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PRIMARY NO₂ EMISSIONS FROM ROAD VEHICLES IN THE HATFIELD AND BELL COMMON TUNNELS

Version: Final

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<table>
<thead>
<tr>
<th>Approvals</th>
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<tbody>
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<td>I McCrae</td>
</tr>
</tbody>
</table>
Contents

Executive summary

1 Introduction
   1.1 Overview
   1.2 Theory
      1.2.1 Calculation of emission factors
      1.2.2 NO₂ formation in the atmosphere
      1.2.3 Reactions in the tunnel environment
      1.2.4 Rates of reaction

2 Experimental method
   2.1 Tunnel descriptions
      2.1.1 Hatfield tunnel
      2.1.2 Bell Common tunnel
   2.2 Study periods
   2.3 Measurement of traffic parameters
      2.3.1 Hatfield tunnel
      2.3.2 Bell Common tunnel
   2.4 Measurement of meteorological parameters
      2.4.1 Hatfield tunnel
      2.4.2 Bell Common tunnel
   2.5 Air pollution measurements
      2.5.1 Hatfield tunnel
      2.5.2 Bell Common tunnel

3 Results of measurements
   3.1 Traffic characteristics
      3.1.1 Hatfield tunnel
      3.1.2 Bell common tunnel
   3.2 Meteorological parameters
      3.2.1 Hatfield tunnel
      3.2.2 Bell Common tunnel
   3.3 Continuous pollution measurements
      3.3.1 Hatfield tunnel
      3.3.2 Bell Common tunnel
   3.4 Diffusion tube measurements
      3.4.1 Hatfield tunnel
      3.4.2 Bell Common tunnel

4 Determination of emission factors
   4.1 Calculation approach
   4.2 Selection of valid data
   4.3 Fleet-weighted NOₓ and NO₂ emission factors
      4.3.1 Hatfield tunnel
      4.3.2 Bell Common tunnel
   4.4 Multiple linear regression analysis
      4.4.1 Hatfield tunnel
      4.4.2 Bell Common tunnel
   4.5 NO₂/NOₓ proportions
   4.6 Comparisons with other data sources
      4.6.1 Comparison with UK emission factors
      4.6.2 Gradient effect
5 Summary and discussion
  5.1 Measurements
    5.1.1 Overview
    5.1.2 Traffic characteristics
    5.1.3 Meteorological parameters
    5.1.4 Air pollution measurements
  5.2 Fleet-weighted emission factors
  5.3 Multiple linear regression analysis
  5.4 Comparison with other data sources

6 Conclusions and recommendations

7 Acknowledgements

8 References

Appendix A: Abbreviations and glossary of terms
Executive summary

This Report describes the results of a research project dealing with emissions of nitrogen dioxide (NO₂) from road vehicles, based upon air pollution measurements conducted in the Hatfield and Bell Common tunnels. In some areas of the UK the concentrations of NO₂ regularly exceed air quality standards, and road vehicles are usually an important source. Road vehicle exhaust contains both NO₂ and nitrogen monoxide (NO). Collectively, these two gases are termed oxides of nitrogen (NOₓ). Most of the NOₓ in vehicle exhaust is usually present as NO, whereas most of the NO₂ in the atmosphere is formed by the reaction of NO with ozone (O₃), and in ambient roadside air NO₂ levels are generally limited by the local concentration of O₃ rather than the emission of NO from vehicles. The NO₂ which is emitted directly from vehicle exhaust is commonly referred to as ‘primary NO₂’.

No commonly-used emission models provide specific emission factors for NO₂. It has generally been assumed for air quality modelling purposes that 5% of the NOₓ from vehicle exhaust is emitted as NO₂. However, laboratory studies and analyses of ambient NO₂ concentrations in urban areas in the UK have indicated that a larger proportion of NO₂ must be emitted directly from the exhaust. A better understanding of the NO₂:NOₓ proportion under different operational conditions would help to improve the accuracy of both emission and air pollution dispersion models, and controlling primary NO₂ would help to reduce ambient NO₂ concentrations.

Due to the limited dispersion and dilution conditions in a tunnel environment, pollutant concentrations tend to be higher than in normal ambient air. In addition, external influences are reduced – these being particularly important in the case of atmospheric NO₂ formation. Consequently, tunnel measurements have been used to derive the emission factors for gaseous pollutants in a number of studies, and such an approach was applied in this work to determine primary NO₂ emissions.

Measurements were conducted in the Hatfield and Bell Common tunnels. In each tunnel, atmospheric concentrations of NO, NO₂ and O₃ were measured continuously at three main sites: near to the tunnel entrance, near to the mid point, and near to the exit. In order to provide greater spatial resolution of NO₂ concentrations, measurements were also conducted inside the tunnel using passive diffusion tubes. Traffic parameters and meteorological parameters were also recorded continuously.

Fleet-weighted NOₓ emission factors were calculated for each hour, based upon the mean concentrations and total traffic flow. The proportion of NOₓ emitted as primary NO₂ (and hence the NO₂ emission factor) was then determined iteratively using three different models, each involving a different set of assumptions regarding the formation of NO₂. In the case of the first model, it was assumed that ozone did not react with NO, and therefore the ozone concentration in the tunnel remained at the level at the tunnel entrance. This led to an over-prediction of the ozone concentration at the tunnel mid-point and tunnel exit. In the second model, the reaction of ozone with NO was taken into account. The effect of this was that the NO₂:NOₓ proportion needed to be lower in this model than in the first model, in order to offset the extra NO₂ produced by the NO-NO-O₂ reaction. The third model included the NO-NO-O₂ reaction, but this had little additional effect on the predicted concentration profiles. This third model was used in the subsequent analyses. There were no strong correlations between NOₓ or NO₂ emissions and meteorological parameters. There was also no strong correlation with traffic speed. However, the average speed did not differ greatly between the study phases, and so all the results can effectively be considered to be for a single type of vehicle operating condition.

A multiple linear regression approach was used to estimate average NOₓ and NO₂ emission factors for different vehicle categories in each tunnel, based upon the overall hourly average emission factors for the traffic and the proportions of vehicles in different categories. Rather different emission factors were obtained for the different vehicle categories in the two tunnels. In the Hatfield tunnel the NOₓ emission factors for rigid HGVs (5.37 g vehicle⁻¹ km⁻¹) and articulated HGVs (3.37 g vehicle⁻¹ km⁻¹) were much higher than those for cars/small vans (0.27 g vehicle⁻¹ km⁻¹) and large vans (1.17 g vehicle⁻¹ km⁻¹). NO₂ emissions in the Bell Common tunnel were dominated by heavy-duty vehicles, for which the overall average emission factor (17.1 g vehicle⁻¹ km⁻¹) was much higher than those obtained in the Hatfield tunnel.
The results for NO\textsubscript{x} from the two tunnel studies were compared with emission estimates obtained using the emission factors which are currently used in the compilation of the UK National Atmospheric Emissions Inventory. The emission factor for cars derived from the Hatfield tunnel measurements was slightly lower than that derived from the UK emission factors. The relative proportions of petrol and diesel cars in the fleet may have been important in this respect. For the calculations using the UK emission factors, it was assumed that 25\% of all cars had diesel engines (diesel cars have higher NO\textsubscript{x} emissions than petrol cars), but the actual proportion in the tunnel was not known, and may have been lower. The emission factors for LGVs from the Hatfield tunnel measurements were higher than the UK emission factor.

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\textsuperscript{-1} km\textsuperscript{-1}) compared with the Hatfield tunnel (around 4-5 g vehicle\textsuperscript{-1} km\textsuperscript{-1}) and the UK emission factors. In addition, the NO\textsubscript{2}/NO\textsubscript{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\textsubscript{x} emission factor at +2\% road gradient and that at level grade was approximately 2. When the Hatfield tunnel NO\textsubscript{x} emission factors for HGVs were multiplied by a factor of two, then this gave a (weighted) value around 8.3 g vehicle\textsuperscript{-1} km\textsuperscript{-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.

The largest NO\textsubscript{2}/NO\textsubscript{x} proportions (16-25\%) were obtained for light-duty vehicles in the Hatfield tunnel, which was a rather surprising result given that a substantial proportion of the light-duty vehicle fleet is composed of vehicles with petrol engines, which have previously been found to have a relatively low NO\textsubscript{2}/NO\textsubscript{x} proportion. The NO\textsubscript{2}/NO\textsubscript{x} proportions for HGVs were 9-11\% in the Hatfield tunnel and 6\% in the Bell Common tunnel. These NO\textsubscript{2} proportions were higher than the 5\% commonly assumed in air pollution prediction models but lower than the proportions recently reported in the literature for roadside sites in the UK. This may be due, in part, to the restriction on atmospheric NO\textsubscript{2} formation in tunnels resulting from the depletion of ozone.

It was concluded that the NO\textsubscript{2} generated in the second half of the Hatfield tunnel is probably all primary in origin, with little or no contribution from atmospheric reactions. In longer tunnels, where NO is present in higher concentrations and the air has a longer residence time, there may be a significant NO\textsubscript{2} contribution from the reactions of NO with oxygen or organic peroxy radicals. Although NO concentrations in the Bell Common tunnel were high, the tunnel is relatively short and, again, the contribution from these reactions was negligible. Such phenomena ought to be investigated in longer tunnels, and consideration ought to be given to the measurement of different hydrocarbon species.

Diffusion tube measurements indicated that the air in the Hatfield tunnel is not well mixed, with higher NO\textsubscript{2} concentrations being observed near to the outside lane of the carriageway. The implication of this is that the absolute levels of the NO\textsubscript{x} and NO\textsubscript{2} emission factors from tunnel studies may be slightly underestimated (by up to 10\%). However, given that the data are from only one tunnel and are rather limited, it is difficult to justify the application of a general correction for this underestimate, and no adjustments were made to the emission factors in this study. The differences in the absolute emission factors should also have little effect on the estimated proportion of NO\textsubscript{x} emitted as NO\textsubscript{2}.

The results of the study ought to be exploited via inclusion in air pollution prediction models, which should then be tested for a range of locations and traffic conditions. This would require the collation and evaluation of existing data on NO\textsubscript{2} emissions, including the results of this study. Consideration should also be given to the relevance of these findings in the context of in-tunnel exposure limits and tunnel ventilation design.
1 Introduction

1.1 Overview

This Report describes the results of a research project dealing with emissions of nitrogen dioxide (NO₂) from road vehicles, based upon air pollution measurements conducted in the Hatfield and Bell Common tunnels. The project was commissioned by the Transport Research Foundation.

Nitrogen dioxide is one of the air pollutants which are currently causing most concern in the UK. In some areas, the concentrations of NO₂ regularly exceed air quality standards, and road vehicles are usually an important source. Road vehicle exhaust contains both NO₂ and nitrogen monoxide (NO). Collectively, these two gases are termed oxides of nitrogen (NOₓ). Most of the NOₓ in vehicle exhaust is usually present as NO, whereas most of the NO₂ in the atmosphere is formed by the reaction of NO with ozone (O₃), and in ambient roadside air NO₂ levels are generally limited by the local concentration of O₃ rather than the emission of NO from vehicles. The NO₂ which is emitted directly from vehicle exhaust is commonly referred to as ‘primary NO₂’.

As NOₓ emissions are regulated at vehicle type approval, most emissions data for road vehicles are stated in this form. Even though NO₂ is an important pollutant there is surprisingly little information on primary emissions. It is generally assumed for air quality modelling purposes that 5% of the NOₓ from vehicle exhaust is emitted as NO₂ (e.g. PORG, 1997). However, laboratory work conducted by TRL (Latham et al., 2001) has shown that the actual proportion varies according to factors such as the vehicle type, the operating conditions and the measurement method, and can be much higher than 5%. The TRL work also showed that diesel vehicles tend to have higher NO₂/NOₓ proportions than petrol vehicles, and for the former an average NO₂ proportion of 25% was obtained. Using a tunable diode laser remote sensing system to measure NO and NO₂ emissions from vehicles under real-world driving conditions, Jimenez et al. (2000) observed NO₂/NOₓ proportions in the range 5.6 to 10.9 vol%² for a diesel truck operated at approximately 30 km h⁻¹ and under mild acceleration. Kurtenbach et al. (2001) used a DOAS³ system to measure NO and NO₂ in the Wuppertal Kiesberg tunnel in Germany. The NO₂/NOₓ proportions for petrol cars, diesel cars and diesel trucks were <0.2 vol%, 5.9 vol% and 11.0 vol% respectively.

Furthermore, analyses of ambient NO₂ concentrations in urban areas in the UK have indicated that a significant proportion of NO₂ must be emitted directly from the exhaust. Measurements of NO, NO₂ and O₃ from the Marylebone Road kerbside monitoring site in London were used by Jenkin (2004) to estimate primary NO₂ emissions from road vehicles. The results suggested that for diesel-fuelled vehicles the proportion of the NOₓ emission which was primary NO₂ was equal to 0.996v⁻₀.⁶ by volume, where v is the mean vehicle speed in km h⁻¹ (valid range = 30-60 km h⁻¹). This corresponded to approximately 12% of NOₓ emissions when integrated over an average day at Marylebone Road. The results also indicated that primary NO₂ emissions from petrol-fuelled vehicles were much less important, with an upper limit NO₂/NOₓ proportion of less than 3%. Analysis of the data from Marylebone Road and an urban background site in London by Carslaw and Beevers (2004) yielded NO₂/NOₓ proportions for petrol and diesel vehicles of 0.5 vol% and 12.7 vol% respectively. Further analysis of roadside concentrations in London by Carslaw (2005) has shown that between 1997 and 2003 there has been a statistically significant downward trend in NOₓ, but not in NO₂. This was in contrast to equivalent data recorded at background sites which demonstrate a downward trend in both NOₓ and, to a lesser extent, NO₂. This discrepancy suggests that there is a significant source of primary NO₂ in the roadside environment. Calculations using a simple chemical model showed that the NO₂/NOₓ emissions proportion from road traffic increased markedly from a mean of around 5-6 vol% in 1997 to around 17 vol% in 2003. It was suggested that the change in the NO₂/NOₓ proportion could have been a result of the introduction of diesel particulate filters on buses, the increased penetration of diesel vehicles in the passenger car fleet, the increased use of oxidation catalysts on diesel vehicles, and the introduction of new light-duty and heavy-duty engine technologies. In Central London, this is thought to be associated with the

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¹ Otherwise known as nitric oxide.
² Vol% = percentage by volume.
³ DOAS = differential optical absorption spectroscopy.
high proportion of diesel vehicles - such as taxis and buses - operating at low-speeds (Carslaw and Beevers, 2004).

According to AQEG (2004; 2006), it is difficult to provide a firm and unambiguous value for the NO$_2$/NO$_x$ proportion for road vehicle exhaust emissions (not least because it appears to be changing). At present, there is little consensus on the typical emission levels of NO$_2$, and the influences of different factors, and there is a need to obtain a greater understanding of the relative contribution of primary NO$_2$ to ambient roadside concentrations. No commonly-used emission models provide specific emission factors for NO$_2$. A better understanding of the NO$_2$/NO$_x$ proportion under different operational conditions would help to improve the accuracy of both emission and air pollution dispersion models, and controlling primary NO$_2$ would help to reduce ambient NO$_2$ concentrations.

This lack of consensus on the proportion of primary NO$_2$ in vehicle exhaust was, in the past, largely ignored by the air pollution modelling community. This was because the air pollution models were traditionally used to predict the total NO$_x$ concentration, with the subsequent prediction of the NO$_2$ concentration through the use of empirical relationships. However, many current air pollution models include atmospheric chemistry schemes which derive NO$_2$ concentrations from first principles. Such models require the proportion of primary NO$_2$ as input, and thus the research described in this Report is timely.

Due to the limited dispersion and dilution conditions in a tunnel environment, pollutant concentrations tend to be higher than in normal ambient air. In addition, external influences are reduced – these being particularly important in the case of atmospheric NO$_2$ formation. Consequently, tunnel measurements have been used to derive the emission factors for gaseous pollutants in a number of studies, and such an approach was applied in this work to determine primary NO$_2$ emissions.

