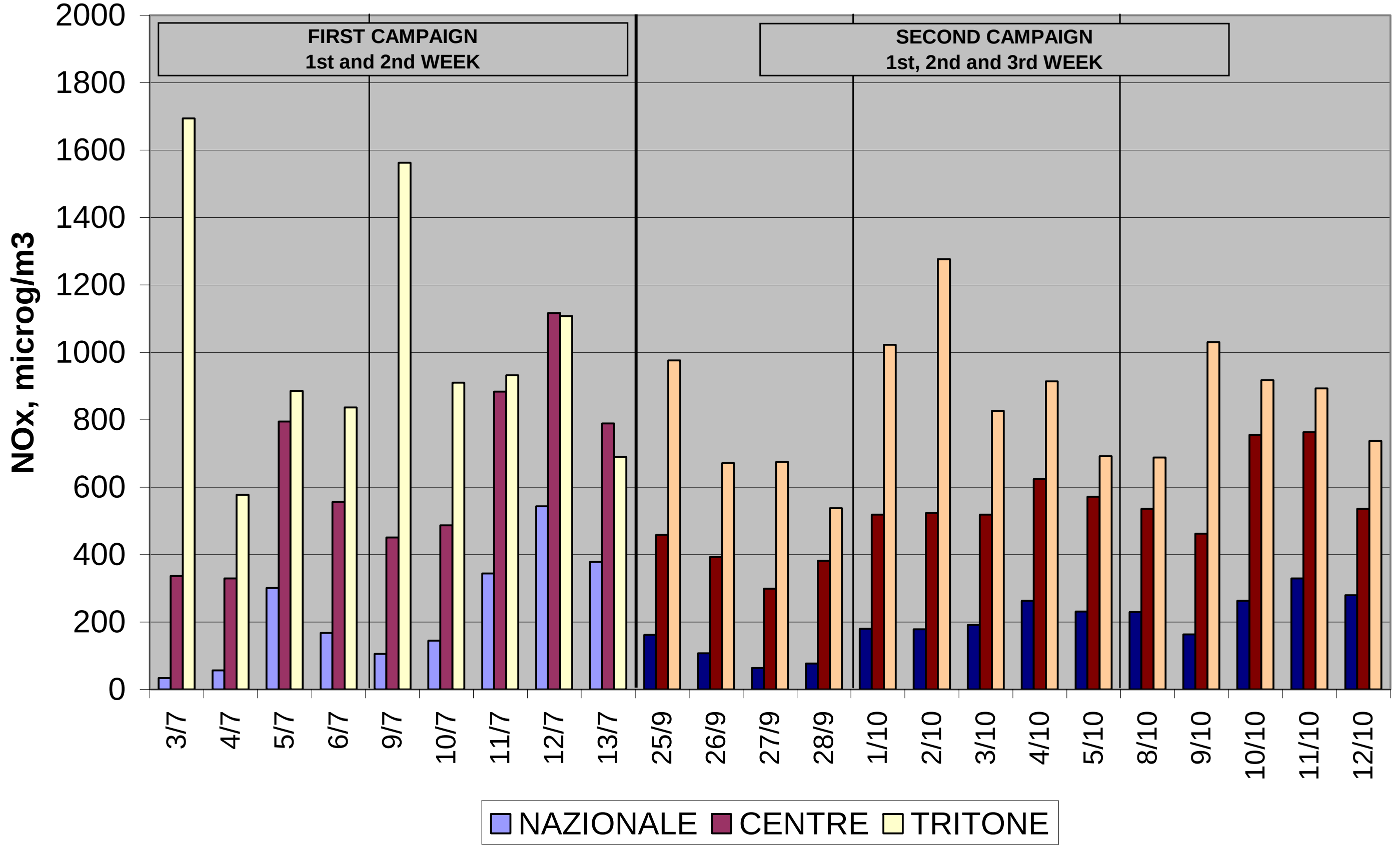


Figure 37 – Daily trends of NOx values in the tunnel (from “Via Nazionale” to “Via del Tritone”) – Values in $\mu g/m^3$

Table 4 – Daily NO_x values in the tunnel ($\mu g/m^3$)

NOX - FIRST CAMPAIGN

NOX - first week

date	712	189	709	188
3/7	34	337	1694	897
4/7	56	329	577	635
5/7	301	795	885	874
6/7	167	556	837	1137
9/7	105	451	1562	1186

NOX - second week

date	712	188	189	709
10/7	145	491	487	910
11/7	344	884	884	932
12/7	543	1136	1117	1107
13/7	378	782	790	690

NOX - third week

date	712	188	189	709
16/7	121	512	516	393
17/7	255	989	956	554
18/7	177	596	600	518
19/7	769	686	684	580
20/7	223	685	733	524

NOX - SECOND CAMPAIGN

NOX - first week

date	189	709	785	712
25/9	162	459	976	566
26/9	107	393	671	855
27/9	64	299	675	519
28/9	77	382	538	415

NOX - second week

date	189	709	712	785
1/10	180	519	506	1023
2/10	179	523	511	1277
3/10	192	519	511	827
4/10	263	624	617	914
5/10	231	572	564	692

NOX - third week

date	189	709	712	785
8/10	229	536	545	688
9/10	164	462	321	1030
10/10	263	756	758	917
11/10	329	763	756	893
12/10	280	536	526	737

Table 5 – Daily NO values in the tunnel ($\mu g/m^3$)

NO - FIRST CAMPAIGN

NO - first week

date	712	189	709	188
3/7	2	124	919	413
4/7	10	129	258	279
5/7	122	368	422	400
6/7	54	242	410	539
9/7	27	188	824	524

NO - second week

date	712	188	189	709
10/7	64	218	225	460
11/7	149	411	426	460
12/7	250	544	551	560
13/7	155	338	358	300

NO - third week

date	712	188	189	709
16/7	30	186	201	135
17/7	96	435	439	232
18/7	53	219	240	200
19/7	423	277	292	221
20/7	72	276	317	208

