Tunnel portal dispersion monitoring

by I S McCrae, J Pittman, P G Boulter and K T Turpin

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Executive summary

Tunnel portal emissions and portal concentrations were estimated for a selection of tunnels on the Highway Agency's road network. These estimates were based upon recorded traffic flows, speeds and fleet compositions and employed simple emission functions. Pollution profiles for nitrogen dioxide were measured in the vicinity of two tunnel ports, the Southwick and Bell Common tunnels. Measurements were undertaken using simple low cost diffusion tubes, with the results biased adjusted against continuous chemiluminescence analysers operated by neighbouring local authorities. Standard Palmes diffusion tubes were employed, in combination with the passive Ogawa samplers. Similar nitrogen dioxide measurements were recorded with the two measurement methods at the Southwick tunnel. However at the Bell Common tunnel the Ogawa samplers recorded significantly higher concentrations when compared to the Palmes tubes. It appears that the Ogawa samplers considerably over-estimated nitrogen dioxide concentrations at this site, characterised by relatively high nitrogen dioxide concentrations.

Tunnel portal emissions may be visualised as horizontal jets, which are emitted at the tunnel exit, in part through the piston effect of the traffic travelling through the tunnel bore. Upon emission this jet plume is subject to interaction and sheer with the prevailing meteorology. The latter will also be influenced by topography in the immediate vicinity of the portal, where the majority of tunnel exits occur within cuttings.

The measured pollution profiles were compared with the results from the tunnel portal air pollution model, GRAL, developed by the Technical University of Graz. From this relatively small study, it may be concluded that the GRAL model appears suitable for the assessment of tunnel portal air quality. Plume stiffness appears to be the most significant parameter in improving the agreement between measured and modelled concentrations.

CONTENTS

1 Introduction

1.1 Overview

In England, the Highways Agency (HA) is responsible for the maintenance and operation of a number of existing road tunnels on the strategic road network, and manages an on-going programme of tunnel improvements and developments. In order to support its programme, the Agency is looking to reduce the uncertainty associated with the estimation of tunnel portal dispersion characteristics and concentration profiles. The objective of this study was to understand how oxides of nitrogen (NO_X) and nitrogen dioxide (NO_2) concentrations change with increasing distance from tunnel portals. This was assessed through the measurement of concentration profiles within the vicinity of two tunnel portals using passive samplers, the use of a tunnel portal air pollution dispersion model and the estimation of tunnel portal emission source strength.

Previous studies during the 1980s have demonstrated that pollutant concentrations reduce to background levels within 300 m of a tunnel portal (Ide *et al*, 1987, Marsault and Gabet, 1985). However, given that the emissions from individual vehicles have reduced by over 90% since the 1980s, it may be estimated (even with the incorporation of traffic growth) that concentrations are now likely to reduce to background levels well within this distance from the portal. In addition, background pollutant concentrations for the conventional traffic-related pollutants – carbon monoxide, nitric oxide, hydrocarbons and particulate matter, have also reduced, and thus the concentration profile upon which the local tunnel portal emissions are superimposed, is now significantly lower. However, as many of UK road tunnels are not vented via stacks, the emissions from the tunnel portal can result in a pollution hotspot, given that the emissions along the length of the tunnel are emitted at the portals (Boulter *et al*., 2008b; Dix, 2006).

Tunnel portal emissions may be visualised as horizontal jets, which are emitted at the tunnel exit, in part through the piston effect of the traffic travelling through the tunnel bore. Upon emission this jet plume is subject to interaction and sheer with the prevailing meteorology. The latter will also be influenced by topography in the immediate vicinity of the portal, where the majority of tunnel exits occur within cuttings. One further complication is that, particularly for those tunnels that pass under rivers, the tunnel entrances and exits will be characterised by road gradients, which can also provide additional buoyancy to the tunnel jet plume.

Whilst there is rather limited information on UK tunnel portal air quality, one earlier study by TRL on behalf of the Highways Agency, highlighted that NO_2 concentrations were likely to exceed the AQS NO_2 annual mean limit value at distances of up to 25 m from the portal for those receptors at an angle to the portal, but would continue to distances in excess of 200 m along the edge of the tunnel approach road (Boulter *et al*, 2003). However, these conclusions from this earlier study were subject to uncertainty, due to difficulties associated with the use of passive diffusion tube measurements employed within that study.

The 1995 UK Environment Act required the UK Government and the devolved authorities for Scotland and Wales to develop and implement a national air quality strategy (AQS). This strategy gave provision for the establishment of standards, objectives and measures for improving ambient air quality. The original AQS was published in 1997, and has subsequently been subject to a number of consultations, revisions and addendums. The most recent revision was released in July 2007 (Defra, 2007). The AQS process requires local authorities to review and assess air quality within their areas, and where concentrations may be expected to exceed the objective, to declare an air quality management area (AQMA) and to establish an action plan, designed to improve local air quality. Whilst it is recognised that tunnel portals on the high speed road network are not geographic areas where the public might be exposed to air pollution, it is within this background of local air quality management, that the impact of tunnel portals on air quality requires additional understanding.

The air quality objectives adopted in the UK are based on the Air Quality Regulations 2000 and (Amendment) Regulations 2002 for the purpose of Local Air Quality Management (LAQM). The latest AQS set amended limits based on the recent revised EU air quality directive 2008/50/EC (EC, 2008). Table 1 provides a summary of the current UK and EU air quality objectives for NO_2 and the date to achieve them by.

Table 1: NO_2 national objectives and European Directive Limit Values for the protection of human health.

Measurement period	**AQS Objective**	**Date to be achieved by and maintained thereafter**	**European Limit Values**	**Date to be achieved by and maintained thereafter**
1-hour mean	200 $\mu g/m^3$ Not to be exceeded more than 18 times a year	31 December 2005	200 $\mu g/m^3$ Not to be exceeded more than 18 times a year	1 January 2010
Annual mean	40 $\mu g/m^3$	31 December 2005	40 $\mu g/m^3$	1 January 2010

Compliance with the AQS objectives (and corresponding EU limit values) for NO_2 have proven difficult within the vicinity of busy roads.

1.2 Aims and objectives

On the 1 January 2010 the European limit value for NO_2 will come into force, and without significant reductions in NO_X emissions from the transport sector, compliance with this Directive limit will similarly be difficult. Emissions from road tunnels are frequently emitted at a single point, and thus depending on the physical characteristics of the tunnel and the traffic passing through the tunnel, emissions and thus pollution concentrations within the vicinity of portals can be significantly elevated above background concentrations. Several tunnels have been proposed by the Agency, over the last 10 years, most notably those at Hindhead, Mottram and Stonehenge. Whilst the latter two have not been confirmed, the 1.8 km twin bored tunnels under the Devil's Punch Bowl Site of Special Scientific Interest (Hindhead) is scheduled to open in mid-2011. Whilst these schemes were proposed for a variety of reasons, their impact on local air quality requires consideration. Existing knowledge is relatively limited, and thus the main objective of this study was to investigate how NO_X and NO_2 concentrations change with increasing distance from typical tunnel exit portals.

A number of tasks were specified to allow the investigation of this issue:

- The examination of each of the 8 HA operated tunnels (restricted to those over 150m in length) and to identify two tunnel portals that would be characteristic of this overall asset. The tunnels were:
    - Dartford tunnel
    - Holmesdale tunnel
    - Bell common tunnel
    - Hatfield tunnel
    - Meir tunnel
    - Round Hill tunnel
    - Southwick tunnel
    - Saltash tunnel,
- To undertaking passive sampling monitoring campaigns, for NO_X and NO_2, within the vicinity of these two tunnel portals,
- With reference to traffic flows, to derive estimated emissions from each of these 8 HA tunnels' and,
- To investigate and employ state-of-the-art dispersion modelling, to characterise concentration profiles with the vicinity of a typical tunnel portal.

1.3 Report structure

The subsequent Chapters of this report are separated into the estimation of emissions from tunnel portals, a description of NO_2 and NO_X monitoring campaigns and the application of a dedicated tunnel portal dispersion model to portal pollution concentrations.

Chapter 2 describes a process by which emissions are estimated for traffic passing through 8 existing and 3 proposed tunnels on the HA high speed road network. These emission estimates are subsequently used to derive the concentration of CO, NO_X and particulate matter (PM_{10}) at the face of the portal. Chapter 3 describes the process by which two tunnel portals, the eastern portal of the Southwick tunnel and the western portal of the Bell Common tunnel were selected for subsequent air pollution monitoring campaigns. The analysis of the derived NO_2 and NO_X transect data are described, and plotted using geographic information systems (GIS), in Chapter 4. Chapter 5 provides a brief summary of tunnel portal dispersion modeling approaches, and provides the rational for the selection and use of the Technical University of Graz, GRAL model to simulate tunnel portal air pollution. Finally, Chapter 6 provides a summary and conclusion of the main outcomes of this study, with particular reference to changes in understanding in the tunnel portal dispersion characteristics of NO_X and NO_2.

2 Estimation of portal emissions and concentrations

2.1 Background

Various atmospheric pollutants are emitted from road vehicles as a result of combustion and other processes. Exhaust emissions of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen and particulate matter are regulated by EU Directives. A range of unregulated gaseous pollutants are also emitted in vehicle exhaust, including the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). For exhaust pollutants, a distinction can also be drawn between ‘hot’ emissions and ‘cold-start’ emissions. Hot exhaust emissions are produced by a vehicle when its engine and exhaust after-treatment system are at their normal operational temperatures. Cold-start emissions are those produced from the exhaust when the temperatures of the engine and emission control system are between the ambient temperature and their full operational temperatures. Evaporative emissions of volatile organic compounds (VOCs) are also regulated by EU Directives. Finally, PM is also generated as a result of a number of (unregulated) non-exhaust processes, including tyre wear, brake wear, road surface wear, and the resuspension of material previously deposited on the road surface.

Due to the limited dispersion and dilution conditions in a tunnel environment, pollutant concentrations tend to be substantially higher than the concentrations in normal ambient air. The concentrations of pollutants will generally increase with distance inside the tunnel, up to a location where the polluted air is vented to the atmosphere. If all the pollution produced within a tunnel is released at the exit portals, then the portals can effectively represent significant ‘point’ emission sources. Here, tunnel portals have been treated as point emission sources, and the portal emission rates for HA tunnels have been calculated. Estimates have also been made of the pollutant concentrations at the exit portals.

For simplicity, within this assessment it has been assumed that all of the tunnels have zero gradient. However, gradient does have an important determinant on vehicle emissions, especially those for HGVs. In a separate study, the Bell Common and Hatfield tunnels were used by TRL to characterise primary NO_2 emissions. One of the most significant findings of the study was the much larger emission factor for heavy-duty vehicles in the Bell Common tunnel (around 17 g vehicle^{-1} km^{-1}) compared with the Hatfield tunnel (around 4-5 g vehicle^{-1} km^{-1}) and the UK emission factors. In addition, the NO_2/NO_x proportion for such vehicles was lower in the Bell Common tunnel. These findings may have been due to the difference in road gradient (0% in Hatfield, around +2% in Bell Common). In this study an emission model called PHEM was used to estimate the likely impact of this difference in gradient. The results indicated that the overall ratio between the NO_x emission factor at +2% road gradient and a level grade was approximately 2. When the Hatfield tunnel NO_x emission factors for HGVs were multiplied by a factor of two, then this gave a (weighted) value around 8.3 g vehicle^{-1} km^{-1}. Consequently, although the gradient has an important effect, it does not fully explain the difference between the HGV emission factors in the two tunnels. It is possible that the HGVs in the Bell Common tunnel have a higher gross weight than those in the Hatfield tunnel, although no information was available to allow this to be tested (Boulter *et al.*, 2007).

2.2 Calculation method

2.2.1 Background

The absolute concentration of a given pollutant at a given location inside a tunnel bore is comprised of the following four contributions:

(i) The background concentration.

(ii) The open-road contribution from the traffic in the direction of travel.

(iii) The in-tunnel contribution from the traffic in the direction of travel.

(iv) The contribution from the other carriageway, including the ingress of polluted air in the tunnel from the exit portal on the other carriageway.

The different contributions - in this case to NO_x concentrations - are illustrated schematically, and in a simplified manner, in Figures 1 and 2.

Figure 1 shows the simplest case - a single-bore tunnel with uni-directional traffic in the bore, longitudinal ventilation, steady-state traffic and steady-state air flow conditions. The Figure shows a 1200 m-long section of road, aligned in a north-south direction and featuring a 600 m-long tunnel. The *y*-axis shows the NO_x concentration at roadside (the 'receptor') in the direction of travel (in this case northbound – there is no southbound carriageway), and the *x*-axis gives the distance along the road section from a starting point 300 m from the tunnel entrance. The change in the NO_x concentration profile at the side of the northbound carriageway as one moves along the *x*-axis of Figure 1 is described below.

Between 0 m and 300 m, the road can be viewed as a simple line source, and the total NO_x concentration at roadside on the northbound carriageway is constant with distance. The total concentration is the sum of the background contribution (assumed to be 15 ppb) and the open-road contribution from the traffic on the northbound carriageway (assumed to be 60 ppb). The values used in the example are arbitrary, and the relative contributions will vary with time and location. The contribution from the traffic will vary according to its flow (volume), speed and composition. Between 300 m and 900 m, the traffic is inside the tunnel, and its contribution increases linearly with distance (1 ppb per metre in Figure 1), assuming that emission rates and air flow rates remain constant, and that there are no outlets for the polluted air other than the exit portal. Between 900 m and 1,100 m, the NO_x concentration decreases fairly rapidly with distance due to dispersion and dilution, and after 1,100 m, the contributions are similar to their values at 0 m. Again, the actual dispersion conditions will vary according to the location.

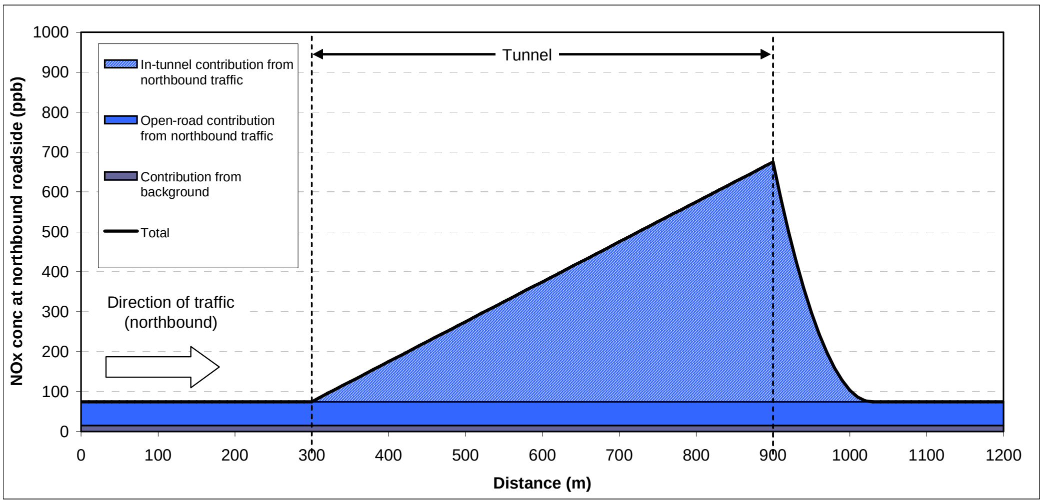

Figure 1: Schematic representation of the NO_x concentration at roadside on the northbound carriageway in the vicinity of a single-bore tunnel.

Figure 2 shows a more complex situation - a twin-bore tunnel (one bore in each direction) with the bores located side-by-side, but still with uni-directional traffic in each bore. Again, the tunnel has longitudinal ventilation. This configuration is typical of HA tunnels. It is assumed that there is no exchange of air between the two tunnel bores, except in the region immediately outside the portals. However, the latter condition means that the recirculation of air must also be considered in any calculations, otherwise concentrations will be underestimated.

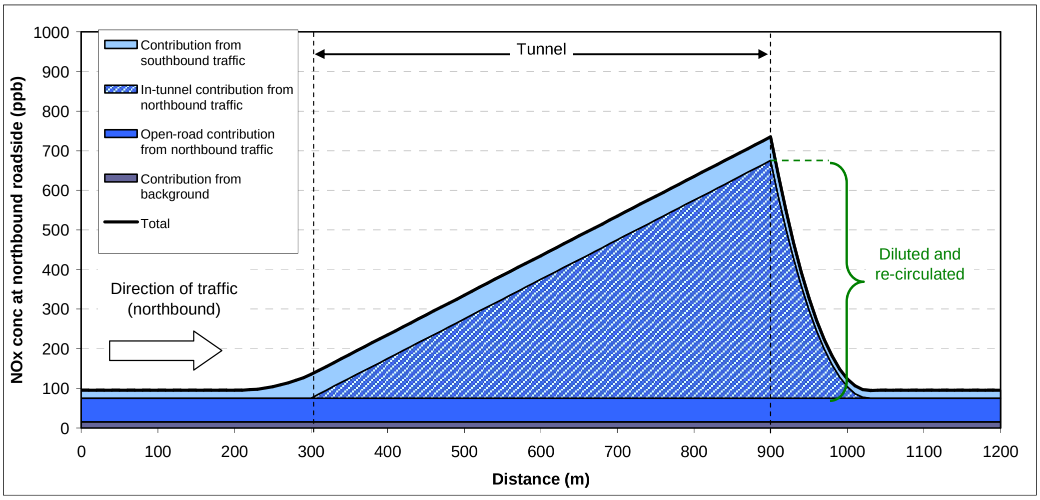

Figure 2: Schematic representation of the NO_x concentration at roadside on the northbound carriageway in the vicinity of a twin-bore tunnel.

Where there are two bores side by side, the air exhausted from the exit portal of one bore can be drawn into the entry portal of the other bore. In those tunnels where significant amounts of portal recirculation occurs at both ends, there can be a continuous pattern of air re-circulation, with polluted air from the exit portal of one bore being re-entrained in the air of the other bore, with subsequent re-entrained in the first bore, and so on. In theory, this could lead to a positive feedback situation, in which concentrations increase to extremely high levels, and could theoretically rise to infinity. Measurements indicate that this does not happen.

Levels could only rise to infinity if the two tunnels have exactly the same air flow rate and the amount of recirculated air is 100%. In a pair of tunnels in which there is a slight imbalance in the rates of air flow, or in which there is less than 100% recirculation, the peak pollution level of the air discharged out of the system will approach a finite, steady-state value. This steady-state value is given by the net amount of pollution divided by the difference in the flow rates between the two tunnels. To illustrate this, one can imagine longitudinally-ventilated tunnel bores which are side by side, and in which the first bore has an air flow of 110 $m^3 s^{-1}$, and the second bore has an air flow of 100 $m^3 s^{-1}$. At both ends, 100 $m^3 s^{-1}$ of air circulates from one bore to the other.

At the inlet end of the first bore, 10 $m^3 s^{-1}$ of clean air is drawn in from the atmosphere and 100 $m^3 s^{-1}$ of polluted air is drawn in from the second bore. At the other end of the first bore, 100 $m^3 s^{-1}$ of polluted air is put into the second tunnel and 10 $m^3 s^{-1}$ is discharged to atmosphere. If the pair of tunnels are treated together as a black box, then the black box draws in 10 $m^3 s^{-1}$ of clean air from atmosphere, adds the pollution from the vehicles in both tunnels then discharges 10 m^3/s of polluted air to atmosphere. If the recirculation of air is allowed to reach a steady state, then the pollution concentration of the outgoing air must equal the total amount of pollutant in the black box divided by the flow rate through the black box (Bennett, 2007). In reality, the traffic flow in intermittent, air flow conditions are not steady-state and are not identical in the two bores, and the proportion of air which is re-entrained may actually be rather small.

Experiments on the amount of air recirculated between two tunnel portals next to one another have shown that in still weather conditions, it can reach 20% of the flow through the bores (Maarsingh and Swaart, 1991). The presence of an anti-recirculation barrier (a dividing wall as high as the tunnel soffit, extending several tens of metres out in the central reserve between the two bores) reduces the amount of recirculation to below 1% in still conditions. For the work reported here, a recirculated proportion of 5% has been assumed (Boulter *et al*., 2008a).

The effect of winds - in particular, crosswinds that blow an outgoing jet of air into the path of incoming traffic - can raise the recirculation at one end of the tunnel to 60-70% (Lepage and Schuyler, 1991). However, at the other end of the tunnel, the same cross-wind will reduce the recirculation to negligible levels. Thus, the prospect of recirculated air causing any significant increase in the pollution level of UK road tunnels is very low.

A notable feature of one recent UK tunnel (the Airside Road Tunnel at Heathrow) is that the west portal ends at a depressed cutting with a tee-junction just outside the portal. An anti-recirculation barrier would have interfered with turning traffic, so it could not be built. Instead, the longitudinal ventilation system was designed to handle all the pollution from one bore being drawn back in to the other bore. At the other portal, a sizeable anti-recirculation barrier was installed to minimize the amount of doubly-recirculated air (Bennett, 2007).

Referring back to Figure 2, between 0 m and 100 m, the road can again be viewed as a simple line source, and the total NO_x concentration at roadside on the northbound carriageway is constant with distance. The total concentration is the sum of the background contribution, the open-road contribution from the traffic on the northbound carriageway, and the open-road contribution from the traffic on the southbound carriageway (assumed to be 20 ppb). The contribution from the northbound carriageway is assumed to be higher (by a factor of three) than that from the southbound carriageway on account of its closer proximity to the receptor.

Between 100 m and 300 m, the contribution from the southbound carriageway increases on the approach to the tunnel, due to the pollution emanating from the exit portal on the southbound carriageway. There will be some dilution of the ‘plume’ between the south portal and the receptor. In Figure 2, it is assumed firstly that the plume from the southbound exit portal has an initial (undiluted) NO_x concentration with is identical to the in-tunnel contribution at the exit portal of the northbound carriageway (from the northbound traffic only), and secondly that it is diluted by a factor of twenty (equivalent to a recirculation proportion of 5%) by the time it arrives at the tunnel entrance on the northbound carriageway. This value of the dilution factor will have a large impact on the absolute concentration inside the tunnel. The contributions from the northbound traffic and the background again remain constant with distance. Between 300 m and 900 m, the traffic on the northbound carriageway is inside the tunnel, and its contribution increases with distance as before. In the example, it is assumed that the plume from the exit portal of the southbound carriageway is re-entrained in the tunnel via the entrance portal of the northbound carriageway, and its contribution is fixed at its value at the entrance portal. As there is no exchange of air between the two portals, the contribution from the southbound carriageway remains constant with distance inside the tunnel. Between 900 m and 1,100 m, the contributions from the northbound and southbound carriageways decrease with distance, and after 1,100 m, the contributions will be similar to their values at 0 m.

When averaged over time, the concentration profile at roadside on the southbound carriageway ought to be similar to that shown for the northbound carriageway in Figure 2, although any prevailing cross wind will result in different profiles. The concentration profiles over short periods, such as one hour, will also be different for the two carriageways on account of differences in traffic flow, speed and composition.

2.2.2 Tunnel portal emission rates

2.2.2.1 Theory

The different factors which contribute to the absolute concentration of a given pollutant at roadside inside a tunnel bore were discussed in the previous Section. Similarly, the rate of emission of a pollutant (in mass per unit time) from the portal can also be expressed in terms of these contributions. Using the ‘north-south’ nomenclature from Figures 1 and 2, and replacing roadside concentrations with portal emissions, the portal emission rate from the north portal can be expressed as follows:

$$\boldsymbol{PE}_{\boldsymbol{total,north}} = \boldsymbol{PE}_{\boldsymbol{background}} + \boldsymbol{PE}_{\boldsymbol{north,}open} + \boldsymbol{PE}_{north,tunnel} + \boldsymbol{PE}_{\boldsymbol{south,recirc}} \quad (\mathrm{g\ h^{-1}}) \qquad \text{(Equation 1)}$$

Where:

$\boldsymbol{PE}_{\boldsymbol{total,north}}$ = total emission rate from north portal (g h^{-1})
$\boldsymbol{PE}_{\boldsymbol{background}}$ = background contribution (g h^{-1})
$\boldsymbol{PE}_{\boldsymbol{north,open}}$ = open-road contribution from traffic on northbound carriageway (g h^{-1})
$\boldsymbol{PE}_{\boldsymbol{north,tunnel}}$ = in-tunnel contribution from traffic on northbound carriageway (g h^{-1})
$\boldsymbol{PE}_{\boldsymbol{south,recirc}}$ = Re-entrained contribution from traffic on southbound carriageway (g h^{-1})

However, if it assumed that the portal represents a point source (with emission rate $\boldsymbol{PE}_{\boldsymbol{point}}$) over and above the contributions from the background and the open road (and that these are modelled separately), then Equation 1 can be simplified to:

$$PE_{point,north} = PE_{north,tunnel} + PE_{south,recirc} \quad (\text{g h}^{-1}) \qquad \text{(Equation 2)}$$

The annual average emission rate of the pollutant from the portal per hour can then calculated as follows:

$$PE_{north,tunnel} = E \cdot L \qquad \text{(Equation 3)}$$

Where:

E = total annual mean hourly emission rate from the portal (g h^{-1})
L = length of the tunnel (km)

The total hot exhaust emission per unit time of a given pollutant from the traffic inside each tunnel can be calculated by combining average-speed emission factors with information on traffic speed, flow and composition, as in Equation 4:

$$E = \sum_{i=1}^{i=n} e_i(v).N_i \qquad \text{(Equation 4)}$$

Where:

E = total emission of the pollutant from the traffic (in g km^{-1} h^{-1})
i = vehicle category
n = total number of vehicle categories
$e_i(v)$ = emission factor of the pollutant (in g vehicle^{-1} km^{-1}) for vehicle category *i*, as a function of average speed *v*
N_i = is the number of vehicles per hour in category *i*

The contribution from the southbound traffic is rather difficult to calculate, as it is not generally known to what extent the polluted air from the exit portal of the southbound carriageway is diluted and re-entrained in the bore of the northbound carriageway. The dilution will depend upon factors such as the wind speed and direction, the local topography and the presence of anti-recirculation walls. In the simplified calculation method presented here, all such factors are incorporated as a simple ‘recirculation dilution factor’.

$$PE_{south,recirc} = \varphi \bullet PE_{north} \quad (\text{g h}^{-1}) \qquad \text{(Equation 5)}$$

Where:

φ = recirculation dilution factor, assumed to be equal to 0.05.

It is also worth noting that the re-entrainment of air from the southbound carriageway will depend upon the time of day, and the traffic flows on the two carriageways will often not follow the same pattern during the day. Nevertheless, it is assumed here that such effects are cancelled out in the calculation of annual average values.

2.2.3 Application to HA tunnels

The method described above was applied to each HA tunnel in turn in order to derive typical (annual mean) portal emission rates. Clearly, not all HA tunnels are aligned in a north-south direction, and so the north portal in the above description was replaced by the portal of interest in each case. The assessment was applied to all 8 of the live HA tunnels, plus the estimated flows and preliminary characteristics of the Hindhead, Mottram and Stonehenge tunnel proposals (Boulter *et al.*, 2008b).

Exhaust emission factors for various categories of vehicle and pollutant are given in the UK Emission

Factor Database (UKEFD) which is used in the NAEI. The emission functions for the pollutants covered in the 2002 UKEFD are also used in the procedure for air pollution estimation in Volume 11 of the Design Manual For Roads and Bridges (DMRB). The DMRB Screening Method spreadsheet (Version 1.03, September 2006) was used to calculate annual average values of ***E*** for each HA tunnel and each pollutant (CO, THC, NO_x and PM_{10}), using a reference year of 2006 and annual average values for daily traffic flow, traffic speed and traffic composition. The traffic data used as input to the calculations are given in Table 2.

Table 2: Traffic data for 2006 used as input to the emission calculation.

Tunnel	Direction	Traffic data		
		One-way AADT (vehicles per day)[a]	% HGV	Speed (km h^{-1})
Bell Common	Eastbound	51,500 [b]	13.8 [b]	99.3 [b]
	Westbound	51,500	13.8	99.3
Dartford	Northbound (W)	30,000	20.0	80.0
	Northbound (E)	30,000	20.0	80.0
Hatfield	Southbound	45,000 [c]	12.6 [c]	104.5 [c]
	Northbound	45,500	12.6	104.5
Hindhead	Northbound	15,500 [d]	10.9 [d]	99.8 [d]
	Southbound	15,500 [d]	10.6 [d]	98.6 [d]
Holmesdale	Westbound	63,000	20.0	113.0
	Eastbound	63,000	20.0	113.0
Meir	Eastbound	30,000	8.0	65.0
	Westbound	29,500	8.0	65.0
Mottram	Eastbound	18,000 [d]	15.0 [d]	80.0 [d]
	Westbound	18,000 [d]	15.0 [d]	80.0 [d]
Roundhill	Eastbound	13,500	15.0	113.0
	Westbound	13,500	15.0	113.0
Saltash	Eastbound	14,500	8.0	48.0
	Westbound	15,500	8.0	48.0
Southwick	Eastbound	21,500 [e]	4.6 [e]	107.7 [e]
	Westbound	21,000 [e]	5.2 [e]	109.5 [e]
Stonehenge	Eastbound	15,000 [f]	12.0 [f]	105 [f]
	Westbound	14,500 [f]	12.0 [f]	105 [f]

a To nearest 500 vehicles.
b Based on measurements by TRL between May and August of 06.
c Based on measurements by TRL between November 2005 and February 06.
d Assumed, based on data from Mott MacDonald (Bennett, 06).
e Based on measurements by TRL between February and May of 06.
f Assumed, based on data from TRADS2[1] for A303 between A360 and A345.