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| Concentrations of NO, NO$_2$ and NO$_x$ are usually reported in either parts per billion ($1,000,000,000$) or microgrammes per cubic metre of air ($\mu$g m$^{-3}$). The former unit describes the ratio between the total number of molecules of a pollutant and the total number of molecules in a given volume of air, and is independent of temperature or pressure. The mass concentration unit, on the other hand, is dependent upon temperature and pressure, and must be corrected to standard conditions ($293$ K and $101.3$ kPa). Under these standard conditions, the following conversion factors can be applied (AQEG, 2004):

- NO$_2$ 1 ppb = 1.913 $\mu$g m$^{-3}$
- NO 1 ppb = 1.248 $\mu$g m$^{-3}$

When expressing NO$_x$ in $\mu$g m$^{-3}$, it is common practice to assume that all the NO has been oxidised to NO$_2$. This is done by adding the ppb values for NO and NO$_2$, and using the conversion factor for NO$_2$ stated above. The resulting unit is therefore ‘$\mu$g m$^{-3}$ as NO$_2$’, and where reference is made in this Report to NO$_x$ mass concentrations, this approach is used. A similar logic applies to exhaust emission factors for NO$_x$, which are usually stated in g km$^{-1}$ as NO$_2$ (in other words, the mass emitted if it is assumed that all NO is emitted as NO$_2$). Where NO$_2$ is stated as a proportion of NO$_x$, if the units are both volumetric the proportion is stated as vol%. If the units are mass-based, the proportion is stated as mass%. If NO$_x$ is stated ‘as NO$_2$’, then the vol% and mass% values are equal.

The Report also deals with chemical reactions in the atmosphere, for which different units are often used. In this study, concentrations of reactants and products have been calculated in molecules cm$^{-3}$ using the equation:

$$\text{Conc. in molec. cm}^{-3} = \frac{\text{Conc. in } \mu\text{g m}^{-3}}{\frac{L}{Mr \cdot 10^{12}}}$$

Where $L$ = Avogadro’s number ($6.023 \times 10^{23}$ mol$^{-1}$).

$Mr$ = Relative molecular mass:

- NO = 30
- O$_3$ = 48
- NO$_2$ = 46
- O$_2$ = 32

The effect of temperature and pressure also need to be taken into account during this conversion.
1.2 Theory

1.2.1 Calculation of emission factors

Pollutant concentrations increase along the length of a tunnel as the emissions from the traffic accumulate. For a given pollutant \( i \), an average emission factor for the vehicles passing through a tunnel during a time period \( t \) can be derived using Equation (1):

\[
EF_i = \frac{(C_{i,\text{exit}} - C_{i,\text{entrance}}) \cdot v_{\text{air}} \cdot t \cdot A}{L \cdot N}
\]

where:

- \( EF_i \) = average vehicle emission factor for pollutant \( i \) (g vehicle\(^{-1}\) km\(^{-1}\))
- \( C_{i,\text{exit}} \) = concentration of pollutant \( i \) at tunnel exit (g m\(^{-3}\))
- \( C_{i,\text{entrance}} \) = concentration of pollutant \( i \) at tunnel entrance (g m\(^{-3}\))
- \( v_{\text{air}} \) = velocity of the air in the tunnel (m s\(^{-1}\))
- \( t \) = time duration of sampling (s)
- \( A \) = tunnel cross-sectional area (m\(^2\))
- \( L \) = tunnel length (km)
- \( N \) = number of vehicles passing during time \( t \)

Equation 1 has been employed extensively to derive emission factors in various tunnel studies (e.g. Gillies et al., 2001; Staehelin et al., 1997; Weingartner et al., 1997; John et al., 1999), but it has normally been applied to total NO\(_x\) and the formation of NO\(_2\) has not generally been considered separately. In principle, Equation 1 can be used to derive emission factors for both NO\(_x\) and NO\(_2\). However, the total NO\(_2\) concentration at the tunnel exit is due to direct exhaust emissions plus NO\(_2\) which is formed by chemical reactions in the tunnel air. Consequently, if these reactions are not taken into account, the magnitude of the primary exhaust emission is likely to be overestimated. NO\(_2\) formation in the atmosphere is described in the following Sections.

1.2.2 NO\(_2\) formation in the atmosphere

NO\(_2\) is predominantly a secondary pollutant, its major atmospheric source being the oxidation of emitted NO. An understanding of the chemical processes which produce and destroy NO\(_2\) is therefore central to the interpretation of ambient measurements, and to the prediction of how NO\(_2\) concentrations are likely to vary with the implementation of NO\(_x\) emissions controls (AQEG, 2004).

Figure 1 shows the main pathways for the inter-conversion of NO and NO\(_2\) in the atmosphere. Under the majority of atmospheric conditions, and in the presence of O\(_3\), the following reaction between NO and ozone will take place:

\[
\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2
\]

This is the dominant pathway by which NO is converted to NO\(_2\). At polluted locations comparatively close to sources of NO\(_x\), NO is in large excess and it is the availability of O\(_3\) which limits the quantity of NO\(_2\) that can be produced by this reaction. The timescale for consumption of O\(_3\) depends on the concentration of NO. At the high end of the range of hourly-average concentrations generally observed at polluted roadside locations in the UK (around 1 ppm), the time constant\(^4\) for O\(_3\) consumption is around two seconds, with this lifetime increasing at lower levels of NO, and in inverse proportion. At unpolluted locations, when O\(_3\) is present in excess, the timescale for conversion of NO to NO\(_2\) is longer - around 90 seconds at a typical background concentration of 30 ppb O\(_3\). When neither NO nor O\(_3\) is in large excess, the reaction progressively depletes both reagents, and the reaction time constant can become very long (AQEG, 2004).

\(^4\) The time constant, \( \tau \), is the time required for the concentration of a reactant to fall to \( 1/e \) of its initial value.
Figure 1: Schematic representation of the main pathways inter-converting NO and NO$_2$ in the atmosphere (AQEG, 2004).

Under normal ambient daytime conditions the reverse process also occurs – the destruction of NO$_2$ by photolysis to form NO and ozone, as shown in reactions (3) and (4):

\[
\begin{align*}
\text{NO}_2 + \text{sunlight} & \rightarrow \text{NO} + \text{O} \quad (3) \\
\text{O} + \text{O}_2 (+\text{M}) & \rightarrow \text{O}_3 (+\text{M}) \quad (4)
\end{align*}
\]

where \( \text{M} \) is a third body, most commonly nitrogen.

As a result of this inter-conversion by reactions (1) – (3), the behaviour of NO and NO$_2$ is highly coupled under atmospheric conditions, and it is convenient to refer to these species collectively as NO$_x$. Because this coupling also involves O$_3$, however, NO$_2$ and O$_3$ are also often collectively defined as ‘oxidant’ (OX). Consequently, reactions (1) - (3) form a cycle with no net chemistry, which has the overall effect of partitioning NO$_x$ between its component forms of NO and NO$_2$, and OX between its component forms of O$_3$ and NO$_2$, but leaving the total concentrations of both NO$_x$ and OX unchanged (AQEG, 2004). The minimum lifetime of NO$_2$ with respect to photolysis in the boundary layer is of the order of 100 seconds, with a mean daylight lifetime of around 3 minutes. In the wintertime, this is typically a factor of two or three longer. Under conditions when photolysis is sufficiently rapid, NO, NO$_2$ and O$_3$ are potentially in chemical equilibrium, a condition usually referred to as the ‘photostationary state’ (AQEG, 2004). The photostationary state concentrations of the three species are related by the expression \([\text{NO}] \times [\text{O}_3]/[\text{NO}_2] = J_2/k_1\), where \( J_2 \) is the rate coefficient of NO$_2$ photolysis, and \( k_1 \) is the rate coefficient for the reaction of NO with O$_3$.

Elevated levels of OX at urban locations (mainly NO$_2$) may be generated either by having a large local source of oxidant (i.e. high NO$_x$ levels), or by having a large regional source of oxidant in the presence of moderate NO$_x$ levels. The former conditions are most likely to occur in wintertime episodes, when levels of NO$_x$ of around 700 ppb are typically required for the hourly air quality standard of 105 ppb (200 µg m$^{-3}$) to be exceeded for NO$_2$. During summertime, when boundary layer depths are much greater, such levels of NO$_x$ are less common and NO$_2$ exceedences are only likely to occur when there is a large regional input of oxidant.

\footnote{In the atmosphere the boundary layer is the layer of air which is nearest to the ground, and which is affected by heat, moisture or momentum transfer to or from the surface.}
resulting from elevated background $O_3$ levels during photochemical pollution episodes (for example, as described by Jenkin et al., (2002)). As stated earlier, a significant proportion of the local contribution is likely to result from primary emission of NO$_2$.

Other chemical processes which can convert NO to NO$_2$ involve the formation of free radicals which can catalyse the oxidation of emitted hydrocarbons (AQEG, 2004). In the presence of hydrocarbons, hydroperoxy radicals ($HO_2$) and organic peroxy radicals ($RO_2$ - where R is an organic group) are produced. These processes will convert NO to NO$_2$ without the destruction of $O_3$, and are therefore net sources of OX:

\[
NO + HO_2 \rightarrow NO_2 + OH \quad (5)
\]

\[
NO + RO_2 \rightarrow NO_2 + RO \quad (6)
\]

For these cycles to contribute significantly to NO to NO$_2$ conversion (and therefore OX formation) under urban conditions, significant amounts of free radicals (hereafter referred to as ‘HO$x$’) are required to initiate the process. A number of thermochemical and photochemical sources of potential significance have been identified, which involve species emitted concurrently with NO$_x$. The formation of HO$_x$ from the thermal reactions of alkenes with $O_3$ has received particular attention (Paulson and Orlando, 1996; Bey et al., 1997). The thermal reactions of NO$_2$ with some conjugated dienes$^6$ emitted from road transport have also been found to generate significant yields of HO$_x$ radicals (Atkinson et al., 1984; Shi and Harrison, 1997; Jenkin et al., 2003). These reactions are comparatively slow, however, such that they are only likely to contribute under wintertime pollution episode conditions when boundary layer levels of NO$_x$ and VOC are significantly elevated (Harrison et al., 1998). Reaction (5) has a larger rate constant than that for the reaction of NO with ozone, but the concentrations of the organic peroxy radicals ($RO_2$) are generally much lower that that of ozone, and so reaction (2) tends to proceed more quickly. Under polluted conditions, the photolysis of formaldehyde, HCHO (and possibly other carbonyls), and nitrous acid (HONO) have been identified as potentially important sources of HO$_x$ radicals (PORG, 1997; Jenkin and Clemitshaw, 2000). A third-order reaction, involving the oxidation of NO by oxygen, is of minor importance under normal atmospheric conditions:

\[
2NO + O_2 \rightarrow 2NO_2 \quad (7)
\]

However, this reaction is rapid at low temperatures and high NO concentrations, such that it is much more rapid at the elevated levels typical of those close to points of emission (AQEG, 2004). For example, the time for 1% conversion of NO to NO$_2$ by this reaction is around 20 seconds at 100 ppm NO in air, but increases dramatically as NO is diluted. At 1 ppm NO (i.e. the high end of the hourly average values observed at roadside locations) the time for 1% conversion is around 30 minutes. The extent to which this reaction can contribute is therefore strongly influenced by the rate at which NO is diluted following emission. It is probable that only limited NO to NO$_2$ conversion by reaction (7) occurs under typical ambient conditions. However, under wintertime pollution episode conditions, when a shallow inversion layer can lead to a combination of high NO$_x$ levels and stagnant air for periods of a day or more, reaction (7) can potentially make a substantial contribution to OX generation (e.g. QUARG, 1993; Bower et al., 1994), as during the high NO$_2$ concentration episode in London in December 1991 (AQEG, 2004).

1.2.3 Reactions in the tunnel environment

Because of the limited dispersion and dilution conditions in a tunnel environment, pollutant concentrations tend to be higher than in normal ambient air. In addition, external meteorological influences are reduced – these being particularly important in the case of atmospheric NO$_2$ formation. As mentioned earlier, the time constant for depletion of $O_3$ in the presence of high NO concentrations is around two seconds. Inside a road tunnel there is usually a high concentration of NO from vehicle exhaust, and any available oxidant - principally ozone – will therefore be rapidly depleted without causing significant conversion of NO to NO$_2$ (Barrefors, 1996). Once the ozone is removed, NO$_2$ formation via reaction (2) will stop. As there is little natural sunlight inside a road tunnel, the destruction of NO$_2$ via reaction (3) is also limited.

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$^6$ Dienes are hydrocarbons which contain two double carbon-to-carbon bonds. In conjugated organic compounds, atoms are covalently bonded with alternate single and multiple bonds. In conjugated dienes, the two double bonds are therefore separated by one single carbon-to-carbon bond.
Consequently, much of the NO\textsubscript{2} in tunnel air is likely to be primary in origin, and the NO\textsubscript{2}/NO\textsubscript{x} proportion in the tunnel air, particularly near to a tunnel exit, ought to provide a reliable indication of the overall average proportion in vehicle exhaust. However, it has been suggested that reaction (7) could be an important mechanism for NO\textsubscript{2} formation in road tunnels (e.g. Barrefors, 1996; Indrehus and Vassbotn, 2001). The formation rate of NO\textsubscript{2} is as high as 1 ppm h\textsuperscript{-1} at a NO concentration of 5 ppm (Lindqvist \textit{et al.}, 1982). This reaction may be particularly significant in longer tunnels without mechanical ventilation, as NO concentrations are likely to be high (Barrefors, 1996). Therefore, the relative rates of reaction need to be determined in order to avoid an overestimation of the exhaust NO\textsubscript{2}/NO\textsubscript{x} proportion.

Little work appears to have been conducted to assess the relevance of reactions (5) and (6) in tunnel air. However, with the constant movement and replenishment of air inside tunnels it seems unlikely that there would be sufficient time for the oxidants to accumulate in large enough quantities for the rates of the reactions to be significant.

1.2.4 Rates of reaction

\textit{Reaction of nitrogen monoxide with ozone}

For reaction (2), NO + O\textsubscript{3} → NO\textsubscript{2} + O\textsubscript{2}, the rate is given by:

\[
\frac{d[NO_2]}{dt} = k_2[NO][O_3]
\]  

(8)

where:

\( [NO_2] \) = NO\textsubscript{2} concentration in molecule cm\textsuperscript{-3}
\( [NO] \) = NO concentration in molecule cm\textsuperscript{-3}
\( [O_3] \) = O\textsubscript{3} concentration in molecule cm\textsuperscript{-3}
\( k_2 \) = second order rate constant

From the Arrhenius equation, the rate constant \( k_2 \) is given by:

\[
k_2 = Ae^{-\frac{Ea}{RT}}
\]  

(9)

where:

\( A \) = pre-exponential factor
\( Ea \) = the activation energy
\( R \) = the gas constant (0.001987 kcal K\textsuperscript{-1} mol\textsuperscript{-1})
\( T \) = absolute temperature (K)

In this work, the values of \( A \) and \( Ea \) used to determine the rate constant were those derived by Atkinson \textit{et al.} (2006) from an extensive review of the literature:

\( A = 1.4 \times 10^{-12} \) cm\textsuperscript{3} molecule\textsuperscript{-1} s\textsuperscript{-1}
\( Ea = 2.60 \) kcal mol\textsuperscript{-1}

\textit{Reaction of nitrogen monoxide with oxygen}

For reaction (7), NO + NO + O\textsubscript{2} → 2NO\textsubscript{2}, the rate is given by:

\[
\frac{d[NO_2]}{dt} = k_3[NO]^2[O_3]
\]  

(10)

where:

\( [O_3] \) = O\textsubscript{3} concentration in molecule cm\textsuperscript{-3}
The concentration of oxygen is much greater that that of NO, and can be assumed to be constant. From Arrhenius, $k_3$ is again determined using Equation (9) and once again in this work, the values of $A$ and $E_a$ were taken from Atkinson et al. (2006):

\[
A = 3.3 \times 10^{-39} \text{ cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}
\]
\[
E_a = 1.05 \text{ kcal mol}^{-1}
\]
2 Experimental method

2.1 Tunnel descriptions

Measurement campaigns were conducted in two similar longitudinally ventilated road tunnels, both of which are operated by the Highways Agency: the Hatfield tunnel and the Bell Common tunnel. These two tunnels are described below.

2.1.1 Hatfield tunnel

The Hatfield tunnel is located between junctions 3 and 4 on the A1(M) motorway in Hertfordshire, and 0.8 km west of Hatfield town centre. The 1,150 m-long tunnel is a rectangular cut-and-cover structure on level terrain, and is equipped with two tubes: the ‘A’ tube which carries traffic in a south-north direction, and the ‘B’ tube which carries traffic in a north-south direction towards London. The monitoring campaign was conducted inside the B tube. Views of the tunnel near to the south and north portals are shown in Figures 2 and 3. A continuous curtain wall separates the two tubes along a central line. The tunnel is longitudinally ventilated by the traffic, supplemented when required by ceiling-mounted jet fans. There are no air extraction or inlet points other than the tunnel portals. Each tube accommodates the full motorway formation of three traffic lanes plus a hard shoulder, and has a nominal cross-sectional area of 127 m². The speed limit in the tunnel is 70 mph (113 km h⁻¹), and the total weekday bi-directional traffic flow is typically around 95,000 vehicles.