NO - SECOND CAMPAIGN

NO - first week

date	189	709	785	712
25/9	52	166	476	242
26/9	32	162	315	488
27/9	15	121	326	256
28/9	20	159	236	210

NO - second week

date	189	709	712	785
1/10	63	215	210	496
2/10	63	219	213	653
3/10	69	213	209	378
4/10	113	274	272	451
5/10	90	252	251	317

NO - third week

date	189	709	712	785
8/10	92	237	240	315
9/10	62	200	139	530
10/10	113	370	373	464
11/10	144	360	362	443
12/10	119	244	241	352

Table 6 – Daily NO_2 values in the tunnel ($\mu g/m^3$)

NO2 - FIRST CAMPAIGN

NO2 - first week

date	**712**	**189**	**709**	**188**
3/7	32	147	423	291
4/7	41	132	196	216
5/7	117	233	244	284
6/7	90	188	252	352
9/7	64	164	385	395

NO2 - second week

date	**712**	**188**	**189**	**709**
10/7	49	158	147	246
11/7	117	256	132	250
12/7	169	305	233	288
13/7	143	265	188	237

NO2 - third week

date	**712**	**188**	**189**	**709**
16/7	77	228	209	188
17/7	113	325	285	201
18/7	106	261	233	213
19/7	210	264	238	243
20/7	114	263	248	208

NO2 - SECOND CAMPAIGN

NO2 - first week

date	**189**	**709**	**785**	**712**
25/9	83	207	299	218
26/9	58	147	218	244
27/9	43	115	209	169
28/9	45	139	180	130

NO2 - second week

date	**189**	**709**	**712**	**785**
1/10	85	188	184	291
2/10	85	188	186	329
3/10	86	194	192	263
4/10	103	205	201	259
5/10	94	186	180	211

NO2 - third week

date	**189**	**709**	**712**	**785**
8/10	90	175	179	220
9/10	70	154	109	265
10/10	90	190	188	233
11/10	111	212	203	246
12/10	103	162	158	212

Table 7 – NO_x values: official stations and Nox-meters in the tunnel
Mean daily values (8.00 a.m. - 6.00 p.m.), $\mu g/m^3$

	Official stations			Tunnel		
date	Villa Ada	Via Fermi	Largo Arenula	TUNNEL CENTRE	ENTRANCE NAZIONALE	ENTRANCE TRITONE
3 July	52	168	111	337	34	1694
4 July	28	109	77	329	57	577
5 July	38	101	83	795	301	885
6 July	62	116	103	556	167	837
9 July	68	142	133	451	105	1562
10 July	16	127	76	487	145	910
11 July	28	100	92	884	344	932
12 July	35	160	122	1117	543	1107
13 July	44	252	125	790	378	690
16 July	82	138	115	516	-	393
17 July	79	259	143	989	-	554
18 July	103	213	155	596	-	518
19 July	81	211	129	686	-	580
20 July	77	-	133	685	-	524
					-	
25 September	68	134	264	459	162	976
26 September	69	176	178	393	107	671
27 September	35	196	195	299	64	675
28 September	19	147	117	382	77	538
1 October	104	259	268	519	180	1023
2 October	131	226	265	523	179	1277
3 October	147	233	288	519	192	827
4 October	112	288	295	624	263	914
5 October	163	175	289	572	231	692
8 October	84	180	225	536	229	688
9 October	88	98	264	462	164	1030
10 October	89	115	302	756	263	917
11 October	89	172	253	763	329	893
12 October	92	0	329	536	280	737

Table 8 – NO_2 values: official stations and Nox-meters in the tunnel
Mean daily values (8.00 a.m. - 6.00 p.m.), $\mu g/m^3$

	Official stations			Tunnel		
date	Villa Ada	Via Fermi	Largo Arenula	TUNNEL CENTRE	ENTRANCE NAZIONALE	ENTRANCE TRITONE
3 July	33	59	98	147	32	423
4 July	23	47	66	132	41	196
5 July	25	48	66	233	117	244
6 July	25	48	66	188	90	252
9 July	48	66	77	164	64	385
10 July	16	47	76	147	49	246
11 July	20	52	70	132	117	250
12 July	28	70	98	233	169	288
13 July	32	74	133	188	143	237
16 July	62	77	97	209	-	188
17 July	49	84	133	285	-	201
18 July	67	94	130	233	-	213
19 July	55	80	127	238	-	243
20 July	51	81		248	-	208
25 September	47	96	130	207	83	299
26 September	34	61	93	147	58	218
27 September	31	58	95	115	43	209
28 September	19	51	82	139	45	180
1 October	45	80	138	188	85	291
2 October	53	83	142	188	85	329
3 October	65	88	131	194	86	263
4 October	59	89	113	205	103	259
5 October	74	82	103	186	94	211
8 October	50	71	90	175	90	220
9 October	48	63	60	154	70	265
10 October	64	59	71	190	90	233
11 October	44	69	83	212	111	246
12 October	52	70		162	103	212