Only hot exhaust emissions were estimated. Cold-start exhaust emissions, evaporative emissions, and non-exhaust emissions of PM_{10} were not included in the calculation. Depending on the tunnel location (*e.g.* if the tunnel is close to a residential area or has a substantial proportion of local traffic), there may also be a need to estimate cold start exhaust emissions. It was assumed that cold-start emissions would not have been significant in each tunnel, given that most of the vehicles passing through would have had warm engines.

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[1] http://www.trads2.co.uk/

2.3 Pollutant concentrations at portals

2.3.1 Theory

By analogy to Equation 1, the total concentration of a pollutant at the tunnel portal is the sum of concentrations due to the same four sources.

$$\overline{C}_{total} = \overline{C}_{background} + \overline{C}_{north,\mathbf{open}} + \overline{C}_{\mathbf{north,tunnel}} + \overline{C}_{south} \quad (\mu\text{g m}^{-3}) \qquad \text{(Equation 6)}$$

Whether the value of $\boldsymbol{PE_{point,north}}$ equates to a low or high concentration of the pollutant at the portal is also dependent upon the total throughput of air during the corresponding time period (*i.e.* $m^3 h^{-1}$). This, in turn, is dictated by the average tunnel air flow velocity and the tunnel cross-sectional area. Hence, the annual average pollutant concentration (*i.e.* excluding background) at a portal which is generated *within the tunnel* (*i.e.* the northbound traffic in Figures 1 and 2) can be estimated using the following equation:

$$\overline{C}_{north,tunnel} = \frac{10^6 \times PE_{point}}{A \times \overline{V}} \qquad \text{(Equation 7)}$$

Where:

$\overline{C}_{\text{traffic}}$	is the average hourly traffic-generated concentration of the pollutant (μg m^{-3}) at the portal.
A	is the cross sectional area of the tunnel (m^2).
$\overline{V}$	is the hourly average air flow velocity in the tunnel bore (m h^{-1}).

The calculation methods for the terms in the equation for the HA tunnels are described below.

2.3.2 Application to HA tunnels

Calculation of $\overline{C}_{background}$

Background pollution concentrations of CO, NO_x and PM_{10} were obtained from the Defra-Netcen Local air Quality Management website[2]. Background values were determined for the 1 km-square areas in the vicinity of the tunnel portals in 06, using year adjustment factors where appropriate.

Calculation of $\overline{C}_{north,\mathbf{open}}$

The contribution of the open-road traffic on the northbound carriageway was calculated using the DMRB. The traffic data given in Table 1 were again used as input to the calculations. The minimum distance which is allowed in DMRB for the road centre to the receptor (2 m) was used.

Calculation of $\overline{C}_{\mathbf{north,tunnel}}$

The tunnel dimensions and air flow speeds are given in Table 3. As the DMRB emission factors do not take road gradient into account, it was assumed that each tunnel is at level grade. This is a significant source of uncertainty.

Table 3: Tunnel dimensions and air flow (N/A = not available).

Tunnel	Direction	Tunnel dimensions		Air flow speed ($m s^{-1}$)[a]
		Length (m)	Cross-sectional Area (m^2)	
Bell Common	Eastbound	470	126.8	2.7
	Westbound	470	126.8	2.7
Dartford	Northbound (W)	1,429	40.2	N/A[b]

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[2] http://www.airquality.co.uk/archive/laqm/laqm.php

	Northbound (E)	1,436	53.0	N/A[b]
Hatfield	Southbound	1,150	126.8	2.7
	Northbound	1,150	126.8	2.7
Hindhead	Northbound	1,860	64.5	3.0
	Southbound	1,860	64.5	3.0
Holmesdale	Westbound	580	110.7	3.0
	Eastbound	580	110.7	3.0
Meir	Eastbound	284	60.0	3.0
	Westbound	284	60.0	3.0
Mottram	Eastbound	200	60.0	3.0
	Westbound	200	60.0	3.0
Roundhill	Eastbound	380	60.1	3.7
	Westbound	380	60.1	3.7
Saltash	Eastbound	408	92.0	3.0
	Westbound	408	92.0	3.0
Southwick	Eastbound	532	81.5	3.0
	Westbound	532	81.5	3.0
Stonehenge	Eastbound	2,100	70.5	3.0
	Westbound	2,100	70.5	3.0

a A value of 3.0 ms-1 is assumed where no data are available.
b Dartford tunnel not pure longitudinal ventilation (semi-transverse).

On of the main areas of uncertainty in the calculation involved the determination of values for the air flow rates in the various tunnels. Measured air flow rates were only available for the Hatfield and Bell Common tunnels. In both tunnels, an average value of 2.7 m s^{-1} was obtained. Capita Symonds (2004) reported an air flow rate in the Roundhill tunnel of 3.7 m s^{-1}. For all other tunnels and directions, an air flow rate of 3.0 m s^{-1} was assumed. The Dartford tunnel has semi-transverse ventilation, and therefore the tunnel air can be vented at locations other than the tunnel portals. Consequently, the calculation method described here cannot be applied. No traffic forecasts could be obtained for the proposed Stonehenge tunnel.

2.3.3 Comparison with measurements

The final stage of the work involved a comparison between the predicted concentrations at the exit portals of the HA tunnels and available measurements.

2.4 Results

2.4.1 Tunnel portal emission rates

The hot exhaust emission rates predicting using the DMRB for 2006 are given by tunnel and pollutant in Table 4. The portal emission rates ($\boldsymbol{PE_{point}}$) are also shown.

Table 4: Traffic emission rates (hot exhaust only) by tunnel and pollutant predicted using the DMRB Screening Method (reference year 2006), and portal emission rates by tunnel and pollutant (with 5% re-circulation).

Tunnel	Direction	Traffic emission rate (kg $year^{-1}$ km^{-1})			Portal emission rate ($\boldsymbol{PE_{point}}$) (g h^{-1})		
		CO	NO_x	PM_{10}	CO	NO_x	PM_{10}
Bell Common	Eastbound	17,814	28,759	867	1,004	1,620	49
	Westbound	17,814	28,759	867	1,004	1,620	49
Dartford	Northbound (W)	9,979	19,939	534	N/A [a]	N/A [a]	N/A [a]
	Northbound (E)	9,979	19,939	534	N/A [a]	N/A [a]	N/A [a]
Hatfield	Southbound	16,297	24,211	775	2,246	3,337	107
	Northbound	16,297	24,211	775	2,246	3,337	107

Hindhead	Northbound	5,301	7,434	235	1,182	1,657	52
	Southbound	5,234	7,236	228	1,167	1,613	51
Holmesdale	Westbound	25,902	48,162	1,501	1,801	3,348	104
	Eastbound	25,902	48,162	1,501	1,801	3,348	104
Meir	Eastbound	9,597	10,093	302	327	344	10
	Westbound	9,437	9,925	297	321	338	10
Mottram	Eastbound	5,765	9,602	265	138	230	6
	Westbound	5,765	9,602	265	138	230	6
Roundhill	Eastbound	5,469	8,462	282	249	385	13
	Westbound	5,469	8,462	282	249	385	13
Saltash	Eastbound	5,623	5,035	166	275	246	8
	Westbound	6,010	5,383	177	294	263	9
Southwick	Eastbound	7,820	6,976	284	499	445	18
	Westbound	7,849	7,272	296	501	464	19
Stonehenge	Eastbound	5,448	7,839	255	1,371	1,973	64
	Westbound	5,266	7,577	246	1,326	1,907	62

a Dartford tunnel not pure longitudinal ventilation (semi-transverse).

2.4.2 *Pollutant concentrations at portals*

The estimated modelled concentrations at the tunnel portals are given in Table 5. Background concentrations were derived from the Defra air pollution background maps. The calculations indicate that the most polluted existing tunnels are Holmesdale and Hatfield. It also appears that concentrations are also likely to be relatively high in the Hindhead and Stonehenge tunnels once they become operational. However, it should be noted that these estimates are rather uncertain, given the modelling errors and assumptions involved.

Table 5: Estimated concentration values for HA tunnels.

Tunnel	Direction	$\overline{C}_{background}$			$\overline{C}_{north,\mathbf{open}}$			$\overline{C}_{\mathbf{north,tunnel}}$			$\overline{C}_{south}$			$\overline{C}_{total}$		
		CO (mg m^{-3})	NO$_x$ (µg m^{-3})	PM$_{10}$ (µg m^{-3})	CO (mg m^{-3})	NO$_x$ (µg m^{-3})	PM$_{10}$ (µg m^{-3})	CO (mg m^{-3})	NO$_x$ (µg m^{-3})	PM$_{10}$ (µg m^{-3})	CO (mg m^{-3})	NO$_x$ (µg m^{-3})	PM$_{10}$ (µg m^{-3})	CO (mg m^{-3})	NO$_x$ (µg m^{-3})	PM$_{10}$ (µg m^{-3})
Bell Common	Eastbound	0.23	33.48	21.95	0.18	113.0	11.36	0.78	1,252	37.76	0.04	63	1.89	1.23	1,461	73.0
	Westbound	0.23	37.04	22.54	0.18	113.0	11.36	0.78	1,252	37.76	0.04	63	1.89	1.22	1,465	73.5
Dartford	Northbound (W)	0.26	49.55	26.68	0.14	110.5	9.04	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Northbound (E)	0.27	53.49	25.40	0.13	106.5	10.32	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hatfield	Southbound	0.28	35.02	23.73	0.18	103.4	11.04	1.72	2,561	82.00	0.09	128	4.10	2.27	2,827	120.9
	Northbound	0.28	35.31	24.12	0.18	103.4	11.04	1.72	2,561	82.00	0.09	128	4.10	2.26	2,828	121.3
Hindhead	Northbound	0.18	14.14	19.20	0.11	60.2	6.34	1.62	2,268	71.67	0.08	113	3.58	1.98	2,455	100.8
	Southbound	0.18	15.20	19.49	0.11	58.6	6.15	1.60	2,207	69.47	0.08	110	3.47	1.96	2,392	98.6
Holmesdale	Westbound	0.26	41.18	23.23	0.23	167.7	17.41	1.43	2,667	83.10	0.07	133	4.16	1.99	3,009	127.9
	Eastbound	0.26	40.21	24.02	0.23	167.7	17.41	1.43	2,667	83.10	0.07	133	4.16	1.99	3,008	128.7
Meir	Eastbound	0.26	33.67	23.63	0.13	54.7	5.46	0.48	505	15.11	0.02	25	0.76	0.90	619	45.0
	Westbound	0.28	40.31	25.70	0.13	54.7	5.46	0.47	497	14.86	0.02	25	0.74	0.91	616	46.8
Mottram	Eastbound	0.23	24.92	18.61	0.11	71.1	6.53	0.20	338	9.32	0.01	17	0.47	0.56	451	34.9
	Westbound	0.23	24.92	18.61	0.11	71.1	6.53	0.20	338	9.32	0.01	17	0.47	0.56	451	34.9
Roundhill	Eastbound	0.19	21.26	21.26	0.12	74.5	8.27	0.30	457	15.24	0.01	23	0.76	0.62	576	45.5
	Westbound	0.19	21.26	21.26	0.12	74.5	8.27	0.30	457	15.24	0.01	23	0.76	0.62	576	45.5
Saltash	Eastbound	0.14	10.77	15.65	0.12	43.0	4.73	0.26	236	7.78	0.01	12	0.39	0.54	302	28.5
	Westbound	0.14	10.77	15.65	0.12	43.0	4.73	0.28	252	8.32	0.01	13	0.42	0.56	319	29.1
Southwick	Eastbound	0.22	19.72	20.48	0.13	46.2	6.26	0.54	481	19.57	0.03	24	0.98	0.91	571	47.3
	Westbound	0.22	19.72	20.48	0.13	49.3	6.68	0.54	502	20.39	0.03	25	1.02	0.92	596	48.6
Stonehenge	Eastbound	0.13	10.39	16.74	0.12	64.2	6.97	1.71	2,467	80.14	0.09	123	4.01	2.05	2,664	107.9
	Westbound	0.14	10.10	16.74	0.11	64.5	6.97	1.66	2,384	77.47	0.08	119	3.87	1.99	2,578	105.1

Figures 3 to 5 show the relative contributions of different traffic sources to the total concentrations of CO, NO_x and PM_{10} at the exit portals. Where traffic flows and absolute concentrations are high, the traffic in the tunnel is the main contributor to the pollution levels at the exit portal. Where traffic flows and concentrations are low, the background and open road contributions become more important, especially for CO and PM_{10}. For NO_x, these other sources are small compared with the in-tunnel contribution.

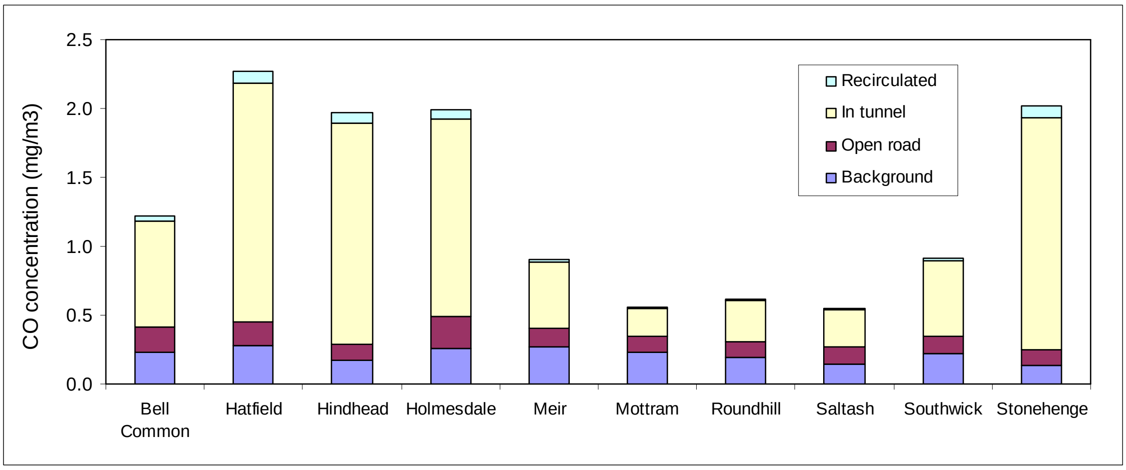

Figure 3: Contributions to CO concentration at tunnel exit portals.

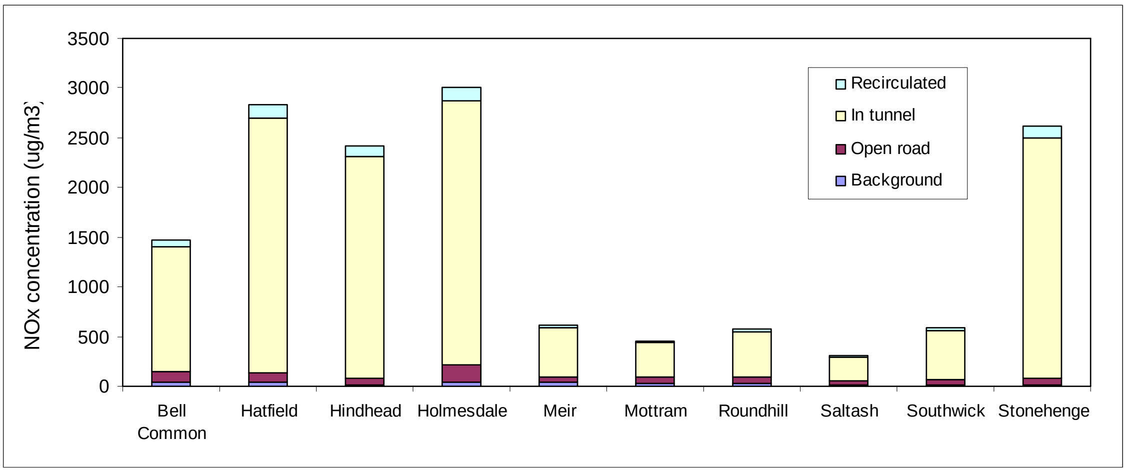

Figure 4: Contributions to NO_x concentration at tunnel exit portals.

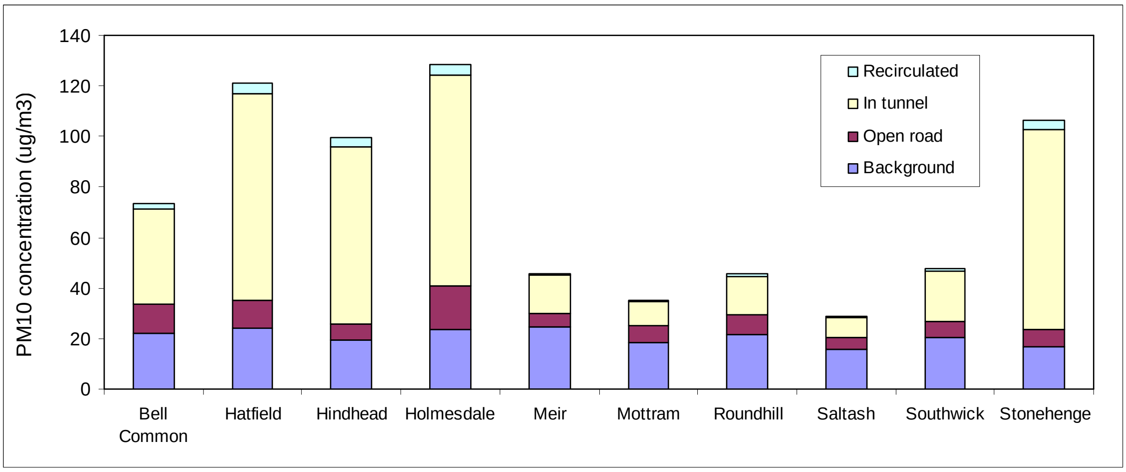

Figure 5: Contributions to PM_{10} concentration at tunnel exit portals.

For a small number of these tunnels, it was possible to test the validity of the overall approach by direct comparison with measurements conducted by TRL. PM_{10} concentrations were measured near the mid-point of the Hatfield tunnel between October and November of 2002, NO_x concentrations were measured near the exit portal of the Hatfield tunnel between November 2005 and February 2006, and NO_x concentrations were also measured near the exit of the Bell Common tunnel between May and August of 2006. These average concentrations from these measurements are compared with the appropriate calculated values in Table 6. The estimates have been adjusted so that they correspond to the measurement points in the respective tunnels and, in the case of PM_{10} in the Hatfield tunnel, the correct year.

Table 6: Comparisons between measured and estimated concentrations.

Tunnel (year)	Pollutant	Average 1-hour concentration during monitoring period (µg m^{-3})	Adjusted estimated annual average concentration at monitoring location (µg m^{-3})
		Measured	Modelled
Hatfield (2002)	PM_{10}	78.9	90.3
Hatfield (2006)	NO_x	1323	2631
Bell Common (2006)	NO_x	2110	1308

The comparisons in Table 6 illustrate the difficulties associated with such calculations, and with comparisons with real monitoring data. There was a reasonably close agreement between the PM_{10} concentration measured in the Hatfield tunnel and the predicted value. However, the estimated value represents an overestimate, even though it does not included non-exhaust sources such as tyre wear, brake wear and the resuspension of road dust. The NO_X comparisons were not particularly conclusive, with there being a large overestimate in the Hatfield tunnel, and a large underestimate in the Bell Common tunnel. The reasons for these differences are unclear. Traffic characteristics can be eliminated, as the traffic data obtained during the measurement campaigns were used in the calculations. The differences may be related to the relatively short-term nature of the measurements, which may not have been representative of the full annual period.

3 Tunnel portal air pollution measurements

3.1 Assessment of tunnel suitability

The Highways Agency is currently responsible for a portfolio of eight tunnels within England, which are greater than 150m in length. These are:

A282	Dartford tunnel
M25	Holmesdale tunnel
M25	Bell Common tunnel
Al (M)	Hatfield tunnel
A50	Meir tunnel, Stoke
A20	Round Hill tunnel, Folkestone
A27	Southwick tunnel, Shoreham
A38	Saltash tunnel, Exeter (single bore)

Project resources allowed for the assessment of pollutant concentrations around a maximum of two tunnel portals. Therefore it was essential that these two tunnels were representative of the HA portfolio. The following criteria were used within this selection process:

- The tunnel should be located away from other roads so that that portal and tunnel road emissions can be detected above the background concentrations,
- The tunnel should be twin bored, so that traffic is unidirectional in each bore and thus allows for the use of relatively simple transverse or semi-transverse ventilation regimes,
- The tunnel should have suitable locations for carrying out the monitoring and safe access to potential monitoring sites, and
- The surrounding terrain should be representative of other tunnel locations (existing or proposed).

Table 7 provides a summary of the analysis of the suitability of each of these 8 tunnels. Four tunnels were considered suitable for further investigation, these being Bell Common, Hatfield, Southwick and Roundhill.

Table 7: Tunnel selection decision matrix.

Tunnel	Suitability	Decision
Dartford	This tunnel is very heavily trafficked, with a complex merging and diverging of lanes on entry and exit to the tunnel. The tunnel entrances are characterised by ramps into and exiting the tunnel, which are not currently typical of the HA estate. The close proximity of significant industrial activity and the Queen Elizabeth II bridge could also complicate pollution profiles.	This tunnel was not considered further.
Holmesdale	This tunnel was subject to renovations during 2006 and 2007, which would impact on traffic flow characteristics through the tunnel. In addition the emissions from plant associated with the engineering works, and the widening of openings in the curtain wall separating the two bores would result in complex air flows and concentration profiles.	This tunnel was not considered further.
Bell common	This tunnel is located on a busy stretch of M25 motorway. The tunnel appeared to be suitable for use, as it has a twin bore and accessible areas around the tunnel portals. Tunnel refurbishment was not scheduled until well after the completion of the field work required within this study.	Further investigation

Hatfield	This tunnel has a similar construction to the Holmesdale and Bell Common tunnels, and had been used in a number of previous air pollution and emission-related studies. Given that this tunnel is relatively well characterised, emphasize was given to other HA tunnels.	Further investigation
Meir	Due to the location of this tunnel, access to monitoring locations within the tunnel portal environment would be relatively difficult.	This tunnel was not considered further.
Round Hill	The tunnel looked suitable in terms of having a twin bore and large central reservation for monitoring equipment deployment. However, one end of the tunnel exits onto a viaduct, and thus dispersion characteristics would not be particularly representative. In addition the tunnel is dominated by cross-channel ferry related traffic, would have a relatively high HGV proportion, and would exhibit a series of flow waves related to the arrival and departure of the ferries.	Further investigation
Southwick	The tunnel looked suitable in terms of having a twin bore, a large central reservation and wide verges, making it ideal for field measurement campaigns.	Further investigation
Saltash	Single bore tunnel which is not representative of the other tunnels in the HA network.	This tunnel was not considered further.

3.2 Site selection

Site visits were made to each of the 4 short listed sites, to appraise each for the geographic constraints to the installation of monitoring transects running from the tunnel portal in various directions, up to a distance in excess of 150m. In addition, a thorough health and safety assessment was undertaken in collaboration with each of the tunnel operators to ensure safe access to these monitoring locations.

A site visit to the Round Hill tunnel indicated that the tunnel would not be suitable due to the nearby location of a slip road at the tunnel exit. This could have caused problems deploying monitoring equipment on the southbound carriageway, and complicated the emission source and pollution profile at this portal. The proximity of the tunnel to Folkestone ferry port resulted in a large number of HGV traffic using this section of road. The hill heading away from the ferry port towards the Roundhill tunnel causes waves of slow moving traffic through the tunnel, shortly after the ferries berth. The traffic flow profile and composition though the tunnel would therefore not be typical of the majority of the other HA tunnels. A subsequent site visit to the Southwick tunnel (of similar construction to the Round Hill tunnel) showed the tunnel portal to be suitable. Here, there were no other nearby main roads, access to the central reservation could easily be carried out and there were safe places to park and access the carriageway verges for equipment deployment.

The Hatfield Tunnel remains an excellent tunnel for pollution monitoring campaigns, but was rejected given that its pollution profile is ‘relatively’ well established. There were thus advantages in undertaking new measurements at a tunnel where limited work had been undertaken in the past.

The northern section of the M25 is one of the busiest sections of motorway within the UK. As such, the Bell Common tunnel was investigated for its suitability. The tunnel has twin bores, and is similar in design to the Holmesdale and Hatfield tunnels, and is thus relatively characteristic of the HA tunnel stock. However, due to the very high traffic flows, and the absence of gantries connecting the motorway verge with the central reservation, access to the central reserve could only be achieved through temporary lane closures. The frequently requirement for pollution monitoring equipment changes, meant that sites in the central reserve were outside the budget available to this task.

In each case, the availability of reliable traffic flow and composition data was an essential site requirement. Automatic traffic counts were available in the vicinity of the Southwick tunnel and

MIDAS (Motorway Incident Detection and Automatic Signalling) loops were available from a number of locations outside the Bell Common tunnel, between junction 26 and 27 of the M25.

The two tunnels, Southwick and Bell Common were selected for the detailed monitoring assessment of portal pollution profiles.

3.2.1 Southwick tunnel

The Southwick tunnel is located outside Brighton and Hove on the A27 Shoreham bypass (Figure 6). The A27 is part of the strategic south coast route running from the A36 Whiteparish, near Salisbury (Wiltshire) to Pevensey (East Sussex). The tunnel was opened in 1996, built through the chalk of Southwick Hill. The tunnel was originally designed for a traffic flow of 32,000 vehicles per day, although the average traffic flow through the tunnel during the 2006 monitoring period was 42,000 vehicles per day. Southwick is circular bore tunnel (Figure 6), with a length of 490m, is dual lane with a 1.5m width footway running along the edge of the nearside lane. There is no hard shoulder within the tunnel or at either of the exits. There is a pull in lay by on the westbound carriageway of the eastern portal and the tunnel offices and services are located at the edge of the eastbound carriageway, again at the eastern portal. At the western end of the tunnel there are hard standing grass verges on both sides of the tunnel. The eastern portal was selected for the monitoring campaign, due in part to the presence of safe parking areas, greater lines of sight and the associated ease of access into the central reservation.

The ground at the eastern portal consisted of a steep slope on the east bound carriageway immediately on exiting the tunnel up to the site offices, at approximately 65m from the tunnel portal (Figure 7). After this point, the ground slopes downwards behind a fence for the site offices. On the westbound carriageway there was approximately 5m of flat ground alongside the carriageway before a steep slope with a fence located at the top. This profile continued away from the tunnel portal to the end of the sampling locations (Figures 8 and 9).

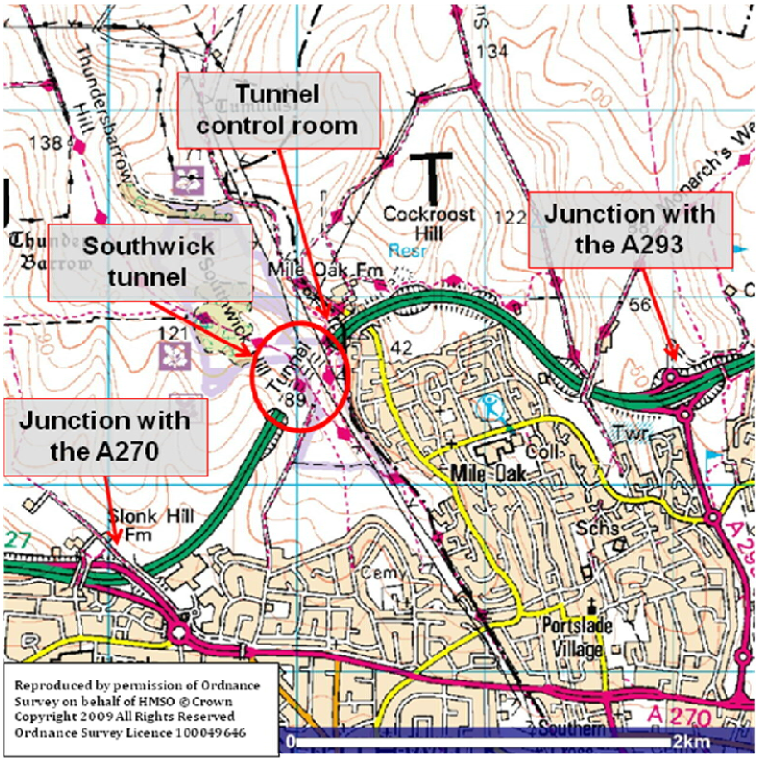

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Figure 6: Location of Southwick Tunnel.

Figure 7: Internal view of the Southwick Tunnel.

Figure 8: Southwick Tunnel, eastern portal looking south.

Figure 9: View of the eastern portal cutting of the Southwick Tunnel, looking west.

Figure 10: View from the eastern portal of the Southwick Tunnel, looking west.