2.1.2 Bell Common tunnel

The Bell Common tunnel is situated between junctions 26 and 27 on the M25 motorway in Essex, at the northern edge of Epping Forest. The tunnel’s design is very similar to that of the Hatfield tunnel. It has a cut-and-cover design with two tubes, again termed A (in this case eastbound) and B (in this case westbound). The monitoring campaign was conducted inside the B tube. As in the Hatfield tunnel, each tube has three traffic lanes and a hard shoulder, and a cross-sectional area of 127 m². Again, a continuous curtain wall separates the two tubes. However, the Bell Common tunnel is somewhat shorter in length at 470 m. The tunnel is also curved, and in the B tube there is an average uphill gradient of around 1.5%. The tunnel is longitudinally ventilated by the traffic, again supplemented by ceiling-mounted jet fans. There are no air extraction or inlet points other than the tunnel portals. The speed limit in the tunnel is 70 mph (113 km h⁻¹), and the total weekday bi-directional traffic flow through the tunnel is typically around 105,000 vehicles. A view of the east portal is shown in Figure 4.
2.2 Study periods

In each tunnel the measurements were divided into two phases. This was partly to introduce a break in the monitoring so that the data from the first phase could be subjected to a preliminary analysis, and partly to examine the effects of different conditions (e.g. ambient temperature, traffic speed) on the results. The measurement periods are shown in Table 1.

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Measurement period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hatfield</td>
<td>04/11/2005 to 15/12/2005</td>
</tr>
<tr>
<td>Bell Common</td>
<td>24/05/2006 to 02/08/2006</td>
</tr>
</tbody>
</table>

2.3 Measurement of traffic parameters

2.3.1 Hatfield tunnel

Induction loops are permanently installed in the road surface of the Hatfield tunnel for the purpose of characterising the traffic. The information from the loops was recorded and interpreted using a bespoke classifier and data logger (Golden River Marksman 661). The classifier provided information on individual vehicle speed (km h\(^{-1}\)), headway\(^7\) (seconds) and vehicle length (cm). Vehicles were classified - according to the so-called ‘LPSIG9’ scheme - based on vehicle length and chassis height. The nine LPSIG9 vehicle classes are shown in Table 2. There is often a mis-match between the classification systems used by traffic engineers and those used to estimate emissions, and this study was no exception. It was therefore necessary to assume an association between the LPSIG9 vehicle classes and emission-related categories, and this association is also shown in Table 2.

---

\(^7\) The time interval between the passing of the front ends of successive vehicles moving in the same direction.
Table 2: LPSIG9 class descriptions (Golden River, 2005), with corresponding emission categories.

<table>
<thead>
<tr>
<th>Class no.</th>
<th>LPSIG9 class</th>
<th>Assumed equivalent emission category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motorcycle</td>
<td>Motorcycle</td>
</tr>
<tr>
<td>2</td>
<td>Car or light van (&lt;2.5m)</td>
<td>Car or small van (&lt;2.5 tonnes GVW&lt;sup&gt;8&lt;/sup&gt;)</td>
</tr>
<tr>
<td>3</td>
<td>Car or light van with trailer</td>
<td>Car or small van (&lt;2.5 tonnes GVW)</td>
</tr>
<tr>
<td>4</td>
<td>Heavy van (≥5.2 m) or minibus</td>
<td>Large van (2.5-3.5 tonnes GVW)</td>
</tr>
<tr>
<td>5</td>
<td>Rigid light goods vehicle (&lt;8.7 m)</td>
<td>Rigid heavy goods vehicle (&gt;3.5 tonnes GVW)</td>
</tr>
<tr>
<td>6</td>
<td>Rigid medium goods vehicle (≥8.7 m)</td>
<td>Rigid heavy goods vehicle (&gt;3.5 tonnes GVW)</td>
</tr>
<tr>
<td>7</td>
<td>Rigid goods vehicle with trailer</td>
<td>Rigid heavy goods vehicle (&gt;3.5 tonnes GVW)</td>
</tr>
<tr>
<td>8</td>
<td>Articulated heavy goods vehicle</td>
<td>Articulated heavy goods vehicle (&gt;3.5 tonnes GVW)</td>
</tr>
<tr>
<td>9</td>
<td>Bus or coach</td>
<td>Bus or coach (&gt;3.5 tonnes GVW)</td>
</tr>
</tbody>
</table>

Only the values for the number of vehicles per class and vehicle speed were used. The number of vehicles in each class passing through the tunnel, and the average speed of the vehicles in each class, were calculated for 5-minute periods, and were subsequently summated over 1-hour periods.

No loss of traffic data was reported during phase 1. However, during phase 2 some of the data for the period 24 January to 2 February were found to be corrupt, and during each hourly period a number of valid and invalid readings were recorded by the traffic data logger. In the case of invalid readings, the presence of a vehicle was identified but its type and speed were not. So that all the traffic data could be used, it was assumed that the traffic composition and speed distribution during a given one-hour period, as determined from the valid readings, could also be applied to those periods having corrupt data.

2.3.2 Bell Common tunnel

A detailed record of the traffic within the Bell Common tunnel was not available. Instead, information from the Motorway Incident Detection And Signing (MIDAS) system was used. TRL analyses the traffic data collected from selected sections of the English motorway network on a regular basis for the Highways Agency. The data are taken from paired inductive loop detectors, which are usually located at intervals of approximately 500 m on the network. The loop detectors are used to determine the flow, speed and length of vehicles passing over them, and the data are reported at one-minute intervals in the following format:

- The total number of vehicles by lane.
- The average speed of the traffic by lane.
- The traffic composition aggregated across the whole carriageway, stated in terms of four vehicle length bands (<5.2 m, 5.2-6.6 m, 6.6-11.6 m and >11.6 m).

Neither the traffic composition by lane nor the average speed by vehicle length band are available from MIDAS.

The MIDAS site chosen for this study was loop 5565B on the M25 just before the tunnel entrance (1.5 km west of the westbound entry slip road at junction 27), and the characteristics of the traffic at this site would therefore have been representative of those in the tunnel. The minute-by-minute data from MIDAS were processed to provide hourly total or average data. The MIDAS vehicle length bands were assigned to vehicle categories which were more useful in relation to emissions.

<sup>8</sup> GVW = gross vehicle weight.
Table 3: Assumed correspondence between MIDAS length bands and emission-related vehicle categories.

<table>
<thead>
<tr>
<th>MIDAS length category</th>
<th>Assumed equivalent emission category</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5.2 m</td>
<td>Cars or small van</td>
</tr>
<tr>
<td>5.2-6.6 m</td>
<td>Large van</td>
</tr>
<tr>
<td>6.6-11.6 m</td>
<td>Rigid HGV</td>
</tr>
<tr>
<td>&gt;11.6 m</td>
<td>Articulated HGV</td>
</tr>
</tbody>
</table>

2.4 Measurement of meteorological parameters

Meteorological measurements were conducted in the Hatfield tunnel by the University of Hertfordshire using a Casella Nomad Met Station near to the mid-point. The Met Station measured air flow velocity with an accuracy of $\pm 0.3 \text{ m s}^{-1}$ below 3 ms$^{-1}$, and $\pm 1\%$ above 3 m s$^{-1}$. It also simultaneously recorded temperature (± 0.3 °C), relative humidity (RH) (± 3%) and pressure (± 1 mbar). An averaging period of 15 minutes was used, further averaged over 1-hour periods.

In the Bell Common tunnel the air flow velocity was measured using a Vector A100 Porton anemometer mounted on the handrail at the exit site. This unit measured air flow velocity with an accuracy of $\pm 1\%$ above 10 m s$^{-1}$, and $\pm 0.3 \text{ m s}^{-1}$ between 0.1 m s$^{-1}$ and 10 m s$^{-1}$. Temperature was measured using a Campbell 105T thermocouple mounted on a stainless steel sheath with an accuracy of ± 0.5 °C. Wind direction, pressure and humidity were not recorded.

2.5 Air pollution measurements

2.5.1 Hatfield tunnel

Continuous measurements

Atmospheric concentrations of NO, NO$_2$ and O$_3$ were measured at three main sites in the B tube of the Hatfield tunnel: near to the tunnel entrance (north portal), near to the mid point, and near to the exit (south portal). NO and NO$_2$ were measured using chemiluminescence analysers (Monitor Labs ML8840) with a range of 0-1000 ppb (0-2000 ppb at the tunnel exit). Ozone was measured using UV absorption analysers (Monitor Labs ML8810 at entrance and exit, Thermo-electron 49c at tunnel mid-point), again with a detection range of 0-1000 ppb. The analysers were positioned on the near-side walkway, and were separated from the traffic by the hard shoulder. The gas inlets for all the analysers were located 2.5 m above the level of the road. The locations of the instruments are shown in Figure 5. Data were collected at TRL on a continuous basis using GSM modem links between the on-site data loggers and TRL data hub. Data and equipment status were inspected on a regular basis, and the data inspection was used to schedule maintenance visits.

All air pollution analysers undergo response and sensitivity drift over time. This may be due to ageing of components such as photo-multiplier tubes, degradation of catalytic scrubbers, (e.g. ozone scrubbers), or drift in electronic components. Periodic calibration is therefore essential, and the analysers in the Hatfield tunnel were calibrated and the start and end of each monitoring phase, and when any new analyser was installed. A two-point calibration method was used to quantify the analyser ‘zero’ and ‘span’ response using clean air and gas of certified concentration. The recorded zero and span values were used to provide linear scaling factors which were then applied to the raw data sets.
During phase 1 no operational problems were encountered with the analysers and data loggers at the tunnel entrance site. However, at the tunnel mid-point site the NOx analyser was removed and reinstalled a number of times between 11 November and 5 December, and no valid data were obtained during this period. In addition, the data logger was not functioning at this site between 29/11 and 5/12. At the tunnel exit site the ozone data showed a large amount of noise, and the analyser was replaced for phase 2.

During phase 2 a number of problems were encountered with the measurement of NOx at the exit site, possibly due to the harsh tunnel environment. A first analyser, which was installed on 5 January 2006, was found to be faulty, and a second unit was installed on 10 January. However, this analyser also stopped working on 14 January 2006, and was removed on 17 January. A third unit was installed on 20 January 2006. In addition, the ozone analyser at the exit site did not function correctly during phase 2. These changes resulted in substantial gaps in the pollution data at the tunnel exit site.

**Diffusion tube measurements**

In order to provide a slightly greater spatial resolution of NO2 concentrations, measurements were also conducted inside the tunnel using passive diffusion (Palmes) tubes. This work was conducted as part of a separate project funded by the Highways Agency (Boulter et al., 2007). The diffusion tubes were supplied and analysed by Gradko International Ltd. Each sampler consisted of an acrylic tube approximately 7 cm long and with a 1 cm internal diameter. The tube could be sealed at both ends. One end of the tube contained a stainless steel grid coated with 50% triethanolamine in water, which absorbed NO2 to produce a nitrate salt which could subsequently be analysed by colourimetry to determine the NO2 concentration.

The NO2 tubes were deployed along two transects inside the tunnel: (i) alongside the inner lane (i.e. on the walkway by the hard shoulder) and (ii) alongside the outer lane (i.e. on the walkway of central reservation), and at a total of 14 locations inside the tunnel. The locations are listed in Table 4. The tubes were deployed between 4 November and 11 December 2005.

In line with best practice, co-located triplets of tubes were mounted vertically and for the whole of each phase (around five weeks). At the end of each sampling period the tubes were sealed and stored in air-tight vials. Travelling/field blanks were also analysed with each sample set to check for contamination during the transport, storage and analytical procedures. At each measurement location the mean NO2 concentration was calculated for the three deployed tubes.

---

9 The tube preparation method was 50% triethanolamine (TEA) in de-ionised water. The tubes were loaded by pipetting 50µl of the absorbent on to the metal gauze. The analytical method was by ultra-violet spectroscopy measuring NO2 absorbed as nitrite by TEA using a variation of the Saltzman reaction.
Table 4: Locations of NO₂ diffusion tubes.

<table>
<thead>
<tr>
<th>Location (inner lane and outer lane)</th>
<th>Distance relative to ‘entrance’ continuous monitoring site (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North portal</td>
<td>-46</td>
</tr>
<tr>
<td>‘Entrance’ monitoring site</td>
<td>0</td>
</tr>
<tr>
<td>Between entrance and mid sites</td>
<td>274</td>
</tr>
<tr>
<td>‘Mid-point’ monitoring site</td>
<td>550</td>
</tr>
<tr>
<td>Between mid and exit sites</td>
<td>784</td>
</tr>
<tr>
<td>‘Exit’ monitoring site</td>
<td>1,022</td>
</tr>
<tr>
<td>South portal</td>
<td>1,104</td>
</tr>
</tbody>
</table>

2.5.2 Bell Common tunnel

Continuous measurements

In the Bell Common tunnel the concentrations of NO, NO₂ and O₃ were again measured at three main sites: near to the tunnel entrance (east portal), near to the mid point, and near to the exit (west portal). The monitoring locations are illustrated in Figure 6.

![Diagram illustrating the sampling locations in the Bell Common tunnel.](image)

NO and NO₂ were measured using chemiluminescence analysers (API model 200A) with a range of 0-2000 ppb at the entrance and 0-8000 ppb at the tunnel middle and exit. Ozone was measured using UV absorption analysers (Monitor Labs ML9810) with a detection range of 0-500 ppb. As in the Hatfield tunnel, the analysers were positioned on the near-side walkway, and were separated from the traffic by the hard shoulder. The gas inlets for all the analysers were again located 2.5 m above the level of the road. The analysers were calibrated and the start and end of each monitoring phase, as in the Hatfield tunnel campaign. No operational problems were encountered with the instruments during either of the Bell Common monitoring campaigns.

Diffusion tube measurements

NO₂ diffusion tubes were also deployed inside the Bell Common tunnel between 24 May 2006 and 21 June 2006. The tubes were located alongside the inner lane (i.e. on the walkway by the hard shoulder) and at a total of five location, as listed in Table 5. The experimental procedures described for the Hatfield tunnel were again
followed, and for each measurement location the mean NO₂ concentration was calculated for the three deployed tubes.

Table 5: Locations of NO₂ diffusion tubes.

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance relative to ‘entrance’ monitoring site (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East portal</td>
<td>-58</td>
</tr>
<tr>
<td>‘Entrance’ monitoring site</td>
<td>0</td>
</tr>
<tr>
<td>‘Mid-point’ monitoring site</td>
<td>172</td>
</tr>
<tr>
<td>‘Exit’ monitoring site</td>
<td>354</td>
</tr>
<tr>
<td>West portal</td>
<td>412</td>
</tr>
</tbody>
</table>
3 Results of measurements

3.1 Traffic characteristics

3.1.1 Hatfield tunnel

An example of the total hourly traffic flow in the B tube of the Hatfield tunnel - during a typical one-week period of the experiment, 7-13 November 2005 - is shown in Figure 7. There was a very regular traffic flow pattern during weekdays, with a morning peak of a typically 5,000 vehicles per hour between 07:00 and 08:00 associated with work-related journeys in the direction of London. There was a smaller afternoon weekday peak of around 3,000 vehicles per hour, as vehicles returning from London were on the northbound carriageway. The peak traffic flow on Saturdays and Sundays was typically around 2,500 vehicles per hour.

Figure 7 also shows that the average hourly speed of the traffic (weighted by vehicle category) in the tunnel during the one-week period described above varied little, and was usually between 100 and 110 km h$^{-1}$. On three of the weekdays in Figure 7 it appears that the traffic flow was somewhat interrupted during the morning peak periods, with the average hourly speed falling to around 70 km h$^{-1}$. However, the data record showed little evidence of prolonged traffic congestion outside the morning peak period, and during the whole of the monitoring period, the average hourly traffic speed varied between 41 km h$^{-1}$ and 118 km h$^{-1}$.

The composition of the traffic during the week 7-13 November is shown in Figure 8. For easier presentation of these data, some of the vehicle categories in Table 2 have been combined. It can be seen that during weekdays at least 80% of the traffic was composed of cars and light vans, except during the early hours of the morning (00:00 to 06:00) when flows were low and heavy goods vehicles formed up to around 60% of the traffic. Few buses or coaches, and very few motorcycles, were present in the tunnel.

Some descriptive statistics for the traffic data obtained during the two phases of the experiment are given in Table 6. The two phases had similar traffic conditions.

3.1.2 Bell common tunnel

Traffic data from the Bell Common for the week 11-17 December 2006 are presented in Figures 9 and 10, and the descriptive statistics are given in Table 7. A comparison between Figure 7 and Figure 9 shows that the peak traffic flows were lower in the Bell Common tunnel than in the Hatfield tunnel, but the data in Table 7 indicate that the traffic flow integrated over the day was substantially higher, particularly at weekends. The morning peak flow in the Bell Common tunnel was typically 4,000 vehicles per hour between 06:00 and 08:00. The afternoon weekday peak was generally less pronounced.