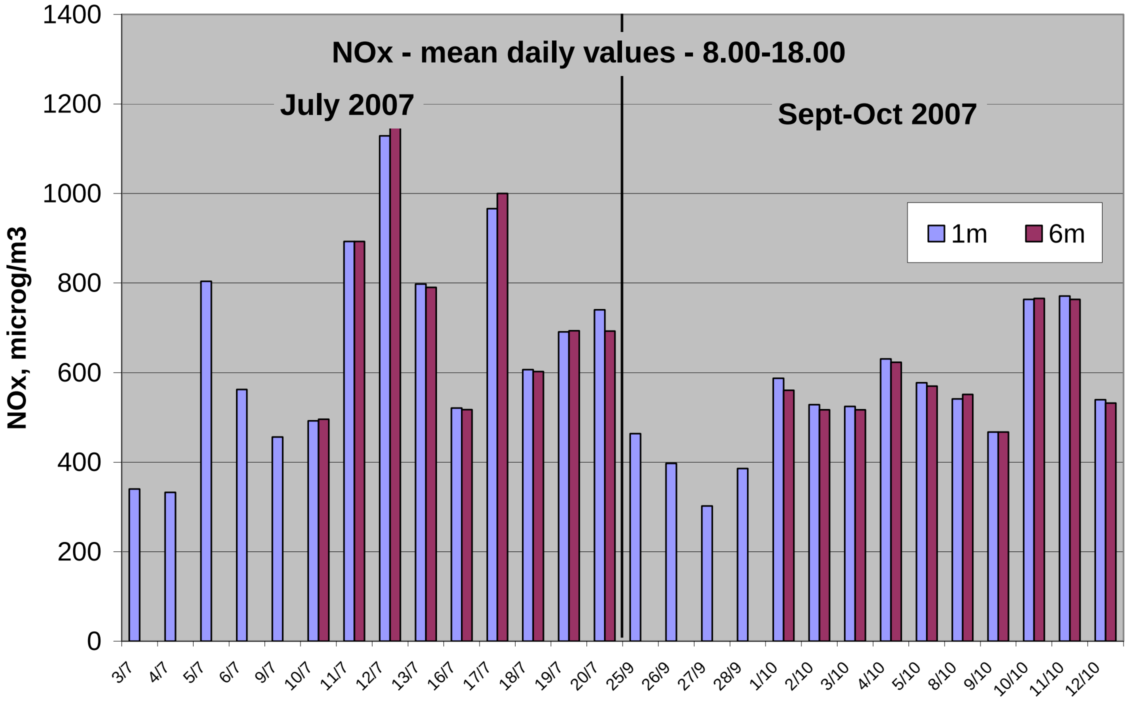


Figure 38 – Comparison of NO_x values, in the centre of the tunnel (1 m and 6 m)