3.2.2 Bell Common Tunnel

The Bell Common Tunnel is located on the northern section of the M25 between Junctions 26 and 27 (Figure 11). The Bell Common tunnel was built to travel under the historic Epping Forrest and Bell Common Cricket ground. The tunnel constructed in 1983 by the cut and cover method, has a length of 471m and a carriageway width of 14.3m. The tunnel includes a hard shoulder. The tunnel has two bores each with three lanes, hard shoulder and also a walkway along the length of the tunnel. The minimum height clearance is 5.03m[3]. The tunnel control complex is located north of the tunnel above and adjacent to the eastbound carriageway of the tunnel (Mouchel Parkman, 2005). This section of the M25 is always very busy as it provides access to the M11 at junction 27. Reported traffic flows of 120,000 vehicles per day, are characteristic of this section of the M25 (Mouchel Parkman, 2005).

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[3] The Bell Common Tunnel is currently being refurbished including the replacement of mechanical, electrical and fire safety equipment. The ventilation system will be upgraded and new monitoring equipment will be installed and linked to new control systems in the Highways Agency's Regional Control Centre at South Mimms. The existing raised walkways are being removed. The works are scheduled for completion in March 2010.

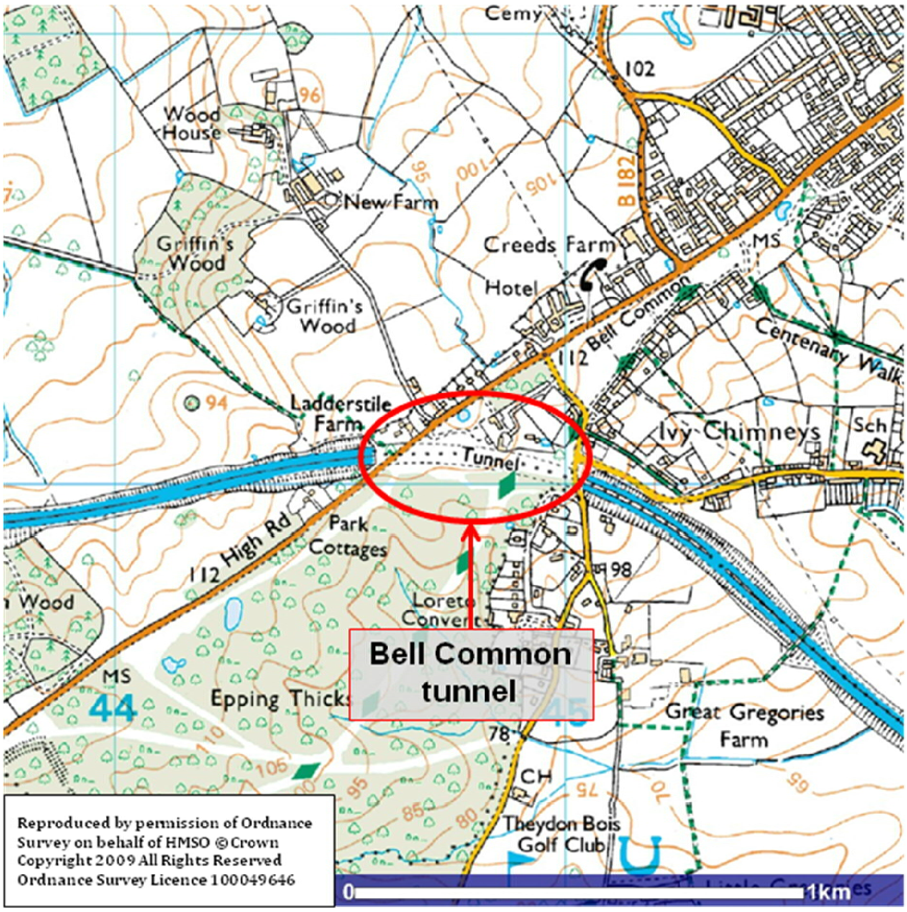

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Figure 11: Location of Bell Common Tunnel.

The western portal was characterised by dense trees on either side of the road, with the road situated within a cutting (Figures 12 and 13). The eastern portal was relatively close to the M11 junction, and was thus characterised by a significant proportion of lane changing and disrupted flows on the approach to the M11 slip road. For this reason the relatively free flowing western portal was selected for monitoring.

Figure 12: View of the western portal of the Bell Common Tunnel, looking southeast.

Figure 13: View of the western portal of the Bell Common Tunnel, looking northeast.

4 Characterisation of portal air quality

4.1 Introduction

The characterisation of the tunnel portal air quality was achieved through a combination of monitoring and modelling. This chapter provides a description of the monitoring strategies, and a presentation of the measured concentrations. Undoubtedly the most robust monitoring strategy would have been to deploy a network of chemiluminescent analysers for the continuous and direct measurement of NO_X and NO. Nitrogen dioxide concentrations would then be derived from the difference between these measurements. However, the deployment of continuous analysers at 30 locations would be a prohibitally high cost, and thus monitoring was undertaken through the use of passive diffusion tubes, and bias adjustment against a single continuous analyser. In addition to the use of the conventional Palmes tubes, a network of Ogawa samplers were deployed, both to measure the concentration of NO_X and NO, but also to assess the robustness of this relatively unproven approach.

4.2 Tunnel portal air pollution monitoring

4.2.1 *Methodology*

In accordance with the project specification, monitoring within the tunnel portal environment was restricted to the measurement of oxides of nitrogen, through the use of passive sampling. Two types of passive diffusion samplers were employed; the conventional NO_2 Palmes tubes, and secondly the NO_2 and NO_X Ogawa sampler (Figures 14 and 15). At both the Southwick and Bell Common tunnels a similar sampling strategy was employed, using a series of linear transects away from the tunnel portal, up to a distance of approximately 200m from the portal. These transects were modified at the individual tunnels to accommodate physical barriers, topography and available space within the motorway boundary. Triplicate NO_2 Palmes tubes and a single Ogawa sampler were deployed at each selected receptor.

Figure 14: Passive samplers installed on the crash barrier on the edge of the westbound carriage way of the Southwick tunnel eastern portal.

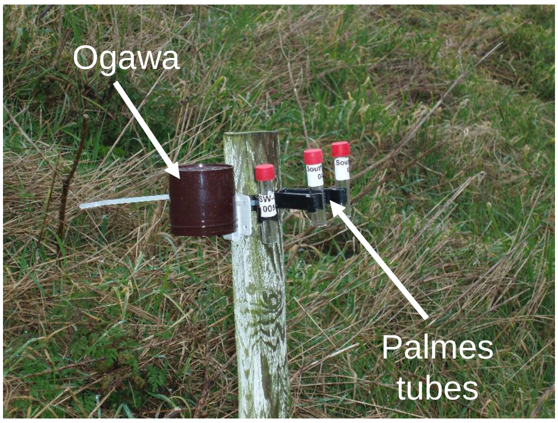


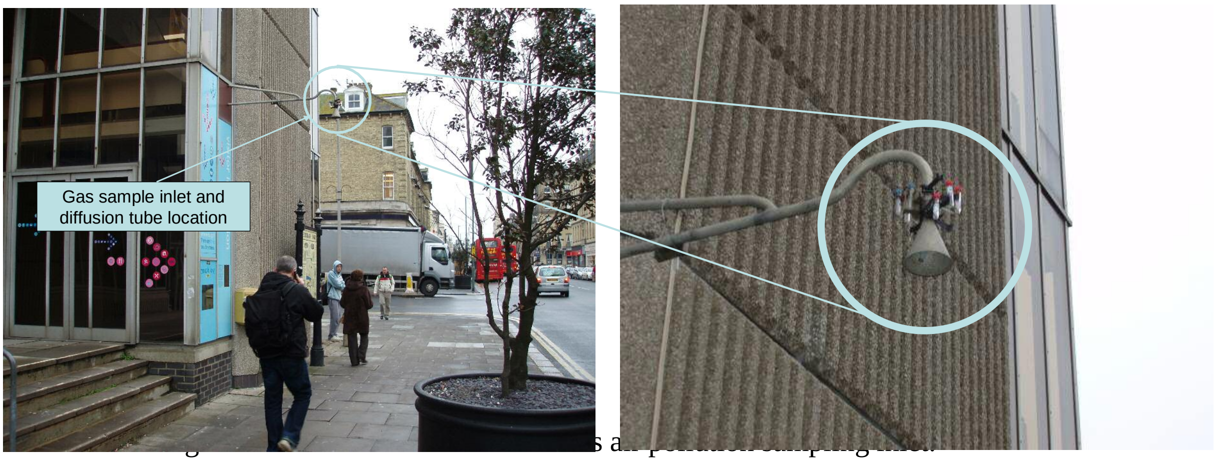
Figure 15: Passive samplers installed on post at the edge of the eastbound carriage way of the Southwick tunnel eastern portal.

4.2.2 *Palmes diffusion tubes*

Palmes tubes are a standard passive measurement device for a range of gases including NO_2. The sampler consists of an acrylic tube, approximately 7 cm long, with a 1 cm internal diameter. During deployment, one end of the tube is opened, with the other end remaining closed and housing a triethanolamine (TEA) treated gauze[4]. Sample gas diffuses along the tube and is absorbed onto the gauze. The TEA converts the NO_2 to nitrate, which can then be analysed using standard wet chemistry and subsequent analysis using colorimitry (AQEG, 2004). Prior to deployment and analysis these tubes were refrigerated. At least one travelling blank was used on each deployment and collection visit, to allow for the identification and correction for contamination during the storage, transport, deployment and collection stages.

In several trials, passive sampling tubes have shown a tendency to overestimate NO_2 concentrations when compared against conventional chemiluminescent techniques. These over-estimates have been credited to a range of possible effects including UV interference with the absorbent and wind-induced turbulence at the tube entrance. In general, passive tubes are thought to over-estimate NO_2 concentrations by between 10 and 27 % (Smith *et. al*. 1999, Heal *et. al*. 1999).

To minimise this uncertainty, best practice recommends the co-location of diffusion tubes with a standard continuous chemiluminescence NO_X analyser. This co-location allows a comparison of the monthly diffusion tube result with the continuous data derived from the reference method analyser. Guidance on the bias adjustment of Palmes NO_2 diffusion tubes is available on the Defra Air Quality Review and Assessment Helpdesk website. A spreadsheet tool is also available to allow the derivation of the most robust biased adjustment factor, through access to other diffusion tube and continuous NO_2 data recorded within the geographic area[5]. The Hove roadside air pollution monitoring site was identified as the closest existing continuous NO_X measurement site to the Southwick Tunnel. Therefore in discussion with the Sussex Air Quality Partnership, three Palmes tubes were co-located at the Hove roadside site[6]. These tubes were changed at the same time as those deployed in the tunnel portal. The Hove site is located in the Town Hall on Church Street in Hove, and has the sample inlet at a height of approximately 3m above the ground level, as illustrated in Figure 16.



Similarly throughout the Bell Common monitoring period, triplicate tubes were co-located at the Broxbourne roadside continuous monitoring station on the A1010 Hertford Road, approximately 40m north of the M25[7]. The site was approximately 7 km to the west of the Bell Common tunnel. This deployment was undertaken in collaboration with the Hertfordshire and Bedfordshire air pollution monitoring network team. The monitoring site was located on top of a residential garage and due to specific access issues, these co-located tubes were deployed by the Broxbourne Borough council local

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[4] There are a variety of ways in which these tubes are prepared, which principally relates to the way in which the gauze is coated with the TEA solution, and the choice of solvent used. Various solvents are used including water and acetone, at a range of concentrations. The analytical method is by subsequent ultra-violet spectroscopy measuring NO_2 absorbed as nitrite by TEA using a variation of the Saltzman reaction (Bush *et al*, 2000).

[5] To download the latest version (v. 02/07) of the bias adjustment spreadsheet, see: http://www.uwe.ac.uk/aqm/review/diffusiontube260207.xls

[6] West Sussex Air (2006). Hove roadside data available at http://www.sussex-air.net/air_quality.html.

[7] Hertfordshire and Bedfordshire air pollution monitoring network (2006). Broxbourne roadside site location details available at http://www.hertsbedsair.org.uk/hertsbeds/asp/PublicDetails.asp?site=BB1&details=&mapview=all

site operator (LSO). These tubes were therefore not deployed or collected at precisely the same time as those deployed in the Bell Common tunnel portal, but where usually exchanged within one or two days of this timetable.

4.2.3 *Ogawa passive samplers*

A second passive oxides of nitrogen sampling method, using a model 3300 Ogawa sampler, was deployed within the transects at each of the tunnel sites. This technique used a two-sided sampler that housed two 14.5 mm diameter pre-coated cellulose filter pads, one to absorb NO_2 and a second to absorb NO_2 and NO, thus allowing the measurement of both NO_2 and NO_X. A schematic of the sampler, developed by Yokohama City Research Institute of Environmental Sciences, is shown in Figure 17.

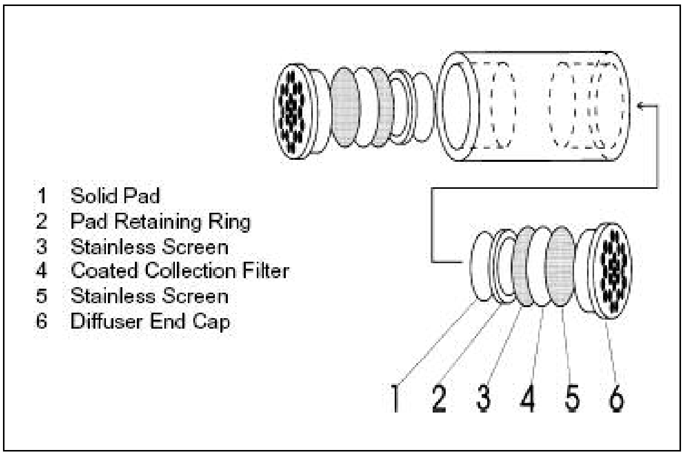

Figure 17: A schematic of the Ogawa sampler (Ogawa & Co, 1998).

The sampling pads were supplied by Air Monitors Limited, and prior to and post deployment were refrigerated. In order to minimise contamination of these filter pads, a rigorous handling regime was adopted. The Ogawa samplers were assembled and loaded with the filter pads under laboratory conditions, with the operator wearing gloves and using tweezers. The operator ensured that the sampling pads were exposed for the least time possible by always replacing the lid to the sampling pads between each preparation. The main bodies of the sampler were labelled to clearly distinguish the NO_X and NO_2 sampling ends. The sampling pads were inserted and the inlet replaced, with the sampler then placed into the Ogawa sampling clip. The sampling clip was then labelled with a unique number and loaded into a clean plastic bag. The bag was then put into the Ogawa container and loaded into the box for transportation. An additional Ogawa sampler was prepared and taken to site each deployment, and used as a travelling blank. The Ogawa samplers were protected from the rain with a protective inverted cup, at each sampling location. The subsequent chemical analysis of the filter pads followed the same procedure as that adopted for the Palmes tubes (Ogawa & Co, 1998).

4.2.4 *Passive sampler monitoring strategy*

The Palmes tubes and Ogawa samplers were deployed at a network of sites in the vicinity of the tunnel portals. At each receptor, three Palmes tubes and one Ogawa sampler were deployed (see Figure 15), normally at a height of 1m above ground level. The sample deployment and collection were undertaken by TRL staff. All contact with the samplers was undertaken using latex gloves to minimise contamination. All samplers were subsequently transported in sealed containers and extracted under laboratory conditions. The sampling location plans for the Southwick and Bell Common Tunnels are shown in Figures 18 and 19. The locations of these receptors are listed in Annex 1. These Figures do not show the location of the local authority continuous monitoring sites, where triplicate tubes were co-located to allow the bias adjustment of the passive tubes.

The Ogawa samplers were changed on a two weekly basis and the Palmes tubes were changed every four weeks. These monitoring durations were determined through discussions with the passive sampler suppliers, to ensure appropriate sensitivity, without overloading the sampling medium. The time and date the samplers were deployed at each sampling location, were recorded and are listed in Annex 2 to 5. Variations to the fortnightly and monthly deployments were occasionally necessary when access to the tunnel portal environment was restricted due to poor weather (largely related to visibility) and other maintenance and incident operations being undertaken by the managing agents.

At both tunnel portals, 30 receptor positions were monitored for a period of approximately 12 weeks. At the Southwick Tunnel measurements were undertaken between 22 February and 10 May 2006. At the Bell Common Tunnel the measurement campaign was undertaken between 24 May and 16 August 2006.

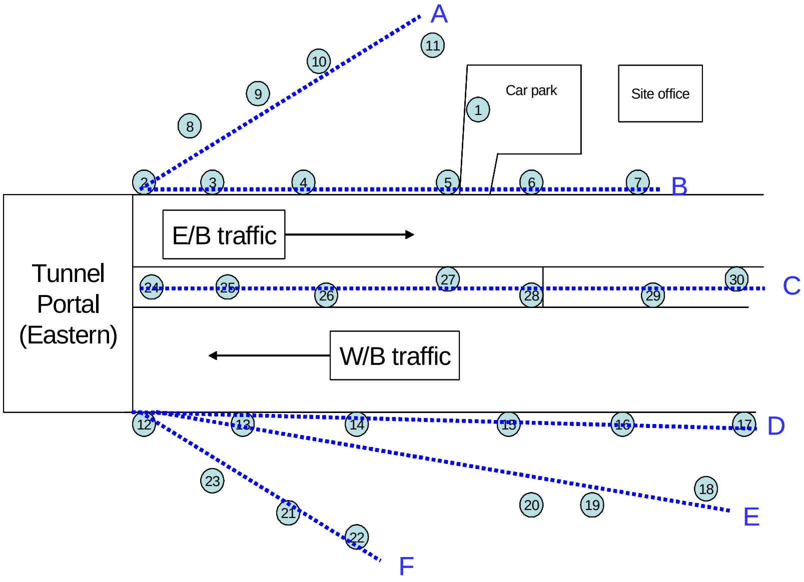

Figure 18: Schematic of the Southwick tunnel portal sampling locations, showing the receptor positions and transects A to F.

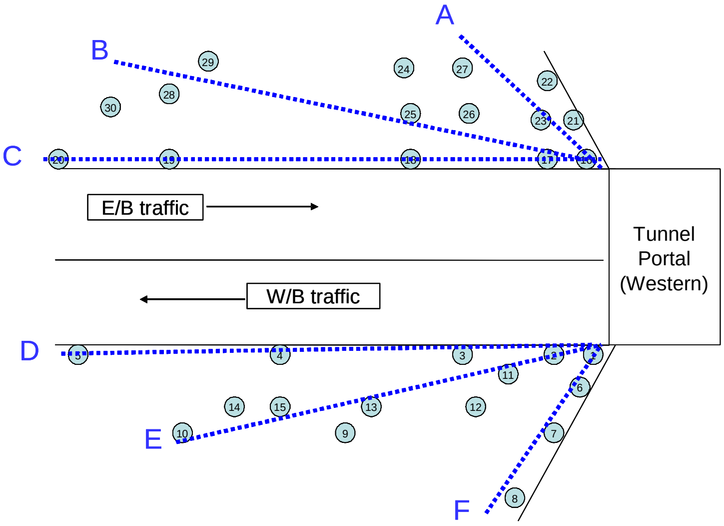

Figure 19: Schematic of the Bell Common tunnel portal sampling locations, showing the receptor positions and transects A to F.

4.3 Results and discussion

The following sections provide a summary of the results from the measurement campaigns at the Southwick and Bell Common tunnels.

4.3.1 Southwick tunnel measurements

Standard NO_2 Palmes tubes were deployed at the Southwick eastern portal in 3 sequential 4-week exposure campaigns. Similarly Ogawa samplers were deployed over the same period as 6 sequential exposures.

For the standard NO_2 diffusion tubes, it is widely acknowledged that they have a tendency to over or under read, sometimes by a significant amount. To improve the precision and accuracy of these measurements, triplicate tubes were deployed and corrected against travelling blanks. In addition the results from these tubes were bias adjusted in accordance with Defra guidance. In this case, the bias adjustment was achieved through an examination of the co-located diffusion tubes against the continuous monitoring site in Hove. This adjustment against local measurements was recommended as the most appropriate technique, given that the full monitoring duration was less than 9-months. Summary measurements at Hove from the chemiluminescence analyser and the diffusion tubes are shown in Table 8. It is evident that the two monitoring techniques are in relatively close agreement, with the diffusion tubes under-reading over the first period, over-reading in the second, and matching those in the third. The average concentration recorded with the continuous analyser over the full 3-month period was 18.4 ppb, which compares favourably with the average of 18.3 ppb recorded from the unadjusted diffusion tubes.

Table 8: Hove, background site chemiluminescence (CLD) and co-located diffusion tube measurements

Period	Palmes NO_2 (average)	CLD period average (ppb)	Relative difference
1	18.0	20.8	0.86
2	16.1	14.0	1.15
3	20.5	20.5	1.00

No bias adjustment guidance was available for the Ogawa samplers, and these results were thus used unadjusted. The combined average bias adjusted diffusion tube measurements and the Ogawa sampler results over the full monitoring period, and are shown in Table 9. The relative difference between the Palmes and Ogawa NO_2 measurements is on average -0.9%, but ranges from -18.4% and 15.4%. Figures 20 and 21 display the relationship between the two monitoring techniques for NO_2 and the relationship between NO_2 and NO_X, respectively. Regression analysis on the data for the two NO_2 monitoring techniques indicates a statistically significant relationship, with a factor of 0.88 for the Ogawa results compared with the standard diffusion tubes. In addition the Ogawa samplers exhibit a positive offset of 2.5 ppb.

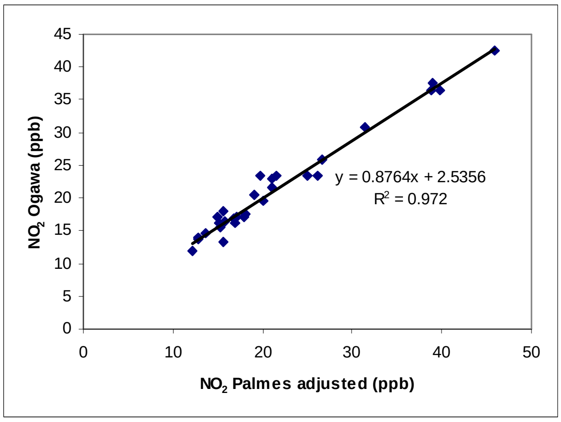

Figure 20: Relationship between NO_2 measured using the adjusted Palmes tubes and Ogawa at the Southwick tunnel portal.

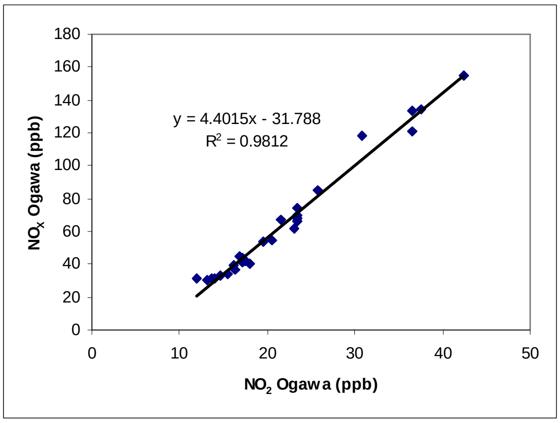

Figure 21: Relationship between NO_2 and NO_X measured using the Ogawa sampler at the Southwick tunnel portal.

Table 9: Southwick tunnel whole period NO_2 and NO_X averages.

Site location	Ordnance Survey grid reference		Palmes NO_2 adjusted (ppb)	Ogawa NO_2 (ppb)	Ogawa NO_X (ppb)	Palmes – Ogawa NO_2 % difference
	Eastings (m)	Northings (m)				
1	524244.1	107853.1	12.10	12.00	31.8	0.8
2	524206.9	107784.7	39.01	37.50	134.2	3.9
3	524218.9	107797.5	45.88	42.50	154.5	7.4
4	524226.6	107805.6	38.77	36.50	133.3	5.8
5	524249.5	107832.7	21.09	21.50	67.5	-1.9
6	524280.1	107855.9	26.69	25.83	85.5	3.2
7	524323.0	107891.6	31.38	30.83	118.2	1.7
8	524214.3	107807.1	39.78	36.50	121.2	8.2
9	524214.3	107814.3	24.94	23.33	74.2	6.5
10	524219.4	107825.8	15.57	13.17	30.8	15.4
11	524229.8	107832.0	15.56	18.00	40.7	-15.7
12	524222.0	107750.7	20.13	19.50	53.8	3.1
13	524250.4	107776.8	21.10	23.00	61.7	-9.0
14	524263.3	107791.0	17.95	17.17	43.5	4.4
15	524281.7	107813.2	16.77	16.83	44.3	-0.4
16	524304.7	107835.8	18.05	17.50	41.8	3.1
17	524353.0	107876.4	17.00	16.17	39.7	4.9
18	524358.9	107872.4	12.81	13.67	31.0	-6.7
19	524313.0	107827.2	13.65	14.67	33.2	-7.5
20	524286.1	107802.4	15.80	16.33	36.5	-3.4
21	524231.2	107756.9	15.27	15.50	33.8	-1.5
22	524262.0	107779.0	12.84	14.00	31.3	-9.0
23	524268.7	107786.5	18.15	17.50	42.3	3.6
24	524214.5	107776.5	19.70	23.33	68.5	-18.4
25	524229.0	107794.0	26.23	23.33	66.2	11.0
26	524245.9	107809.0	19.04	20.50	54.5	-7.7
27	524262.4	107825.1	21.54	23.33	69.5	-8.3
28	524287.0	107848.0	17.14	17.17	40.8	-0.1
29	524332.3	107885.5	15.06	16.17	39.0	-7.4
30	524367.0	107909.0	14.99	17.17	42.3	-14.5

Figure 22 provides an insight into the change in NO_2 concentration with distance from the eastern portal of the Southwick tunnel. The figure plots the concentration profile along each of the transects, described in Figure 18. Each plot provides the monthly average data for each of the three months, plus a trend line fitted to the overall 3-month average concentrations. The trend line has been derived using a range of simple functions, selected based upon the highest correlation coefficient. The highest concentrations are recorded at the portal of the eastbound carriageway (associated with traffic moving out of the tunnel). However, rather than the NO_2 concentration being highest at the portal face, concentrations increase at distances of between 20m and 60m, and then reduce again at greater distances. This implies an additional local source of NO_2 or the generation of NO_2 through NO titration with oxidants such as ozone. In contrast to the pollution profiles measured at the Bell Common tunnel described in Section 4.3.2, relatively complex relationships appear between NO_2 concentration and distance from the portal for all 6 transects at the Southwick tunnel.

Figure 23 provides an analysis of the change in the ratio between NO_2 and NO_X with distance from the portal, measured using the Ogawa samplers. On the assumption that the majority of NO_X is emitted as NO, then the formation of NO_2 through titration with ozone, would result in an increase in this ratio with distance and thus time, from the tunnel portal. This is evident at all of the transects other than transect B, which runs parallel to the eastbound hard shoulder. The NO_2 proportion of NO_X is between 22.5% and 52.0%, with an average of 22.5%. One further complication to the explanation of this ratio, would be the variation in the proportion of primary NO_2 in the vehicle exhaust, from vehicles passing through the tunnel.

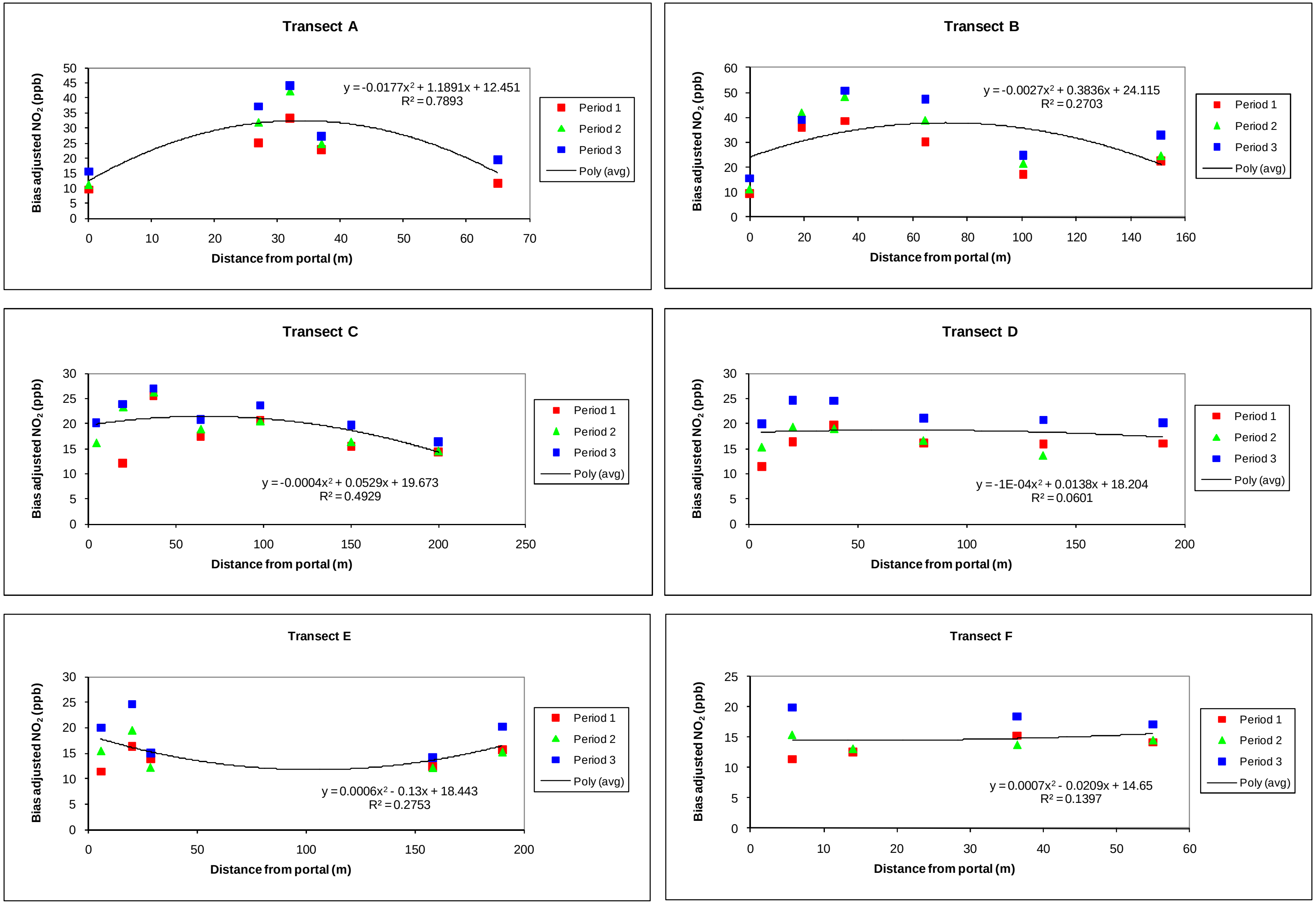

Figure 22: Changes in NO_2 concentration with distance from the Southwick tunnel portal, along transects A to F.