Figure 5 shows that the average hourly speed of the traffic (weighted by vehicle category) in the tunnel during was usually between 100 and 110 km h$^{-1}$. However, the average hourly speed occasionally fell to around 20 km h$^{-1}$, usually on weekdays. The overall average speed in the Bell Common tunnel was slightly lower than that in the Hatfield tunnel.

The composition of the traffic in the Bell Common tunnel during the week 11-17 December is shown in Figure 10. The vehicles in the length categories 6.6-11.6 m and >11.6 m were combined into a single ‘heavy-duty vehicle’ category. Given the different systems of traffic classification in the two tunnels, direct comparisons are not possible. However, it appears that the proportion of heavy-duty vehicles in the Bell Common tunnel (around 17%) was slightly higher than that in the Hatfield tunnel (around 12-13%).
Figure 7: Total one-hour traffic flow and average hourly speed in the Hatfield tunnel between 7 and 13 November 2005.

Figure 8: Traffic composition in the Hatfield tunnel between 7 and 13 November 2005.

Table 6: Traffic statistics for the Hatfield tunnel.

<table>
<thead>
<tr>
<th>Statistic (based on 1-hour values)</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average weekday traffic flow</td>
<td>47,993</td>
<td>45,794</td>
</tr>
<tr>
<td>Average weekend day traffic flow</td>
<td>33,701</td>
<td>29,857</td>
</tr>
<tr>
<td>% HDV</td>
<td>13.1</td>
<td>12.1</td>
</tr>
<tr>
<td>Mean traffic-weighted speed (km h(^{-1}))</td>
<td>104.9</td>
<td>104.1</td>
</tr>
<tr>
<td>Minimum traffic-weighted speed (km h(^{-1}))</td>
<td>41.1</td>
<td>48.9</td>
</tr>
<tr>
<td>Maximum traffic-weighted speed (km h(^{-1}))</td>
<td>117.7</td>
<td>116.1</td>
</tr>
<tr>
<td>% time &lt; 80 km h(^{-1})</td>
<td>2%</td>
<td>5%</td>
</tr>
</tbody>
</table>
Primary NO₂ emissions from road vehicles in the Hatfield and Bell Common tunnels

Version: Final

Figure 9: Total one-hour traffic flow and average hourly speed in the Bell Common tunnel between 11 and 17 December 2006.

Figure 10: Traffic composition in the Bell Common tunnel between 11 and 17 December 2006.

Table 7: Traffic statistics for the Bell Common tunnel.

<table>
<thead>
<tr>
<th>Statistic (based on 1-hour values)</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average weekday traffic flow</td>
<td>51,647</td>
<td>51,872</td>
</tr>
<tr>
<td>Average weekend day traffic flow</td>
<td>48,131</td>
<td>43,915</td>
</tr>
<tr>
<td>% HDV</td>
<td>17.1</td>
<td>16.6</td>
</tr>
<tr>
<td>Mean traffic-weighted speed (km h⁻¹)</td>
<td>98.9</td>
<td>101.0</td>
</tr>
<tr>
<td>Minimum traffic-weighted speed (km h⁻¹)</td>
<td>7.0</td>
<td>20.1</td>
</tr>
<tr>
<td>Maximum traffic-weighted speed (km h⁻¹)</td>
<td>120.6</td>
<td>126.9</td>
</tr>
<tr>
<td>% time &lt; 80 km h⁻¹</td>
<td>9%</td>
<td>4%</td>
</tr>
</tbody>
</table>
3.2 Meteorological parameters

3.2.1 Hatfield tunnel

No losses of meteorological data were reported during either phase of the Hatfield tunnel work, although during phase 2 it was only possible to commence monitoring on 9 January 2006, four days after the start of the air pollution monitoring. The wind direction was usually in the direction of the traffic, except at very low traffic flows. The small number of measurements obtained during periods when the hourly mean wind direction was more than 15° less than or greater than the mean were excluded from the analysis in order to reduce the influence of cosine errors in the wind speed.

The hourly average wind speed varied between 0.1 m s⁻¹ and 5.3 m s⁻¹, and followed a similar pattern to total traffic flow – the fitting of a logarithmic regression function gave an $R^2$ value of 0.65. The hourly average temperature during the period of the experiment is shown in Figure 8. The hourly average temperature ranged from 0.7 °C to 17.3 °C. There was a substantial drop in temperature after 16 November. The mean values of the meteorological parameters during the two phases of the experiment are given in Table 8, from which it can be seen that the meteorological conditions were rather similar during the two phases.

![Figure 11: Hourly average temperature in the B tube of the Hatfield tunnel.](image)

<table>
<thead>
<tr>
<th>Statistic (1-hour value)</th>
<th>Phase 1 mean</th>
<th>Phase 2 mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed (m/s)</td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Pressure (mbar)</td>
<td>1,011</td>
<td>1,018</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>9.1</td>
<td>7.0</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>76</td>
<td>74</td>
</tr>
</tbody>
</table>

3.2.2 Bell Common tunnel

Only wind speed and ambient temperature were measured in the Bell Common tunnel. Wind direction, pressure and humidity were not recorded. The hourly average wind speed varied between 0.03 m s⁻¹ and 5.2 m s⁻¹. Inside a tunnel the aerodynamic drag of vehicles induces a flow of air in the direction of the traffic.
Surprisingly, there was no strong relationship between total traffic flow and wind speed, although during phase 2 the wind speed did appear to be dependent upon the number of heavy-duty vehicles – for which the fitting of a logarithmic regression function gave an $R^2$ value of 0.60. The east-west orientation of the tunnel may have meant that, due to prevailing winds, the external wind had more of an influence in Bell Common than in Hatfield (orientation north-south), although no external wind speed data were available and the in-tunnel wind speeds were very similar in the two tunnels. No temperature data were obtained between 17/7/06 and 2/8/06. The hourly average temperature in the tunnel is shown in Figure 12. The hourly average temperature ranged from a minimum of 8.0 °C during the winter campaign to a maximum of 27.8 °C during the summer campaign. The average values for wind speed and temperature obtained during the two phases of the experiment are given in Table 9.

![Figure 12: Hourly average temperature in the B tube of the Bell Common tunnel.](image)

Table 9: Meteorological data for the Bell Common tunnel.

<table>
<thead>
<tr>
<th>Statistic (1-hour value)</th>
<th>Phase 1 mean</th>
<th>Phase 2 mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed (m/s)</td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>20.2</td>
<td>15.3</td>
</tr>
</tbody>
</table>

### 3.3 Continuous pollution measurements

#### 3.3.1 Hatfield tunnel

Figure 13 shows the 1-hour average concentrations of NO$_x$, NO$_2$ and O$_3$ during the two phases of the Hatfield tunnel work. Summary statistics describing the data are given in Table 10. Only complete hourly data are included in the plots (i.e. periods for which all twelve 5-minute average values were recorded). It can be seen from the Figure that there were significant losses of NO$_x$ and NO$_2$ data at the mid-point location during phase 1, and also some losses of ozone data at the mid-point and exit locations. As mentioned earlier, during phase 2 NO$_x$ and NO$_2$ data losses occurred at the tunnel exit site, and the ozone analyser at the exit site failed repeatedly. Based upon the results from phase 1, it was assumed that the ozone concentrations at the exit site were equivalent to those at the mid-point (which were close to zero). In spite of the loss of data, a substantial database of pollutant concentrations was obtained for the calculation of emission factors.
Figure 13: One-hour mean concentrations of NO$_x$, NO$_2$ and O$_3$ in the Hatfield tunnel during the two phases of the experiment.
Table 10: Summary statistics for NO, NO\textsubscript{x}, NO\textsubscript{2} and O\textsubscript{3} concentrations in the Hatfield tunnel.

<table>
<thead>
<tr>
<th>Location</th>
<th>Pollutant</th>
<th>Mean conc. (ppb)</th>
<th>Minimum conc. (ppb)</th>
<th>Maximum conc. (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
<td>Phase 1</td>
</tr>
<tr>
<td>Tunnel entrance</td>
<td>NO</td>
<td>147.2</td>
<td>127.0</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{x}</td>
<td>197.5</td>
<td>170.0</td>
<td>21.7</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{2}</td>
<td>50.3</td>
<td>43.0</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>O\textsubscript{3}</td>
<td>3.3</td>
<td>4.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Tunnel middle</td>
<td>NO</td>
<td>292.3</td>
<td>350.5</td>
<td>146.5</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{x}</td>
<td>386.7</td>
<td>432.3</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{2}</td>
<td>94.4</td>
<td>81.8</td>
<td>48.0</td>
</tr>
<tr>
<td></td>
<td>O\textsubscript{3}</td>
<td>0.6</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Tunnel exit</td>
<td>NO</td>
<td>491.6</td>
<td>637.4</td>
<td>30.0</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{x}</td>
<td>660.6</td>
<td>748.7</td>
<td>90.0</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{2}</td>
<td>169.0</td>
<td>111.3</td>
<td>60.0</td>
</tr>
<tr>
<td></td>
<td>O\textsubscript{3}</td>
<td>0.3</td>
<td>1.0</td>
<td>-0.7</td>
</tr>
</tbody>
</table>

The increases in the concentrations of NO\textsubscript{x} (and NO\textsubscript{2}) along the length of the tunnel are apparent from Figure 13 and Table 10, with the highest concentrations being recorded at the tunnel exit site and the lowest concentrations being recorded at the tunnel entrance site. During phase 1 the maximum hourly average NO\textsubscript{x} and NO\textsubscript{2} concentrations (at the exit) were 1,489 ppb and 321 ppb respectively. During phase 2, the corresponding maximum hourly concentrations were 1,784 ppb and 380 ppb. The peak NO\textsubscript{x} (or NO\textsubscript{2}) concentrations in Figure 13 broadly corresponded to the peak traffic flow levels.

The ozone concentration profiles were rather different, as would be expected in a road tunnel, where NO is in excess and the reaction with ozone can proceed rapidly. At the tunnel mid-point and exit, ozone concentrations were close to zero. At the tunnel entrance site the ozone concentration varied substantially, and did not show any systematic correlation with traffic flow. The maximum hourly ozone concentration at the entrance site was 16 ppb during phase 1, and 18 ppb during phase 2.

However, there appear to be some inconsistencies in these data, bearing in mind that the traffic and meteorological conditions were broadly similar during the two phases of the experiment. For example, whereas NO\textsubscript{x} concentrations appeared to be roughly at the same general level during the two phases, NO\textsubscript{2} concentrations decreased somewhat towards the end of the experiment, particularly at the tunnel exit site. It also appears that this reduction in NO\textsubscript{2} coincided with the installation of the replacement NO\textsubscript{x} analyser at the exit on 20 January.

The differences between phase 1 and phase 2 are also illustrated in Figures 14 and 15, which show the average diurnal concentration profiles for NO\textsubscript{x} and NO\textsubscript{2}. For phase 2, only the period from 20 January onwards (when the new analyser was in place) has been included. Figure 14 shows that in the case of NO\textsubscript{x}, similar concentration profiles were obtained during phase 1 and phase 2 at both the entrance and exit sites. The mid-point data for phase 1 are not included, as they only covered a relatively short time period. However, the NO\textsubscript{2} results in Figure 15 clearly show that although similar concentrations were obtained at the entrance site during phase 1 and phase 2, the NO\textsubscript{2} concentrations at the exit site were much lower during phase 2. Given that the factors affecting the NO\textsubscript{x} and NO\textsubscript{2} concentrations at the tunnel exit site changed little, it seemed unlikely that both the phase 1 and phase 2 data sets were robust.
Evidence of problems with the pollution data prior to 20 January 2006 (i.e. all the phase 1 data and some of the phase 2 data) is provided in Figure 16. In theory, for equivalent time periods there should be no difference between the NOx increment between the tunnel entrance and the tunnel mid-point, and the increment between the tunnel mid-point and the tunnel exit, everything else (e.g. traffic flow, traffic speed, traffic composition, tunnel cross-sectional area, road gradient, etc.) being equal. In the Hatfield tunnel, there is no reason to believe that any of these parameters were different between the two tunnel sections. Indeed, for the period after 20 January there is a 1:1 relationship, as one would expect. However, the data prior to 20 January are much less consistent, and this suggests that they must be treated with caution. Figure 17 shows the results for NO2. Again, there is a much better correlation after 20 January, but in this case the increment between the entrance and the mid-point is systematically higher than that between the mid-point and the exit.
3.3.2 Bell Common tunnel

Figure 18 shows the 1-hour average concentrations of NO\textsubscript{x}, NO\textsubscript{2} and O\textsubscript{3} in the Bell Common tunnel, and summary statistics describing the data are given in Table 11. There were no significant losses of data during either monitoring phase. During phase 1 the maximum hourly average NO\textsubscript{x} and NO\textsubscript{2} concentrations (at the exit) were around 4,500 ppb and 540 ppb respectively – considerably higher than in the Hatfield tunnel, even though the peak traffic flows were lower and the tunnel is shorter. During phase 2, the maximum hourly NO\textsubscript{x} and NO\textsubscript{2} concentrations were 4,118 ppb and 564 ppb. The ozone concentration profiles were dramatically different during phase 1 and phase 2. For the tunnel entrance site phase one was characterised by much higher concentrations (maximum 73.2 ppb) than phase 2 (maximum 18.8). Again, at the tunnel mid-point and exit ozone concentrations were much lower, although some significant peaks were still observed at the tunnel mid-point site.
Figure 18: One-hour mean concentrations of NOx, NO2 and O3 in the Bell Common tunnel during the two phases of the experiment.
Table 11: Summary statistics for NO, NO\textsubscript{x}, NO\textsubscript{2} and O\textsubscript{3} concentrations in the Bell Common tunnel.

<table>
<thead>
<tr>
<th>Location</th>
<th>Pollutant</th>
<th>Mean conc. (ppb)</th>
<th>Minimum conc. (ppb)</th>
<th>Maximum conc. (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
<td>Phase 1</td>
</tr>
<tr>
<td>Tunnel entrance</td>
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<td>245.2</td>
<td>21.7</td>
<td>1,643.1</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{X}</td>
<td>323.6</td>
<td>51.5</td>
<td>1,370.2</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{2}</td>
<td>79.3</td>
<td>18.8</td>
<td>210.2</td>
</tr>
<tr>
<td></td>
<td>O\textsubscript{3}</td>
<td>9.1</td>
<td>0.5</td>
<td>73.2</td>
</tr>
<tr>
<td>Tunnel middle</td>
<td>NO</td>
<td>603.6</td>
<td>106.8</td>
<td>2,517.5</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{X}</td>
<td>703.0</td>
<td>160.2</td>
<td>2,961.4</td>
</tr>
<tr>
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<td>NO\textsubscript{2}</td>
<td>99.3</td>
<td>34.7</td>
<td>443.9</td>
</tr>
<tr>
<td></td>
<td>O\textsubscript{3}</td>
<td>1.2</td>
<td>0.0</td>
<td>22.7</td>
</tr>
<tr>
<td>Tunnel exit</td>
<td>NO</td>
<td>979.6</td>
<td>193.4</td>
<td>3,959.1</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{X}</td>
<td>1,104.9</td>
<td>252.2</td>
<td>4,499.0</td>
</tr>
<tr>
<td></td>
<td>NO\textsubscript{2}</td>
<td>125.4</td>
<td>39.7</td>
<td>539.9</td>
</tr>
<tr>
<td></td>
<td>O\textsubscript{3}</td>
<td>1.3</td>
<td>0.1</td>
<td>3.9</td>
</tr>
</tbody>
</table>

3.4 Diffusion tube measurements

3.4.1 Hatfield tunnel

Passive diffusion tubes were used to measure NO\textsubscript{2} along two transects in the Hatfield tunnel: (i) alongside the inner lane (i.e. on the walkway by the hard shoulder) and (ii) alongside the outer lane (i.e. on the walkway of central reservation). The diffusion tubes were deployed between 4 November and 11 December 2005. The mean NO\textsubscript{2} concentrations from these measurements are shown in Figure 19. The mean NO\textsubscript{2} concentrations based upon the continuous measurements during the same period are also shown. At the entrance site there was a good agreement between the average NO\textsubscript{2} concentrations measured using the continuous analyser (52.3 ppb) and the diffusion tubes (56.9 ppb). At the tunnel mid-point, the average value from the continuous measurements (91.8 ppb) was higher than that from the diffusion tubes (81.3 ppb), but remained within the 95% confidence intervals of the diffusion tube measurements (though it should also be noted that valid continuous data were only available for around one third of the period). However, at the tunnel exit, the value from the continuous analyser (169.6 ppb) was much higher than that from the diffusion tubes (108.1 ppb), and whereas a linear and systematic increase in NO\textsubscript{2} concentrations with distance is apparent from the diffusion tube data, the continuous measurements at the exit site suggest a larger gradient. Furthermore, the average NO\textsubscript{2} concentration of 108.1 ppb measured using diffusion tubes at the tunnel exit site during phase 1 was very close to the average concentration at the same site from the continuous measurements during the period after 20 January 2006 (104.1 ppb). This again suggests that the NO\textsubscript{2} data from the tunnel exit site during phase 1 of the study may have been incorrect. The selection of valid data for the calculation of emission factors, following these findings, is described in the next Chapter of the Report.