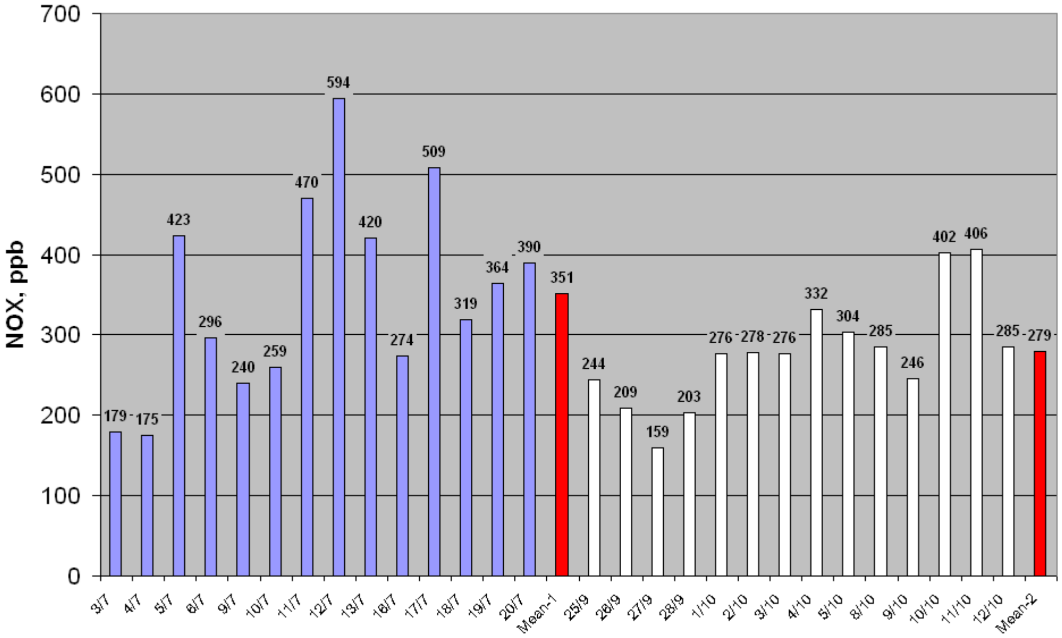


Figure 39 – NO_x values in the centre of the tunnel, 1m

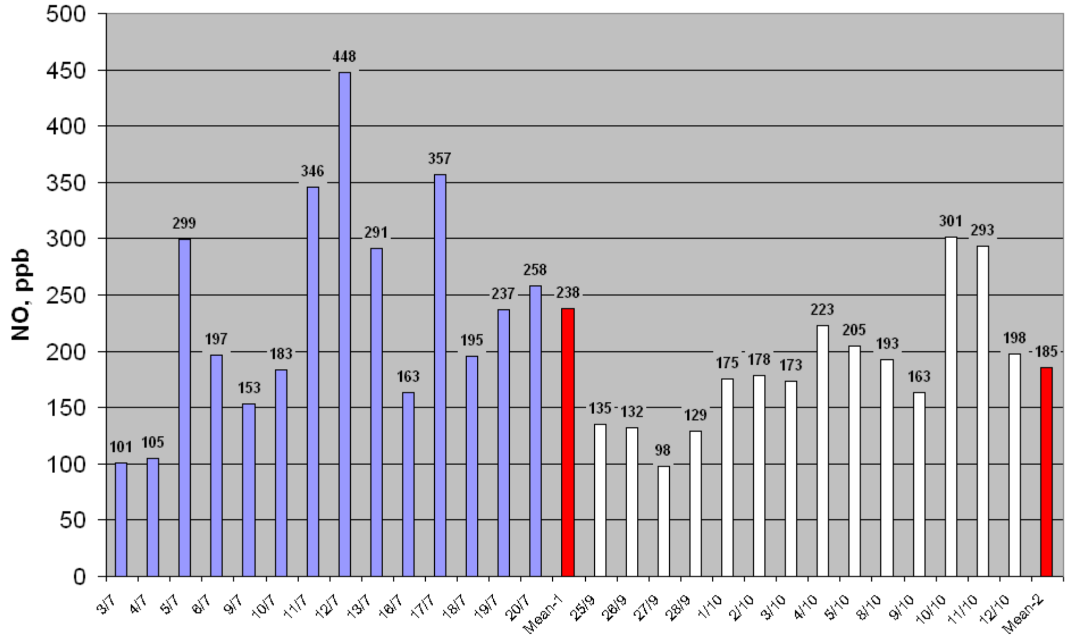


Figure 40 – NO values in the centre of the tunnel, 1m

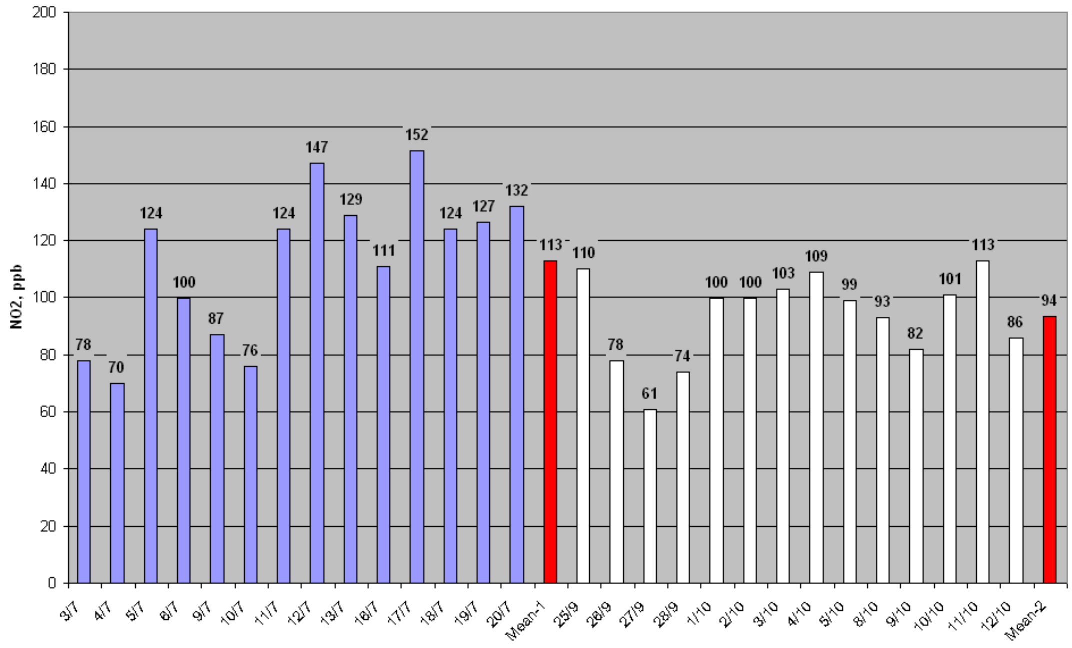


Figure 41 – NO_2 values in the centre of the tunnel, 1 m

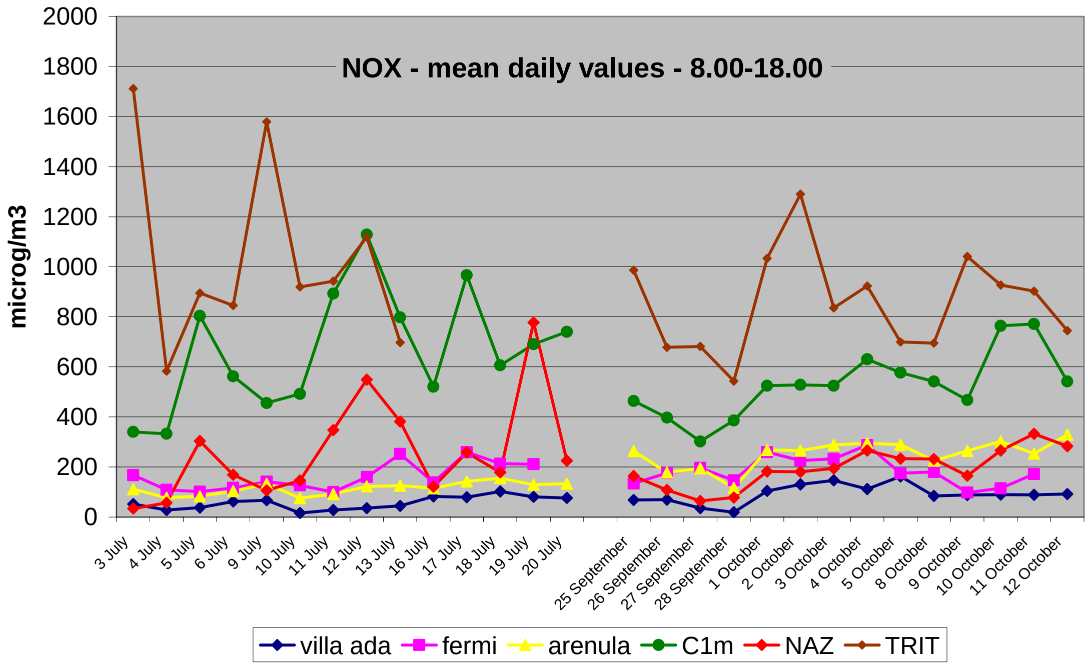


Figure 42 – A comparison of NO_x mean daily values (8.00 a.m. - 6.00 p.m.)

