Local Measures for NO_2 Hotspots in London

Project 18447

Final Report

March 2010







Experts in air quality
management & assessment

Document Control

Client	TfL	Principal Contact	Elliot Treharne

Job Number	J948

Report Prepared By:	Stephen Moorcroft (AQC), Dr Ian McCrae (TRL), Dr Paul Boulter (TRL) and Prof Duncan Laxen (AQC)

Document Status and Review Schedule

Report No.	Date	Status	Reviewed by
948/3/F2	11 March 2010	Final Report	Prof Duncan Laxen (AQC) Dr Paul Boulter (TRL)

Air Quality Consultants Ltd
23 Coldharbour Road, Bristol BS6 7JT Tel: 0117 974 1086
12 Airedale Road, London SW12 8SF Tel: 0208 673 4313
aqc@aqconsultants.co.uk

Registered Office: 12 St Oswalds Road, Bristol, BS6 7HT
Companies House Registration No: 2814570

Contents

1 Introduction 2

2 Overview of NOx and NO_2 Emissions and Concentrations in London 5

3 Overview of Borough Action Plan Measures 17

4 Review of Abatement Measures.. 20

5 Local Measures for NO_2 Hotspots in London.. 27

6 Eco-Driving 35

7 References 37

8 Glossary.. 39

A1 Appendix 1 – The effects of eco-driving on fuel consumption and exhaust emissions . 40

1 Introduction

Background

1.1 Air Quality Consultants (AQC) and the Transport Research Laboratory (TRL) were commissioned by Transport for London (TfL) in August 2009 to prepare a report on potential local measures that could be implemented to address PM_{10} hotspots in London (Moorcroft et al, 2009). This report builds upon that previous study, but specifically addresses local measures that could be applied to reduce nitrogen dioxide (NO_2) concentrations. In addition, this report also quantifies the potential benefits associated with so-called "eco-driving".

1.2 This report has been completed to present a range of local measure options for consideration during an early stage of the Strategy development process, and accordingly does not take account of the MAQS that will be issued for public consultation in April 2010 or indeed the final MAQS, and nor does it take account of any revised modelling work that may supersede the studies cited in this report.

1.3 The European Union (EU) limit values for NO_2 are to be achieved by the end of 2010 (see Table 1). However, it is clear from both monitoring and modelling studies that the limit values will not be met within this time frame across many parts of the UK, and particularly within Greater London. Defra is therefore currently preparing a Time Extension Notification to the European Commission to extend the deadline for the limit values to 2015.

Table 1: Air quality limit values for NO_2

Averaging Period	Objective
1-hour	200 $\mu g/m^3$ not to be exceeded more than 18 times a year
Annual mean	40 $\mu g/m^3$

1.4 The revised Mayor's Air Quality Strategy (MAQS) (GLA, 2009a) was published for consultation in 2009. The analyses carried out to support the MAQS show that annual mean concentrations of NO_2 will still exceed the limit value by 2015 across 45 percent of London, including 65 percent of roads, unless further action is taken. The predicted exceedence areas are shown in Figure 1, and are predominantly located in central London and in the vicinity of Heathrow Airport, but also at the roadside of major roads. The modelling studies also indicate that the 1-hour mean limit value for NO_2 may also be exceeded close to a few major roads in London.