Figure 19 also shows that the NO\textsubscript{X} concentrations near the outer lane were systematically higher than those by the inner lane, indicating that the air in the Hatfield tunnel is not well mixed. This is likely to affect the emission factors derived using the continuous measurements by the inner lane, in both this study and other studies. However, these differences should have little effect on the estimated proportion of NO\textsubscript{X} emitted as NO\textsubscript{2}. If it is assumed that the concentrations near the outer lane represent the ‘true’ traffic contribution, then it appears that the use of the values from the measurement sites located near the inside lane, as in this study, could lead to an underestimation of emission factors by around 10-15%.
3.4.2 Bell Common tunnel

In the Bell Common tunnel there was a very good agreement between the diffusion tube measurements and the continuous measurements at the entrance site (Figure 20). Again, as in the Hatfield tunnel the agreement became worse further into the tunnel, although in Bell Common the diffusion tube results at the mid-point and exit sites were lower than the results from the continuous measurements.

Figure 20: Mean concentrations of NO₂ in the Bell Common tunnel. Recorded using diffusion tubes between 24 May and 21 June 2006, and average concentrations based upon continuous measurements during the same period.
4 Determination of emission factors

4.1 Calculation approach

The following steps were followed to derive emission factors for NOx and NO2 in each tunnel:

(i) NOx emission factors for an ‘average vehicle’ (i.e. fleet-weighted) were calculated on an hourly basis by inserting the hourly mean concentrations and hourly total traffic flows in the tunnel into Equation 1. The latter excluded motorcycles, which formed only 0.002% of the total traffic flow during the Hatfield tunnel study, and were not specifically identified in Bell Common.

(ii) Again for an ‘average vehicle’, the proportion of NOx emitted as primary NO2 (and hence the NO2 emission factors) was determined iteratively - the proportion of NO2 was changed until the target (measured) NO2 concentration was attained. This was conducted using three different models, each involving a different assumption regarding the formation of NO2:

Model M1: In this model, it was assumed that ozone was conserved. In other words, no NO2 formation reactions occurred in the tunnel air, and all NO2 measured at the tunnel middle and exit was derived solely from vehicle exhaust.

Model M2: In this model, it was assumed that NO2 in the tunnel air was derived from both vehicle exhaust and via the reaction of nitrogen monoxide with ozone (Equation 2).

Model M3: In this model, it was assumed that, as well as the NO2 production mechanisms used in model M2, NO2 was also formed by the reaction of NO with oxygen (Equation 4). The two NO2 formation reactions proceed at different rates, according to the concentrations of NO and ozone (the concentration of oxygen could be assumed to be constant).

(iii) The emission factors for different vehicle categories were derived using multiple regression analysis.

In the Hatfield tunnel, maximum use of the available data was made by considering the following sections separately:

- **ENT-MID** - The section between the monitoring sites near the tunnel entrance and the mid-point.
- **MID-EXIT** - The section between the monitoring sites near the mid-point and the exit.
- **ENT-EXIT** - The section between the monitoring sites near the tunnel entrance and the exit (i.e. the full length of the tunnel).

Given that the Bell Common tunnel was rather short, only the ENT-EXIT data were used for the calculation of emission factors, although the data for the ENT-MID and MID-EXIT sections were used to check the internal consistency of the data.

Using each of the three models, the concentrations of NO, NO2 and O3 were calculated at 10 m intervals between the tunnel entrance monitoring site (taken to be located at 0 m), and the tunnel exit monitoring site (taken to be located at 1020 m for the Hatfield tunnel, and 354 m for the Bell Common tunnel). Some of the results for the Hatfield tunnel are shown in Figures 21 and 22. Figure 21 shows the concentration profiles for a given 1-hour period, as predicted using model M1. As it is assumed in model M1 that ozone is not involved in reaction with NO, the ozone concentration remains constant. This has clearly led to an over-prediction of the ozone concentration at the tunnel mid-point and tunnel exit. In model M2, the reaction of ozone with NO is taken into account, and the predicted ozone concentrations at the mid-point and exit are closer to the observed values. The effect of this is that, for the ENT-MID section (0-550 m) the NO2/NOx proportion needs to be lower in model M2 than in model M1, in order to offset the extra NO2 produced by the NO-O3 reaction and to result in the correct concentration of NO2 at the mid-point. In general, model M3 had little further effect on the predicted concentration profiles. According to Barrefors (1996), the NO-NO-O2 reaction is important in long tunnels when the NO concentration exceeds 5 ppm. Similarly, Indrehus and Vassbotn (2001) noted that this fast oxidation route is very likely when the air flow velocity is low and the NO concentration exceeds a few
Primary NO₂ emissions from road vehicles in the Hatfield and Bell Common tunnels

The Hatfield tunnel is only around 1 km long, and the 1-hour mean NO concentration rarely exceeded 1 ppm. It is probably therefore not surprising that this reaction was not found to be particularly important. The same conclusions were drawn from the Bell Common data, even though NO concentrations were substantially higher than those in the Hatfield tunnel.

![Model 1](image1)

Figure 21: Example of predicted NO, NO₂ and O₃ concentration profiles in the Hatfield tunnel (model M1) (15 December 2005, 02:00-03:00).

![Model 2](image2)

Figure 22: Examples of predicted NO, NO₂ and O₃ concentration profiles in the Hatfield tunnel (model M2) (15 December 2005, 02:00-03:00).

It should be noted that none of the models could be used to predict ozone concentrations accurately at the tunnel mid-point and exit sites - in the case of model M1 this was because of the assumption of ozone conservation, whereas in the case of models M2 and M3 the predicted ozone concentrations were either zero or very close to zero.
4.2 Selection of valid data

Not all the air pollution and traffic data were taken to be valid for the calculation of emission factors. In the case of the Hatfield tunnel, as a result of the apparent errors in the air pollution measurements identified in the previous Chapter, there was a need to define a restricted data set for the calculation of emission factors. It has already been noted, for example, that the air pollution data at the tunnel exit site after 20 January 2006 appeared to be more reliable to those prior to this date. In fact, the most reliable results during the experiment were defined at the post-processing stage rather than via the analysis of the input data. The emission factors which were selected as being valid were those in which there was a good agreement between the NO\(_x\) emission factors and between the NO\(_2\) emission factors (as calculated using model \textit{M3}) in the two tunnel sections, and for a prolonged period rather than intermittently. This proved to restrict the valid data to the period 22 January to 8 February inclusive. For the Bell Common tunnel, no extended periods with invalid data were observed. However, for both tunnels, where there were obvious errors in the traffic or air pollution data, the values were deleted. Any data resulting in negative emission factors were also removed.

4.3 Fleet-weighted NO\(_x\) and NO\(_2\) emission factors

4.3.1 Hatfield tunnel

Table 12 shows the overall average fleet-weighted emission factors for NO\(_x\) and NO\(_2\) derived for the different sections of the Hatfield tunnel, for the three different models, and for the valid hourly periods. The NO\(_x\) emission factors are independent of the model used to derive the NO\(_2\) emission factors, and are based purely on the measurements. For NO\(_2\), the results of model \textit{M3} were assumed to be the most accurate, as they included the most important NO\(_2\)-formation reactions.

Table 12: Average NO\(_x\) and NO\(_2\) emission factors and %NO\(_2\) for hourly periods with valid data (22 January to 8 February 2006).

<table>
<thead>
<tr>
<th>Section</th>
<th>Model</th>
<th>NO(_x) (g vehicle(^{-1}) km(^{-1}))</th>
<th>NO(_2) (g vehicle(^{-1}) km(^{-1}))</th>
<th>%NO(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EF 95%</td>
<td>EF 95%</td>
<td>Mean 95%</td>
</tr>
<tr>
<td>ENT-MID</td>
<td>\textit{M1}</td>
<td>1.142 0.096 0.151 0.010</td>
<td>14.421 0.236</td>
<td></td>
</tr>
<tr>
<td></td>
<td>\textit{M2}</td>
<td>1.142 0.096 0.120 0.008</td>
<td>12.135 0.346</td>
<td></td>
</tr>
<tr>
<td></td>
<td>\textit{M3}</td>
<td>1.142 0.096 0.120 0.008</td>
<td>12.114 0.346</td>
<td></td>
</tr>
<tr>
<td>MID-EXIT</td>
<td>\textit{M1}</td>
<td>1.401 0.114 0.095 0.006</td>
<td>8.159 0.301</td>
<td></td>
</tr>
<tr>
<td></td>
<td>\textit{M2}</td>
<td>1.401 0.114 0.094 0.006</td>
<td>8.156 0.301</td>
<td></td>
</tr>
<tr>
<td></td>
<td>\textit{M3}</td>
<td>1.401 0.114 0.094 0.006</td>
<td>8.096 0.301</td>
<td></td>
</tr>
<tr>
<td>ENT-EXIT</td>
<td>\textit{M1}</td>
<td>1.261 0.104 0.125 0.008</td>
<td>11.147 0.249</td>
<td></td>
</tr>
<tr>
<td></td>
<td>\textit{M2}</td>
<td>1.261 0.104 0.108 0.006</td>
<td>10.028 0.290</td>
<td></td>
</tr>
<tr>
<td></td>
<td>\textit{M3}</td>
<td>1.261 0.104 0.108 0.006</td>
<td>9.984 0.290</td>
<td></td>
</tr>
</tbody>
</table>

The average NO\(_x\) and NO\(_2\) emission factors determined over the full length of the tunnel and using model \textit{M3} were 1.26 g vehicle\(^{-1}\) km\(^{-1}\) and 0.11 g vehicle\(^{-1}\) km\(^{-1}\) respectively. The average NO\(_2\)/NO\(_x\) proportion was approximately 10%. It is not clear why slightly different NO\(_x\) emission factors were observed over the two road sections. The error on the NO\(_x\) measurement will have contributed to the unexplained variation, but other possible factors might have included differences in traffic speed, wind speed (associated with variation in traffic operation), and tunnel cross-sectional area and gradient between the two tunnel sections although, as stated earlier, there is little reason to believe that these would have differed significantly in the two sections.

The effects of NO\(_2\) formation in the tunnel atmosphere are also evident in Table 12. For example, it can be seen that the NO\(_2\) emission factor derived using model \textit{M1} is overestimated in the \textit{ENT-MID} section, as atmospheric formation of NO\(_2\) is not included. This overestimation is corrected by the inclusion of the reaction...
of NO with ozone in model \( M2 \), with model \( M3 \) having no additional effect. In the \( MID-EXIT \) section model \( M2 \) offers little benefit over model \( M1 \), as all the ozone has already been depleted in the \( ENT-MID \) section.

A common first step of data analyses which involve more than a few variables is to run a correlation matrix, and to examine it for significant relationships. The relationships between the total NO \(_x\) and NO \(_2\) emissions (i.e. the average emission factor multiplied by the total number of vehicles), the \%NO\(_2\), meteorological parameters (air temperature; pressure; relative humidity; wind speed) and traffic parameters were examined by simple linear regression analysis. The resulting correlation matrix is shown in Table 13. There were no strong correlations between the NO\(_x\) or NO\(_2\) emission factors and the meteorological parameters and traffic speed, with the exception of wind speed. The relationship between emissions and wind speed is essentially due to the dependence of wind speed on traffic flow. The relationship between the NO\(_x\) and NO\(_2\) emission factors and wind speed was poor. To simplify the analysis the meteorological parameters and traffic speed were excluded from the subsequent calculations.

Table 13: Correlation matrix – Hatfield tunnel (R values). The vehicle categories are defined in Equation 11.

<table>
<thead>
<tr>
<th>Total NO(_x)</th>
<th>Total NO(_2)</th>
<th>% NO(_2)</th>
<th>Air temp.</th>
<th>Wind speed</th>
<th>Pressure</th>
<th>RH</th>
<th>No. CSV</th>
<th>No. LV</th>
<th>No. rHDV</th>
<th>No. aHDV</th>
<th>No. BC</th>
<th>Traffic speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total NO(_x)</td>
<td>1.00</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total NO(_2)</td>
<td>0.97</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>% NO(_2)</td>
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<td>0.79</td>
<td>1.00</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Air temp.</td>
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<td>0.16</td>
<td>0.39</td>
<td>1.00</td>
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<td></td>
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<tr>
<td>Wind speed</td>
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<td>0.59</td>
<td>0.07</td>
<td>1.00</td>
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<td>Pressure</td>
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<td>-0.22</td>
<td>-0.36</td>
<td>0.26</td>
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<td>0.79</td>
<td>0.80</td>
<td>0.14</td>
<td>0.64</td>
<td>-0.08</td>
<td>-0.24</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. LV</td>
<td>0.84</td>
<td>0.87</td>
<td>0.64</td>
<td>-0.01</td>
<td>0.56</td>
<td>-0.24</td>
<td>-0.17</td>
<td>0.75</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. rHDV</td>
<td>0.82</td>
<td>0.81</td>
<td>0.54</td>
<td>-0.02</td>
<td>0.52</td>
<td>-0.31</td>
<td>-0.20</td>
<td>0.57</td>
<td>0.89</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. aHDV</td>
<td>0.68</td>
<td>0.65</td>
<td>0.39</td>
<td>-0.06</td>
<td>0.38</td>
<td>-0.43</td>
<td>-0.22</td>
<td>0.36</td>
<td>0.71</td>
<td>0.85</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>No. BC</td>
<td>0.65</td>
<td>0.68</td>
<td>0.51</td>
<td>0.04</td>
<td>0.50</td>
<td>-0.18</td>
<td>-0.21</td>
<td>0.61</td>
<td>0.72</td>
<td>0.67</td>
<td>0.53</td>
<td>1.00</td>
</tr>
<tr>
<td>Traffic speed</td>
<td>0.12</td>
<td>0.09</td>
<td>0.35</td>
<td>0.26</td>
<td>0.21</td>
<td>0.10</td>
<td>0.03</td>
<td>0.10</td>
<td>0.02</td>
<td>0.01</td>
<td>0.05</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

4.3.2 Bell Common tunnel

Table 14 shows the overall average fleet-weighted emission factors for NO\(_x\) and NO\(_2\) derived for the Bell Common tunnel. As stated earlier, emission factors were only calculated for the \( ENT-EXIT \) section, but for both phases of the work (and overall). Again, for NO\(_2\), the results of model \( M3 \) were assumed to be the most accurate, as they included the most important NO\(_2\)-formation reactions.

Table 14: Average NO\(_x\) and NO\(_2\) emission factors and \%NO\(_2\) for hourly periods with valid data (\( ENT-EXIT \) only).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Model</th>
<th>NO(_x) (g vehicle(^{-1}) km(^{-1}))</th>
<th>NO(_2) (g vehicle(^{-1}) km(^{-1}))</th>
<th>%NO(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EF 95%</td>
<td>EF 95%</td>
<td>Mean 95%</td>
</tr>
<tr>
<td>Phase 1</td>
<td>( M1 )</td>
<td>3.59 0.20</td>
<td>0.18 0.01</td>
<td>6.09 0.13</td>
</tr>
<tr>
<td></td>
<td>( M2 )</td>
<td>3.59 0.20</td>
<td>0.15 0.01</td>
<td>4.48 0.12</td>
</tr>
<tr>
<td></td>
<td>( M3 )</td>
<td>3.59 0.20</td>
<td>0.14 0.01</td>
<td>4.45 0.12</td>
</tr>
<tr>
<td>Phase 2</td>
<td>( M1 )</td>
<td>4.26 0.24</td>
<td>0.47 0.02</td>
<td>13.07 0.49</td>
</tr>
<tr>
<td></td>
<td>( M2 )</td>
<td>4.26 0.24</td>
<td>0.45 0.02</td>
<td>12.39 0.38</td>
</tr>
<tr>
<td></td>
<td>( M3 )</td>
<td>4.26 0.24</td>
<td>0.45 0.02</td>
<td>12.36 0.38</td>
</tr>
<tr>
<td>Overall</td>
<td>( M1 )</td>
<td>3.86 0.15</td>
<td>0.30 0.01</td>
<td>8.86 0.26</td>
</tr>
<tr>
<td></td>
<td>( M2 )</td>
<td>3.86 0.15</td>
<td>0.27 0.01</td>
<td>7.62 0.24</td>
</tr>
<tr>
<td></td>
<td>( M3 )</td>
<td>3.86 0.15</td>
<td>0.27 0.01</td>
<td>7.59 0.24</td>
</tr>
</tbody>
</table>
Based on the results from model M3 for the ENT-EXIT sections, the average NOx and NO2 emission factors in the Bell Common tunnel (3.86 and 0.27 g vehicle\(^{-1}\) km\(^{-1}\) for NOx and NO2) were substantially higher than those for the Hatfield tunnel, although the proportion of NO2 was lower (7.6% in Bell Common, compared with 10% in Hatfield). It can also be seen from Table 14 that the emission factors obtained during phase 2 were higher than those obtained during phase 1, and the NO2 proportion was also higher. Furthermore, as the Bell Common tunnel is much shorter than the Hatfield tunnel, for the estimation of NO2 emission factors the benefits of model M2 compared with model M1 appear to still be apparent at the tunnel exit site.