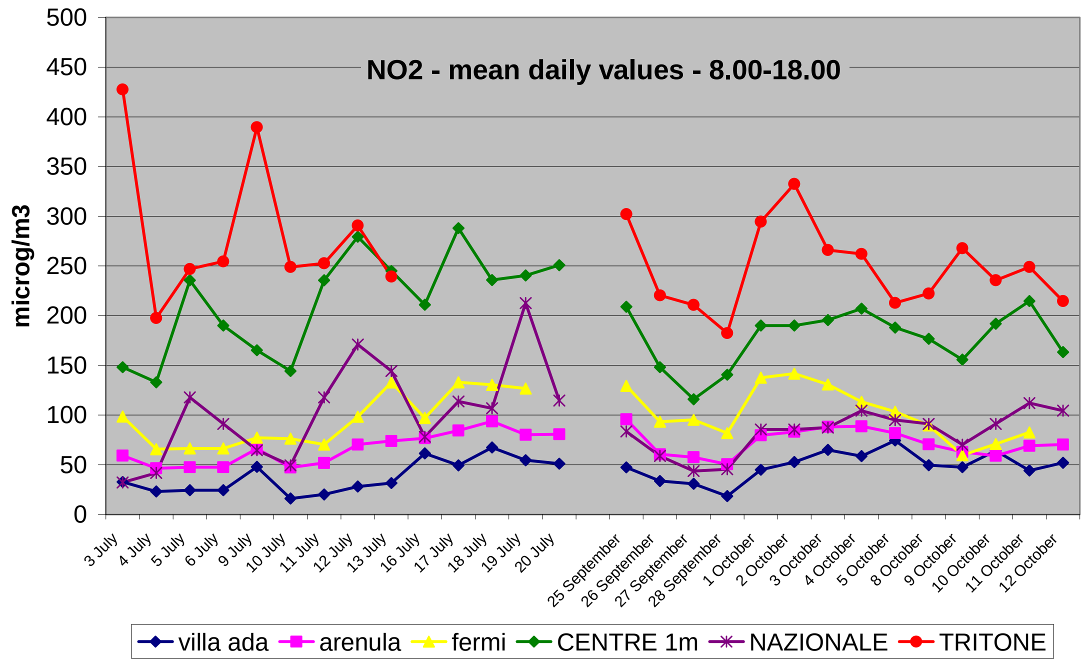


Figure 43 – A comparison of NO_2 mean daily values (8.00 a.m. - 6.00 p.m.)

Table 9 summarizes the mean values in reference zones (official stations) and in the centre of the tunnel, before and after the renovation phase.

By comparing these values, after the renovation there was a NO_x reduction of 21%: [(667-530)*100]/667.

Indeed, if we consider that there is an increase of pollution levels in Rome, passing from the first to the second period, corresponding to +61% for “Villa Ada” and +121% in “Largo Arenula”, it is reasonable to consider an increase of pollutants in the tunnel, without any renovation work

Table 9 - Mean values in reference zones and in the tunnel, for both periods (g/m^3)

	Ada July 07	**Ada Sept-Oct 07**	**Arenula July 07**	**Arenula Sept-Oct 07**	**Tunnel July 07**	**Tunnel Sept-Oct 07**
mean values	108	175	216	479	667	530
Difference		*+61%*		*+121%*		*-21%*

For example, considering the pollution increase in Villa Ada, “background” station (+61%), the real value in the tunnel should be: 1.61*667=1074 g/m^3, with a **theoretical abatement of 51%**: [(1074-530)*100]/(1.61*667).

However, the pollution level in the tunnel should be closer to the values registered in “Largo Arenula” station, which is not far from the tunnel, with a similar traffic volume. Assuming the same pollution increase of “Largo Arenula”, we should obtain a pollution level of 1474 g/m^3 (maximum calculated NO_x concentration), with a theoretical abatement of **64%**: [(1474-530)*100]/(2.21*667).

This calculation can also be justified if we consider the correlation coefficient which is a dimensionless quantity determined as a ratio between the covariance and the mean quadratic squares of two variables x and y:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

Taking into consideration the two reference stations (“Largo Arenula” and “Villa Ada”) and the tunnel, we could evaluate the pollution trend for these positions, considering the two periods: (July and September-October).
Tables 10 and 11 show the correlation coefficients, for both periods.

Table 10 - Correlation coefficient – July

	Villa Ada	Largo Arenula	Tunnel
Villa Ada	1	0.8342	-0.0443
Largo Arenula	0.8342	1	0.2693
Tunnel	-0.0443	0.2693	1

Table 11 - Correlation coefficient – September/October

	Villa Ada	Largo Arenula	Tunnel
Villa Ada	1	0.7215	0.4765
Largo Arenula	0.7215	1	0.5681
Tunnel	0.4765	0.5681	1

Indeed, in July a close correlation value between "Largo Arenula" and "Villa Ada" stations is observed (0.8342), whereas the correlation between the tunnel (semi-confined area)and the official stations (open spaces) is not acceptable (coefficients: -0.0443 and 0.2693). In September-October period the correlation between the official stations shows the same trend (0.7215), whereas the situation in the tunnel is more similar to the surrounding open spaces thus obtaining higher correlation coefficients (0.4765 and 0.5681).

Other statistical considerations can be made in terms of variance and peak reduction.

The variance is a measure of the average distance between each of a set of data points and their mean value, in other words an evaluation of the "data similarity":

$$\sigma^2 = \frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n}$$

The variance (Table 12) is increased for the two open stations, due to the increase of pollution and of the number of peaks, in September-October.

On the contrary, the variance for the tunnel is high in July (because of the influence of semi-confined environment on the number of pollution peaks) but decreases dramatically, due to the presence of photocatalytic paint, Table 12.

Table 12 – Variance of average values, NOx

	Villa Ada	Largo Arenula	Tunnel centre	Via Nazionale	Via Tritone
July	631	577	51915	25897	148796
Sept-Oct	1808	3236	7560	3675	40602
Differ. %	*+187%*	*+421%*	*-85%*	*-86%*	*-73%*

The same considerations can be made for instantaneous NO_x and NO_2 values, registered in the tunnel, whose decrease in number is clearly illustrated in Figures 44-46.

For example, the variance determined on instantaneous values of NO_x decreases of **75%** (passing from 327,028 to 82,138), Table 13.

The same results were obtained for NO and NO_2 instantaneous values.