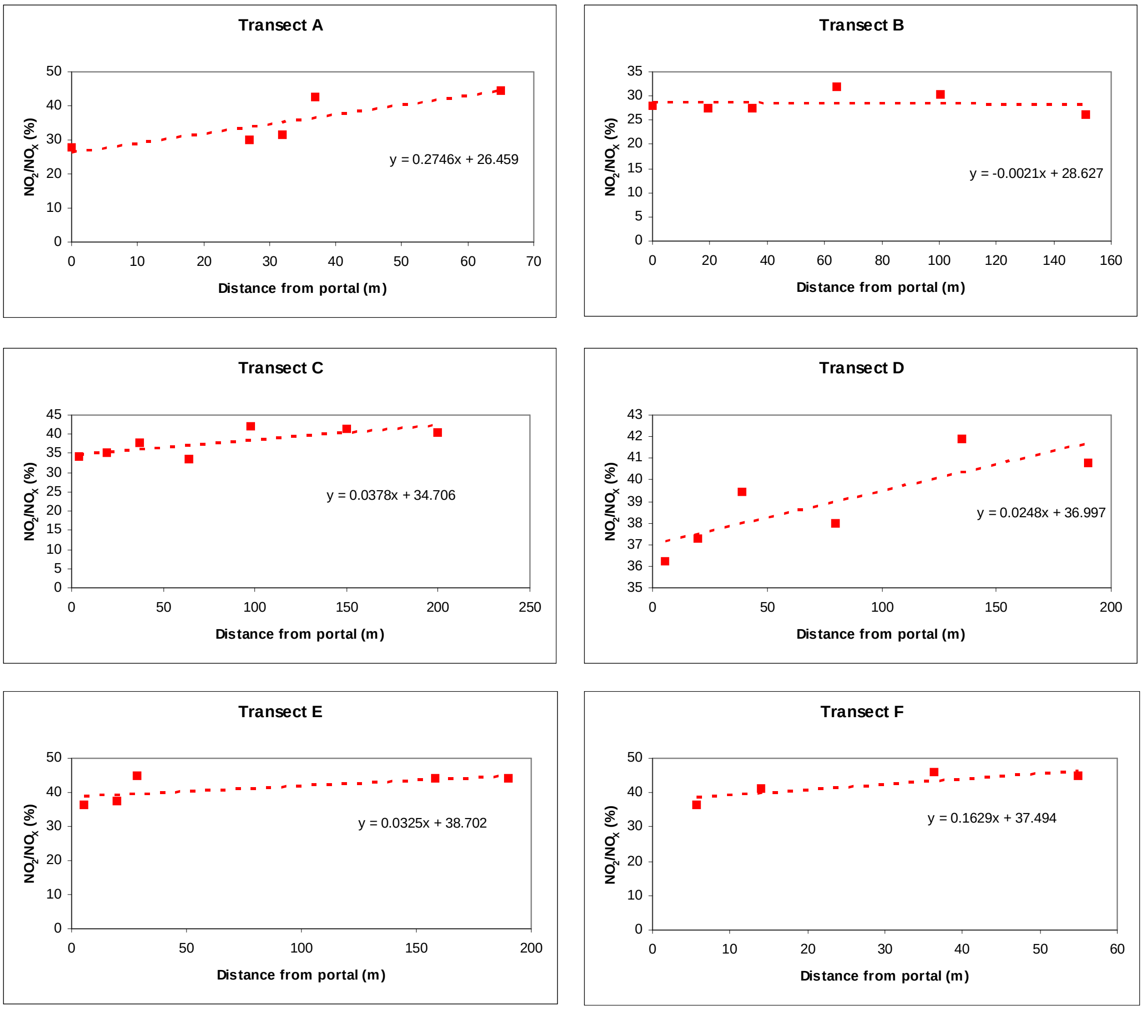

Figure 23: Changes in NO_2/NO_X ratio with distance from the Southwick tunnel portal.

4.3.2 Bell Common tunnel measurements

Standard NO_2 Palmes tubes were also deployed at the Bell Common western portal in 3 sequential 4-week exposure campaigns. Similarly Ogawa samplers were deployed over the same period as 6 sequential, fortnightly exposures. Bias adjustment of the NO_2 diffusion tubes was undertaken through the use of the results from co-located triplicate tubes deployed at the Borough of Broxbourne's roadside monitoring site on Hertford Road. This site, operated to AURN and LAQN QA/QC standards, is approximately 100m north of the M25, and 8 km to the west of the Bell Common tunnel. The average NO_2 concentration recorded over the 3-month monitoring period was 18.6 ppb from the continuous analyser and 26 ppb from the co-located diffusion tubes. In comparison with the Southwick site, the NO_2 diffusion tubes, were thus subject to a significant over-estimation of NO_2 concentrations.

Table 10 provides a summary of the NO_2 measurements averaged over the full monitoring period. The Palmes tube data is reported as bias adjusted values, and again the Ogawa results are reported unadjusted. Concentrations at the Bell Common site are significantly higher than those at the Southwick tunnel, reflecting the very high traffic flows at this location. Significant differences are evident between the NO_2 concentrations recorded with the adjusted NO_2 diffusion tubes and the Ogawa samples, ranging from -138% to -24%, with an average difference of -57%. Indeed closer agreement between the two monitoring methods was evident before the diffusion tube data were bias adjusted.

Table 10: Bell Common tunnel whole period NO_2 and NO_X averages.

Site location	Ordnance Survey grid reference		Palmes NO_2 adjusted (ppb)	Ogawa NO_2 (ppb)	Ogawa NO_X (ppb)	Palmes – Ogawa NO_2 % difference
	Eastings (m)	Northings (m)				
1	544573.4	201040.6	101.7	136.3	288.2	-34.0
2	544567.3	201041.0	92.0	140.5	270.2	-52.7
3	544542.4	201039.0	55.6	104.0	300.2	-87.1
4	544502.3	201033.7	57.4	77.7	309.7	-35.2
5	544431.1	201023.6	40.4	68.7	278.3	-70.1
6	544567.3	201032.7	56.2	88.7	305.3	-57.7
7	544561.5	201028.8	48.0	90.0	278.7	-87.5
8	544547.4	201019.9	34.9	52.8	234.8	-51.4
9	544509.2	201018.9	26.6	41.2	162.3	-54.5
10	544478.9	201014.4	21.4	37.3	151.8	-74.1
11	544553.1	201035.8	51.3	89.3	282.0	-74.1
12	544545.3	201029.9	34.5	58.8	250.5	-70.4
13	544517.7	201026.0	27.9	46.7	193.5	-67.1
14	544489.8	201025.0	27.4	46.0	195.2	-67.9
15	544503.7	201025.3	28.7	46.2	194.8	-60.6
16	544569.8	201078.6	40.9	54.2	231.8	-32.3
17	544564.8	201078.1	42.9	53.0	225.8	-23.6
18	544525.6	201072.8	42.8	56.7	238.8	-32.5
19	544474.8	201067.3	45.6	58.0	239.0	-27.3
20	544426.2	201060.3	43.4	57.0	224.5	-31.2
21	544566.7	201087.5	21.2	50.5	102.8	-138.2
22	544559.6	201093.9	16.0	27.0	83.3	-68.3
23	544562.1	201085.0	19.1	27.7	109.3	-44.9
24	544521.6	201095.7	22.1	33.2	99.3	-50.2
25	544524.2	201082.7	22.6	33.3	108.7	-47.3
26	544555.4	201087.5	20.5	31.3	104.3	-52.6
27	544542.3	201098.0	20.7	30.7	102.7	-47.8
28	544474.7	201076.4	25.2	35.5	125.7	-40.6
29	544485.0	201090.2	23.6	34.0	119.8	-44.2
30	544442.7	201074.9	22.2	38.8	132.2	-75.0

Figures 24 and 25 display the relationship between the two monitoring techniques for NO_2 and the relationship between NO_2 and NO_X, respectively. Regression analysis on the data for the two NO_2 monitoring techniques indicates a statistically significant relationship, but with a factor of 1.4 for the Ogawa samplers when compared with the standard diffusion tubes. In addition, the Ogawa samplers exhibit a positive offset of 5.1 ppb.

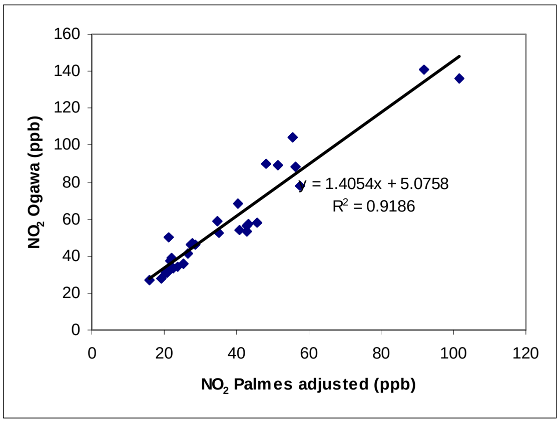

Figure 24: Relationship between NO_2 concentrations measured using the adjusted Palmes tubes and Ogawa, measured at the Bell Common tunnel portal.

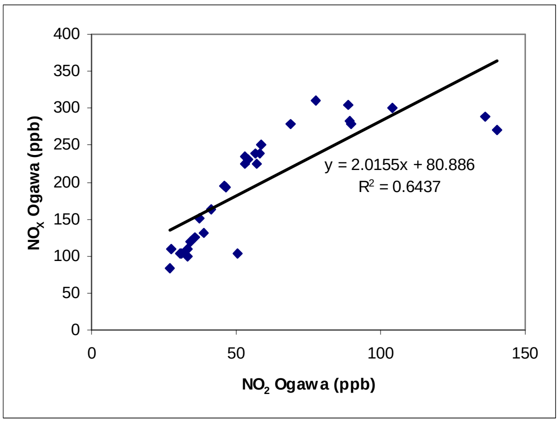

Figure 25: Relationship between NO_2 and NO_X concentrations measured using the Ogawa sampler at the Bell Common tunnel portal.

Figure 26 provides a simple insight into the change in NO_2 concentration with distance from the western portal of the Bell Common tunnel. The figure plots the concentration profile along each transects, described in Figure 19. Each plot provides the monthly average data for each of the three months, plus a trend line fitted to the overall 3-month average concentrations. The trend line has been derived using a range of simple functions, selected based upon the highest correlation coefficient. Transects C and D are parallel to the road. Transect C shows the smallest influence of distance from the portal, which is not surprising given that it runs along the edge of the hard shoulder of the eastbound carriageway, towards the entrance of the tunnel. A small increase in concentration is evident closest to the tunnel portal. In contrast, transect D, runs along the edge of the hard shoulder of the westbound carriageway, and the highest concentrations are evident at the face of the portal, diminishing rapidly to a relatively stable concentration after a distance of 40m.

The highest concentrations are recorded at the portal of the westbound carriageway (traffic moving out of the tunnel). Concentrations in the vicinity of the traffic exiting the tunnel are over twice the level of those measured on the other side of the road, where the traffic is entering the tunnel. It is clear that concentrations generally fall off sharply with distance from the portal, and that stable (possibly background) concentrations are reached at distances of 40m from the portal.

Figure 27 provides an analysis of the changes in the NO_2 to NO_X ratio with distance from the tunnel portal. Although the overall concentrations may be expected to reduce with distance from the portal, it might be expected that the proportion of NO_2 would increase due to reactions with ozone. However, this is only evident at two of the transects, B and C. Both of these are located close to the eastbound carriageway, where traffic is moving into the tunnel portal. The highest ratios are consistently found close to the exit portal for the westbound traffic, suggesting a significant source of primary NO2 being emitted from the tunnel.

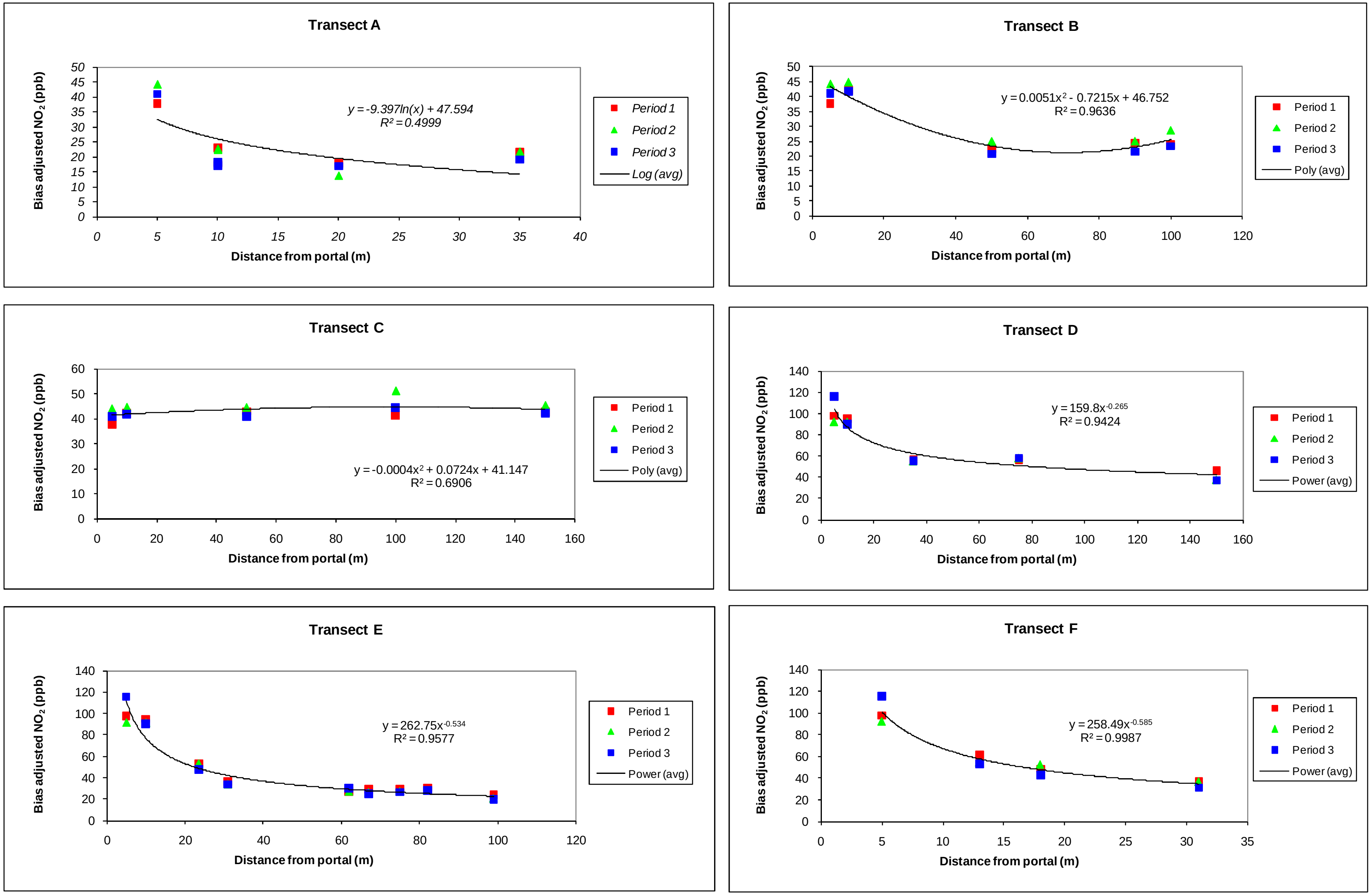

Figure 26: Changes in NO_2 concentration with distance from the Bell Common tunnel portal, along transects A to F.

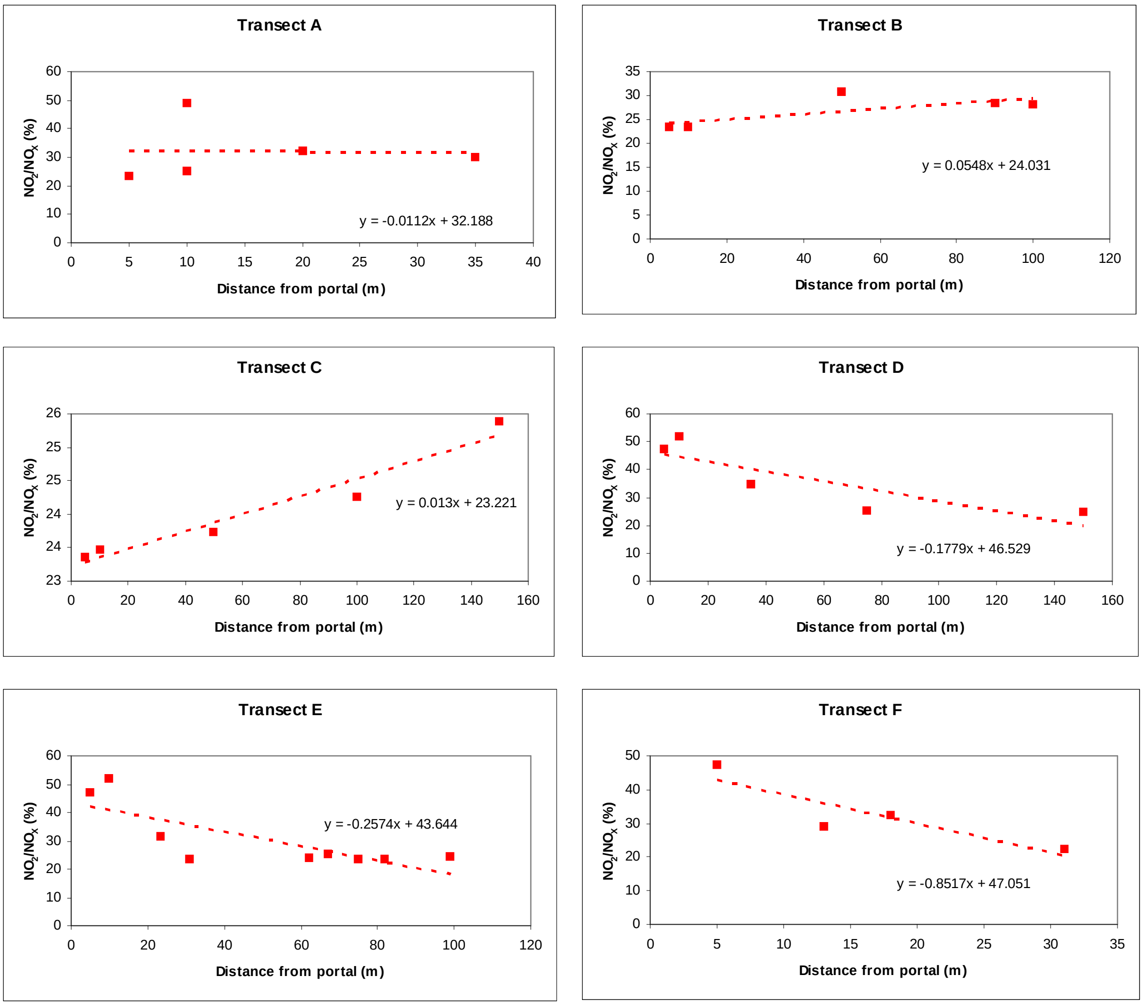

Figure 27: Changes in NO_2/NO_X ratio with distance from the Bell Common tunnel portal.

4.4 Surface concentration mapping

The production of a spatial representation of NO_2 concentrations from the point measurements requires the use of an interpolation procedure. Natural neighbour interpolation is a geometric estimation technique that uses natural neighbour regions generated around each data point. This technique is particularly effective for dealing with a variety of spatial data themes exhibiting clustered or highly linear distributions. The natural neighbour technique is designed to optimise local minimum and maximum values in the point file and can be configured to limit overshooting of local high values and undershooting of local low values. This technique thereby enables the creation of optimal surface for typical air pollution data distributions (Northwood Technologies, 2001).

Natural neighbour interpolation makes use of an area-weighting technique to determine a new value for every grid node. As shown in Figure 28, a natural neighbour region is first generated for each data point. Then, a new natural neighbour region is generated at every node in the new grid which effectively overlays various portions of the surrounding natural neighbour regions defining each point. The new grid value is calculated as the average of the surrounding point values proportionally weighted according to the intersecting area of each point (Northwood Technologies, 2001).

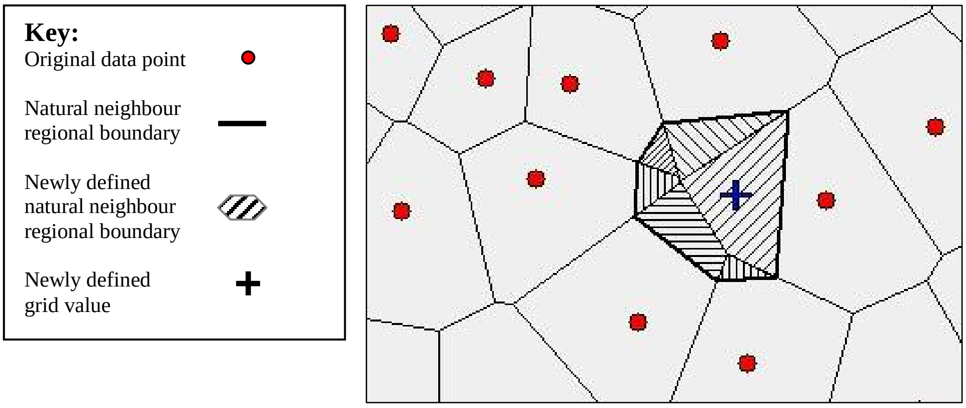

Figure 28: A display of the natural neighbour regions around the point file as well as those created around a grid node (Northwood Technologies, 2001).

The slope-based solution is where the grid value is determined by averaging the extrapolated slope of each surrounding natural neighbour region and area. By examining the adjacent points, a determination is made as to whether that point represents a local maximum or minimum value. If it does, a slope value of zero is assigned to that value and the surface maintains that specific point. Vertical mapper in combination with MapInfo, was employed using the meta data summarised in Table 11, to derive the concentration surfaces shown in Figures 29 and 30.

Table 11: Meta data used in the GIS mapping of the air pollution measurements undertaken within the vicinity of the Southwick and Bell Common tunnel portals.

Southwick	Bell Common
Creation method: Natural neighbour interpolator (3.0)	Creation method: Natural neighbour interpolator (3.0)
Aggregation type: Forward stepping	Aggregation type: Forward stepping
Aggregation distance: 0.33 m	Aggregation distance: 0.25 m
Aggregation value: Minimum value	Aggregation value: Minimum value
Cell size: 0.45 m	Cell size: 0.33 m
Maximum triangle side length: 225.2 m	Maximum triangle side length: 169.2 m
Hull margin: 14.5372	Hull margin: 10.1236
Corner increment: 15	Corner increment: 15
Solution method: Slope	Solution method: Slope
Slope weight factor: 2	Slope weight factor: 2
Slope exponent: 2	Slope Exponent: 2
Skewness factor: 1	Skewness factor: 1
Allow overshoot / Undershoot: No	Allow overshoot / Undershoot: No

Derived surface concentration show the concentration surfaces estimated from the monitoring data for the full duration of the monitoring periods at the Southwick and Bell Common sites, respectively. They show three plots for each site: adjusted NO_2 data from the Palmes tubes, NO_2 data from the Ogawa samplers, plus a further plot of the NO_X data from the Ogawa samplers.

The surface concentration plot for the Southwick tunnel, Figure 29, clearly highlights a strong emission from the eastbound carriageway of the eastern portal. Upon release, this plume appears diverted to the north, in accordance with the prevailing wind direction. A second pollution peak is also evident from this plot, which can be explained by traffic emissions associated with vehicles travelling along Mile Oak Road, which passes under the A27, approximately 180m east of the eastern portal of the tunnel. Similar profiles are evident for the NO_2 and NO_X concentrations measured using the Ogawa samplers.

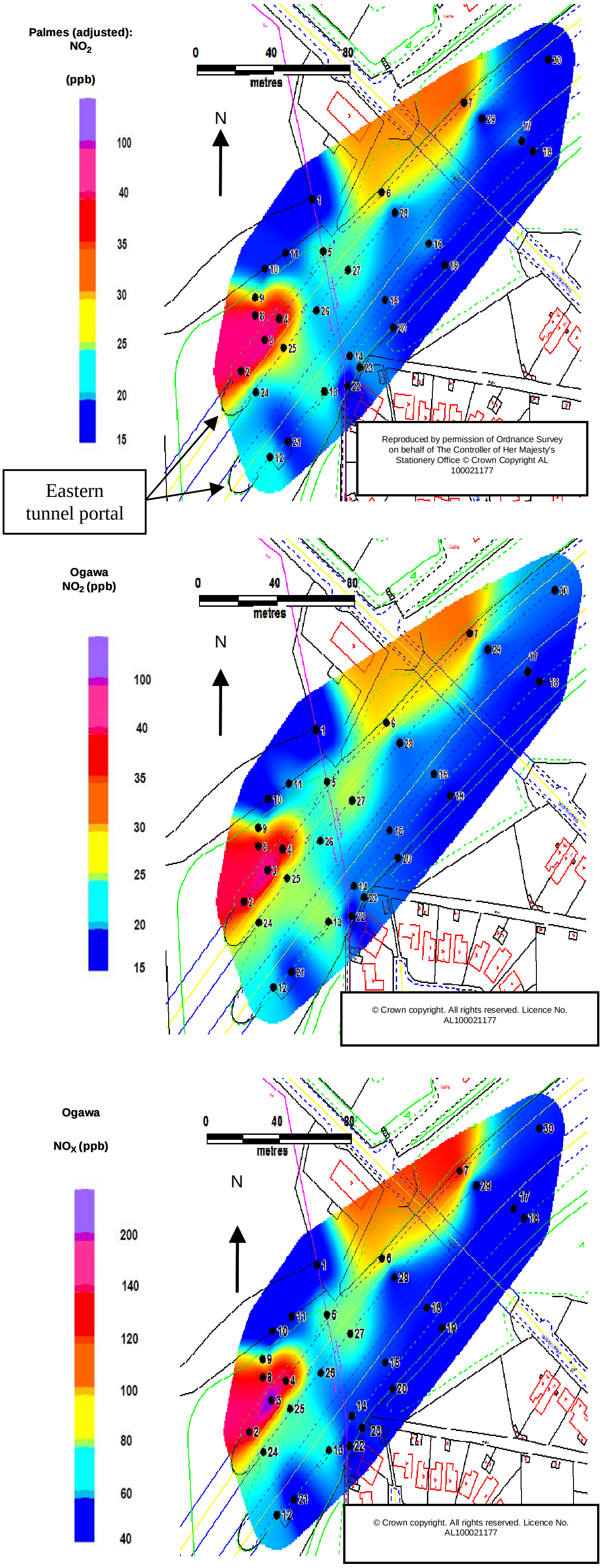

Figure 29: Southwark tunnel portal concentration profiles, based upon measurement data over the period 22/2/06 to 10/5/06. Measurement site positions are numbered.

Figure 30 provides a surface concentration plot, derived from the measurement data. Once again, a strong emission source is evident at the portal, where the westbound traffic exits. Some of the lowest concentrations occur just to the north of the portal, close to the edge of the westbound carriageway.