Tables 15-17 show the correlation matrices for phase 1, phase 2 and the whole study period. As in the Hatfield tunnel, no strong relationships were observed between the emission factors and the meteorological parameters (except wind speed, as before) or traffic speed, and again these parameters were excluded from the subsequent analysis. Furthermore, the correlation of total NOx and total NO2 with the number of cars and small vans was weaker than in the Hatfield tunnel.

### Table 15: Correlation matrix – Bell Common phase 1 (R values).

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Total NOx</th>
<th>Total NO2</th>
<th>%NO2</th>
<th>Air temp.</th>
<th>Wind speed</th>
<th>No. CSV</th>
<th>No. LV</th>
<th>No. HDV</th>
<th>Traffic speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total NOx</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total NO2</td>
<td>0.72</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%NO2</td>
<td>0.10</td>
<td>0.69</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air temp.</td>
<td>0.02</td>
<td>0.12</td>
<td>0.15</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.72</td>
<td>0.34</td>
<td>-0.18</td>
<td>0.01</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. CSV</td>
<td>0.15</td>
<td>0.27</td>
<td>0.28</td>
<td>0.31</td>
<td>0.01</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. LV</td>
<td>0.71</td>
<td>0.63</td>
<td>0.25</td>
<td>0.11</td>
<td>0.45</td>
<td>0.53</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. HDV</td>
<td>0.84</td>
<td>0.67</td>
<td>0.18</td>
<td>0.05</td>
<td>0.60</td>
<td>0.41</td>
<td>0.92</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Traffic speed</td>
<td>-0.22</td>
<td>-0.37</td>
<td>-0.35</td>
<td>-0.05</td>
<td>0.18</td>
<td>-0.13</td>
<td>-0.36</td>
<td>-0.28</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Table 16: Correlation matrix – Bell Common phase 2 (R values).

<table>
<thead>
<tr>
<th>Phase 2</th>
<th>Total NOx</th>
<th>Total NO2</th>
<th>%NO2</th>
<th>Air temp.</th>
<th>Wind speed</th>
<th>No. CSV</th>
<th>No. LV</th>
<th>No. HDV</th>
<th>Traffic speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total NOx</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total NO2</td>
<td>0.94</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%NO2</td>
<td>-0.51</td>
<td>-0.35</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air temp.</td>
<td>0.12</td>
<td>0.02</td>
<td>-0.23</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.83</td>
<td>0.75</td>
<td>-0.56</td>
<td>0.16</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. CSV</td>
<td>0.42</td>
<td>0.56</td>
<td>-0.05</td>
<td>0.14</td>
<td>0.38</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. LV</td>
<td>0.87</td>
<td>0.83</td>
<td>-0.36</td>
<td>0.21</td>
<td>0.68</td>
<td>0.55</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. HDV</td>
<td>0.95</td>
<td>0.86</td>
<td>-0.51</td>
<td>0.24</td>
<td>0.78</td>
<td>0.43</td>
<td>0.93</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Traffic speed</td>
<td>-0.21</td>
<td>-0.11</td>
<td>0.14</td>
<td>-0.08</td>
<td>-0.03</td>
<td>0.12</td>
<td>-0.19</td>
<td>-0.21</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Table 17: Correlation matrix – Bell Common overall (R values).

<table>
<thead>
<tr>
<th>Overall</th>
<th>Total NOx</th>
<th>Total NO2</th>
<th>%NO2</th>
<th>Air temp.</th>
<th>Wind speed</th>
<th>No. CSV</th>
<th>No. LV</th>
<th>No. HDV</th>
<th>Traffic speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total NOx</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total NO2</td>
<td>0.76</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%NO2</td>
<td>-0.10</td>
<td>0.39</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air temp.</td>
<td>-0.06</td>
<td>-0.35</td>
<td>-0.47</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.77</td>
<td>0.48</td>
<td>-0.26</td>
<td>0.02</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. CSV</td>
<td>0.28</td>
<td>0.31</td>
<td>0.02</td>
<td>0.19</td>
<td>0.19</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. LV</td>
<td>0.77</td>
<td>0.52</td>
<td>-0.15</td>
<td>0.15</td>
<td>0.56</td>
<td>0.54</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. HDV</td>
<td>0.86</td>
<td>0.53</td>
<td>-0.24</td>
<td>0.15</td>
<td>0.68</td>
<td>0.42</td>
<td>0.92</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Traffic speed</td>
<td>-0.17</td>
<td>-0.11</td>
<td>0.00</td>
<td>-0.10</td>
<td>0.11</td>
<td>-0.06</td>
<td>-0.29</td>
<td>-0.25</td>
<td>1.00</td>
</tr>
</tbody>
</table>
4.4 Multiple linear regression analysis

Multiple linear regression can be used to test how well a dependent variable can be predicted on the basis of multiple independent variables. A multiple linear regression approach was used to determine average NO$_x$ and NO$_2$ emission factors for different vehicle categories, based upon the overall hourly average emission factors for the traffic, and the proportions of vehicles in different categories. Similar models have been used in earlier studies to derive emission factors (e.g., Imhof et al., 2005; Colberg et al., 2005). Slightly different approaches were required for the Hatfield and Bell Common tunnels, and these are described below.

It should be noted that there ought to be at least around 10-20 times more observations than variables, otherwise the estimates of the regression can be unstable. The number of observations (hourly periods) in the Hatfield tunnel study was more than 300, and there were only four variables. In the Bell Common tunnel study, the numbers of observations in phases 1 and 2 were around 1,190 and 780 respectively, with only two variables. Consequently, this broad pre-requisite condition was not violated. Meteorological parameters and traffic speed – which were shown in the previous section to have little influence on the average emission factor – were excluded.

4.4.1 Hatfield tunnel

For the Hatfield tunnel the following vehicle categories were considered:

- Cars and small vans
- Light goods vehicles
- Rigid heavy goods vehicles
- Articulated heavy goods vehicles

Motorcycles, buses and coaches formed a very small proportion of the traffic, and were therefore excluded from the analysis.

The following regression model was applied to derive emission factors for both NO$_x$ and NO$_2$:

$$E_{total} = (N_{CSV} \times E_{CSV}) + (N_{LGV} \times E_{LGV}) + (N_{rHGV} \times E_{rHGV}) + (N_{aHGV} \times E_{aHGV}) + c$$

where:

- $E_{total}$ = the total hourly emissions from the traffic (the average emission factor per v.km multiplied by the total number of vehicles).
- $N_{CSV}$ = the number of cars and small vans per hour
- $N_{LGV}$ = the number of large vans per hour
- $N_{rHGV}$ = the number of rigid heavy goods vehicles per hour
- $N_{aHGV}$ = the number of articulated heavy goods vehicles per hour
- $E_{CSV}$ = the emission factor for cars and small vans
- $E_{LGV}$ = the emission factor for large vans
- $E_{rHGV}$ = the emission factor for rigid heavy goods vehicles
- $E_{aHGV}$ = the emission factor for articulated heavy goods vehicles
- $c$ = a constant (intercept on y-axis)

The analysis was based upon the data for the whole length of the tunnel and the results from model $M3$. As there are no sources of NO$_x$ or NO$_2$ in the tunnel other than the traffic, it could be considered logical to run the regression model with the constant constrained to zero. However, the results are presented with the constant term included to illustrate the potential importance of emission sources which are not accounted for.

**NO$_x$ emissions**

Tables 18 to 20 show the results of the multiple linear regression calculation for total NO$_x$. Table 18 gives the model parameter estimates, Table 19 the results of the analysis of variance (ANOVA), and Table 20 the model
summary. These Tables are explained in the following paragraphs. Figure 23 shows the observed and predicted values.

Table 18: Results of multiple regression analysis for NO\textsubscript{x} in the Hatfield tunnel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard error</th>
<th>t statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{CSV}$</td>
<td>0.27</td>
<td>0.027</td>
<td>9.658</td>
<td>0.000</td>
</tr>
<tr>
<td>$E_{LV}$</td>
<td>1.17</td>
<td>0.604</td>
<td>1.929</td>
<td>0.055</td>
</tr>
<tr>
<td>$E_{HGV}$</td>
<td>5.37</td>
<td>1.129</td>
<td>4.754</td>
<td>0.000</td>
</tr>
<tr>
<td>$E_{dHGV}$</td>
<td>3.78</td>
<td>1.131</td>
<td>3.343</td>
<td>0.001</td>
</tr>
<tr>
<td>$C$</td>
<td>372.58</td>
<td>50.482</td>
<td>7.380</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 19: Analysis of variance for NO\textsubscript{x} in the Hatfield tunnel.

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F-ratio</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>4</td>
<td>206961584</td>
<td>51740396</td>
<td>339.70</td>
<td>0.0000</td>
</tr>
<tr>
<td>Residual</td>
<td>382</td>
<td>58182853</td>
<td>152311</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>386</td>
<td>265144438</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 20: Regression model summary for NO\textsubscript{x} in the Hatfield tunnel.

<table>
<thead>
<tr>
<th>Multiple R</th>
<th>R squared</th>
<th>Adjusted R squared</th>
<th>Standard error</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.88</td>
<td>0.78</td>
<td>0.78</td>
<td>390.3</td>
<td>387</td>
</tr>
</tbody>
</table>

Figure 23: Observed and predicted total NO\textsubscript{x} emissions – Hatfield tunnel.
The values in the ‘Estimate’ column of Table 18 are equivalent to the emission factors (in g vehicle\(^{-1}\) km\(^{-1}\)) for the different vehicle categories. The p-values indicate whether a variable has statistically significant predictive capability in the presence of the other variables. In this case – with the exception of large vans - these emission factors were significantly different from zero (p<0.05). Consequently, the model could be re-constructed excluding large vans (with, of course, no emission factor being available for these vehicles).

The ANOVA (Table 19) partitions the variability in the dependent variable into two parts. One portion is fitted by the model. This corresponds to the reduction in uncertainty that occurs when the regression model is used to predict the responses. The remaining portion is the uncertainty that remains even after the model is used. The model is considered to be statistically significant if it can account for a large amount of variability in the dependent variable. The null hypothesis for ANOVA is that the average value of the dependent variable is the same for all groups. The ANOVA test procedure produces an F-ratio, which is used to calculate the p-value. If p is less than 0.05, the null hypothesis can be rejected, and it can be concluded that the average of the dependent variable is not the same for all groups. This is the case here.

The model summary (Table 20) shows that the R\(^2\) value for the regression model was 0.78. In other words, the model accounted for 78% of the variability in the average NO\(_x\) emission factor.

Calculation of the Durbin-Watson statistic (not shown) was used to test the residuals to determine if there was any significant correlation based on the order in which the values occurred. There was some indication of possible serial correlation (a correlation in the measurements from one time step to the next). However, when the residuals were plotted against row order no pattern was observed, and thus the level of correlation from the Durbin-Watson statistic appeared to have no substantial practical importance.

**NO\(_2\) emissions**

Tables 21 to 23 show the results of the multiple regression analysis for NO\(_2\). Again, the values in the ‘Estimate’ column of Table 21 are equivalent to the emission factors for the vehicle categories. The p-values show that these were significantly different from zero (p<0.05). Table 23 shows that the R\(^2\) value for the model was 0.83, and the observed and predicted values are plotted in Figure 24. Again, calculation of the Durbin-Watson statistic indicated the possibility of serial correlation, but when residuals were plotted against row order no pattern was observed, and again it appeared that the level serial correlation was of little practical importance.

### Table 21: Results of multiple regression analysis for NO\(_2\) in the Hatfield tunnel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard error</th>
<th>‘t’ statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(_{CSV})</td>
<td>0.04</td>
<td>0.003</td>
<td>12.538</td>
<td>0.000</td>
</tr>
<tr>
<td>E(_{LV})</td>
<td>0.29</td>
<td>0.073</td>
<td>3.917</td>
<td>0.000</td>
</tr>
<tr>
<td>E(_{HGV})</td>
<td>0.59</td>
<td>0.137</td>
<td>4.293</td>
<td>0.000</td>
</tr>
<tr>
<td>E(_{aHGV})</td>
<td>0.33</td>
<td>0.137</td>
<td>2.371</td>
<td>0.018</td>
</tr>
<tr>
<td>c</td>
<td>13.535</td>
<td>6.124</td>
<td>2.210</td>
<td>0.028</td>
</tr>
</tbody>
</table>

### Table 22: Analysis of variance for NO\(_2\) in the Hatfield tunnel.

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F-ratio</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>4</td>
<td>4280895</td>
<td>1070224</td>
<td>477.47</td>
<td>0.0000</td>
</tr>
<tr>
<td>Residual</td>
<td>382</td>
<td>856236</td>
<td>2241</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>386</td>
<td>5137131</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 23: Regression model summary for NO$_2$ in the Hatfield tunnel.

<table>
<thead>
<tr>
<th>Multiple R</th>
<th>R squared</th>
<th>Adjusted R squared</th>
<th>Standard error</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91</td>
<td>0.83</td>
<td>0.83</td>
<td>47.3</td>
<td>387</td>
</tr>
</tbody>
</table>

\[ y = 0.8333x + 26.171 \]
\[ R^2 = 0.8333 \]

Figure 24: Observed and predicted NO$_2$ emissions- Hatfield tunnel.

4.4.2 Bell Common tunnel

For the Bell Common tunnel the following vehicle categories were considered:

- Cars and small vans
- Large vans
- Heavy-duty vehicles

The following regression model was applied to derive emission factors for both NO$_x$ and NO$_2$:

\[ E_{\text{total}} = (N_{\text{CSV}} \cdot E_{\text{CSV}}) + (N_{\text{LV}} \cdot E_{\text{LV}}) + (N_{\text{HDV}} \cdot E_{\text{HDV}}) + c \]  

(12)

where:

- \( E_{\text{total}} \) = the total hourly emissions from the traffic (the average emission factor per v.km multiplied by the total number of vehicles).
- \( N_{\text{CSV}} \) = the number of cars and small vans per hour
- \( N_{\text{LV}} \) = the number of large vans per hour
- \( N_{\text{HDV}} \) = the number of heavy-duty vehicles per hour
- \( E_{\text{CSV}} \) = the emission factor for cars and small vans
- \( E_{\text{LV}} \) = the emission factor for large vans
- \( E_{\text{HDV}} \) = the emission factor for heavy-duty vehicles
- \( c \) = a constant (intercept on y-axis)

However, a first analysis indicated that the inclusion of large vans led to no significant improvement in the model, and that the model could therefore be simplified by reducing the number of vehicle categories to two: LDVs (all cars and vans) and HDVs. Again, a non-zero constant was used in the revised model.
**NO\textsubscript{x} emissions**

Tables 24 to 26 show the multiple linear regression model results for NO\textsubscript{x}. Separate results are provided for the two phases of the Bell Common study, and overall results are also shown. The application of a t-test showed that these were, with one exception (LDVs during phase 2), statistically significantly. For both phases of the study, and overall, NO\textsubscript{x} emissions in the Bell Common tunnel were dominated by heavy-duty vehicles, for which the emission factors were much higher than those obtained in the Hatfield tunnel. The NO\textsubscript{x} emission factors for HDVs were also slightly higher during phase 2 than during phase 1. For LDVs, a negative emission factor was obtained during phase 1, and an emission factor slightly greater than zero was obtained during phase 2. Figure 25 shows the observed and predicted NO\textsubscript{x} values. The R\textsuperscript{2} values for the regression models for phase 1 and phase 2 were 0.75 and 0.91 respectively.