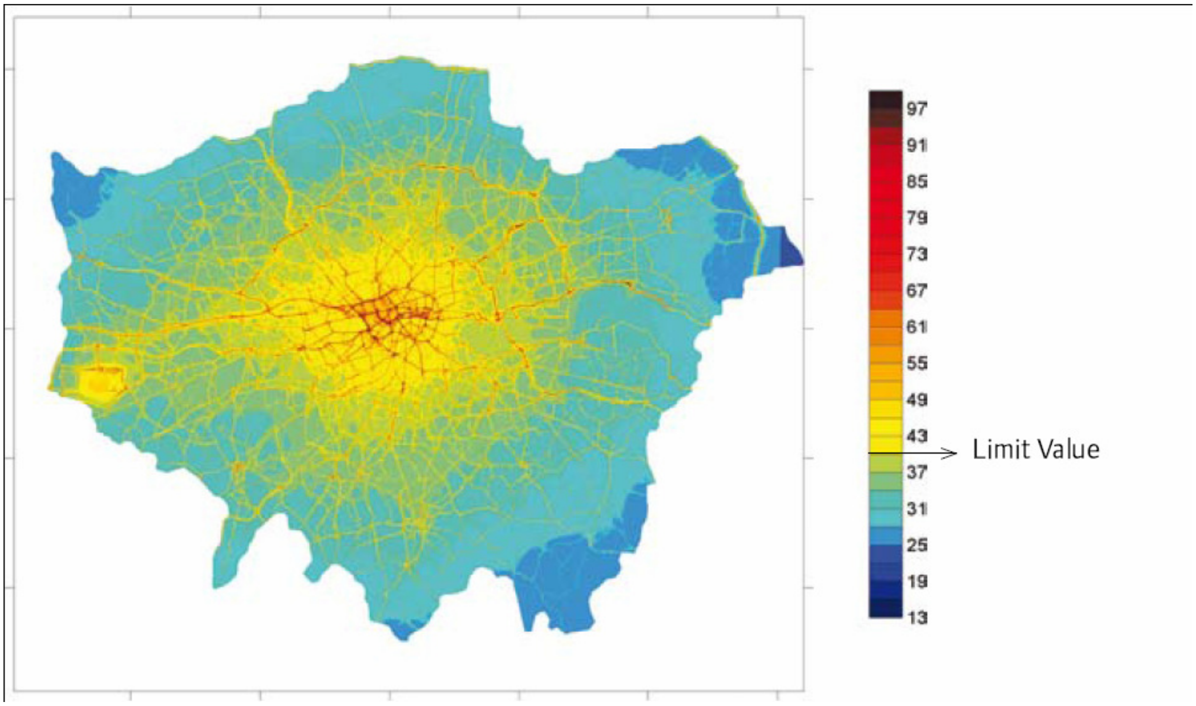

Figure 1: Predicted annual mean NO_2 concentrations in 2015 (source: Greater London Authority, 2009)

1.5 The draft MAQS (GLA, 2009)) sets out a range of proposed interventions that should be taken forward at both the national and London-wide levels. However, specific local measures, implemented by both TfL and the London boroughs, and targeted at hotspot areas, can also help to reduce exceedences of the limit values. This report sets out advice on potential local measures that could be applied for NO_2.

1.6 It is important to note that this study focuses on local measures that could be applied within specific street settings and that may be transferable to other locations. It is not the purpose of this study to identify or address wider-scale measures that may be implemented to reduce emissions and concentrations; such measures are being considered separately by the Mayor.

1.7 As shown in Figure 1, the predicted exceedences cover a large area of London, and it would not be practicable to carry out detailed assessments across all of these locations. The approach taken in this report has therefore been to focus on seven specific locations in London, with the assumption that any measures which can be applied to these locations could also be readily transferred to other parts of London with similar characteristics and conditions.

1.8 In selecting these locations, the following issues were taken into consideration:

- Locations were selected so as to represent different conditions across London, and within different geographical areas, e.g. inner and outer areas, proximity to major roads with free-flowing traffic or congested traffic conditions, etc.

- Proximity to an automatic monitoring station in the London Air Quality Network; this was an important consideration, as high quality oxides of nitrogen (NOx) and NO_2 data were needed to derive trends and to determine the magnitude of the required improvement.

1.9 The seven selected locations, and the associated monitoring stations were as follows:

1. Central London – Marylebone Road,
2. Central/Inner London - Holloway Road
3. Central/Inner London - Putney High Street
4. Central/Inner London - New Cross
5. Heathrow area – Hillingdon Oxford Avenue (A4)
6. Brent, A406 (North Circular) - Brent IKEA
7. Havering, A13 – Rainham New Road

1.10 A summary of the traffic flows, traffic composition and estimated NOx emissions for each road link at these locations is provided in Chapter 2. These data indicate that a range of conditions has been included in the assessment, and support the inclusion of the selected sites in this study.