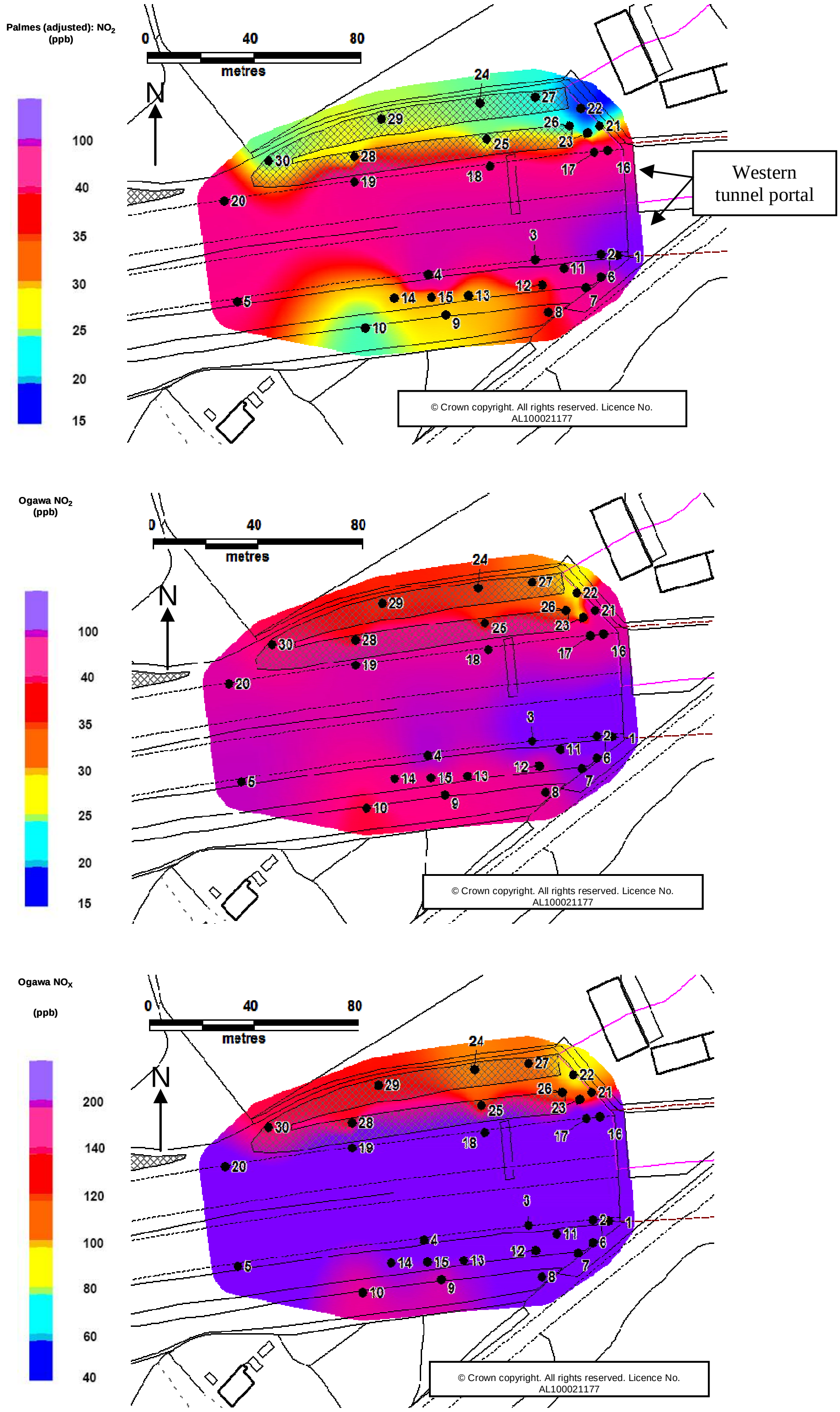

Figure 30: Bell Common tunnel portal concentration profiles, based upon measurement data over the period 24/5/06 to 16/8/06. Measurement site positions are numbered.

5 Portal dispersion modelling

5.1 Background

Road tunnels are increasingly being used, not just to pass through hilly areas, but also to provide a separation between sources of emissions and particularly sensitive locations. However, whilst emissions generated along the length of the tunnel are restricted with respect to horizontal and vertical dispersion, these emissions are eventually emitted at the tunnel portals. In addition, these portal environments are often characterised by complex topography, and thus there is an increasing need to develop and apply air pollution modelling tools that can reflect these specific conditions.

Measurements around UK tunnel portals were undertaken over 30-years ago, but limited work has been subsequently undertaken. In 1980 a number of surveys were undertaken at the portals of the Blackwell and Heathrow tunnels. These studies were undertaken to provide, for example, experimental data with which to assess the environmental impact of the then proposed Hatfield Tunnel. At this time it was evident that certain fundamental factors regarding the dispersion at tunnel portals were not fully understood (Haerter, 1991).

Considerable international activity in this area also commenced in the early 1980s, through the use of wind tunnel simulations leading to the development and optimisation of empirical predictive models (Ide *et al*, 1987) and ventilation system designs to limit emissions at the portals (Sato *et. al.*, 1985). Fundamental to improving knowledge on portal dispersion characteristics is the measurement of pollution profiles in the portal environment. These were initially restricted to measurements of CO (Marsault and Gabet, 1985), but expanded to the measurement of specifically introduced tracers such as sulphur hexafluoride (SF_6) and bromotrifluoromethane ($CBrF_3$) (Peteron and Tonnesen, 1990).

5.2 Modelling road tunnel portal emissions

In order to estimate tunnel portal emissions and associated air quality, it is evident that a range of processes and influences need to be accommodated. The most significant of these are listed in Table 12.

Table 12: Determinants of tunnel portal air quality and dispersion (adapted from Oettl *et al*, 2002).

Parameter	Function
Emission source strength	Function of the vehicle composition, flow and speed and the tunnel bore volume.
Exit velocity	Function of the jet stream associated with the piston effect of the vehicles through the bore, the forced ventilation associated with fans and the pressure difference between the entry and exit portals.
Buoyancy	Caused by the temperature difference between the tunnel jet plume and the ambient air.
Traffic induced turbulence	A particularly significant effect associated with HGVs that cause the tunnel jet to be orientated more along the roadway, than the free jet.
Jet entrainment	The entrainment of ambient air into the tunnel jet, through sheer (formed through differences in velocity and direction) between the jet and the free air.
Interaction of the ambient wind field and the jet stream	The jet stream from the tunnel portal will be immediately influenced by the ambient wind field. However, this ambient wind field is extremely variable, and this variability will have significant impacts on short term concentration profiles within the vicinity of the tunnel portal.
Interaction with portal geometry and topography	In many cases the tunnel portal has specific topographic characteristics. Typically portals are position in cuttings, and thus immediate dispersion is restricted. In addition, tunnel portal roads (particularly those emerging from under river links) are characterised by inclines (positive gradients), which can provide additional buoyancy to the emitted jet plume.

Extensive studies have been undertaken in Japan on tunnel portal dispersion monitoring and modelling, commencing in the early 1980s. These involved a combination of wind tunnel and field experiments. The outcomes of this early work were portal dispersion models, suitable for flat terrain. During the late 1990s, this work was extended to incorporate tunnel portals in complex terrain (Matsumoto *et al*, 1998). The resulting model was essentially a 3-D numerical model, including two major modules; one for the wind field and the other for the simulation of diffusion and advection processes within the plume. The wind field over the complex terrain was calculated using the MASCON variation wind field model (Dickerson, 1978). The jet stream from the tunnel portal was modelled by a traffic piston equation, and the traffic induced wind over the roadway using empirical data, incorporating the approach developed by Ueyama (1995). The derived model outputs were then compared to field measurements of NO_X and SF_6 at three road tunnels: the Ninomiya, Hitachi and Enrei tunnels.

It was evident from this relatively early work that tunnel portal emissions and air pollution concentrations are a function of the horizontal jet from the portal (which itself will be influenced by tunnel ventilation regimes and the relative cross sectional area of the tunnel relative to the typical vehicle frontal cross section), the influence and magnitude of vehicle induced turbulence (related to the length and formation of vehicle platoons passing through the tunnel, and the overall vehicle compositional mix) and the interaction of the tunnel portal topography and prevailing wind fields (Nadel *et al*, 1994; Lacour *et al*, 2003). Field measurement have indicated that traffic may influence local wind speed and portal emission rates with both short term events (individual HGVs passing through the tunnel) and longer time events (such as vehicle platoons).

Oettl *et al* (2002) concluded that very few tunnel portal models are available for use in regulatory applications. One of the simplest is the empirical model developed by Vanderheyden and Nadel (2000), which is essentially a tunnel portal screening tool. This operates through the use of an empirically derived relationship between the pollution concentration at the tunnel portal and the concentration at a receptor at a distance from the portal. The measurements used to derive this relationship were recorded at a number of tunnel portals, and given that it was based upon an envelope of these field measurements, may be considered a worse case pollution estimate. Where air quality limits or objectives are predicted to be breeched through the use of this tool, more sophisticated modelling is recommended.

A further model based upon field measurements is outlined in the German regulations MLuS-92. Within this approach concentrations at any receptor point assume an exponential decay of the concentration along the jet centre line from the portal, combined with a function that describes the concentration decay for the plume cross section.

Other models including an adaptation of the Gaussian-based DMRB screening model PORTOCO[8] (Boulter *et al*, 2003) and supplementary modules for the Gaussian Highway-2 models have been developed (Zumsteg and Graf, 1993). One of the most sophisticated models remaining in use for regulatory applications was developed by Okamoto *et al* 1998. This combines the MASCON wind field model with a finite element method to solve the advection-diffusion equation. The wind field combines the ambient wind field with the portal jet, with the latter assuming a Gaussian-type concentration decay. The model has been subject to tracer gas comparisons, which have revealed over-estimation of pollutant concentrations.

Empirical models are inherently difficult to apply with confidence outside those specific environments evaluated during their development. This potential site specific characteristic of empirical models limits their use for regulatory purposes, without the use of comprehensive and dedicated field measurements for subsequent ratification. In addition, the Gaussian formulation is particularly weak at modelling low wind speed conditions and those conditions where the wind direction is parallel with the road. In addition inhomogeneous wind fields, arising for example from topography, cannot easily be accounted for with Gaussian models. Finally, the model

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[8] The PORTOCO model incorporated Gaussian dispersion profiles from the TRL PREDCO model, which formed the basis for the DMRB air pollution screening tool.

developed by Okamoto et al is limited due to its time consuming pre-processing procedures and neglect of buoyancy effects (Oettl *et al*, 2002).

Explicit computational fluid dynamic (CFD) simulation of tunnel portal emissions and air quality remains very processor-time consuming, and is relatively difficult to use. In many cases these models can be adjusted to simulate processes around specific individual tunnel portals, but consequently they remain poor for universal application. In addition, their ability to derive statistical concentration values is relatively limited (Jaeschke *et al*, 1997).

5.3 The GRAL (Graz Lagrangian[9]) model formulation

In order to have a reliable dispersion model for calm wind conditions, a Lagrange particle model was developed at the Institute for Internal Combustion Engines and Thermodynamics, Technical University Graz, Austria (Oettl *et al,* 2002; Oettl *et al*, 2003; Oettl *et al*, 2005). The model system, originally developed in 1999, consisted of two key modules:

- The prognostic wind field model GRAMM used for analysing stationary wind fields suitable for characterising pollution dispersion in complex topography including urban areas.
- The dispersion model GRAL developed for application under calm wind conditions and from tunnel portals.

The analysis of wind fields with GRAMM offers the advantage of being able to accommodate dynamic effects (*e.g.* obstacle influenced flows), and is thus capable of accommodating complex topography. The application of three-dimensional wind fields from GRAMM is optional. For flat terrain either classified meteorological situations (wind direction and wind speed, dispersion classes and frequency) or time-series of vertical profiles of friction velocity, Monin-Obukhov length, standard deviations of the normal components of the wind, various components of the mean wind speed, and other quantities can be used. When using classified meteorological situations a meteorological pre-processor calculates all other parameters. The pre-processor is based mainly on the works of Golder (1972), Venkatram (1996) and Zannetti (1990).

GRAL also has the advantage that it can simultaneously calculate line sources, point sources and tunnel portals. The following parameters can also be taken into account for the individual source types:

- Point sources: Source strengths, exit velocity, temperature differences, and diameter.
- Line sources: Widths, source strengths, heights of noise barriers.
- Area sources: Same as line sources.
- Tunnel portals: Source strengths, exit velocity, temperature differences, traffic influence on tunnel jet.

Further general parameters required by the program comprises roughness length (which can presently be specified homogeneous for the investigated area only), dispersion time, number of traced particles (influences the statistical accuracy of results), counting grids (variable in all three directions), as well as size of the investigated area. The model system is designed to be compatible with GIS applications.

5.3.1 GRAL tunnel module version 3.5

The dispersion of pollutants from longitudinal ventilated tunnels is considered to differ significantly from those of other sources, such as line or point sources. In order to take all the

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[9] An Eulerian dispersion model is similar to a Lagrangian model in that it also tracks the movement of a large number of pollution plume parcels as they move from their point of release. The difference between a Lagrangian and an Eulerian model is that the latter uses a fixed frame of reference, whilst the former uses a moving frame of reference.

peculiarities of the dispersion from tunnel portals into account a special software module has been developed.

The polluted air jet emitted from the tunnel portal is strongly influenced by ambient wind in the portal area, whereby it is forced to change direction according to it (Oettl *et al*, 2005). In addition, fluctuations in the ambient wind direction force the jet plume to change its position, and thus promote dispersion and dilution. In addition, near to the tunnel portal, differences in temperature and velocity between the tunnel air and the ambient air will undoubtedly occur. Plume buoyancy (promoted when there are temperature differences between the jet plume and ambient air) is further accommodated within GRAL through the incorporation of a modified version of van Dop's model for plume rise for stacks (Van Dop, 1992; Oettl *et al* 2002). Other empirical parameters within the GRAL model were determined from a series of tracer experiments in the Ninomiya, Hatachi and Enrei tunnels in Japan, and the Ehrentalerberg and Kaisermuehlen tunnels in Austria. GRAL TM 3.5 has been tested against five data sets from different tunnel portals in complex and flat terrain with different meteorological conditions (high/low wind velocities, stable/unstable atmospheric conditions).

In summary, the impact of the tunnel jet plume on dispersion is influenced by a number of forces, which are incorporated into the GRAL tunnel module:

- Turbulent friction due to differences in the velocity of the ambient wind parallel to the jet stream and the jet stream which causes it to slow down.
- A pressure force caused by the ambient wind perpendicular to the jet stream which bends the jet stream towards the ambient wind direction.
- The module accounts for wind direction fluctuations, which cause the tunnel jet also to vary in space.

Based on the performance of the GRAL model, and intercomparisons with three other models – ADMS, LASAT, MUMO, GRAL is now recommended for dispersion modelling from road tunnel emissions in Austria[10].

However, GRAL contains two empirical parameters which are adjusted depending on the traffic volume and specifics of the tunnel design. It is not currently possible to establish a fixed rule for the selection of values for these parameters, and thus these are adjusted through professional judgement. In addition, GRAL 3.5 has not been extensively tested when temperature differences between the tunnel air and the ambient air become negative. Under-estimation of the vertical mixing will result in over-estimations in pollutant concentrations (Oettl *et al*, 2005).

5.4 Southwick tunnel simulation

The GRAL model was tested through its application to the Southwick tunnel eastern portal. Meteorological data from Shoreham airport was used, covering the period 22 February to 10 May 2006. The average wind speed over this period was 4.7 m/s. A wide variability in wind direction is evident, dominated by a South westerly and north easterly winds.

The terrain within the vicinity of the portal was measured from field surveys, and digitised. The following traffic and emission data were employed:

NO_X: 0.80494 kg/km/h

PM: 0.03244 kg/km/h

CO: 0.88258 kg/km/h

Background concentrations for the different pollutants, were derived from the Defra mapping:

NO_X: 19.72 $\mu g\ m^{-3}$

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[10] The Austrian guideline RVS 9.263 requires the use of the GRAL tunnel module for environmental assessment studies concerning emissions from road tunnels.

NO_2: 16.3 µg m^{-3}
PM_{10}: 20.48 µg m^{-3}
CO: 220 µg m^{-3}

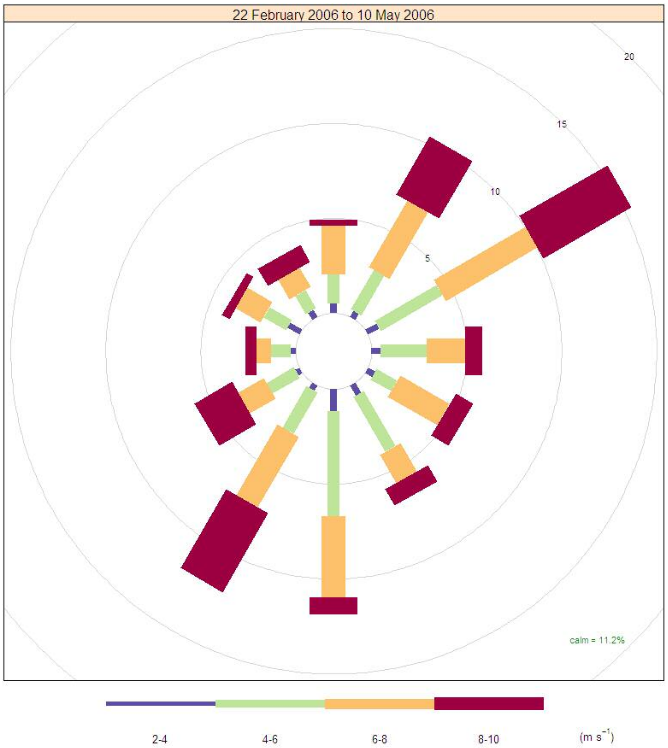

Figure 31: Wind rose for the period 22/2/06 to 10/5/06, Shoreham airport.

The dispersion simulation was undertaken using GRAL version 3 TM linked to a wind field simulation derived from the GRAMM (Grazer MesoscaleModel) model. The A27 was treated as two line sources eastbound and westbound, and it was assumed that at the tunnel portal all emissions from the eastbound tube were released.

The input parameters used for the calculation of tunnel portals were:

V_{tun}:	Velocity of the tunnel jet
Dt_{tun}:	Temperature difference between tunnel air and ambient air
Stiffness:	Stiffness of the tunnel jet (low stiffness is where the influence of the ambient wind is high, and vice versa).

As the ‘real’ stiffness of the tunnel jet plume was unknown three different model runs were carried out with different stiffness values. These were:

1) V_{tun}= 4 m/s, dt_{tun}=1 K, stiff= 50
2) V_{tun}= 4 m/s, dt_{tun}=1 K, stiff= 60
3) V_{tun}= 4 m/s, dt_{tun}=1 K, stiff= 80

Estimated concentrations were derived for NO_X, PM_{10} and CO for the three different averaging periods:

- 3 month mean value
- daily mean value (valid for 24 hours, calculated as 98th percentile), and

- hourly mean value

Nitrogen dioxide concentrations were subsequently derived using the Defra guidance on the semi-empirical relationship between NO_X and NO_2. The results are provided as plots and data files for all pollutants and averaging periods. The data files include data for all calculated grid points within the simulation area (simulation was carried out on a 5 x 5m mesh), representing some 6241 receptors.

5.5 Results and discussion

Figures 32 to 35 plot the average pollution estimates for the 3-month period coinciding with the NO_2 monitoring campaign. Plots for additional averaging periods are provided in Annex 6. Example plots are provided for CO, NO_X, NO_2 and PM_{10}, assuming a mid-estimate tunnel jet stiffness of 60. All plots show the total ambient concentration, with the lowest colour banding representing receptors where concentrations are forecast to be just above the assumed background level. The highest concentrations are modelled at the tunnel portal, associated with the eastbound traffic. For the primary pollutants CO, NO_X and PM_{10} it is estimated that the jet of tunnel air will influence roadside air quality over a plume with a width of approximately 125m. The highest concentrations are predicted along the roadway, associated both with the tunnel jet plume combined with the emissions from the moving traffic. With increasing distance along the carriageway from the portal, concentrations fall by approximately 50% within 100m of the portal. Concentrations fall off very rapidly with distances perpendicular to the road, associated both with the tunnel jet effect, but also in response to the tunnel mouth topography.

For NO_2 concentrations, the tunnel appears to have a much wider area of influence, with the plume from the tunnel impacting on an ‘arc’ extending some 300m in width. However, as noted for the primary pollutants, concentrations similarly fall off rapidly with distance from the portal. This extended area of influence represents are relatively modest increase in NO_2 above the assumed background concentration.

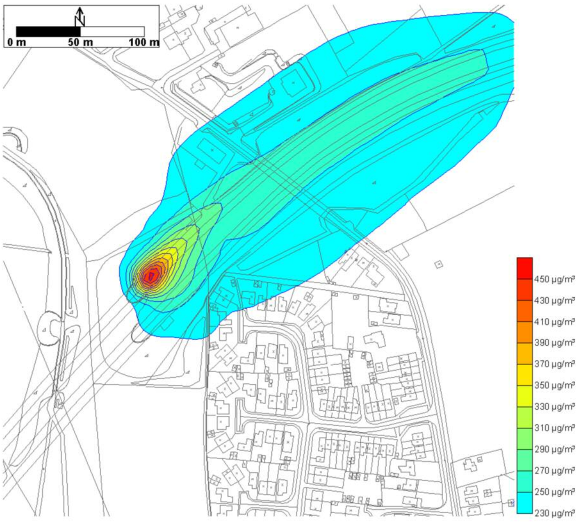

Figure 32: Estimated CO concentrations derived from the GRAL model, expressed as a 3-month average.

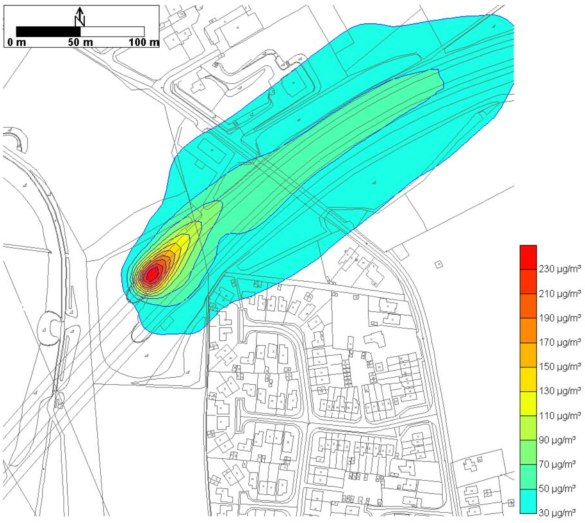

Figure 33: Estimated NO_X concentrations derived from the GRAL model, expressed as a 3-month average.

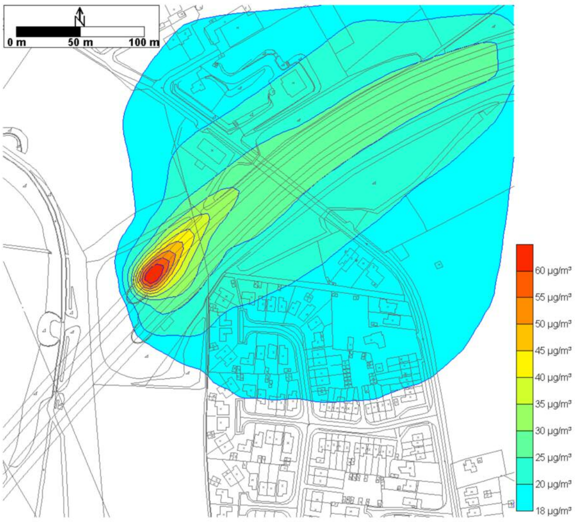

Figure 34: Estimated NO_2 concentrations derived from the GRAL model, expressed as a 3-month average.

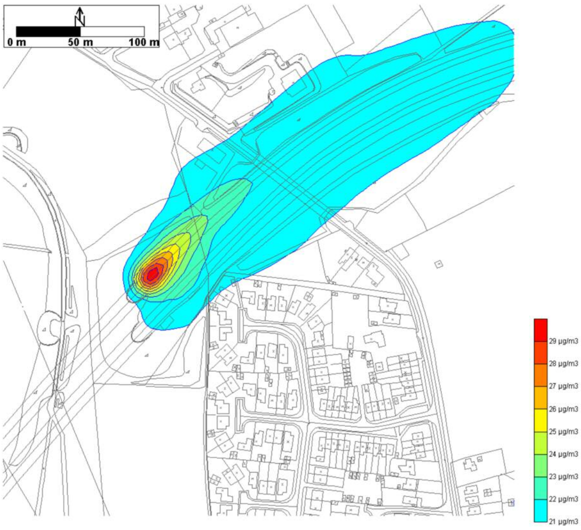

Figure 35: Estimated PM_{10} concentrations derived from the GRAL model, expressed as a 3-month average.

A comparison of these modelled outputs with measurement data, may be undertaken for NO_2 and NO_X. Figure 29 provides surface plots of the 3-month average pollutant data for the Southwick tunnel portal. It is immediately evident that these plots are very similar for the two monitoring techniques, and for NO_2 and NO_X. In contrast to the modelled data, two discrepancies may be noted. Firstly the monitoring data implies that the tunnel jet plume is relatively weak, and is immediately moved to the north upon release from the tunnel. This displays itself through the pollution concentration peak occurring to the north of the tunnel portal. Secondly, a second pollution peak is evident in the monitoring data, which is not replicated in the modelled data. This occurs to the northern side of the road, where the A27 passes over the top of Mile Oak Road. Here the explanation for this difference is relatively simple. Whilst the monitoring data captures the influence of traffic on this minor road, this link was not incorporated within the GRAL model domain, and thus emissions from this link were excluded. During the monitoring campaign, ad-hoc observations of traffic flows on Mile Oak Road were undertaken, and it was concluded that the link had very modest flows which were considered unimportant for roadside concentrations on the A27. However, the monitoring data presented in Figure 29 contradicts this conclusion and highlights the importance of this relatively minor link.

A sensitivity check of the GRAL model to plume stiffness was undertaken. Figures 36, shows two extremes of NO_X plume stiffness. It is clear that the higher stiffness value results in a stronger jet of emission from the tunnel. However, even with the lower stiffness value of 50, the plume is not diverted as much as that indicated by the monitoring data.

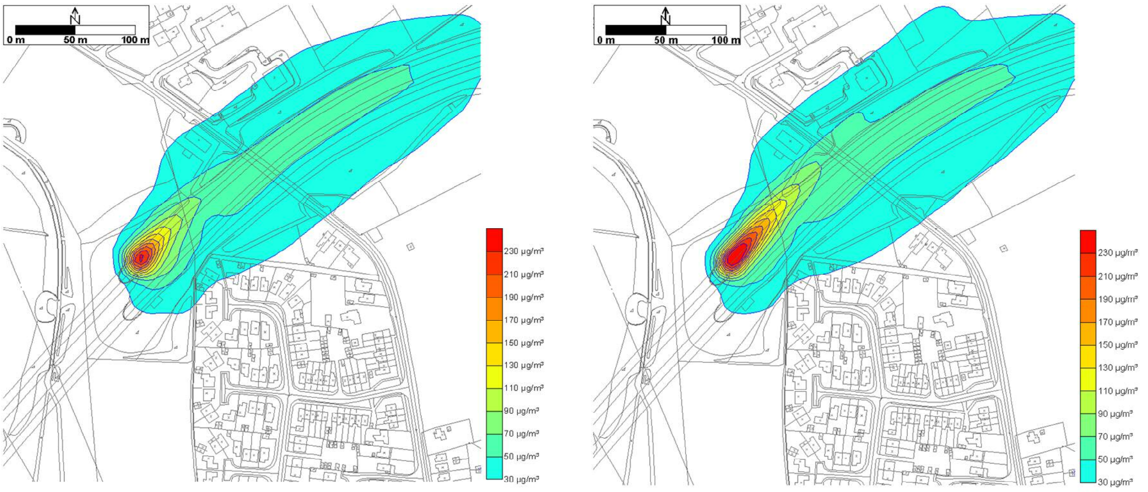

Figure 36: Estimated NO_X concentrations derived from the GRAL model, expressed as a 3-month average. The left hand plot employs a plume stiffness of 50 and the right hand plot a value of 80.

Tables 13 to 15 provides a summary of the measured and modelled results at each of the receptors, for the 3 different plume stiffness. The modelled data were taken from the nearest grid point to the monitored receptor, and given the 5m grid resolution, could introduce some uncertainty into the modelled concentration estimate. On the assumption that the NO_2 data derived from the Palmes tubes are the most reliable measurement, it may be noted that the average variation between measured and predicted concentrations was 19%, 17% and 15% for each of the modelled stiffness values, 50, 60 and 80 respectively. In modelling terms this is a relatively small difference, but significantly the range in the difference between measured and modelled concentrations varies significantly. Some of this variation may be explained by the modelled concentrations being taken from the nearest grid point, and the omission of the inclusion of the emissions from Mile Oak Road. However, an examination of the receptors closest to the tunnel portal (where the environment should be dominated by the portal emissions) does not provide an improved agreement between the measured and modelled concentrations. It is therefore evident that the model does not appropriately account for the shift of the tunnel jet plume northwards, upon emission from the tunnel, under the prevailing meteorological conditions.

Table 13: Measured and modelled pollutant concentrations at the selected Southwick tunnel measurement sites in µg m^{-3}. Tunnel jet stiffness 50 and measurement data expressed in NO_2 equivalents.