Table 13 – Variance of NOx instantaneous values (tunnel)

	NO_x, Mean Value g/m^3	Variance
July	681	327,028
Sept-Oct	529	82,138

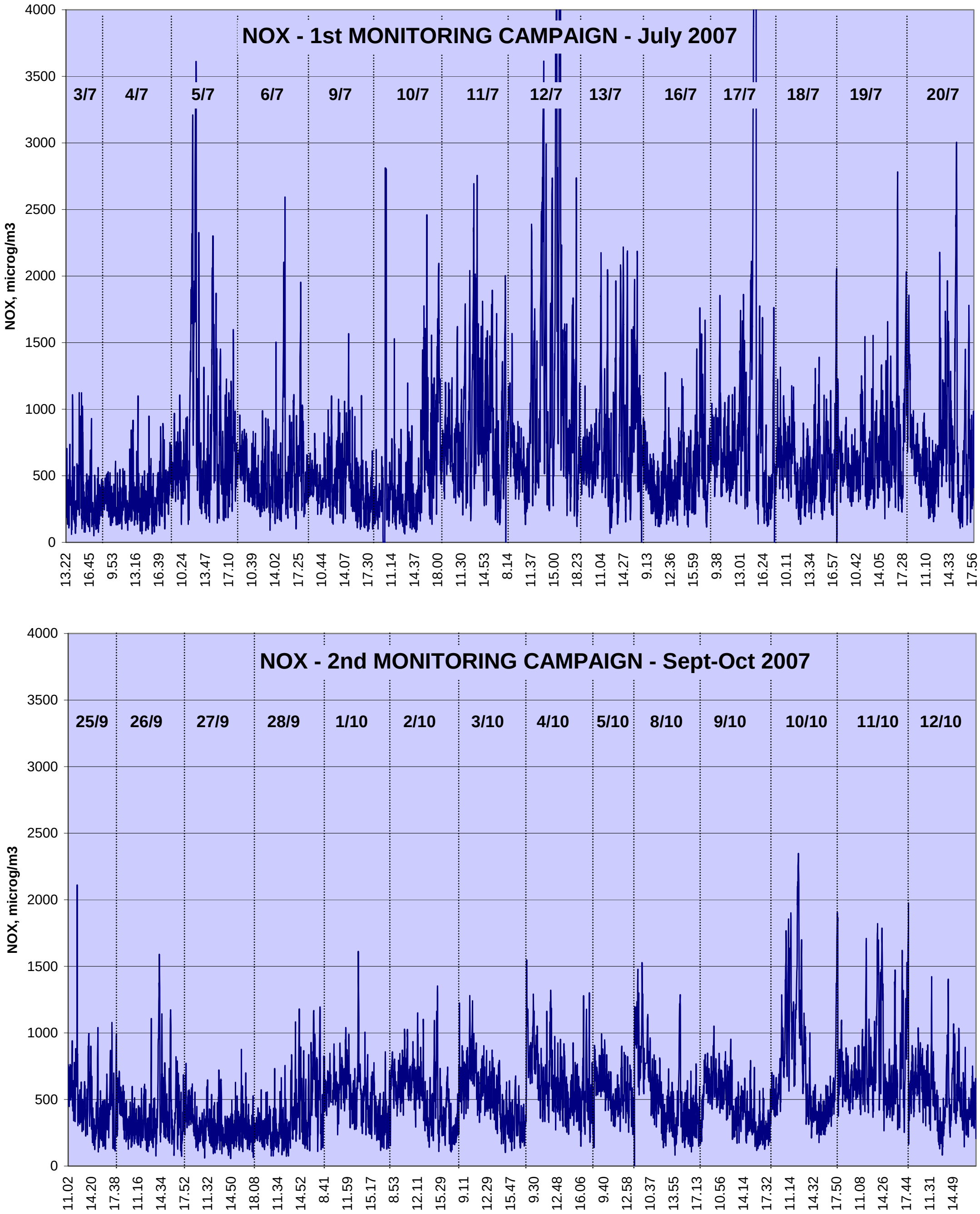


Figure 44 – A comparison of the number of NO_x peaks, before/after the renovation