2 Overview of NOx and NO_2 Emissions and Concentrations in London

2.1 In order to reduce exposure to NO_2 in London it is necessary to have an understanding of its characteristics, emission sources and formation mechanisms. A brief overview of the characteristics and sources of NOx and NO_2 emissions in London is therefore provided, together with specific information on NOx and NO_2 emissions and concentrations at the selected hotspots.

NOx and NO_2 Chemistry

2.2 Combustion processes result in the emission of nitric oxide (NO) and NO_2 (jointly referred to as NOx). Nitrogen dioxide is also formed in the atmosphere by the reaction of NO and ozone (O_3). After dilution of NO in ambient air, a photo-stationary equilibrium involving NO, NO_2 and O_3 is approached, with sunlight destroying NO_2, only for it to be reformed through the reaction of NO and O_3. A variety of pathways subsequently convert NOx to other species, such as nitric acid and particulate nitrate.

2.3 The concentration of NO_2 at a given location is determined by a number of factors, including background NOx and O_3 concentrations, the magnitude and proximity of NOx emissions from local sources, solar intensity, and the rate at which emissions are dispersed (which in turn is related to factors such as wind speed and the degree of turbulent mixing, that may be strongly influenced by local settings, such as street canyons etc). Another important factor is the proportion of NOx that is emitted directly from vehicle exhaust as NO_2.

Role of Primary NO_2 Emissions

2.4 NO_2 emitted directly in vehicle exhaust is termed "primary NO_2", while NO_2 formed in the atmosphere is termed "secondary NO_2" (the proportion of primary NO_2 is termed "f-NO_2"). During the 1990s it was generally assumed that f-NO_2 for vehicle exhaust was around 5% (the other 95% being nitric oxide (NO)). Since around the year 2000, f-NO_2 has increased ostensibly as a result of the after-treatment technologies used in modern diesel vehicles (e.g. diesel oxidation catalysts and particle filters) (e.g. Carslaw, 2005). In the development of the Network Emissions Model (NEMO) in Austria, Rexeis and Hausberger (2009) noted that the percentage of NO_2 in the total of tailpipe NOx emissions for diesel cars increased from 7% for conventional diesel without an oxidation catalyst to 60% for a Euro 4 vehicle with a diesel particulate filter (DPF). For Euro 5 and Euro 6 diesel cars the share of NO_2 in the tailpipe NOx is also assumed to be 60%.

2.5 Heavy-duty vehicles and buses show a smaller f-NO_2, but the fitting of DPFs to buses substantially increases the f-NO_2. All TfL pre-Euro IV buses now operate with such traps.

2.6 The type approval procedures for new vehicles include the measurement of NOx emissions, but the air quality limit values are for NO_2 concentrations. Away from roads, the effect of increasing primary NO_2 emissions is limited, but at roadside sites the higher f-NO_2 values can have a significant effect on roadside concentrations of NO_2.

2.7 Figure 2 shows forecasts of f-NO_2 in London up to 2025, for all traffic including for London buses. Clearly buses have had high f-NO_2 values, which were probably brought about in part by the introduction of DPFs to reduce PM emissions. This has contributed to increased NO_2 concentrations during the last decade alongside roads with a high proportion of buses. The projection is for a strong decline in fNO_2, as new buses are introduced that use selective catalytic reduction (SCR) technology downstream of the DPF to reduce NOx emissions, but which also gives rise to lower f-NO_2 values. This should prove beneficial alongside those roads with a high proportion of buses. However, the overall picture for London roads is of an increase in f-NO_2. This is largely driven by the penetration vehicle with higher Euro standards in the diesel car/LGV fleet, which are associated with higher f-NO_2 values than vehicles with lower Euro standards. This will continue to have an effect on roadside concentrations, counteracting some of the expected improvements from declining NOx emissions.