Site	Measured*			Modelled				Measured : Modelled (%)		
	NO_2 Palmes	NO_2 Ogawa	NO_X Ogawa	NO_X	NO_2	PM_{10}	CO	NO_2 Palmes / modelled	NO_2 Ogawa / modelled	NO_X Ogawa / modelled
1	23.1	22.9	60.7	38.0	22.9	21.2	240.1	0.7	-0.1	37.4
2	74.5	71.6	256.3	260.3	70.4	30.1	484.6	5.5	1.7	-1.6
3	87.6	81.2	295.1	253.8	69.4	29.8	477.5	20.8	14.5	14.0
4	74.1	69.7	254.6	170.4	54.8	26.5	385.7	26.0	21.4	33.1
5	40.3	41.1	128.9	76.9	34.2	22.8	282.8	15.2	16.8	40.4
6	51.0	49.3	163.3	60.6	29.8	22.1	264.9	41.6	39.7	62.9
7	59.9	58.9	225.8	55.4	28.3	21.9	259.1	52.8	52.0	75.5
8	76.0	69.7	231.5	78.8	34.7	22.8	285.0	54.4	50.3	65.9
9	47.6	44.6	141.7	27.5	19.3	20.8	228.5	59.5	56.7	80.6
10	29.7	25.2	58.8	41.0	23.9	21.3	243.4	19.6	4.9	30.3
11	29.7	34.4	77.7	51.0	27.0	21.7	254.4	9.1	21.4	34.3
12	38.4	37.2	102.8	41.7	24.1	21.4	244.0	37.2	35.2	59.4
13	40.3	43.9	117.8	39.8	23.5	21.3	242.0	41.6	46.4	66.2
14	34.3	32.8	83.1	41.3	24.0	21.4	243.6	29.9	26.7	50.2
15	32.0	32.1	84.6	47.4	25.9	21.6	250.3	19.1	19.4	44.0
16	34.5	33.4	79.8	54.7	28.1	21.9	258.3	18.5	15.9	31.4
17	32.5	30.9	75.8	48.8	26.3	21.7	251.8	18.9	14.7	35.7
18	24.5	26.1	59.2	40.9	23.9	21.3	243.2	2.4	8.5	30.9
19	26.1	28.0	63.4	38.4	23.1	21.2	240.5	11.5	17.6	39.4
20	30.2	31.2	69.7	37.1	22.6	21.2	239.0	25.0	27.4	46.8
21	29.2	29.6	64.6	44.2	24.9	21.5	246.8	14.5	15.8	31.5
22	24.5	26.7	59.8	36.4	22.4	21.2	238.3	8.6	16.1	39.0
23	34.7	33.4	80.8	35.5	22.1	21.1	237.3	36.2	33.8	56.0
24	37.6	44.6	130.8	131.4	46.9	25.0	342.8	-24.7	-5.3	-0.5
25	50.1	44.6	126.4	159.0	52.6	26.1	373.1	-4.9	-18.0	-25.8
26	36.4	39.2	104.1	93.2	38.2	23.4	300.7	-5.2	2.3	10.5
27	41.1	44.6	132.7	73.4	33.2	22.6	278.9	19.2	25.4	44.7
28	32.7	32.8	77.9	62.0	30.2	22.2	266.4	7.9	8.0	20.5
29	28.8	30.9	74.5	55.7	28.4	21.9	259.5	1.4	8.1	25.3
30	28.6	32.8	80.8	58.5	29.2	22.0	262.5	-1.9	11.0	27.6
Min	23.1	22.9	58.8	27.5	19.3	20.8	228.5	-24.7	-18.0	-25.8
Avg	41.0	40.8	118.8	75.1	32.1	22.7	280.8	18.7	19.6	36.9
Stdev	17.1	15.2	67.6	60.5	13.4	2.4	66.5	19.4	17.5	23.3
Max	87.6	81.2	295.1	260.3	70.4	30.1	484.6	59.5	56.7	80.6

*: Measured data are expressed as NO_2 equivalent concentrations in µg m^{-3}

Table 14: Measured and modelled pollutant concentrations at the selected Southwick tunnel measurement sites in µg m^{-3}. Tunnel jet stiffness 60 and measurement data expressed in NO_2 equivalents.

Site	Measured*			Modelled				Measured : Modelled (%)		
	NO_2 Palmes	NO_2 Ogawa	NO_X Ogawa	NO_X	NO_2	PM_{10}	CO	NO_2 Palmes / modelled	NO_2 Ogawa / modelled	NO_X Ogawa / modelled
1	23.1	22.9	60.7	39.6	23.5	21.3	241.8	-1.5	-2.4	73.7
2	74.5	71.6	256.3	254.7	69.5	29.9	478.4	6.7	3.0	93.8
3	87.6	81.2	295.1	295.7	75.8	31.5	523.4	13.5	6.6	94.6
4	74.1	69.7	254.6	207.7	61.6	28.0	426.7	16.8	11.6	93.7
5	40.3	41.1	128.9	90.3	37.5	23.3	297.6	6.8	8.6	87.6
6	51.0	49.3	163.3	66.5	31.4	22.4	271.4	38.4	36.3	90.2
7	59.9	58.9	225.8	55.3	28.3	21.9	259.1	52.8	52.0	92.9
8	76.0	69.7	231.5	73.4	33.3	22.6	279.0	56.2	52.3	93.1
9	47.6	44.6	141.7	27.4	19.3	20.8	228.4	59.6	56.8	88.7
10	29.7	25.2	58.8	42.2	24.3	21.4	244.7	18.2	3.4	72.8
11	29.7	34.4	77.7	53.5	27.7	21.8	257.1	6.7	19.4	79.4
12	38.4	37.2	102.8	40.0	23.6	21.3	242.1	38.7	36.7	84.4
13	40.3	43.9	117.8	39.6	23.5	21.3	241.8	41.8	46.6	86.4
14	34.3	32.8	83.1	41.5	24.1	21.4	243.8	29.8	26.6	80.7
15	32.0	32.1	84.6	47.7	26.0	21.6	250.6	18.8	19.1	81.1
16	34.5	33.4	79.8	55.6	28.3	21.9	259.2	17.8	15.2	80.0
17	32.5	30.9	75.8	49.1	26.4	21.7	252.1	18.6	14.4	78.9
18	24.5	26.1	59.2	41.4	24.0	21.4	243.7	1.8	8.0	73.0
19	26.1	28.0	63.4	38.8	23.2	21.2	240.8	11.1	17.2	74.8
20	30.2	31.2	69.7	37.2	22.7	21.2	239.1	24.9	27.3	77.0
21	29.2	29.6	64.6	43.1	24.6	21.4	245.6	15.7	16.9	75.2
22	24.5	26.7	59.8	36.6	22.5	21.2	238.5	8.3	15.9	73.2
23	34.7	33.4	80.8	35.4	22.1	21.1	237.1	36.3	34.0	80.2
24	37.6	44.6	130.8	115.1	43.4	24.3	324.9	-15.2	2.7	87.8
25	50.1	44.6	126.4	182.3	57.0	27.0	398.8	-13.8	-28.0	87.3
26	36.4	39.2	104.1	101.4	40.2	23.8	309.8	-10.6	-2.7	84.6
27	41.1	44.6	132.7	76.0	34.0	22.7	281.9	17.5	23.8	87.9
28	32.7	32.8	77.9	63.2	30.5	22.2	267.8	6.8	7.0	79.5
29	28.8	30.9	74.5	56.1	28.5	21.9	260.0	0.9	7.7	78.5
30	28.6	32.8	80.8	58.5	29.2	22.0	262.6	-2.0	11.0	80.2
Min	23.1	22.9	58.8	27.4	19.3	20.8	228.4	-15.2	-28.0	72.8
Avg	41.0	40.8	118.8	78.8	32.9	22.9	284.9	17.4	18.2	83.0
Std	17.1	15.2	67.6	67.4	14.6	2.7	74.2	19.7	18.7	6.9
Max	87.6	81.2	295.1	295.7	75.8	31.5	523.4	59.6	56.8	94.6

*: Measured data are expressed as NO_2 equivalent concentrations in µg m^{-3}

Table 15: Measured and modelled pollutant concentrations at the selected Southwick tunnel measurement sites in µg m^{-3}. Tunnel jet stiffness 80 and measurement data expressed in NO_2 equivalents.

Site	Measured*			Modelled				Measured: Modelled (%)		
	NO_2 Palmes	NO_2 Ogawa	NO_X Ogawa	NO_X	NO_2	PM_{10}	CO	NO_2 Palmes / modelled	NO_2 Ogawa / modelled	NO_X Ogawa / modelled
1	23.1	22.9	60.7	41.0	23.9	21.3	243.4	-3.5	-4.4	32.5
2	74.5	71.6	256.3	256.3	69.8	29.9	480.1	6.4	2.6	0.0
3	87.6	81.2	295.1	347.4	83.2	33.6	580.4	5.1	-2.5	-17.7
4	74.1	69.7	254.6	286.2	74.4	31.1	513.0	-0.5	-6.7	-12.4
5	40.3	41.1	128.9	138.6	48.4	25.2	350.7	-20.2	-17.9	-7.5
6	51.0	49.3	163.3	85.2	36.3	23.1	292.0	28.8	26.4	47.8
7	59.9	58.9	225.8	57.6	28.9	22.0	261.6	51.7	50.9	74.5
8	76.0	69.7	231.5	47.5	25.9	21.6	250.5	65.8	62.8	79.5
9	47.6	44.6	141.7	26.2	18.8	20.7	227.1	60.5	57.8	81.5
10	29.7	25.2	58.8	37.0	22.6	21.2	238.9	24.0	10.1	37.1
11	29.7	34.4	77.7	49.1	26.4	21.7	252.3	11.1	23.1	36.8
12	38.4	37.2	102.8	39.0	23.3	21.3	241.1	39.5	37.5	62.0
13	40.3	43.9	117.8	38.0	22.9	21.2	240.0	43.1	47.8	67.7
14	34.3	32.8	83.1	40.5	23.7	21.3	242.7	30.8	27.6	51.3
15	32.0	32.1	84.6	47.7	26.0	21.6	250.6	18.8	19.1	43.6
16	34.5	33.4	79.8	57.3	28.8	22.0	261.1	16.4	13.7	28.2
17	32.5	30.9	75.8	50.0	26.7	21.7	253.1	17.8	13.5	34.1
18	24.5	26.1	59.2	42.0	24.2	21.4	244.4	0.9	7.1	29.0
19	26.1	28.0	63.4	39.6	23.5	21.3	241.8	10.0	16.3	37.5
20	30.2	31.2	69.7	36.7	22.5	21.2	238.6	25.4	27.8	47.3
21	29.2	29.6	64.6	42.6	24.4	21.4	244.9	16.3	17.5	34.1
22	24.5	26.7	59.8	35.2	22.0	21.1	236.9	10.2	17.7	41.1
23	34.7	33.4	80.8	34.4	21.7	21.1	236.1	37.3	34.9	57.4
24	37.6	44.6	130.8	110.8	42.4	24.1	320.1	-12.6	4.9	15.3
25	50.1	44.6	126.4	216.6	63.2	28.4	436.5	-26.1	-41.8	-71.3
26	36.4	39.2	104.1	119.8	44.4	24.5	330.0	-22.1	-13.4	-15.1
27	41.1	44.6	132.7	88.4	37.1	23.2	295.5	9.8	16.8	33.4
28	32.7	32.8	77.9	69.0	32.1	22.5	274.2	2.0	2.1	11.4
29	28.8	30.9	74.5	57.9	29.0	22.0	261.9	-0.8	6.1	22.3
30	28.6	32.8	80.8	59.7	29.5	22.1	263.8	-3.1	10.0	26.1
Min	23.1	22.9	58.8	26.2	18.8	20.7	227.1	-26.1	-41.8	-71.3
Avg	41.0	40.8	118.8	86.6	34.2	23.2	293.4	14.8	15.6	30.3
Std	17.1	15.2	67.6	82.3	17.1	3.3	90.5	23.0	22.6	32.8
Max	87.6	81.2	295.1	347.4	83.2	33.6	580.4	65.8	62.8	81.5

*: Measured data are expressed as NO_2 equivalent concentrations in µg m^{-3}

6 Summary and recommendations

6.1 Summary

Previous studies during the 1980s have demonstrated that pollutant concentrations reduce to background levels within 300 m of a tunnel portal. However, this is dependent amongst other factors on the emission source strength at the tunnel portal and the magnitude of the jet plume emitted from the portal. This relatively large distance has a significant consequence for the determination of the zone of influence of a tunnel portal on local air quality, and therefore on optimal designs of portal environments. This study aimed at investigating this zone of influence, by characterising the NO_2 pollution profiles, with distance from tunnel portals.

Based on traffic flows, speeds and composition from the 8 existing tunnels on the Highways Agency road network, the most polluted tunnels were estimated to be Holmesdale and Hatfield. Based on preliminary design specifications for the Hindhead and Stonehenge tunnels, it also appeared that concentrations in their portal environments are also likely to be relatively high, once they become operational. However, it should be noted that these estimates are rather uncertain, given the modelling errors and assumptions involved.

Tunnel portal emissions may be visualised as horizontal jets, which are emitted at the tunnel exit, in part through the piston effect of the traffic travelling through the tunnel bore. Upon emission this jet plume is subject to interaction and sheer with the prevailing meteorology. The latter will also be influenced by topography in the immediate vicinity of the portal, where the majority of tunnel exits occur within cuttings.

Measurements were undertaken at two tunnels, Bell Common and Southwick. This involved the use of a series of measurement transects, where a total of 30 measurement sites were chosen. At each of these sites the standard Palmes NO_2 diffusion tubes were employed, plus an additional Ogawa sampler designed to measure both NO_2 and NO.

At the Southwick tunnel the Palmes tubes and the Ogawa samplers produced similar results for NO_2 concentrations. However, at the Bell Common site, characterised by higher traffic flows and thus higher emissions when compared to the Southwick tunnel, the Ogawa samplers recorded significantly higher concentrations than the Palmes tubes. The performance of the Ogawa samplers to measure NO_X was not directly investigated, but a comparison of the measured and modelled data at the Southwick tunnel indicated a larger variation than that for NO_2.

It therefore appears that the performance of the Ogawa sampler may be relative to the ambient concentration, whereby the performance reduces with higher NO and NO_2 concentrations.

The pollution profiles derived from the monitoring data are generally simpler at the Bell Common tunnel, than those at the Southwick tunnel. The latter appears to be significantly influenced by emissions from a minor road, just to the east of the tunnel portal. In hindsight it would have been beneficial to test the performance of the GRAL model against the simpler dispersion characteristics at the Bell Common site. However, the GRAL modelling was undertaken independently and during the period of the measurement campaigns and thus the measured dispersion characteristics were not considered in the choice of which tunnel to model.

The monitoring and modelling results from the Bell Common tunnel appeared to broadly agree in terms of the shape of the pollution profiles. However, for the Southwick tunnel, the measurements suggested a much weaker jet plume giving rise to the highest concentrations to the north of the portal. The two tunnels differ considerably in relation to their flows, with 103,000 vehicle/day at the Bell Common tunnel compared to 43,000 vehicles/day at the Southwick tunnel. In addition the proportion of HGVs was much higher at the Bell Common at 13.8%, compared to a value of 4.9% at the

Southwick tunnel. It is therefore possible that the reduced vehicle flow and in particular the lower proportion of HGVs at the Southwick tunnel, combined with the different portal shapes and cross sectional areas, allow the emissions to drift out of the portal with a less significant jet plume and then be blown northwards rather than following the line of the road. Differences in the plume stiffness can explain the variation in the observed concentrations at the two tunnels.

The measurement campaigns indicated that the impact of the tunnel emissions were largely restricted to a narrow corridor, with the concentrations in the first 50m from the tunnel being most significant. Measurements also indicated that the tunnel jet plume is strongly influenced by local meteorology. This meteorological effect was underestimated in the various runs of the GRAL model for the Southwick tunnel. It maybe concluded that the zone of influence remains significant around a tunnel portal, although the highest concentrations, as might be expected, occur relatively close to the portal. However the emissions from the tunnel portal can be detected within a zone measuring some 100m from the portal.

6.2 Recommendations

Since the measurement campaigns reported within this study, little evidence has been published on the robustness of the Ogawa sampler for the measurement of roadside NO and NO_2 concentrations. However, new NO Palmes tubes are now being offered by a range of suppliers, so the use of paired NO and NO_2 tubes to estimate the concentration of NO_X has increased. Whilst this has obvious benefits for model validation, it is recommended that a full validation and equivalence trial is undertaken between these ‘new’ passive monitoring techniques and the reference method.

Monitoring data in the vicinity of tunnel portals remain limited. Whilst many of the UK tunnel portals may not be classified as relevant receptor for compliance with the EU limit values, tunnel portals do remain significant hotspots of traffic related pollution. Given the construction of the Hindhead tunnel and the refurbishments of various other tunnels including the Hatfield, Holmesdale and Bell Common, it is recommended that new monitoring campaigns are undertaken for both PM and NO_2.

The tunnel portal geometry and the influence of the local meteorology on the tunnel jet plume, warrants further investigation. It is possible that tunnel portals could be designed to limit the spread of pollution through an improved understanding of this interaction. Further modelling runs with the GRAL model are thus recommended to establish the sensitivity of the tunnel plume to the various portal characteristics.

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8 References

AQEG (2004). Nitrogen dioxide in the United Kingdom. First report of the Air Quality Expert Group. Defra, London.

Bennett E (2007). Personal communication from Ewan Bennett of Mott MacDonald to Paul Boulter of TRL Limited.

Boulter P G, McCrae I S and Taylor K (2003). Road tunnel air pollution monitoring. TRL report PR/SE/746/03. TRL Limited, Crowthorne.

Boulter P G, McCrae I S and Green J (2007). Primary NO_2 emissions from road vehicles in the Hatfield and Bell Common tunnels. TRL report PPR 262. TRL Limited, Wokingham.

Boulter P G, McCrae I S and Carder D (2008a). Impact of revised HSE NOx standards on road tunnels. Report 1: Current practices for limiting exposure to NO and NO_2 in road tunnels. TRL Report UPR/IE/031/06. TRL Limited, Wokingham.

Boulter P G, McCrae I S, Carder D R and Bennett E (2008b). Impact of revised HSE NOx standards on road tunnels: summary report. TRL Project Report UPR/IE/113/07. TRL Limited, Wokingham.

Bush T, Mooney D and Loader A (2000). UK diffusion tube network instruction manual. Report AEAT 3675. AEA Technology, Culham.

Bush T, Smith S, Stevenson K and Moorcroft S (2001). Validation of nitrogen dioxide diffusion tube methodology in the UK. *Atmospheric Environment*, Vol. 35, pp. 289-296.

Capita Symonds (2004). Impact of proposed occupational exposure limits for nitrogen monoxide in Highways Agency road tunnels. December 2004.

Defra (2007). Department for Environment, Food and Rural Affairs, The Scottish Executive, Welsh Assembly Government and The Department of the Environment for Northern Ireland. The Air Quality Strategy for England, Scotland, Wales and Northern Ireland: July 2007, Cm 7169 NIA 61/07-07. Defra, London.

Dickerson M H (1978). MASCON-A mass consistent atmospheric flux model for region and complex terrain. *Journal of Applied Meteorology*. Vol. 17, pp. 241-253.

Dix A (2006). Managing air outside of tunnels. Report for Rijkswaterstaat, Contract 6400/3003.

EC (2008). Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0050:EN:NOT

Golder D (1972). Relations among stability parameters in the surface layer. *Boundary-Layer Meteorology*. Vol. 3, pp. 47-58.

Haerter A (1991). Road tunnel air and the environment. Aerodynamics and Ventilation of Vehicle Tunnels. Elsevier.

Heal M R, O'Donaghue M A and Cape J N (1999). Overestimation of urban nitrogen dioxide by passive diffusion tubes: a comparative exposure and model study. *Atmospheric Environment*, Vol. 33, pp. 513-524.

Ide Y, Ueyama S and Kobayashi K (1987). Wind tunnel modelling of gas diffusion from a road tunnel outlet. *The Science of the Total Environment*. Vol. 59, pp. 211-222.

Jaeschke W, von Truembach J, Beltz N, Reis R and Hel O (1997). Dispersion modelling near tunnel exists: simulation and measurement. *International Journal of Environment and Pollution*. Vol. 8, pp. 683-689.

Lacour S, Meguelle C, Sportisse B, Carlotti P and Soulhac L (2003). Unsteady effects on pollutant dispersion around a tunnel portal. Proceedings of the 4th Int. conf. on urban air quality, measurement, modelling and management. 25-27 March 2003, Prague. pp. 465–468.

Lepage M F and Schuyler G D (1991). Re-entrainment of exhaust gases in a longitudinally ventilated tunnel. Paper presented at the 7th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels, Brighton.

Maarsingh R A and Swaart L (1991). Wind-tunnel experiments on wind effects at tunnel portals. Paper presented at the 7th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels, Brighton.

Marsault J P and Gabet M C (1985). Pollution dispersion: Insitu measurements at tunnel portals. 5th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels. Lille, 20-22 May 1985.

Matsumoto K, Sakai K, Horiuchi K, Takahashi H and Okamoto S (1998). Advanced air quality simulation model for road tunnel portals in complex terrain. *Int. J. Vehicle Design*. Vol. 20, (1-4) (Special issue), pp. 71–78.

Mouchel Parkman (2005). Tunnel data- Bell Common Tunnel, M25 Motorway. Emergency Plan. Report reference W:\150043\14.0\AC010\Emergency Plan Nov05. Issue 2.0.

Nadel C, Vanderheyden M, Lepage M, Davies A, Wan P, Ginzburg H and Schattanek G (1994). Physical modelling of dispersion of a tunnel portal exhaust plume. 8th Int. Symposium on the aerodynamics and ventilation of vehicle tunnels, Liverpool.

Northwood Technologies (2001). Vertical mapper contour modelling and display software for MapInfo Professional: User guide. Northwood Technologies, Canada.

Okamoto S, Sakai K, Matsumoto K, Horiuchi K and Kobayashi K (1998). Development and application of a three-dimensional Taylor-Galerkin numerical model for air quality simulation near roadway tunnel portals. *Journal of Applied Meteorology*. Vol. 37, pp. 1010-1025.

Oettl D, Sturm P J, Bacher M, Pretterhofer G and Almbauer R A (2002). A simple model for the dispersion of pollutants from a road tunnel portal. *Atmospheric Environment.* Vol. 36, pp. 2943-2953.

Oettl D, Sturm P J and Almbauer R A (2005). Evaluation of GRAL for the pollutant dispersion from a city street tunnel portal at depressed level. *Environmental Modelling and Software*. Vol. 20, pp. 499-504.

Oettl D, Sturm P J, Almbauer R A, Okamoto S and Horiuchi K (2003). Dispersion from road tunnel portals: comparison of two different modelling approaches. *Atmospheric Environment.* Vol. 37, pp. 5165-5175.

Ogawa & Co (1998). NO, NO_2, NO_X and SO_2 sampling protocol using the Ogawa sampler. Version 4.0. Ogawa & Co, USA Inc.

Peterson H G and Tonnesen D A (1990). A tracer investigation of traffic emissions from the Valerenga tunnel at Etterstad. Norwegian Institute for Air Research. NILU report OR 39/90, Lillestrom.

Sato N, Ohta Y and Komatsu K (1995). Discharge of exhaust pollutant from portal of one-way traffic automobile tunnel with exhaust shaft. 5th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels. Lille, 20-22 May 1985.

Smith S, Bush T, Stevenson K and Moorcroft S (1999). Validation of the nitrogen dioxide diffusion tube methodology. Report by Stanger Science and Technology and NETCEN.

Ueyama S (1985). Dispersion estimates for automobile exhaust gas from a tunnel portal. Tech. Memo. Japan Highway Public Corporation. Vol. 79, pp. 38–45.

Vanderheyden M D and Nadel C B (2000). Relationships for determining the dispersion of portal emissions from one-way roadway tunnels. Proceedings of the 10th international symposium on aerodynamics and ventilation of vehicle tunnels, Boston, 1-3 November 2000.

Venkatram A (1996). An examination of the Pasquill-Gifford-Turner dispersion scheme. *Atmospheric Environment.* Vol. 30, pp. 1283-1290.

Zannetti P (1990). Air pollution modelling. Theories, computational methods and available software. Computational Mechanics Publications, Southampton, Boston.

Zumsteg F and Graf E (1993). Bestimmung von emissioen und immissionen in portalzonen. Messkampagne Baregg 1992. Technical Paper 92-104-03.

Annex 1: Diffusion tube locations

Table A1.1: The location of the monitoring positions around the Southwick tunnel portal.

Receptor	Location	Distance from road/portal (m)
1	N/B compound car park fence	18.8m from roadside
2	N/B carriageway edge	0m from portal
3	N/B carriageway edge	19.2m from portal
4	N/B carriageway edge	35m from portal
5	N/B carriageway edge	64.5m from portal
6	N/B carriageway edge	100.5m from portal
7	N/B carriageway edge	151m from portal
8	N/B carriageway, bank	27m from portal 7m from roadside
9	N/B carriageway, bank	32m from portal 14m from roadside
10	N/B carriageway, bank	37m from portal 20m from roadside
11	N/B carriageway, bank	65m from portal 25m from roadside
12	S/B carriageway, edge	5.7m from portal
13	S/B carriageway, edge	20m from portal
14	S/B carriageway, edge	39m from portal
15	S/B carriageway, edge	80m from portal
16	S/B carriageway, edge	135m from portal
17	S/B carriageway, edge	190m from portal
18	S/B carriageway, bank	11m from roadside, 190m from portal
19	S/B carriageway, bank	7m from roadside, 158m from portal
20	S/B carriageway, bank	9.4m from roadside, 28.4m from tunnel portal
21	S/B carriageway, bank	10m from roadside, 36.4M from tunnel portal
22	S/B carriageway, bank	13.7m from roadside, 54.9m from portal
23	S/B carriageway, bank	5m from roadside, 14m from portal
24	Central reserve	4.2m from portal
25	Central reserve	19.5 m from portal
26	Central reserve	37m from portal
27	Central reserve	64m from portal
28	Central reserve	98m from portal
29	Central reserve	150m from portal
30	Central reserve	200m from portal

Table A1.2: The location of the monitoring positions around the Bell Common tunnel portal.

Receptor	Location	Distance from road/portal (m)
1	W/B carriageway edge	5
2	W/B carriageway edge	10
3	W/B carriageway edge	35
4	W/B carriageway edge	75
5	W/B carriageway edge	150
6	W/B carriageway bank	13
7	W/B carriageway bank	18
8	W/B carriageway bank	31
9	W/B carriageway bank	67
10	W/B carriageway bank	99
11	W/B carriageway bank	23.5
12	W/B carriageway bank	31
13	W/B carriageway bank	62
14	W/B carriageway bank	75
15	W/B carriageway bank	82
16	E/B carriageway edge	5
17	E/B carriageway edge	10
18	E/B carriageway edge	50
19	E/B carriageway edge	100
20	E/B carriageway edge	150
21	E/B carriageway edge	10
22	E/B carriageway edge	20
23	E/B carriageway edge	10
24	E/B carriageway edge	50
25	E/B carriageway edge	50
26	E/B carriageway edge	30
27	E/B carriageway edge	35
28	E/B carriageway edge	100
29	E/B carriageway edge	90
30	E/B carriageway edge	130

Annex 2: Diffusion tube (Palmes) results, Southwick Tunnel

Table A2.1: Period 1.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NO_2 raw (ppb) Tube 1	NO_2 raw (ppb) Tube 2	NO_2 raw (ppb) Tube 3	NO_2 bias adjusted (ppb) whole average
1	22/02/06	12:26	22/03/06	12:31	672:05	9.49	9.46	9.37	9.5
2	22/02/06	12:35	22/03/06	12:34	671:59	34.72	36.84	13.79	36.1
3	22/02/06	12:40	22/03/06	12:36	671:56	37.17	39.99	37.49	38.6
4	22/02/06	12:45	22/03/06	12:47	672:02	26.96	31.78	30.82	30.2
5	22/02/06	12:47	22/03/06	12:46	671:59	17.23	15.8	17.58	17.0
6	22/02/06	12:52	22/03/06	12:53	672:01	23.92	21.06	21.9	22.5
7	22/02/06	12:55	22/03/06	12:55	672:00	25.2	30.35	19.07	25.1
8	22/02/06	13:00	22/03/06	12:35	671:35	31.89	37.1	29.33	33.1
9	22/02/06	13:10	22/03/06	12:39	671:29	24.3	22.66	20.93	22.9
10	22/02/06	13:15	22/03/06	12:42	671:27	10.06	13.07	11.26	11.6
11	22/02/06	13:17	22/03/06	12:44	671:27	10.75	11.91	11.11	11.4
12	22/02/06	13:40	22/03/06	11:33	669:53	12.92	18.51	17.22	16.4
13	22/02/06	13:45	22/03/06	11:37	669:52	19.52	20.54	18.6	19.7
14	22/02/06	13:47	22/03/06	11:42	669:55	15.82	15.85	16.09	16.1
15	22/02/06	13:50	22/03/06	11:40	669:50	15.76	16.27	15.1	15.9
16	22/02/06	13:55	22/03/06	11:48	669:53	17.04	15.61	14.92	16.0
17	22/02/06	14:00	22/03/06	11:53	669:53	16.15	14.03	16.45	15.7
18	22/02/06	14:05	22/03/06	11:55	669:50	12.3	11.91	12.39	12.3
19	22/02/06	14:07	22/03/06	11:50	669:43	13.02	13.79	14.09	13.8
20	22/02/06	14:12	22/03/06	11:39	669:27	8.72	14.6	15.62	15.3
21	22/02/06	14:15	22/03/06	11:40	669:25	12.96	14.52	14.67	14.2
22	22/02/06	14:17	22/03/06	11:44	669:27	12.34	13.23	11.98	12.6
23	22/02/06	n/a	22/03/06	n/a	672:00	13.85	n/a	n/a	n/a
24	22/02/06	13:10	22/03/06	12:14	671:04	26.07	12.75	11.11	12.0
25	22/02/06	12:40	22/03/06	12:15	671:35	24.26	27.57	23.94	25.5
26	22/02/06	12:43	22/03/06	12:17	671:34	17.92	17.33	16.61	17.5
27	22/02/06	12:46	22/03/06	12:18	671:32	19.26	21.77	20.22	20.6
28	22/02/06	12:50	22/03/06	12:20	671:30	15.87	14.23	15.84	15.5
29	22/02/06	12:53	22/03/06	12:22	671:29	13.85	14.56	14.05	14.3
30	22/02/06	12:55	22/03/06	12:24	671:29	14.05	12.75	13.7	13.6
Town Hall, Hove	22/02/06	14:30	22/03/06	11:07	668:37	15.7	19.07	19.08	n/a

n/a Individual tubes missing on collection.