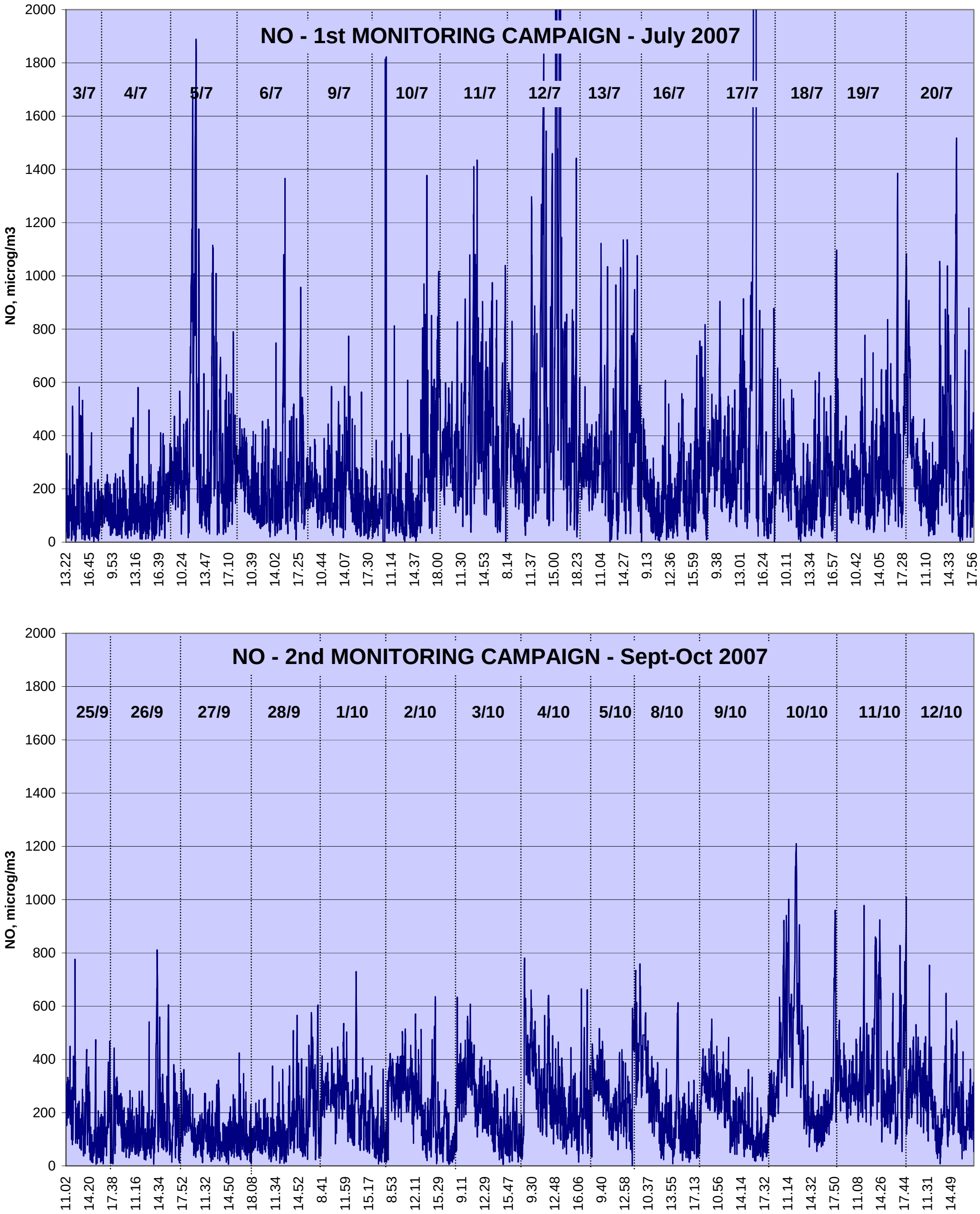
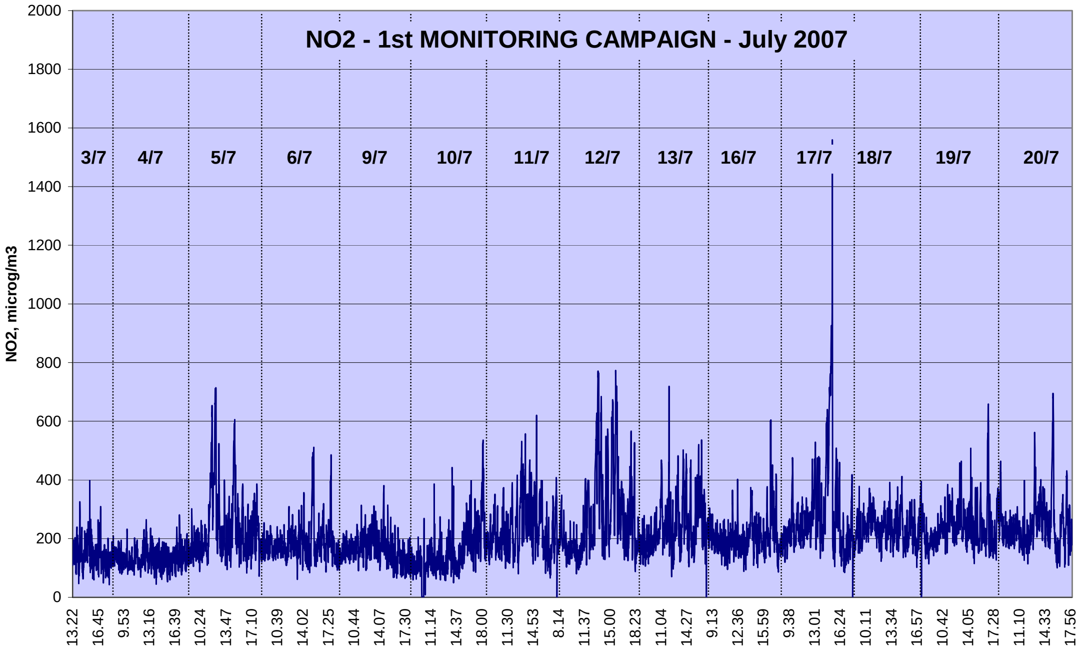


Figure 45 – A comparison of the number of NO_2 peaks, before/after the renovation



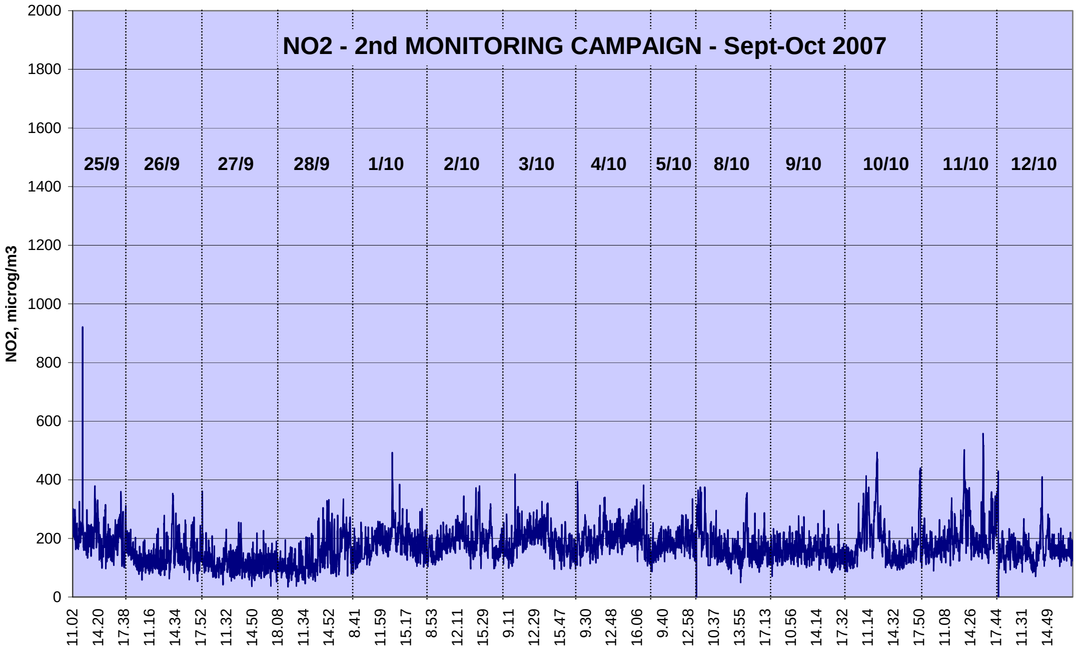


Figure 46 – A comparison of the number of NO_x peaks, before/after the renovation