### Table 24: Results of multiple regression analysis for NO\textsubscript{x} in Bell Common tunnel.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard error</th>
<th>‘t’ statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E\textsubscript{LDV}</td>
<td>-0.68</td>
<td>0.04</td>
<td>-15.2</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>E\textsubscript{HDV}</td>
<td>15.89</td>
<td>0.27</td>
<td>58.3</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>1907.6</td>
<td>93.4</td>
<td>20.4</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>E\textsubscript{LDV}</td>
<td>0.06</td>
<td>0.04</td>
<td>1.43</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>E\textsubscript{HDV}</td>
<td>19.19</td>
<td>0.25</td>
<td>76.8</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>1207.8</td>
<td>83.0</td>
<td>14.6</td>
<td>0.00</td>
</tr>
<tr>
<td>Overall</td>
<td>E\textsubscript{LDV}</td>
<td>-0.32</td>
<td>0.04</td>
<td>-8.38</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>E\textsubscript{HDV}</td>
<td>17.12</td>
<td>0.24</td>
<td>72.7</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>1508.5</td>
<td>79.6</td>
<td>18.96</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Table 25: Analysis of variance for NO\textsubscript{x} in the Bell Common tunnel.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F-ratio</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Model</td>
<td>2</td>
<td>6.131E+09</td>
<td>3.066E+09</td>
<td>1773.9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1182</td>
<td>2.043E+09</td>
<td>1728149.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1184</td>
<td>8.174E+09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Model</td>
<td>2</td>
<td>1E+10</td>
<td>5.02E+09</td>
<td>3844.1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>781</td>
<td>1.02E+09</td>
<td>1305128</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>783</td>
<td>1.11E+10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>Model</td>
<td>2</td>
<td>1.5E+10</td>
<td>7.48E+09</td>
<td>3044.9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1966</td>
<td>4.83E+09</td>
<td>2457878</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1968</td>
<td>1.98E+10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 26: Regression model summary for NO\textsubscript{x} in the Bell Common tunnel.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Multiple R</th>
<th>R squared</th>
<th>Adjusted R squared</th>
<th>Standard error</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.87</td>
<td>0.75</td>
<td>0.75</td>
<td>1314.6</td>
<td>1185</td>
</tr>
<tr>
<td>2</td>
<td>0.95</td>
<td>0.91</td>
<td>0.91</td>
<td>1142.4</td>
<td>784</td>
</tr>
<tr>
<td>Overall</td>
<td>0.87</td>
<td>0.76</td>
<td>0.76</td>
<td>1567.8</td>
<td>1969</td>
</tr>
</tbody>
</table>
$y = 0.7501x + 1329.1 \quad R^2 = 0.7501$

$y = 0.9078x + 592.03 \quad R^2 = 0.9078$

Figure 25: Observed and predicted total NOx emissions – Bell Common tunnel.

**NOx emissions**

Tables 27 to 29 show the results for NOx. The application of a t-test showed that these were, in general, statistically significantly. As with NOx, NOx emissions in the Bell Common tunnel were dominated by heavy-duty vehicles, and the NOx emission factors were higher during phase 2 than during phase 1 (see also Figure 25). The reasons for these differences are unclear. Factors such as the ambient temperature and the traffic speed were not strongly correlated with the emission factors. The large difference in ozone concentrations between phase 1 and phase 2 (Figure 18) may have affected the NOx calculations although these differences would, to a large extent, have been taken into account via the use of model $M3$ (and would not have affected NOx anyway).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard error</th>
<th>'t' statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$E_{LDV}$</td>
<td>0.00</td>
<td>0.004</td>
<td>-0.083</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>$E_{HDV}$</td>
<td>0.75</td>
<td>0.028</td>
<td>27.378</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
<td>21.94</td>
<td>9.43</td>
<td>2.327</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>$E_{LDV}$</td>
<td>0.08</td>
<td>0.01</td>
<td>12.36</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$E_{HDV}$</td>
<td>1.47</td>
<td>0.04</td>
<td>39.24</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
<td>164.17</td>
<td>12.44</td>
<td>13.19</td>
<td>0.00</td>
</tr>
<tr>
<td>Overall</td>
<td>$E_{LDV}$</td>
<td>0.04</td>
<td>0.01</td>
<td>5.20</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$E_{HDV}$</td>
<td>0.98</td>
<td>0.04</td>
<td>22.49</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
<td>75.04</td>
<td>14.78</td>
<td>5.08</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 27: Results of multiple regression analysis for NOx in Bell Common tunnel.
Table 28: Analysis of variance for NO$_2$ in the Bell Common tunnel.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F-ratio</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Model</td>
<td>2</td>
<td>16554530</td>
<td>8277265</td>
<td>469.7</td>
<td>8E-151</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1182</td>
<td>20828872</td>
<td>17621.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1184</td>
<td>37383401</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Model</td>
<td>2</td>
<td>80642457</td>
<td>40321228</td>
<td>1374.93</td>
<td>1.4E-256</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>781</td>
<td>22903598</td>
<td>29325.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>783</td>
<td>1.04E+08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>Model</td>
<td>2</td>
<td>68983867</td>
<td>34491934</td>
<td>406.6</td>
<td>1.6E-148</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1966</td>
<td>1.67E+08</td>
<td>84821.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1968</td>
<td>2.36E+08</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 29: Regression model summary for NO$_2$ in the Bell Common tunnel.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Multiple R</th>
<th>R squared</th>
<th>Adjusted R squared</th>
<th>Standard error</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.67</td>
<td>0.44</td>
<td>0.44</td>
<td>132.7</td>
<td>1185</td>
</tr>
<tr>
<td>2</td>
<td>0.88</td>
<td>0.78</td>
<td>0.78</td>
<td>171.2</td>
<td>784</td>
</tr>
<tr>
<td>Overall</td>
<td>0.54</td>
<td>0.29</td>
<td>0.29</td>
<td>291.2</td>
<td>1969</td>
</tr>
</tbody>
</table>

Figure 25: Observed and predicted total NO$_2$ emissions – Bell Common tunnel.
4.5 NO$_2$/NO$_x$ proportions

The NO$_x$ and NO$_2$ emission factors from the two tunnels are summarised in Table 30. For the Bell Common tunnel only the overall results are used, as the reasons for the differences in the emission factors obtained during phase 1 and phase 2 could not be determined. The values are rounded to two decimal places and are shown with 95% confidence intervals. The emission factor values for NO$_x$ and NO$_2$ were then used to calculate the NO$_2$/NO$_x$ proportions, expressed as percentages, and these results are also given in Table 30. As the NO$_x$ emission factors are calculated as NO$_2$ equivalents, the NO$_2$/NO$_x$ proportions would be the same if converted to volumetric units.

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Vehicle type</th>
<th>Emission factor (g vehicle$^{-1}$ km$^{-1}$)</th>
<th>NO$_2$/NO$_x$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NO$_x$</td>
<td>NO$_2$</td>
</tr>
<tr>
<td>Hatfield</td>
<td>Cars and small vans</td>
<td>0.27 (± 0.05)</td>
<td>0.04 (± 0.01)</td>
</tr>
<tr>
<td></td>
<td>Large vans</td>
<td>1.17 (± 1.19)</td>
<td>0.29 (± 0.14)</td>
</tr>
<tr>
<td></td>
<td>Rigid HGVs</td>
<td>5.37 (± 2.22)</td>
<td>0.59 (± 0.27)</td>
</tr>
<tr>
<td></td>
<td>Articulated HGVs</td>
<td>3.78 (± 2.22)</td>
<td>0.33 (± 0.27)</td>
</tr>
<tr>
<td>Bell Common</td>
<td>All LDVs</td>
<td>-0.32 (± 0.08)</td>
<td>0.04 (± 0.01)</td>
</tr>
<tr>
<td></td>
<td>All HDVs</td>
<td>17.12 (± 0.46)</td>
<td>0.98 (± 0.05)</td>
</tr>
</tbody>
</table>

These final results show rather different situations in the two tunnels, with emissions in the Bell Common tunnel being dominated by heavy-duty vehicles. On the other hand, the largest NO$_2$/NO$_x$ proportions were obtained for light-duty vehicles in the Hatfield tunnel, which is a rather surprising result given that a substantial proportion of the light-duty vehicle fleet is composed of vehicles with petrol engines, which have previously been found to have a relatively low NO$_2$/NO$_x$ proportion.

Although more detailed information on traffic composition was available, this information could not be used to refine the emission factor calculations. For example, it was possible to estimate the proportions of petrol-engined and diesel-engined vehicles in the Hatfield tunnel fleet using national statistics, given that no local data were available. However, a single proportion of this type cannot be used to provide more detailed information in multiple regression analyses because of co-linearity.

There was, however, evidence of multiple co-linearity between the supposedly independent variables in the regression procedure. When multiple co-linearity occurs, the variances are large and the parameter estimates obtained from the regression may not be stable. Ridge regression is an effective methodology to reduce this problem because it allows better interpretation of the regression coefficients by imposing some bias on the regression coefficients and reducing their variances (Morris, 1982; Pagel and Lunneberg, 1985; Nooney and Duval, 1993). This should result in more stable estimates, and should be considered in further work.
4.6 Comparisons with other data sources

4.6.1 Comparison with UK emission factors

The results for NO\textsubscript{x} from the two tunnel studies (Table 30) were compared with the emission factors which are currently used in the compilation of the National Atmospheric Emissions Inventory, as well as in local inventories and air pollution models. Details of the NAEI methodology are available from the NETCEN web site\textsuperscript{10}, and it is also described in the UK annual report of greenhouse gas emissions for submission under the Framework Convention on Climate Change (Bagcott \textit{et al.}, 2006). For each vehicle category and pollutant, the average speed functions are expressed in the general form:

\[ E = (a + b.v + c.v^2 + d.v^3 + f.\ln(v) + g.v^3 + h/v + i/v^2 + j/v^3).x \]  

(Equation 1)

Where:  
\(E\) is the emission rate expressed in g km\textsuperscript{-1}  
\(v\) is the average vehicle speed in km h\textsuperscript{-1}  
\(a\) to \(j\), and \(x\) are coefficients

The coefficients are provided in a spreadsheet produced by NETCEN\textsuperscript{11}. Aggregated emission factors for other pollutants are provided on the NAEI web site.

For the Hatfield tunnel, average NO\textsubscript{x} emission factors for each vehicle category in Table 30 (cars and small vans, large vans, Rigid HGVs and articulated HGVs) was calculated for the study period using the UK emission factors and the hourly speed data from the tunnel. In the case of the Bell Common tunnel, only an average NO\textsubscript{x} emission factor for all HGVs was derived (for comparison with the value in Table 30). The relative proportions of rigid and articulated HGVs were assumed to be the average values in the Hatfield tunnel traffic data (49.3% rigid, 50.7% articulated).

The comparisons between the NO\textsubscript{x} emission factors derived from the tunnel measurements, and the emission factors for the corresponding conditions and periods derived using the UK emission factors, are shown in Figures 26, 27 and 28.

It can be seen from Figure 26 that the emission factor for cars and small vans derived from the Hatfield tunnel measurements is slightly lower than the UK emission factor. The relative proportions of petrol and diesel cars in the fleet may have been important in this respect. For the calculation of the UK emission factor, it was assumed that 25% of all cars had diesel engines (diesel cars have higher NO\textsubscript{x} emissions than petrol cars), but the actual proportion in the tunnel was not known, and may have been lower. No corresponding emission factor could be derived from the Bell Common measurements although, as noted in Table 30, a negative emission factor was observed for ‘all LDVs’. The calculated emission factors for the Bell Common tunnel are shown for comparison with the Hatfield tunnel in Figure 26. Indeed, there was little difference between the values calculated using the UK emission factors for the two tunnels. On the other hand, the emission factor for large vans from the Hatfield tunnel measurements was higher than the UK emission factor (Figure 27). Again, no directly comparable emission factor could be obtained for the Bell Common tunnel, and the UK emission factors for the Hatfield and Bell Common tunnels were similar.

One of the most significant findings of the study was the much larger measured emission factor for heavy-duty vehicles in the Bell Common tunnel (around 17 g vehicle\textsuperscript{-1} km\textsuperscript{-1}) compared with the Hatfield tunnel measurements (around 4-5 g vehicle\textsuperscript{-1} km\textsuperscript{-1}) and the UK emission factors (Figure 28). In addition, the NO\textsubscript{2}/NO\textsubscript{x} proportion for such vehicles was lower in the Bell Common tunnel. These findings may have been due in part to differences in the composition of the HDV fleet and vehicle load factors, but a more likely explanation is the difference in road gradient, and this was examined further.

\textsuperscript{10} http://www.aeat.co.uk/netcen/airqual/naei/annreport/annrep99/app1_29.html.

\textsuperscript{11} Available from http://www.naei.org.uk/data_warehouse.php.
Figure 26: NOx emission factors for cars and small vans based on the measurements in the Hatfield tunnel (‘Hat, meas.’) and derived using the UK emission factors for the Hatfield (‘Hat, UK EFs’) and Bell Common (‘BC, UK EFs’) tunnels.

Figure 27: NOx emission factors for large vans based on the measurements in the Hatfield tunnel (‘Hat, meas.’) and derived using the UK emission factors for the Hatfield (‘Hat, UK EFs’) and Bell Common (‘BC, UK EFs’) tunnels.

Figure 28: NOx emission factors for HGVs based on the measurements in the Hatfield and Bell Common tunnels. The values derived using the UK emission factors are also shown.
4.6.2 Gradient effect

Road gradient is known to have a significant effect on emissions from heavy-duty vehicles, and in this study an emission model called PHEM\(^\text{12}\) was used to investigate the magnitude of the effect at Bell Common. PHEM was produced in the European Commission 5th Framework project ARTEMIS\(^\text{13}\) (Rexeis et al., 2005). The model estimates fuel consumption and emissions based on the engine power demand and engine speed during a driving cycle, and can also take into account vehicle load and road gradient (in increments of 2%). Some examples of functions relating NO\(_x\) emissions to average trip speed and road gradient are given in Figure 29. Even a slight increase in gradient can lead to a substantial increase in emissions.

![Figure 29: Effect of gradient on NOx emissions at 50% vehicle load. (Euro II articulated HGV, 34-40 tonnes).](image)

The road in the Hatfield tunnel is at level gradient, whereas in the B tube of the Bell Common tunnel there is an average uphill gradient of around 1.5%, although near the entrance to the tunnel the gradient is closer to 2.5%. PHEM was used to estimate the likely impact of this difference in gradient.

Using PHEM, emission factors were calculated for 48 categories of rigid HGV (8 weight bands, 6 levels of emission control), and 36 categories of articulated HGV (6 weight bands, 6 levels of emission control). The maximum speed allowed for HGVs in the model (86 km h\(^{-1}\)) was used. The results per vehicle category are shown in Table 30. For each weight band, a weighted value for the UK has been calculated, based on the proportions of vehicles in each emission control category. These proportions were taken from the NAEI fleet model for a reference year of 2006 (NETCEN, 2005).

The results indicate that, assuming the speed remains at 86 km h\(^{-1}\), NO\(_x\) emission factors at +2% road gradient are between around 1.4 and 2.2 times higher than those at level grade. It is difficult to determine the relative proportions of vehicle in each of the weight bands in Table 30, and hence an overall ratio between the emission factors at +2% gradient and those at level grade. If it is assumed that the weight bands are evenly distributed within a vehicle type, and the rigid HGVs constitute around 40% of total HGVs (based on the Hatfield tunnel traffic data), then the overall ratio between the NO\(_x\) emission factor at +2% road gradient and that at level grade is 1.93. If it is further assumed that the uphill gradient leads to a reduction in speed of 10 km h\(^{-1}\), then this ratio increases to 1.98 (or roughly 2). When the Hatfield tunnel NO\(_x\) emission factors for HGVs were multiplied by a factor of two (i.e. introducing a hypothetical 2% uphill gradient in the tunnel), the resulting (weighted) emission factor was 8.3 g vehicle\(^{-1}\) km\(^{-1}\).

\(^{12}\) PHEM = Passenger car and Heavy-duty vehicle Emission Model
\(^{13}\) ARTEMIS = Assessment and Reliability of Transport Emission Models and Inventory Systems
Table 30: NO\textsubscript{x} emission factors for different HGV categories and road gradients at 86 km h\textsuperscript{-1} (based on PHEM model).

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Weight band (max. allowable)</th>
<th>UK-weighted NO\textsubscript{x} emission factor by road gradient (g veh\textsuperscript{-1} km\textsuperscript{-1})</th>
<th>EF(2%)/EF(0%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid HGVs</td>
<td>&lt;=7.5 tonnes</td>
<td>3.10 4.38</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>7.5-12 tonnes</td>
<td>4.17 6.60</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>12-14 tonnes</td>
<td>4.36 7.32</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>14-20 tonnes</td>
<td>5.18 8.94</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>20-26 tonnes</td>
<td>6.32 11.36</td>
<td>1.80</td>
</tr>
<tr>
<td></td>
<td>26-28 tonnes</td>
<td>6.25 11.37</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>28-32 tonnes</td>
<td>7.05 12.89</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>&gt;32 tonnes</td>
<td>7.10 13.34</td>
<td>1.88</td>
</tr>
<tr>
<td>Artic. HGVs</td>
<td>14-20 tonnes</td>
<td>4.67 8.31</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>20-28 tonnes</td>
<td>5.54 10.89</td>
<td>1.97</td>
</tr>
<tr>
<td></td>
<td>28-34 tonnes</td>
<td>5.75 11.62</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>34-40 tonnes</td>
<td>6.71 13.57</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>40-50 tonnes</td>
<td>7.42 15.51</td>
<td>2.09</td>
</tr>
</tbody>
</table>

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 are generally heavier than those in the Hatfield tunnel, although no information was available to allow this to be tested.
5 Summary and discussion

In this study air pollution and traffic measurements in the Hatfield and Bell Common tunnels have been analysed to derive emission factors for NO\textsubscript{x} and NO\textsubscript{2}, and hence the proportion of NO\textsubscript{x} emitted as NO\textsubscript{2}, for different vehicle categories.