Table A2.2: Period 2.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NO_2 raw (ppb) Tube 1	NO_2 raw (ppb) Tube 2	NO_2 raw (ppb) Tube 3	NO_2 bias adjusted (ppb) period average
1	22/03/06	12:31	19/04/06	13:20	672:49	10.32	12.01	n/a	11.3
2	22/03/06	12:34	19/04/06	13:23	672:49	41.55	43.53	39.27	41.9
3	22/03/06	12:36	19/04/06	13:25	672:49	53.5	45.51	44.52	48.3
4	22/03/06	12:47	19/04/06	13:34	672:47	39.39	38.87	37.12	38.8
5	22/03/06	12:46	19/04/06	13:33	672:47	21.08	21.23	21.75	21.6
6	22/03/06	12:53	19/04/06	13:35	672:42	23.36	24.58	25.22	24.6
7	22/03/06	12:55	19/04/06	13:37	672:42	31.17	31.93	31.46	31.8
8	22/03/06	12:35	19/04/06	13:27	672:52	39.56	41.13	44.63	42.2
9	22/03/06	12:39	19/04/06	13:30	672:51	24.11	24.48	25.01	24.8
10	22/03/06	12:42	19/04/06	13:31	672:49	14.26	15.95	16.18	15.6
11	22/03/06	12:44	19/04/06	13:31	672:47	15.13	15.8	14.7	15.4
12	22/03/06	11:33	19/04/06	12:09	672:36	19.31	19.04	19.28	19.4
13	22/03/06	11:37	19/04/06	12:12	672:35	18.72	12.51	19.02	19.1
14	22/03/06	11:42	19/04/06	12:16	672:34	17.06	17	15.49	16.7
15	22/03/06	11:40	19/04/06	12:27	672:47	13.21	14.05	13.44	13.7
16	22/03/06	11:48	19/04/06	12:45	672:57	n/a	n/a	n/a	n/a
17	22/03/06	11:53	19/04/06	12:32	672:39	15.89	14.76	14.32	15.1
18	22/03/06	11:55	19/04/06	12:33	672:38	11.81	11.43	12.57	12.1
19	22/03/06	11:50	19/04/06	12:31	672:41	10.91	12.51	12.6	12.1
20	22/03/06	11:39	19/04/06	12:13	672:34	14.2	13.77	12.77	13.7
21	22/03/06	11:40	19/04/06	12:18	672:38	13.04	12.83	17.09	14.5
22	22/03/06	11:44	19/04/06	12:06	672:22	13.54	n/a	12.28	13.0
23	22/03/06	12:01	19/04/06	12:11	672:10	15.12	16.69	15.99	16.1
24	22/03/06	12:14	19/04/06	13:10	672:56	20.23	23.29	25.42	23.2
25	22/03/06	12:15	19/04/06	13:11	672:56	22.82	25.01	29.94	26.2
26	22/03/06	12:17	19/04/06	13:12	672:55	21.63	17.02	17.26	18.8
27	22/03/06	12:18	19/04/06	13:13	672:55	20.76	20.55	19.27	20.4
28	22/03/06	12:20	19/04/06	13:14	672:54	15.42	17.37	15.54	16.3
29	22/03/06	12:22	19/04/06	13:16	672:54	14.69	14.61	13.7	14.5
30	22/03/06	12:24	19/04/06	13:16	672:52	14.63	13.56	14.96	14.5
Town Hall, Hove	22/03/06	11:07	19/04/06	11:48	672:41	17.12	15.48	15.69	n/a

n/a Individual tubes missing on collection. For site 16, the crash barrier against which these tubes were mounted was destroyed by a road traffic accident.

Table A2.3: Period 3.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NO_2 raw (ppb) Tube 1	NO_2 raw (ppb) Tube 2	NO_2 raw (ppb) Tube 3	NO_2 bias adjusted (ppb) period average
1	19/04/06	13:20	10/05/06	12:58	503:38	15.73	15.85	14.45	15.5
2	19/04/06	13:23	10/05/06	12:59	503:36	37.63	36.43	41.84	39.0
3	19/04/06	13:25	10/05/06	13:00	503:35	48.32	47.2	55.13	50.7
4	19/04/06	13:34	10/05/06	13:01	503:27	47.77	45.29	47.45	47.3
5	19/04/06	13:33	10/05/06	13:05	503:32	25.26	25.3	22.7	24.7
6	19/04/06	13:35	10/05/06	13:07	503:32	35.64	31.19	30.95	32.9
7	19/04/06	13:37	10/05/06	13:09	503:32	36.12	36.44	37.88	37.2
8	19/04/06	13:27	10/05/06	13:02	503:35	44.32	37.47	49.04	44.0
9	19/04/06	13:30	10/05/06	13:03	503:33	26.3	25.7	28.79	27.2
10	19/04/06	13:31	10/05/06	13:04	503:33	19.58	19.3	19.1	19.5
11	19/04/06	13:31	10/05/06	13:06	503:35	22.54	19.02	17.66	19.9
12	19/04/06	12:09	10/05/06	12:32	504:23	25.58	23.62	23.87	24.6
13	19/04/06	12:12	10/05/06	12:33	504:21	24.02	24.42	24.34	24.5
14	19/04/06	12:16	10/05/06	12:35	504:19	20.99	20.71	20.95	21.1
15	19/04/06	12:27	10/05/06	12:39	504:12	19.91	20.67	21.03	20.7
16	19/04/06	12:45	10/05/06	12:41	503:56	18.36	20.92	20.4	20.1
17	19/04/06	12:32	10/05/06	12:42	504:10	21.67	18.75	19.47	20.2
18	19/04/06	12:33	10/05/06	12:43	504:10	13.56	13	15.2	14.1
19	19/04/06	12:31	10/05/06	12:45	504:14	15.55	13.95	15.19	15.0
20	19/04/06	12:13	10/05/06	12:34	504:21	20.11	16.55	18.07	18.4
21	19/04/06	12:18	10/05/06	12:36	504:18	16.67	16.47	17.79	17.1
22	19/04/06	12:06	10/05/06	12:37	504:31	n/a	n/a	n/a	n/a
23	19/04/06	12:01	10/05/06	12:34	504:33	21.22	19.14	19.66	20.2
24	19/04/06	13:10	10/05/06	13:11	504:01	23.36	24.6	22.88	23.8
25	19/04/06	13:11	10/05/06	13:12	504:01	27.6	25.52	27.04	27.0
26	19/04/06	13:12	10/05/06	13:14	504:02	20.64	19.96	21.32	20.8
27	19/04/06	13:13	10/05/06	13:15	504:02	24.08	22.96	23.08	23.6
28	19/04/06	13:14	10/05/06	13:17	504:03	18.88	19.76	19.84	19.7
29	19/04/06	13:16	10/05/06	13:19	504:03	15.88	16.56	16.28	16.4
30	19/04/06	13:16	10/05/06	13:20	504:04	18.16	15.12	16.68	16.8
Town Hall, Hove	19/04/06	11:48	10/05/06	13:50	506:02	21	20.8	19.8	n/a

n/a Individual tubes missing on collection.

Annex 3: Ogawa results, Southwick Tunnel

Table A3.1: Period 1.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	22/02/06	12:26	14/03/06	13:10	480:44	21	10	11	
2	22/02/06	12:35	14/03/06	13:13	480:38	n/a	37	n/a	No NOx filter
3	22/02/06	12:40	14/03/06	13:15	480:35	164	40	125	
4	22/02/06	12:45	14/03/06	13:23	480:38	131	35	97	
5	22/02/06	12:47	14/03/06	13:22	480:35	55	18	38	
6	22/02/06	12:52	14/03/06	13:26	480:34	75	21	54	
7	22/02/06	12:55	14/03/06	13:28	480:33	114	27	86	
8	22/02/06	13:00	14/03/06	13:16	480:16	135	34	100	
9	22/02/06	13:10	14/03/06	13:18	480:08	81	25	56	
10	22/02/06	13:15	14/03/06	13:19	480:04	29	12	18	
11	22/02/06	13:17	14/03/06	13:20	480:03	26	15	11	
12	22/02/06	13:40	14/03/06	11:47	478:07	48	18	30	
13	22/02/06	13:45	14/03/06	11:50	478:05	53	18	35	
14	22/02/06	13:47	14/03/06	12:00	478:13	43	16	27	
15	22/02/06	13:50	14/03/06	12:14	478:24	47	18	29	
16	22/02/06	13:55	14/03/06	12:16	478:21	41	16	25	
17	22/02/06	14:00	14/03/06	12:18	478:18	41	15	26	
18	22/02/06	14:05	14/03/06	12:20	478:15	29	13	16	
19	22/02/06	14:07	14/03/06	12:21	478:14	34	14	20	
20	22/02/06	14:12	14/03/06	11:58	477:46	37	16	21	
21	22/02/06	14:15	14/03/06	12:02	477:47	35	15	20	
22	22/02/06	14:17	14/03/06	12:05	477:48	32	15	17	
23	22/02/06	n/a	14/03/06	n/a	n/a	n/a	n/a	n/a	No sample
24	22/02/06	13:10	14/03/06	12:52	479:42	73	23	50	
25	22/02/06	12:40	14/03/06	12:53	480:13	68	21	47	
26	22/02/06	12:43	14/03/06	12:55	480:12	56	19	36	
27	22/02/06	12:46	14/03/06	12:57	480:11	79	22	58	
28	22/02/06	n/a	14/03/06	n/a	n/a	n/a	n/a	n/a	No sample
29	22/02/06	12:53	14/03/06	13:01	480:08	34	14	20	
30	22/02/06	12:55	14/03/06	13:03	480:08	36	14	22	
Blank						3	1	2	

Table A3.2: Period 2.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	14/03/06	13:10	22/03/06	12:31	191:21	46.5	11	35	
2	14/03/06	13:13	22/03/06	12:34	191:21	161	39	122	
3	14/03/06	13:15	22/03/06	12:36	191:21	123	34	89	
4	14/03/06	13:23	22/03/06	12:47	191:24	87	27	60	
5	14/03/06	13:22	22/03/06	12:46	191:24	47	15	31	
6	14/03/06	13:26	22/03/06	12:53	191:27	93	29	64	
7	14/03/06	13:28	22/03/06	12:55	191:27	113	31	82	
8	14/03/06	13:16	22/03/06	12:35	191:19	72	27	45	
9	14/03/06	13:18	22/03/06	12:39	191:21	47	18	29	
10	14/03/06	13:19	22/03/06	12:42	191:23	29	13	16	
11	14/03/06	13:20	22/03/06	12:44	191:24	27	13	14	
12	14/03/06	11:47	22/03/06	11:33	191:46	54	19	36	
13	14/03/06	11:50	22/03/06	11:37	191:47	49	19	31	
14	14/03/06	12:00	22/03/06	11:42	191:42	37	15	23	
15	14/03/06	12:14	22/03/06	11:40	191:26	32	13	19	
16	14/03/06	12:16	22/03/06	11:48	191:32	33	14	19	
17	14/03/06	12:18	22/03/06	11:53	191:35	32	13	18	
18	14/03/06	12:20	22/03/06	11:55	191:35	28	11	17	
19	14/03/06	12:21	22/03/06	11:50	191:29	27	12	15	
20	14/03/06	11:58	22/03/06	11:39	191:41	32	13	18	
21	14/03/06	12:02	22/03/06	11:40	191:38	30	14	16	
22	14/03/06	12:05	22/03/06	11:44	191:39	22	11	11	
23	14/03/06		22/03/06	11:35	203:35	39	16	22	
24	14/03/06	12:52	22/03/06	12:14	191:22	96	28	67	
25	14/03/06	12:53	22/03/06	12:15	191:22	72	24	48	
26	14/03/06	12:55	22/03/06	12:17	191:22	46	17	29	
27	14/03/06	12:57	22/03/06	12:18	191:21	63	23	40	
28	14/03/06	12:59	22/03/06	12:20	191:21	30	14	16	
29	14/03/06	13:01	22/03/06	12:22	191:21	40	15	25	
30	14/03/06	13:03	22/03/06	12:24	191:21	50	19	31	
Blank						3	0	3	

Table A3.3: Period 3.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	22/03/06	12:31	05/04/06	13:05	336:34	n/a	5	n/a	No NOx filter
2	22/03/06	12:34	05/04/06	13:22	336:48	134	38	96	
3	22/03/06	12:36	05/04/06	13:24	336:48	168	45	123	
4	22/03/06	12:47	05/04/06	13:25	336:38	142	38	104	
5	22/03/06	12:46	05/04/06	13:29	336:43	71	23	48	
6	22/03/06	12:53	05/04/06	13:30	336:37	85	24	61	
7	22/03/06	12:55	05/04/06	13:32	336:37	112	29	83	
8	22/03/06	12:35	05/04/06	13:27	336:52	131	39	92	
9	22/03/06	12:39	05/04/06	13:25	336:46	97	273	97	
10	22/03/06	12:42	05/04/06	13:26	336:44	n/a	n/a	n/a	No sample
11	22/03/06	12:44	05/04/06	12:44	336:00	52	19	33	
12	22/03/06	11:33	05/04/06	11:33	336:00	53	19	34	
13	22/03/06	11:37	05/04/06	11:37	336:00	110	39	71	
14	22/03/06	11:42	05/04/06	11:42	336:00	39	16	24	
15	22/03/06	11:40	05/04/06	11:40	336:00	n/a	12	0	
16	22/03/06	11:48	05/04/06	11:48	336:00	n/a	n/a	n/a	No sample
17	22/03/06	11:53	05/04/06	11:53	336:00	37	14	22	
18	22/03/06	11:55	05/04/06	11:55	336:00	26	12	14	
19	22/03/06	11:50	05/04/06	11:50	336:00	29	13	16	
20	22/03/06	11:39	05/04/06	11:39	336:00	32	15	18	
21	22/03/06	11:40	05/04/06	11:40	336:00	31	14	17	
22	22/03/06	11:44	05/04/06	11:44	336:00	30	12	18	
23	22/03/06	11:35	05/04/06	11:35	336:00	42	17	25	
24	22/03/06	12:14	05/04/06	12:14	336:00	65	21	44	
25	22/03/06	12:15	05/04/06	12:15	336:00	61	21	40	
26	22/03/06	12:17	05/04/06	12:17	336:00	51	19	32	
27	22/03/06	12:18	05/04/06	12:18	336:00	63	21	41	
28	22/03/06	12:20	05/04/06	12:20	336:00	42	16	26	
29	22/03/06	12:22	05/04/06	12:22	336:00	36	15	21	
30	22/03/06	12:24	05/04/06	12:24	336:00	35	15	20	
blank						3	0	3	

Table A3.4: Period 4.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	05/04/06	13:05	19/04/06	13:20	336:15	18.9	10	9	
2	05/04/06	13:22	19/04/06	13:23	336:01	94	33	61	
3	05/04/06	13:24	19/04/06	13:25	336:01	137	38	99	
4	05/04/06	13:25	19/04/06	13:34	336:09	113	34	79	
5	05/04/06	13:29	19/04/06	13:33	336:04	57	19	37	
6	05/04/06	13:30	19/04/06	13:35	336:05	60	21	39	
7	05/04/06	13:32	19/04/06	13:37	336:05	109	28	81	
8	05/04/06	13:26	19/04/06	13:27	336:01	99	33	66	
9	05/04/06	13:25	19/04/06	13:30	336:05	49	19	30	
10	05/04/06	13:26	19/04/06	13:31	336:05	7	7	n/a	
11	05/04/06	13:27	19/04/06	13:31	336:04	26	12	15	
12	05/04/06	12:00	19/04/06	12:09	336:09	40	16	24	
13	05/04/06	12:01	19/04/06	12:12	336:11	38	16	22	
14	05/04/06	12:05	19/04/06	12:16	336:11	35	14	21	
15	05/04/06	12:10	19/04/06	12:27	336:17	40	17	23	
16	05/04/06		19/04/06			n/a	n/a	n/a	Site destroyed no Ogawa deployed
17	05/04/06	12:22	19/04/06	12:32	336:10	30	14	17	
18	05/04/06	12:23	19/04/06	12:33	336:10	24	12	11	
19	05/04/06	12:20	19/04/06	12:31	336:11	29	13	15	
20	05/04/06	12:02	19/04/06	12:13	336:11	26	13	14	
21	05/04/06	12:04	19/04/06	12:18	336:14	26	13	13	
22	05/04/06	12:06	19/04/06	12:35	336:29	n/a	n/a	n/a	Ogawa removed from site
23	05/04/06	12:01	19/04/06	12:11	336:10	32	14	18	
24	05/04/06	13:10	19/04/06	13:02	335:52	47	20	27	
25	05/04/06	13:11	19/04/06	13:04	335:53	58	22	36	
26	05/04/06	13:12	19/04/06	13:05	335:53	50	20	30	
27	05/04/06	13:13	19/04/06	13:06	335:53	65	22	43	
28	05/04/06	13:14	19/04/06	13:06	335:53	37	17	20	
29	05/04/06	13:16	19/04/06	13:07	335:53	33	13	20	
30	05/04/06	13:16	19/04/06	13:09	322:44	38	15	23	
Blank						4	2	3	

Table A3.5: Period 5.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	19/04/06	13:20	03/05/06	12:20	335:00	40.7	18	23	
2	19/04/06	13:23	03/05/06	12:08	334:45	139	39	100	
3	19/04/06	13:25	03/05/06	12:09	334:44	151	47	104	
4	19/04/06	13:34	03/05/06	12:10	334:36	151	39	113	
5	19/04/06	13:33	03/05/06	12:14	334:41	82	26	56	
6	19/04/06	13:35	03/05/06	12:16	334:41	100	29	72	
7	19/04/06	13:37	03/05/06	12:17	334:40	129	34	95	
8	19/04/06	13:27	03/05/06	12:10	334:43	147	41	106	
9	19/04/06	13:30	03/05/06	12:11	334:41	88	30	58	
10	19/04/06	13:31	03/05/06	12:12	334:41	55	20	35	
11	19/04/06	13:31	03/05/06	12:13	334:42	53	20	32	
12	19/04/06	12:09	03/05/06	11:13	335:04	66	23	43	
13	19/04/06	12:12	03/05/06	11:17	335:05	59	23	36	
14	19/04/06	12:16	03/05/06	11:21	335:05	53	21	32	
15	19/04/06	12:27	03/05/06	11:32	335:05	50	20	30	
16	19/04/06	12:45	03/05/06	11:34	334:49	43	19	24	
17	19/04/06	12:32	03/05/06	11:36	335:04	48	22	26	
18	19/04/06	12:33	03/05/06	11:37	335:04	43	17	26	
19	19/04/06	12:31	03/05/06	11:35	335:04	40	18	23	
20	19/04/06	12:13	03/05/06	11:18	335:05	43	20	23	
21	19/04/06	12:18	03/05/06	11:20	335:02	39	18	21	
22	19/04/06	12:35	03/05/06	11:28	334:53	42	13	29	
23	19/04/06	12:11	03/05/06	11:15	335:04	51	21	29	
24	19/04/06	13:02	03/05/06	11:56	334:54	69	25	44	
25	19/04/06	13:04	03/05/06	11:57	334:53	73	26	47	
26	19/04/06	13:05	03/05/06	11:58	334:53	62	24	37	
27	19/04/06	13:06	03/05/06	12:00	334:54	77	26	51	
28	19/04/06	13:06	03/05/06	12:01	334:55	49	20	29	
29	19/04/06	13:07	03/05/06	12:03	334:56	43	21	22	
30	19/04/06	13:09	03/05/06	12:04	334:55	43	18	25	
Blank						6	0	5	

Table A3.6: Period 6.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	03/05/06	12:25	10/05/06	12:58	168:34	44.6	18	26	
2	03/05/06	12:08	10/05/06	12:59	168:52	116	39	77	
3	03/05/06	12:09	10/05/06	13:00	168:52	184	51	134	
4	03/05/06	12:10	10/05/06	13:01	168:55	176	46	130	
5	03/05/06	12:14	10/05/06	13:05	168:53	93	28	65	
6	03/05/06	12:16	10/05/06	13:07	168:53	100	31	69	
7	03/05/06	12:17	10/05/06	13:09	168:45	132	36	96	
8	03/05/06	12:10	10/05/06	13:02	168:53	143	45	99	
9	03/05/06	12:11	10/05/06	13:03	168:53	83	29	54	
10	03/05/06	12:12	10/05/06	13:04	168:53	58	20	37	
11	03/05/06	12:14	10/05/06	13:05	168:18	60	29	31	
12	03/05/06	11:14	10/05/06	12:32	169:19	62	22	39	
13	03/05/06	11:17	10/05/06	12:33	169:18	61	23	39	
14	03/05/06	11:21	10/05/06	12:35	169:18	54	21	33	
15	03/05/06	11:32	10/05/06	12:39	169:09	57	21	36	
16	03/05/06	11:34	10/05/06	12:41	169:08	50	21	29	
17	03/05/06	11:36	10/05/06	12:42	169:07	50	19	31	
18	03/05/06	11:37	10/05/06	12:43	169:08	36	17	19	
19	03/05/06	11:35	10/05/06	12:45	168:59	40	18	23	
20	03/05/06	11:19	10/05/06	12:34	169:17	49	21	28	
21	03/05/06	11:20	10/05/06	12:36	169:18	42	19	22	
22	03/05/06	11:28	10/05/06	12:38	169:05	32	17	15	
23	03/05/06	11:15	10/05/06	12:33	169:56	51	21	30	
24	03/05/06	11:56	10/05/06	13:11	169:16	61	23	38	
25	03/05/06	11:57	10/05/06	13:12	169:17	65	26	40	
26	03/05/06	11:58	10/05/06	13:14	169:17	62	24	38	
27	03/05/06	12:00	10/05/06	13:15	169:16	70	26	44	
28	03/05/06	12:01	10/05/06	13:16	169:16	57	22	35	
29	03/05/06	12:03	10/05/06	13:17	169:16	48	19	29	
30	03/05/06	12:04	10/05/06	13:19	155:56	52	22	30	
Blank						8	1	6	

Annex 4: Diffusion tube (Palmes) results, Bell Common Tunnel

Table A4.1: Period 1.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NO_2 raw (ppb) Tube 1	NO_2 raw (ppb) Tube 2	NO_2 raw (ppb) Tube 3	NO_2 bias adjusted (ppb) period average
1	24/05/06	12:40	21/06/06	14:35	673:55	142.93	113.68	134.2	97.7
2	24/05/06	12:42	21/06/06	14:40	673:58	116.56	129.68	132.69	94.7
3	24/05/06	14:45	21/06/06	15:20	672:35	82.32	69.56	72.98	56.2
4	24/05/06	12:50	21/06/06	15:17	674:27	71.87	75.78	77.58	56.3
5	24/05/06	12:52	21/06/06	15:15	674:23	62.56	60.01	62.56	46.3
6	24/05/06	13:05	21/06/06	14:45	673:40	83.39	81.59	80.08	61.3
7	24/05/06	13:10	21/06/06	14:47	673:37	68.5	60.52	65.49	48.6
8	24/05/06	13:12	21/06/06	14:53	673:41	51.37	48.42	49.2	37.2
9	24/05/06	13:25	21/06/06	15:00	673:35	36.81	35.06	43.1	28.7
10	24/05/06	13:25	21/06/06	15:10	673:45	33.91	31.32	31.14	24.1
11	24/05/06	13:30	21/06/06	14:50	673:20	74.4	63.41	76.21	53.5
12	24/05/06	13:46	21/06/06	14:56	673:10	45.93	51.29	47.55	36.2
13	24/05/06	13:50	21/06/06	15:05	673:15	39.3	40.44	28.52	27.1
14	24/05/06	13:50	21/06/06	15:08	673:18	40.38	37.49	38.03	29.0
15	24/05/06	13:55	21/06/06	15:07	673:12	37.55	43.1	41.11	30.4
16	24/05/06	14:15	21/06/06	13:30	671:15	46.36	52.82	51.62	37.7
17	24/05/06	14:15	21/06/06	13:33	671:18	55.9	57.17	55.5	42.1
18	24/05/06	14:18	21/06/06	13:55	671:37	57.32	56.96	35.53	42.9
19	24/05/06	14:20	21/06/06	14:17	671:57	59.23	60.98	44.8	41.3
20	24/05/06	14:22	21/06/06	14:15	671:53	60.23	52.23	58.15	42.7
21	24/05/06	14:50	21/06/06	13:38	670:48	27.87	32.37	31.89	23.0
22	24/05/06	14:35	21/06/06	13:41	671:06	26.19	21.33	23.23	17.7
23	24/05/06	14:50	21/06/06	13:46	670:56	24.81	20.03	25.41	17.6
24	24/05/06	15:00	21/06/06	13:59	670:59	27.22	27.83	28.8	21.0
25	24/05/06	15:02	21/06/06	13:55	670:53	28.65	30.31	30.91	22.5
26	24/05/06	15:08	21/06/06	14:02	670:54	29.13	n/a	27.68	21.3
27	24/05/06	15:09	21/06/06	14:04	670:55	26.08	33.93	25.96	21.5
28	24/05/06	15:10	21/06/06	14:10	671:00	33.93	28.37	33.45	23.9
29	24/05/06	15:10	21/06/06	14:08	670:58	38.1	28.89	30.79	24.4
30	24/05/06	15:13	21/06/06	14:13	671:00	31.39	29.88	18.16	23.0
Broxbourne site	31/05/06	10:30	27/06/06	11:30	649:00	27.08	23.49	26.08	19.2

Table A4.2: Period 2.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NO_2 raw (ppb) Tube 1	NO_2 raw (ppb) Tube 2	NO_2 raw (ppb) Tube 3	NO_2 bias adjusted (ppb) period average
1	21/06/06	14:35	19/07/06	13:24	670:49	111.27	124.95	130.68	91.7
2	21/06/06	14:40	19/07/06	13:26	670:46	130.09	115.14	120.44	91.4
3	21/06/06	15:20	19/07/06	13:28	670:08	75.00	67.61	77.72	55.1
4	21/06/06	15:17	19/07/06	13:30	670:13	72.88	79.82	78.61	57.8
5	21/06/06	15:15	19/07/06	14:05	670:50	51.72	55.94	43.1	37.7
6	21/06/06	14:45	19/07/06	13:33	670:48	75.23	72.82	69.05	54.3
7	21/06/06	14:47	19/07/06	13:36	670:49	74.94	66.94	66.79	52.2
8	21/06/06	14:53	19/07/06	13:48	670:55	46.83	55.2	43.69	36.4
9	21/06/06	15:00	19/07/06	13:41	670:41	34.61	35.33	33.94	26.0
10	21/06/06	15:10	19/07/06	13:58	670:48	27.85	26.28	18.14	20.3
11	21/06/06	14:50	19/07/06	13:38	670:48	70.71	65.43	75.83	53.0
12	21/06/06	14:56	19/07/06	13:43	670:47	43.64	44.55	46.36	33.6
13	21/06/06	15:05	19/07/06	13:52	670:47	35.2	36.11	36.29	26.9
14	21/06/06	15:08	19/07/06	13:56	670:48	33.33	39.84	33.94	26.8
15	21/06/06	15:07	19/07/06	13:54	670:47	37.07	39.97	34.24	27.8
16	21/06/06	13:30	19/07/06	12:20	670:50	59.73	55.63	61.06	44.1
17	21/06/06	13:33	19/07/06	12:22	670:49	55.76	61.36	61.66	44.7
18	21/06/06	13:55	19/07/06	12:55	671:00	57.73	58.75	61.95	44.6
19	21/06/06	14:17	19/07/06	12:51	670:34	69.07	67.11	68.02	51.1
20	21/06/06	14:15	19/07/06	12:49	670:34	58.25	62.74	32.74	45.4
21	21/06/06	13:38	19/07/06	12:07	670:29	31.25	28.53	29.46	22.3
22	21/06/06	13:41	19/07/06	12:11	670:30	20.29	15.26	19.06	13.7
23	21/06/06	13:46	19/07/06	12:15	670:29	30.58	31.12	28.65	22.6
24	21/06/06	13:59	19/07/06	12:36	670:37	28.85	32.62	32.26	23.4
25	21/06/06	13:55	19/07/06	12:33	670:38	32.62	33.4	33.04	24.8
26	21/06/06	14:02	19/07/06	12:28	670:26	27.2	30.52	30.34	22.0
27	21/06/06	14:04	19/07/06	12:31	670:27	29.82	29.31	27.53	21.7
28	21/06/06	14:10	19/07/06	12:43	670:33	37.21	38.53	38.17	28.5
29	21/06/06	14:08	19/07/06	12:40	670:32	35.46	31.6	32.26	24.8
30	21/06/06	14:13	19/07/06	12:46	670:33	33.95	31.12	35.16	25.1
Broxbourne site	27/06/06	11:30	01/08/06	11:30	840:00	33.07	32.06	32.64	24.4