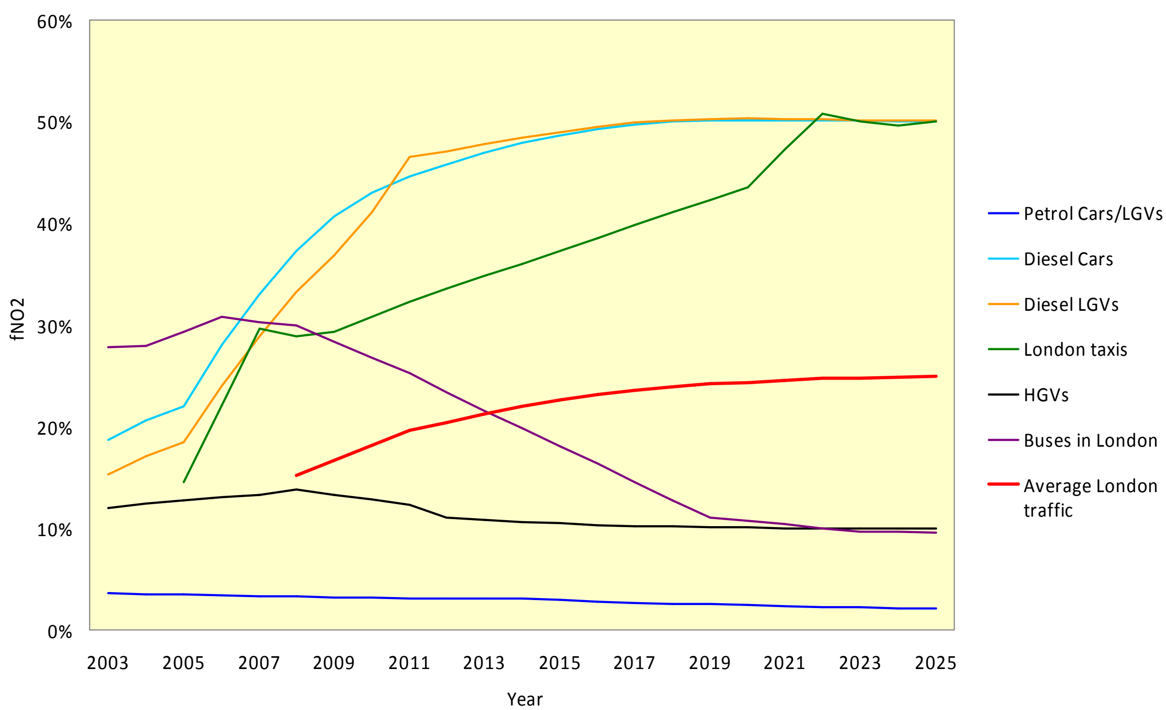

Figure 2: Forecasts of Primary NO_2 (f-NO_2) Proportions from London Traffic Including London Buses (source NOx:NO_2 calculator, Defra 2010)

Trends in NOx Emissions

2.8 The Air Quality Expert Group (AQEG, 2007), in its review of *Trends in Primary Nitrogen Dioxide in the UK*, concluded that the increase in f-NO_2 from certain vehicles was counteracting the expected decline in NOx emissions. However, AQEG also concluded that the evidence at that time suggested that reductions in total NOx emissions would be sufficient to reduce NO_2 concentrations. This view was predicated on the forecasts of significant reductions in emissions of NOx associated with the progressive introduction of light-duty vehicles meeting the Euro 4, Euro 5 and Euro 6 standards, and heavy-duty vehicles meeting the Euro IV, Euro V and Euro VI standards. A recent study in London by Beevers et al. (2009) calculated the impact of these changes over the period 2003 to 2008 as being a 20% reduction in NOx emissions from road traffic in inner London, and a 29% reduction in outer London.

2.9 It is important to recognise that emission factors are based on relatively few test data, which are absent completely for new vehicles that will have to meet standards not yet in place. It is commonly assumed that the emission levels for new vehicle types will decrease relative to earlier types (e.g. Euro 3/III) in proportion to the type approval limit values for the relevant pollutants. This approach has been used in the development of the UK emission factors.