5.1 Measurements

5.1.1 Overview

Measurements were conducted in the Hatfield tunnel during two phases between November 2005 and February 2006. In the Bell Common tunnel, the measurements were conducted between May and August of 2006, and again between November 2006 and January 2007. In each tunnel, atmospheric concentrations of NO, NO\textsubscript{2} and O\textsubscript{3} were measured continuously at three main sites: near to the tunnel entrance, near to the mid point, and near to the exit. In order to provide greater spatial resolution of NO\textsubscript{2} concentrations, measurements were also conducted inside the tunnel using passive diffusion tubes. Traffic parameters and meteorological parameters were also recorded continuously.

5.1.2 Traffic characteristics

The peak weekday traffic flows at Hatfield and Bell Common were typically 5,000 vehicles per hour and 4,000 vehicles per hour respectively. However, the traffic flow integrated over the day was substantially higher at Bell Common, particularly at weekends. In both tunnels the average hourly speed of the traffic (weighted by vehicle category) varied little, and was usually 100-110 km h\textsuperscript{-1} at Hatfield and 100-120 km h\textsuperscript{-1} at Bell Common. The average hourly speed at Bell Common occasionally fell to around 20 km h\textsuperscript{-1}, usually on weekdays, and the overall average speed was slightly lower. In both tunnels, during weekdays the traffic was dominated by cars and light vans, except during the early hours of the morning when flows were low and heavy goods vehicles formed a large proportion of the traffic. The overall average proportion of heavy-duty vehicles in the Bell Common tunnel (around 17\%) was slightly higher than that in the Hatfield tunnel (around 12-13\%). Few buses, coaches and motorcycles were present.

5.1.3 Meteorological parameters

The hourly average wind speed was just below 3 m s\textsuperscript{-1} in both tunnels. In the Hatfield tunnel the hourly average temperature ranged from 0.7 °C to 17.3 °C. There was a substantial drop in temperature after 16 November. At Bell Common, the hourly average temperature ranged from a minimum of 8.0 °C during the winter campaign to a maximum of 27.8 °C during the summer campaign.

5.1.4 Air pollution measurements

Hatfield tunnel

Although there were significant losses of air pollution data, a substantial database of pollutant concentrations was obtained for the calculation of emission factors. However, there were also a number of inconsistencies in the air pollution data. For example, whereas NO\textsubscript{x} concentrations appeared to be roughly at the same general level during the two phases, NO\textsubscript{2} concentrations were somewhat lower towards the end of the experiment, particularly at the tunnel exit site. It appeared that this reduction in NO\textsubscript{2} coincided with the installation of a replacement NO\textsubscript{x} analyser at the tunnel exit on 20 January 2006. Given that the factors affecting the NO\textsubscript{x} and NO\textsubscript{2} concentrations at the tunnel exit site changed little, it was considered unlikely that both the phase 1 and phase 2 data sets were correct. In addition, prior to 20 January there was a poor relationship between the NO\textsubscript{x} increment over the first tunnel section (entrance to mid-point) and the increment over the second tunnel section (mid-point to exit). For the period after 20 January, there was a 1:1 relationship, as would have been expected. Furthermore, although there was a reasonably good agreement between the average NO\textsubscript{2}
concentrations measured using the continuous analyser and the diffusion tubes at the entrance and mid point sites during phase 1, at the tunnel exit the value from the continuous analyser (169.6 ppb) was much higher than that from the diffusion tubes (108.1 ppb). On the other hand, the average NO2 concentration measured using diffusion tubes at the tunnel exit site during phase 1 was very close to the average concentration at the same site from the continuous measurements during the period after 20 January 2006 (104.1 ppb). Consequently, the air pollution data prior to 20 January were not used.

The diffusion tube measurements indicated that the NO2 concentrations near the outer lane were systematically higher than those by the inner lane, indicating that the air in the Hatfield tunnel is not well mixed. This is likely to affect the emission factors derived using the continuous measurements by the inner lane, in both this study and other studies. However, these differences should have little effect on the estimated proportion of NOx emitted as NO2.

**Bell Common tunnel**

The maximum hourly average NOx and NO2 concentrations (at the exit) were around 4,500 ppb and 560 ppb respectively – considerably higher than in the Hatfield tunnel, even though the peak traffic flows were lower and the tunnel is shorter. For the tunnel entrance site phase one was characterised by much higher ozone concentrations (maximum 73.2 ppm) than phase 2 (maximum 18.8). Again, at the tunnel mid-point and exit ozone concentrations were much lower, although some significant peaks were still observed at the tunnel mid-point site.

In the Bell Common tunnel there was a very good agreement between the diffusion tube measurements and the continuous measurements at the entrance site, but as in the Hatfield tunnel the agreement became worse further into the tunnel, although in Bell Common the diffusion tube results at the mid-point and exit sites were lower than the results from the continuous measurements.

### 5.2 Fleet-weighted emission factors

Fleet-weighted NOx emission factors were calculated for each hour based upon the mean concentrations and total traffic flow. The proportion of NOx emitted as primary NO2 (and hence the NO2 emission factors) was then determined iteratively using three different models, each involving a different set of assumptions regarding the formation of NO2.

In the case of model $M1$, it was assumed that ozone did not react with NO, and therefore the ozone concentration in the tunnel remained at the level at the tunnel entrance. This led to an over-prediction of the ozone concentration at the tunnel mid-point and tunnel exit. In model $M2$, the reaction of ozone with NO was taken into account, and the predicted ozone concentrations at the mid-point and exit were closer to the observed values. The effect of this was that the NO2/NOx proportion needed to be lower in model $M2$ than in model $M1$ in order to offset the extra NO2 produced by the NO-O3 reaction, and to result in the correct concentration of NO2 at the mid-point. Model $M3$, which also included the NO-NO-O2 reaction, had little further effect on the predicted concentration profiles, but this reaction may become more important in longer tunnels. It was assumed that model $M3$, which included the most important reactions leading to the formation of NO2 in tunnel air, resulted in the most accurate predictions. In each tunnel, emission factors were calculated separately for the two tunnel sections (entrance-mid point and mid point-exit), as well as for the whole tunnel.

In the Hatfield tunnel the average NOx and NO2 emission factors determined over the full length of the tunnel and using model $M3$ were 1.26 g vehicle$^{-1}$ km$^{-1}$ and 0.11 g vehicle$^{-1}$ km$^{-1}$ respectively. The average NOx and NO2 emission factors in the Bell Common tunnel (3.86 and 0.27 g vehicle$^{-1}$ km$^{-1}$ for NOx and NO2) were substantially higher than those for the Hatfield tunnel, although the proportions of NO2 was lower (7.6% in Bell Common, compared with 10% in Hatfield). There were no strong correlations between the average NOx and NO2 emission factors and meteorological parameters or traffic speed.
5.3 Multiple linear regression analysis

A multiple linear regression approach was used to estimate average NO\textsubscript{x} and NO\textsubscript{2} emission factors for different vehicle categories in each tunnel, based upon the overall hourly average emission factors for the traffic and the proportions of vehicles in different categories.

In the Hatfield tunnel the NO\textsubscript{x} emission factors for rigid HGVs (5.37 g vehicle\textsuperscript{-1} km\textsuperscript{-1}) and articulated HGVs (3.37 g vehicle\textsuperscript{-1} km\textsuperscript{-1}) were much higher than those for cars/small vans (0.27 g vehicle\textsuperscript{-1} km\textsuperscript{-1}) and large vans (1.17 g vehicle\textsuperscript{-1} km\textsuperscript{-1}). This result was in line with expectations, given that the car and small van fleet contains a large number of petrol-engined vehicles, and modern petrol-engined vehicles tend to emit very little NO\textsubscript{x} compared with large diesel engines. The proportion of large vans having diesel engines is somewhat higher. It is a little surprising to see that the emission factor for articulated HGVs is lower than that for rigid HGVs, given that the former have, on average, a greater weight and a larger engine size, although it is possible that the load factors for rigid vehicles were higher.

NO\textsubscript{x} emissions in the Bell Common tunnel were dominated by heavy-duty vehicles, for which the overall average emission factor (17.1 g vehicle\textsuperscript{-1} km\textsuperscript{-1}) was much higher than those obtained in the Hatfield tunnel. The overall average emission factor for LDVs was slightly negative – again, a slightly surprising result.

However, the largest NO\textsubscript{2}/NO\textsubscript{x} proportions (16-25%) were obtained for light-duty vehicles in the Hatfield tunnel, which again is a rather surprising result given that a substantial proportion of the light-duty vehicle fleet is composed of vehicles with petrol engines, which have previously been found to have a relatively low NO\textsubscript{2}/NO\textsubscript{x} proportion. The NO\textsubscript{2}/NO\textsubscript{x} proportions for HGVs were 9-11% in the Hatfield tunnel and 6% in the Bell Common tunnel.

There was evidence of multiple co-linearity between independent variables in the regression procedure, and as a consequence the parameter estimates obtained from the regression may not be stable. Alternative statistical procedures should therefore be considered in further work. For example, ridge regression is an effective methodology to reduce the problem of co-linearity because it allows better interpretation of the regression coefficients by imposing some bias on the regression coefficients and shrinking their variances.

5.4 Comparison with other data sources

The results for NO\textsubscript{x} from the two tunnel studies were compared with emission estimates obtained using the emission factors which are currently used in the compilation of the UK National Atmospheric Emissions Inventory, as well as in local inventories and air pollution models. The emission factor for cars derived from the Hatfield tunnel measurements was slightly lower than that derived from the UK emission factors. The relative proportions of petrol and diesel cars in the fleet may have been important in this respect. For the calculations using the UK emission factors, it was assumed that 25% of all cars had diesel engines (diesel cars have higher NO\textsubscript{x} emissions than petrol cars), but the actual proportion in the tunnel was not known, and may have been lower. The emission factors for LGVs from the Hatfield tunnel measurements were higher than the UK emission factor.

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\textsuperscript{-1} km\textsuperscript{-1}) compared with the Hatfield tunnel (around 4-5 g vehicle\textsuperscript{-1} km\textsuperscript{-1}) and the UK emission factors. In addition, the NO\textsubscript{2}/NO\textsubscript{x} proportion for such vehicles was lower in the Bell Common tunnel. These findings may have been due in part to differences in the composition of the HDV fleet and vehicle load factors, but a more likely explanation is 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\textsubscript{x} emission factor at +2% road gradient and that at level grade was approximately 2. When the Hatfield tunnel NO\textsubscript{x} emission factors for HGVs were multiplied by a factor of two (i.e. introducing a hypothetical 2% uphill gradient in the tunnel), then this gave a (weighted) value around 8.3 g vehicle\textsuperscript{-1} km\textsuperscript{-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.
6 Conclusions and recommendations

The following conclusions and recommendations have been drawn from this study:

1. A substantial database of pollutant concentrations in the Hatfield and Bell Common tunnel was obtained for the calculation of emission factors. However, because of apparent inconsistencies some of the air pollution data were not used. These data should be re-examined to determine whether they may be of use in the future.

2. The NO₂ generated in the second half of the Hatfield tunnel is probably all primary in origin, with little or no contribution from atmospheric reactions. In longer tunnels where NO is present in higher concentrations and the air has a longer residence time, there may be a significant NO₂ contribution from the reactions of NO with oxygen or organic peroxy radicals. Although NO concentrations in the Bell Common tunnel were high, the tunnel is relatively short and, again, the contribution from these reactions was negligible. Such phenomena ought to be investigated in longer tunnels, and consideration ought to be given to the measurement of different hydrocarbon species.

3. The average fleet-weighted NOₓ and NO₂ emission factors, determined over the full length of the Hatfield tunnel and using model M3, were 1.26 g vehicle⁻¹ km⁻¹ and 0.11 g vehicle⁻¹ km⁻¹ respectively. This equated to an average NO₂/NOₓ proportion of approximately 10%. The average NOₓ and NO₂ emission factors in the Bell Common tunnel (3.86 and 0.27 g vehicle⁻¹ km⁻¹ for NOₓ and NO₂) were substantially higher than at Hatfield, although the proportion of NO₂ was lower (7.6%). These NO₂ proportions were higher than the 5% commonly assumed in air pollution prediction models but lower than the proportions recently reported in the literature for roadside sites in the UK. This may be due, in part, to the restriction on atmospheric NO₂ formation in tunnels resulting from the depletion of ozone.

4. There were no strong correlations between the fleet-weighted NOₓ or NO₂ emission factors and meteorological parameters. There was also no strong correlation with traffic speed. However, the average speed did not differ greatly between the study phases, and so all the results can effectively be considered to be for a single type of vehicle operating condition. Studies in other tunnels with more varied traffic regimes and meteorological conditions will be required to assess the effects of different factors in more detail.

5. Rather different emission factors were obtained for the different vehicle categories in the two tunnels. At Hatfield the NOₓ emission factors for rigid and articulated HGVs (5.37 and 3.37 g vehicle⁻¹ km⁻¹ respectively) were much higher than those for cars/small vans (0.27 g vehicle⁻¹ km⁻¹) and large vans (1.17 g vehicle⁻¹ km⁻¹). This result was broadly in line with expectations, given that the car and light van fleet contains a large number of petrol-engined vehicles, and modern petrol-engined vehicles tend to emit very little NOₓ compared with large diesel engines. However, It was surprising to see that the emission factor for articulated HGVs was lower than that for rigid HGVs, given that the former have, on average, a greater weight and a larger engine size, although it is possible that the load factors for rigid vehicles were higher. NOₓ emissions in the Bell Common tunnel were dominated by heavy-duty vehicles, for which the overall average emission factor (17.1 g vehicle⁻¹ km⁻¹) was much higher than those obtained in the Hatfield tunnel. The overall average emission factor for LDVs was slightly negative – again, a slightly surprising result.

6. The largest NO₂/NOₓ proportions (16-25%) were obtained for light-duty vehicles in the Hatfield tunnel, which was also a rather surprising result given that a substantial proportion of the light-duty vehicle fleet is composed of vehicles with petrol engines, which have previously been found to have a relatively low NO₂/NOₓ proportion. This warrants further investigation, possibly via the conduct of tunnel studies in which the vehicle fleet is restricted to certain types of vehicle at certain times. The NO₂/NOₓ proportions for HGVs were 9-11% in the Hatfield tunnel and 6% in the Bell Common tunnel.

7. The results from PHEM indicated that the overall ratio between the NOₓ emission factor at +2% road gradient and that at level grade was approximately 2. If the Hatfield tunnel NOₓ emission factors for HGVs are multiplied by a factor of two, then this gives 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.

8. Diffusion tube measurements indicated that the air in the Hatfield tunnel is not well mixed, with higher NO$_2$ concentrations being observed near to the outside lane of the carriageway. The implication of this is that the absolute levels of the NO$_x$ and NO$_2$ emission factors from tunnel studies may be slightly underestimated (by up to 10%). However, given that the data are from only one tunnel and are rather limited, it is difficult to justify the application of a general correction for this underestimate, and no adjustments were made to the emission factors in this study. The differences in the absolute emission factors should also have little effect on the estimated proportion of NO$_x$ emitted as NO$_2$.

9. The results for the study ought to be exploited via inclusion in air pollution prediction models, which should then be tested for a range of locations and traffic conditions. This would require the collation and evaluation of existing data on NO$_2$ emissions, including the results of this study. Consideration should also be given to the relevance of these findings in the context of in-tunnel exposure limits and tunnel ventilation design.
7 Acknowledgements

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8 References


Appendix A: Abbreviations and glossary of terms

DOAS          differential optical absorption spectroscopy
HO$_2$        hydroperoxy radical
NO            nitrogen monoxide (otherwise known as nitric oxide)
NO$_2$        nitrogen dioxide
NO$_x$        oxides of nitrogen (NO + NO$_2$)
O$_3$         ozone
OX            total oxidant
primary NO$_2$ NO$_2$ which is emitted directly to the atmosphere (in this case from vehicle exhaust)
ppb           parts per billion
RO$_2$        organic peroxy radicals