Table A4.3: Period 3.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NO_2 raw (ppb) Tube 1	NO_2 raw (ppb) Tube 2	NO_2 raw (ppb) Tube 3	NO_2 bias adjusted (ppb) period average
1	19/07/06	13:24	16/08/06	11:49	670:25	203.46	139.81	119.83	115.8
2	19/07/06	13:26	16/08/06	11:51	670:25	109.33	125.8	124.6	89.9
3	19/07/06	13:28	16/08/06	12:16	670:48	73.56	73.27	75.05	55.5
4	19/07/06	13:30	16/08/06	12:18	670:48	76.54	79.52	76.54	58.2
5	19/07/06	14:05	16/08/06	12:20	670:15	56.08	46.6	45.88	37.1
6	19/07/06	13:33	16/08/06	11:54	670:21	68.84	68.99	74.81	53.2
7	19/07/06	13:36	16/08/06	11:55	670:19	51.89	57.75	63.33	43.2
8	19/07/06	13:48	16/08/06	11:58	670:10	46.66	33.59	43.92	31.0
9	19/07/06	13:41	16/08/06	12:10	670:29	32.39	34.95	33.59	25.2
10	19/07/06	13:58	16/08/06	12:06	670:08	9.91	22.94	30.19	19.9
11	19/07/06	13:38	16/08/06	11:57	670:19	62.43	68.1	59.36	47.5
12	19/07/06	13:43	16/08/06	12:14	670:31	47.65	44.07	43.36	33.8
13	19/07/06	13:52	16/08/06	12:01	670:09	73.27	38.37	41.17	29.8
14	19/07/06	13:56	16/08/06	12:04	670:08	32.27	35.92	37.47	26.4
15	19/07/06	13:54	16/08/06	12:03	670:09	35.56	38.79	37.47	28.0
16	19/07/06	12:20	16/08/06	10:55	670:35	56.9	52.27	54.75	41.0
17	19/07/06	12:22	16/08/06	10:56	670:34	56.31	58.44	52.56	41.8
18	19/07/06	12:55	16/08/06	11:17	670:22	54.88	54.4	54.04	40.8
19	19/07/06	12:51	16/08/06	11:15	670:24	63.32	32.15	55.14	44.4
20	19/07/06	12:49	16/08/06	11:13	670:24	56.2	58.58	54.52	42.3
21	19/07/06	12:07	16/08/06	10:52	670:45	24.57	19.45	28.97	18.2
22	19/07/06	12:11	16/08/06	10:49	670:38	23.49	22.67	21.05	16.8
23	19/07/06	12:15	16/08/06	10:54	670:39	23.77	21.56	23.23	17.1
24	19/07/06	12:36	16/08/06	11:02	670:26	28.81	12.88	29.46	21.9
25	19/07/06	12:33	16/08/06	11:01	670:28	31.06	24.75	26.87	20.7
26	19/07/06	12:28	16/08/06	10:57	670:29	24.75	23.91	24.45	18.3
27	19/07/06	12:31	16/08/06	10:59	670:28	23.83	25.47	26.99	19.1
28	19/07/06	12:43	16/08/06	11:07	670:24	32.44	29.65	31.14	23.3
29	19/07/06	12:40	16/08/06	11:05	670:25	29.44	27.84	28.51	21.4
30	19/07/06	12:46	16/08/06	11:10	670:24	25.32	28.04	20.82	18.5
Broxbourne site	01/08/06	11:30	29/08/06	14:30	675:00	20.33	20.18	20.39	15.2

Annex 5: Ogawa results, Bell Common Tunnel

Table A5.1: Period 1.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	24/05/06	12:40	07/06/06	13:10	336:30	136.2	130	7	NOx sample pad turned white
2	24/05/06	12:42	07/06/06	13:10	336:28	120	128	-8	NOx sample pad turned white
3	24/05/06	14:45	07/06/06	13:23	334:38	162	93	70	NOx sample pad turned white
4	24/05/06	12:50	07/06/06	13:28	336:38	n/a	52	n/a	No NOx sample
5	24/05/06	12:52	07/06/06	13:30	336:38	128	65	63	
6	24/05/06	13:05	07/06/06	13:11	336:06	131	78	53	NOx sample pad turned white
7	24/05/06	13:10	07/06/06	13:11	336:01	56	99	-44	NOx sample pad turned white
8	24/05/06	13:12	07/06/06	13:13	336:01	172	50	123	
9	24/05/06	13:25	07/06/06	13:15	335:50	190	43	147	
10	24/05/06	13:25	07/06/06	13:16	335:51	190	41	150	
11	24/05/06	13:30	07/06/06	13:21	335:51	131	75	55	NOx sample pad turned white
12	24/05/06	13:46	07/06/06	13:20	335:34	154	54	101	
13	24/05/06	13:50	07/06/06	13:19	335:29	190	48	142	
14	24/05/06	13:50	07/06/06	13:16	335:26	190	51	139	
15	24/05/06	13:55	07/06/06	13:18	335:23	176	47	129	
16	24/05/06	14:15	07/06/06	14:15	336:00	187	47	140	
17	24/05/06	14:15	07/06/06	14:16	336:01	168	45	124	
18	24/05/06	14:18	07/06/06	14:21	336:03	196	42	154	
19	24/05/06	14:20	07/06/06	14:40	336:20	180	42	138	
20	24/05/06	14:22	07/06/06	14:35	336:13	155	51	104	
21	24/05/06	14:50	07/06/06	14:17	335:27	106	24	81	
22	24/05/06	14:35	07/06/06	14:17	335:42	75	20	55	
23	24/05/06	14:50	07/06/06	14:18	335:28	97	20	77	
24	24/05/06	15:00	07/06/06	14:18	335:18	75	21	55	
25	24/05/06	15:02	07/06/06	14:26	335:24	87	23	64	
26	24/05/06	15:08	07/06/06	14:23	335:15	78	22	55	
27	24/05/06	15:09	07/06/06	14:25	335:16	113	21	92	
28	24/05/06	15:10	07/06/06	14:21	335:11	87	25	62	
29	24/05/06	15:10	07/06/06	14:20	335:10		22		No NOx sample
30						n/a	n/a	n/a	No Ogawa deployed clip put on upside down
Blank						7	0	7	

Table A5.2: Period 2.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	07/06/06	13:10	21/06/06	14:35	337:25	188.2	170	18	NOx sample pad turned white
2	07/06/06	13:10	21/06/06	14:40	337:30	157	168	-11	NOx sample pad turned white
3	07/06/06	13:23	21/06/06	15:20	337:57	267	123	144	NOx sample pad turned white
4	07/06/06	13:28	21/06/06	15:17	337:49	263	97	166	NOx sample pad turned white
5	07/06/06	13:30	21/06/06	15:15	337:45	285	81	204	NOx sample pad turned white
6	07/06/06	13:11	21/06/06	14:45	337:34	286	116	170	NOx sample pad turned white
7	07/06/06	13:11	21/06/06	14:47	337:36	318	132	186	NOx sample pad turned white
8	07/06/06	13:13	21/06/06	14:53	337:40	260	63	197	
9	07/06/06	13:15	21/06/06	15:00	337:45	122	42	81	
10	07/06/06	13:16	21/06/06	15:10	337:54	114	40	74	
11	07/06/06	13:21	21/06/06	14:50	337:29	178	110	67	NOx sample pad turned white
12	07/06/06	13:20	21/06/06	14:56	337:36	266	70	196	
13	07/06/06	13:19	21/06/06	15:05	337:46	160	49	111	
14	07/06/06	13:16	21/06/06	15:08	337:52	168	45	123	
15	07/06/06	13:18	21/06/06	15:07	337:49	177	47	129	
16	07/06/06	14:15	21/06/06	13:30	335:15	257	68	189	
17	07/06/06	14:16	21/06/06	13:33	335:17	272	63	209	
18	07/06/06	14:21	21/06/06	13:55	335:34	277	70	207	
19	07/06/06	14:40	21/06/06	14:17	335:37	287	73	215	NOx sample pad turned white
20	07/06/06		21/06/06			n/a	n/a	n/a	No sampler deployed
21	07/06/06	14:17	21/06/06	13:38	335:21	131	40	91	
22	07/06/06	14:17	21/06/06	13:41	335:24	90	34	56	
23	07/06/06	14:18	21/06/06	13:46	335:28	123	40	83	
24	07/06/06	14:18	21/06/06	13:59	335:33	115	42	73	
25	07/06/06	14:26	21/06/06	13:55	335:32	121	43	78	
26	07/06/06	14:23	21/06/06	14:02	335:37	120	39	81	
27	07/06/06	14:25	21/06/06	14:04	350:04	108	41	67	
28	07/06/06		21/06/06			n/a	n/a	n/a	No sampler deployed
29	07/06/06	14:20	21/06/06	14:08	335:44	134	45	88	
30	07/06/06	14:24	21/06/06	14:13	350:13	146	45	101	
Blank						2	1	1	

Table A5.3: Period 3.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	21/06/06	14:35	05/07/06	14:42	336:07	73.6	114	-41	NOx sample pad turned white
2	21/06/06	14:40	05/07/06	14:44	336:04	78	123	-45	NOx sample pad turned white
3	21/06/06	15:20	05/07/06	14:46	335:26	93	103	-10	NOx sample pad turned white
4	21/06/06	15:17	05/07/06	14:49	335:32	93	84	10	NOx sample pad turned white
5	21/06/06	15:15	05/07/06	15:18	336:03	96	78	18	
6	21/06/06	14:45	05/07/06	14:51	336:06	116	82	34	NOx sample pad turned white
7	21/06/06	14:47	05/07/06	14:52	336:05	113	84	29	NOx sample pad turned white
8	21/06/06	14:53	05/07/06	14:55	336:02	125	57	68	
9	21/06/06	15:00	05/07/06	15:07	336:07	126	44	82	
10	21/06/06	15:10	05/07/06	15:05	335:55	125	36	89	
11	21/06/06	14:50	05/07/06	15:14	336:24	92	92	0	NOx sample pad turned white
12	21/06/06	14:56	05/07/06	15:12	336:16	104	64	40	
13	21/06/06	15:05	05/07/06	14:57	335:52	102	49	53	
14	21/06/06	15:08	05/07/06	15:02	335:54	101	47	54	
15	21/06/06	15:07	05/07/06	14:59	335:52	111	49	62	
16	21/06/06	13:30	05/07/06	15:47	338:17	121	52	69	
17	21/06/06	13:33	05/07/06	15:48	338:15	95	55	40	
18	21/06/06	13:55	05/07/06	16:20	338:25	103	61	42	
19	21/06/06	14:17	05/07/06	16:20	338:03	90	63	28	
20	21/06/06	14:15	05/07/06	16:15	338:00	108	70	38	
21	21/06/06	13:38	05/07/06	15:50	338:12	91	33	58	
22	21/06/06	13:41	05/07/06	15:52	338:11	57	25	33	
23	21/06/06	13:46	05/07/06	15:56	338:10	98	32	66	
24	21/06/06	13:59	05/07/06	16:06	338:07	100	38	62	
25	21/06/06	13:55	05/07/06	16:04	338:09	108	37	72	
26	21/06/06	14:02	05/07/06	16:00	337:58	92	32	59	
27	21/06/06	14:04	05/07/06	16:02	337:58	n/a	32	n/a	NOx filter pad lost in lab
28	21/06/06	14:10	05/07/06	16:08	337:58	110	44	66	
29	21/06/06	14:08	05/07/06	16:12	338:04	106	37	68	
30	21/06/06	14:13	05/07/06	16:15	338:02	128	39	89	
Blank						5	1	4	

Table A5.4: Period 4.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	05/07/06	14:42	19/07/06	13:24	334:42	382	150	231	NOx sample pad turned white
2	05/07/06	14:44	19/07/06	13:26	334:42	365	145	220	NOx sample pad turned white
3	05/07/06	14:46	19/07/06	13:28	334:42	384	118	266	NOx sample pad turned white
4	05/07/06	14:49	19/07/06	13:30	334:41	389	84	305	NOx sample pad turned white
5	05/07/06	15:18	19/07/06	14:05	334:47	367	61	306	
6	05/07/06	14:51	19/07/06	13:33	334:42	389	95	294	NOx sample pad turned white
7	05/07/06	14:52	19/07/06	13:36	334:44	404	84	320	NOx sample pad turned white
8	05/07/06	14:55	19/07/06	13:48	334:53	287	51	236	
9	05/07/06	15:07	19/07/06	13:41	334:34	157	39	118	
10	05/07/06	15:05	19/07/06	13:58	334:53	146	36	110	
11	05/07/06	15:14	19/07/06	13:38	334:24	372	101	271	NOx sample pad turned white
12	05/07/06	15:12	19/07/06	13:43	334:31	326	59	267	
13	05/07/06	14:57	19/07/06	13:52	334:55	216	42	174	
14	05/07/06	15:02	19/07/06	13:56	334:54	205	44	161	
15	05/07/06	14:59	19/07/06	13:54	334:55	218	45	173	
16	05/07/06	15:47	19/07/06	12:20	332:33	289	63	227	
17	05/07/06	15:48	19/07/06	12:22	332:34	298	59	239	
18	05/07/06	16:20	19/07/06	12:55	332:35	295	65	229	
19	05/07/06	16:20	19/07/06	12:51	332:31	295	62	233	
20	05/07/06	16:15	19/07/06	12:49	332:34	310	62	247	
21	05/07/06	15:50	19/07/06	12:07	332:17	33	145	-113	
22	05/07/06	15:52	19/07/06	12:11	332:19	109	35	74	
23	05/07/06	15:56	19/07/06	12:15	332:19	117	20	97	NOx sample pad turned white
24	05/07/06	16:06	19/07/06	12:36	332:30	118	38	80	
25	05/07/06	16:04	19/07/06	12:33	332:29	126	38	88	
26	05/07/06	16:00	19/07/06	12:28	332:28	128	36	92	
27	05/07/06	16:02	19/07/06	12:31	332:29	108	34	74	
28	05/07/06	16:08	19/07/06	12:43	332:35	168	46	122	
29	05/07/06	16:12	19/07/06	12:40	332:28	123	39	84	
30	05/07/06	16:15	19/07/06	12:46	332:31	124	38	86	
Blank						3	0	3	

Table A5.5: Period 5.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	19/07/06	13:24	02/08/06	11:49	334:25	482	134	348	NOx sample pad turned white
2	19/07/06	13:26	02/08/06	11:50	334:24	448	145	303	NOx sample pad turned white
3	19/07/06	13:28	02/08/06	12:10	334:42	451	97	354	NOx sample pad turned white
4	19/07/06	13:30	02/08/06	12:27	334:57	436	73	363	
5	19/07/06	14:05	02/08/06	12:31	334:26	348	60	288	
6	19/07/06	13:33	02/08/06	11:53	334:20	466	90	376	NOx sample pad turned white
7	19/07/06	13:36	02/08/06	11:57	334:21	353	80	273	NOx sample pad turned white
8	19/07/06	13:48	02/08/06	12:04	334:16	248	49	199	
9	19/07/06	13:41	02/08/06	12:16	334:35	111	34	78	
10	19/07/06	13:58	02/08/06	12:20	334:22	81	28	53	
11	19/07/06	13:38	02/08/06	12:08	334:30	451	86	365	NOx sample pad turned white
12	19/07/06	13:43	02/08/06	12:06	334:23	279	52	226	
13	19/07/06	13:52	02/08/06	12:13	334:21	153	37	116	
14	19/07/06	13:56	02/08/06	12:17	334:21	146	36	110	
15	19/07/06	13:54	02/08/06	12:24	334:30	153	36	118	
16	19/07/06	12:20	02/08/06	12:53	336:33	309	60	249	
17	19/07/06	12:22	02/08/06	12:56	336:34	301	62	239	
18	19/07/06	12:55	02/08/06	13:10	336:15	335	68	267	
19	19/07/06	12:51	02/08/06	13:37	336:46	344	70	274	
20	19/07/06	12:49	02/08/06	12:34	335:45	323	64	258	
21	19/07/06	12:07	02/08/06	12:58	336:51	184	44	140	
22	19/07/06	12:11	02/08/06	13:01	336:50	128	36	93	
23	19/07/06	12:15	02/08/06	13:07	336:52	161	40	121	
24	19/07/06	12:36	02/08/06	13:22	336:46	138	45	93	
25	19/07/06	12:33	02/08/06	13:15	336:42	157	44	113	
26	19/07/06	12:28	02/08/06	13:11	336:43	156	44	112	
27	19/07/06	12:31	02/08/06	13:13	336:42	132	42	90	
28	19/07/06	12:43	02/08/06	13:25	336:42	216	54	162	
29	19/07/06	12:40	02/08/06	13:28	336:48	159	45	115	
30	19/07/06	12:46	02/08/06	13:31	336:45	177	49	129	
Blank						2	0	2	

Table A5.6: Period 6.

Site	Date on	Time on	Date off	Time off	Exposure time (hr:min)	NOx (ppb)	NO_2 (ppb)	NO (ppb)	Comments
1	02/08/06	11:49	16/08/06	11:49	336:00	467	120	347	NOx sample pad turned white
2	02/08/06	11:50	16/08/06	11:51	336:01	453	134	319	NOx sample pad turned white
3	02/08/06	12:10	16/08/06	12:16	336:06	444	90	354	NOx sample pad turned white
4	02/08/06	12:27	16/08/06	12:18	335:51	414	76	338	
5	02/08/06	12:31	16/08/06	12:20	335:49	446	67	379	
6	02/08/06	11:53	16/08/06	11:54	336:01	444	71	373	
7	02/08/06	11:57	16/08/06	11:55	335:58	428	61	367	
8	02/08/06	12:04	16/08/06	11:58	335:54	317	47	270	
9	02/08/06	12:16	16/08/06	12:10	335:54	268	45	223	
10	02/08/06	12:20	16/08/06	12:06	335:46	255	43	212	
11	02/08/06	12:08	16/08/06	11:57	335:49	468	72	396	
12	02/08/06	12:06	16/08/06	12:14	336:08	374	54	320	
13	02/08/06	12:13	16/08/06	12:01	335:48	340	55	285	
14	02/08/06	12:17	16/08/06	12:04	335:47	361	53	308	
15	02/08/06	12:24	16/08/06	12:03	335:39	334	53	282	
16	02/08/06	12:53	16/08/06	10:55	334:02	228	35	193	
17	02/08/06	12:56	16/08/06	10:56	334:00	221	34	186	
18	02/08/06	13:10	16/08/06	11:17	334:07	227	34	192	
19	02/08/06	13:37	16/08/06	11:15	333:38	238	38	200	
20	02/08/06	12:34	16/08/06	11:13	334:39	296	44	252	
21	02/08/06	12:58	16/08/06	10:52	333:54	72	17	55	
22	02/08/06	13:01	16/08/06	10:49	333:48	41	12	29	
23	02/08/06	13:07	16/08/06	10:54	333:47	60	14	46	
24	02/08/06	13:22	16/08/06	11:02	333:40	50	15	36	
25	02/08/06	13:15	16/08/06	11:01	333:46	53	15	38	
26	02/08/06	13:11	16/08/06	10:57	333:46	52	15	38	
27	02/08/06	13:13	16/08/06	10:59	333:46	47	14	33	
28	02/08/06	13:25	16/08/06	11:07	333:42	86	19	67	
29	02/08/06	13:28	16/08/06	11:05	333:37	63	16	47	
30	02/08/06	13:31	16/08/06	11:10	333:39	72	17	55	
Blank						4	0	4	

Annex 6: GRAL model outputs for the Southwick Tunnel, stiffness 60

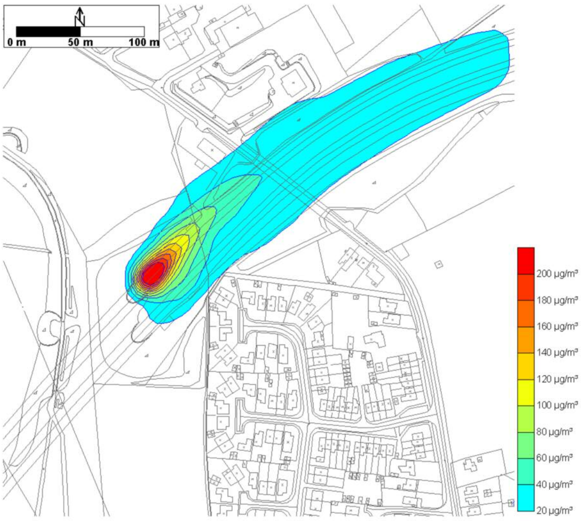

Figure A6.1: CO 3-month mean value.

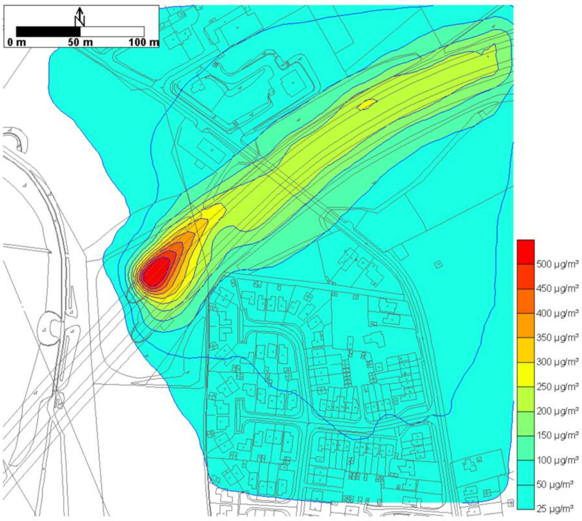

Figure A6.2: CO daily mean value.

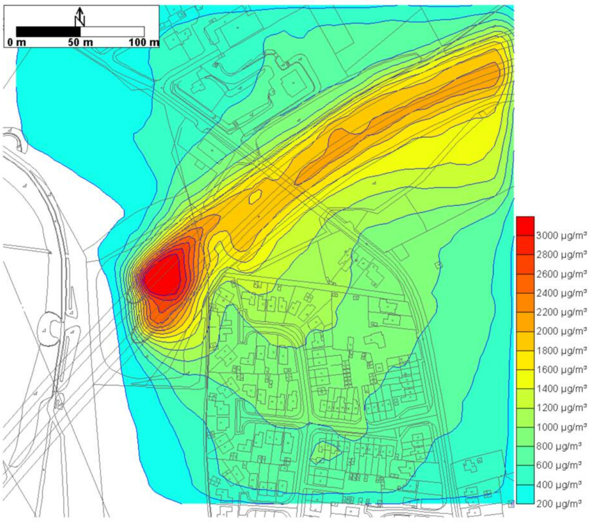

Figure A6.3: CO hourly mean value.

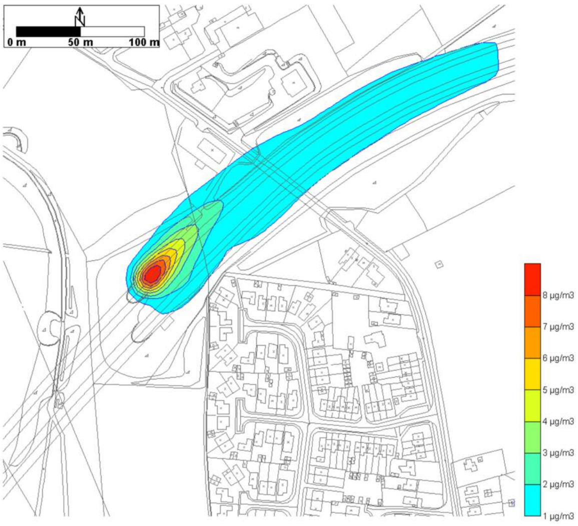

Figure A6.4: PM_{10} 3-month mean value.

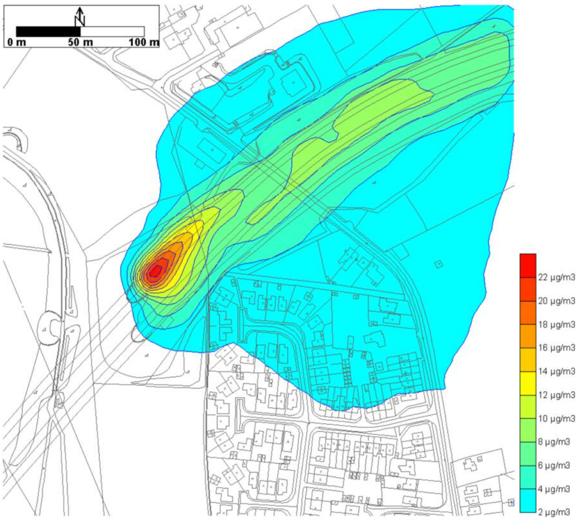

Figure A6.5: PM_{10} daily mean value.

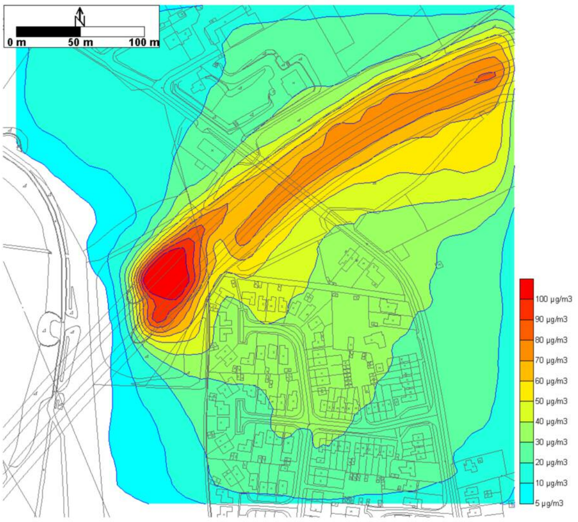

Figure A6.6: PM_{10} hourly mean value.

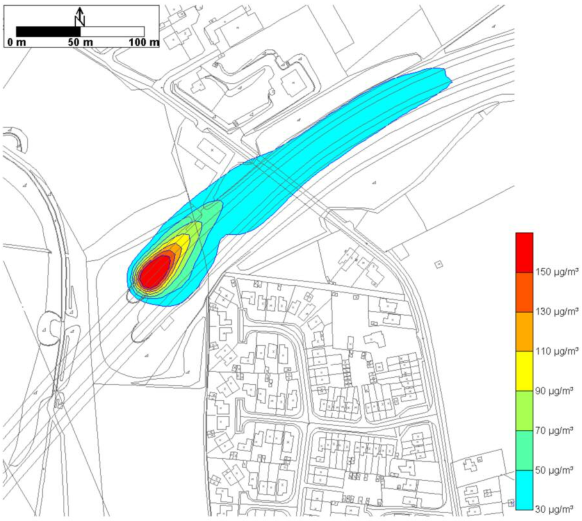

Figure A6.7: NO_X 3-month mean value.

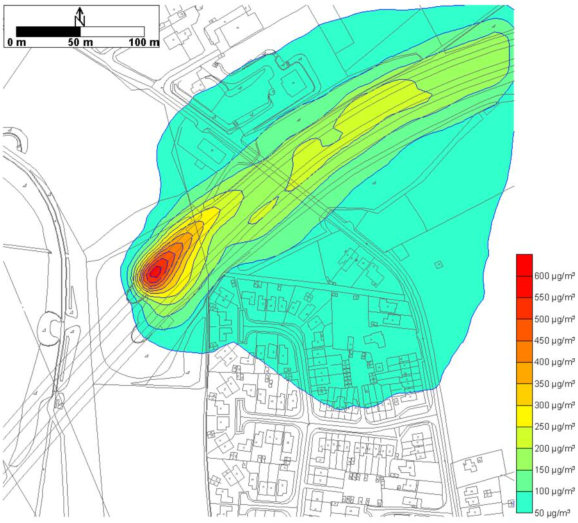

Figure A6.8: NO_X daily mean value.

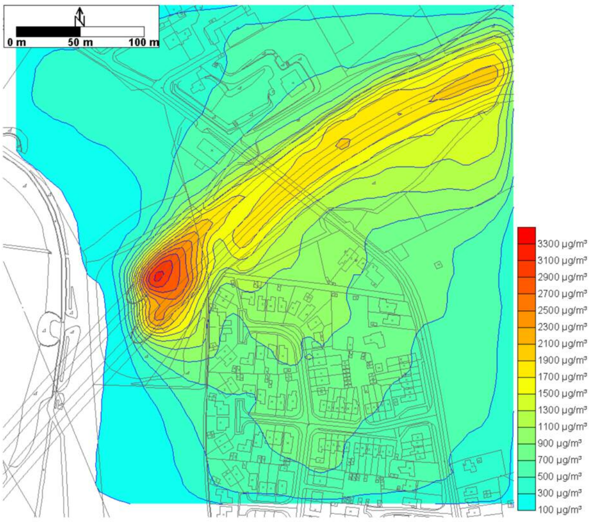

Figure A6.9: NO_X hourly mean value.