PARTICULATE MATTER (PM) ANALYSIS

During the two NOx monitoring periods (July 2007 and September-October 2007), some environmental analysis were carried out in the tunnel centre with reference to the total particulate matter (PM total).
As to these analysis, an automatic sampling portable equipment (by TCR Tecora Pollution Check – model: Bravo Plus M) was used for a sampling of the total particulate, by collecting on a filter the powders dispersed in the tunnel, before and after the renovation work, Figures 47-48.
The sampling analysis were carried out for about 10 hours per day. The flow rate of the air drawn by means of a membrane pump was 10 liter/hour.
The collected powders were analysed in order to quantify the presence of TiO_2, as a percentage of the total amount of powder.

The collected powders were analysed by mass spectrometry (Inductively coupled plasma-mass spectrometry - ICPMS ELAN DRC, Perkin Elmer). The results are shown in Table 14. there aren't any relevant differences between the two periods, in terms of TiO_2 content. These percentages were also found in a similar sampling recently carried out in another monitoring campaign in Bergamo, Italy (see the corresponding CTG report n. 6-2008).

Table 14

Filters, #		Date	Total weight of powder (g)	Ti (μg)	TiO_2 (g)	TiO_2 (%)
2	3	17-18 July	0,0034	0,68	0,00102	0,30
4	5	19-20 July	0,0026	0,36	0,00055	0,21
6	9	5-8 October	0,0022	0,26	0,00046	0,21
10	11	9-10 October	0,0025	0,33	0,00068	0,27
12	13	11-12 October	0,0023	0,40	0,00078	0,34

In addition, a chemical analysis was carried out in order to compare the composition of powders collected and that of the tunnel pavement (cobblestones, the so-called "sampietrino", typical paving stones used in the centre of Rome), Figure 49.
A comparison of crystallite species determined by means of X-rays analysis is summarized in Table 15.

Indeed, calcite and quartz are typical phases commonly found in the dispersed particulate matter of the urban environment, whereas the other phases – reported in Table 15, 1st column – can be referred to the pavement, as a consequence of the traffic abrasion, Table 15, 2nd column.
TiO_2 cannot be detected by X-rays analysis, owing to its small amount present in the powders collected.
Finally, organic analysis and image analysis allowed to detect the presence of wood fibers, cellulosic fibers, spores, and tyre scraps. The average organic total content was about 6%.

Table 15

PM (tunnel environment)	Paving blocks
Calcite, quartz, dolomite, mica (muscovite), gypsum, feldspates (albite), leucite, piroxene (augite), analcime.	feldspatoides (leucite and nepheline), piroxene (augite), mica .

Figure 47 – TCR Tecora “Bravo M Plus” equipment, over the NOx analyser

Figure 48 – TCR Tecora pollution check equipment, over the NOx analyser

Figure 49 – Pavement of the tunnel: cobblestones (Sampietrini)

CONCLUSIONS

Results obtained from the monitoring program have confirmed the high efficiency of photocatalytic paint used for the renovation of the tunnel “Umberto I” in Rome, the first significant example of an indoor application for depollution abatement.

The high performances of photocatalytic cement-based products have already been determined in other pilot projects, in outdoor applications (e.g. Via Borgo Palazzo, in Bergamo, Italy).

Two monitoring campaigns were carried out before and after the renovation work of the tunnel for a significant period of time, in order to collect an adequate quantity of data collected for the numerical and statistical evaluation.

Indeed, the complexity of statistical analysis is lower, in comparison with outdoor conditions: in the tunnel, the main parameters to be considered for the variation of polluting level are traffic volumes and wind speed.

Other weather conditions are to be considered less critical, in order to evaluate possible variations in data collection.

Besides, according to the adopted approach, light irradiation can be considered constant along the two monitoring periods, thus simplifying the evaluation of results.

Another interesting result was obtained by making the comparison of tunnel pollution levels with official stations, set up near the tunnel: this information have been very useful for an adequate evaluation of the obtained monitoring results.

Considering the absolute values numerically calculated, **a reduction of NOx values over 20%** was determined, in particular, in the centre of the tunnel:

- A 25% reduction of NO values;
- A 23% reduction of NO_x values;
- A 19% reduction of NO_2 values.

However, since the second campaign (September-October 2007) the pollution values registered in the city of Rome are higher than the corresponding values in July 2007, we can conclude that the real depolluting effect induced by the system (paint + lighting system) is really higher than the above mentioned values (20-25%).

In this sense, according to the statistical approach applied to the data evaluation, the reduction of pollution level in the centre of the tunnel results to be **higher than 50%** (calculated abatements range from 51% until 64%).

Furthermore, another relevant effect derived form the photocatalytic degradation of polluting gases is the **reduction of pollution peaks** (individual values) observed for all NO_x gases (NO and NO_2), also confirmed by the statistical calculation of the variance for data population.

The photocatalytic treatment of the vault is really effective and enables reduce the pollution level up to nearly outdoor conditions, for the city of Rome.

In reference with the quantitative chemical analysis of powders sampled with a dedicated equipment, results confirmed that the presence of TiO_2 after the renovation work was unchanged. The origin of powder seems to be referred to the abrasion of paving stoned used for the pavement.

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