2.10 However, there is some recent evidence to suggest that NOx emissions from Euro V HDVs in use are not as low as might be expected from the reduction in the limit value at type approval (e.g. Ligterink et al., 2009; Rexeis and Hausberger, 2009). The differences appear to be particularly pronounced for urban driving conditions, as explained by Rexeis and Hausberger (2009). Euro V HDVs equipped with selective catalytic reduction (SCR) after-treatment have very low emission levels during rural and motorway driving, but not under the low engine loads associated with urban or driving. The reason for this is that the SCR system needs to attain a certain temperature for efficient NOx reduction. As the type approval procedure for Euro IV and Euro-V HDVs consists of little urban driving, there is no incentive for the optimisation of emissions under these conditions. This implies that measures and policies which are designed to increase the proportion of the newest vehicles (e.g. replacing older HGVs with Euro V HGVs in a low-emission zone (LEZ)) may have less of an effect that previously anticipated, particularly in urban areas (although they will still be beneficial).

Trends in NOx and NO_2 Concentrations

2.11 Annual mean NO_2 and NOx concentrations at each of the seven locations selected for this study are summarised in Figures 3 and 4, while the numbers of hours with NO_2 above 200 $\mu g/m^3$ are set out in Table 2. Care should be taken in comparing results between sites, due to the different distances of the monitors from the kerb. For example, the Hillingdon Oxford Avenue monitor is more than 20m back from the main road (which compares with adjacent properties just 12m from the road), whilst the Marylebone Road monitor is situated right at the kerb (which compares with adjacent buildings which are approximately 7m back from the kerb). These differences in distances will have an appreciable influence on the measurements, since concentrations of NOx and NO_2 reduce rapidly on moving away from roads.

2.12 The highest average NOx measurements during 2009 were observed at Putney High Street, although it should be recognised that fewer than 6 months of data were available for this site and the data were un-ratified, whilst the data for the other sites were for full calendar years. NOx concentrations at Marylebone Road have been consistently between 280 $\mu g/m^3$ and 312 $\mu g/m^3$ since 2003, with no obvious reduction over time. Similarly, NOx concentrations at Brent Ikea have been consistently greater than 250 $\mu g/m^3$ since the site was commissioned, again with no obvious downward trend. There appears to be some evidence for reducing NOx concentrations at Holloway Road. The reductions have, however, been fairly small, with concentrations falling from 186 $\mu g/m^3$ in 2003 to 146 $\mu g/m^3$ in 2009. New Cross, Oxford Avenue, and Rainham New Road (with the exception of 2009) also appear to show some evidence of reducing NOx concentrations, but the reductions are not particularly pronounced. The absence of any clear downward trend at the study sites is consistent with the findings of the study by Beevers et al. (2009) for a wider range of sites across London. This showed an increase in NOx concentrations at roadside sites in inner London of around 7%, with a decrease of around 8-9% at outer London sites.

2.13 Annual mean NO_2 concentrations at Marylebone Road have been consistently higher than 100 $\mu g/m^3$ since 2003, and the annual mean concentration in 2009 was effectively unchanged from that in 2003. With the exception of the very high period-mean concentration measured at Putney High Street (which at 148 $\mu g/m^3$ is more than three times the annual mean limit value), all of the other annual means were less than 80 $\mu g/m^3$ in every year. Brent Ikea tended, on average, to have the next highest concentrations, with Rainham New Road and Oxford Avenue tending to have the lowest. There is no clear trend of falling concentrations at any site.

2.14 In terms of the limit value for 1-hour mean NO_2 concentrations, Table 2 sets out the numbers of exceedences at each site during 2009. The limit value (no more than 18 exceedences per year) was exceeded by a substantial margin at Marylebone Road and Putney High Street, but not at the other sites.

Table 2: Number of Exceedences of 200 µg/m³ as a 1-hour Mean NO_2 Concentration in 2009 [a]

Site	Number of Exceedences
Brent Ikea	14
Rainham New Rd	0
Oxford Ave	0
Holloway Road	6
Marylebone Road	477
New Cross	6
Putney High Street	1002 [b]

[a] Partly non-ratified data.

[b] Less than half of a year and all data unratified.

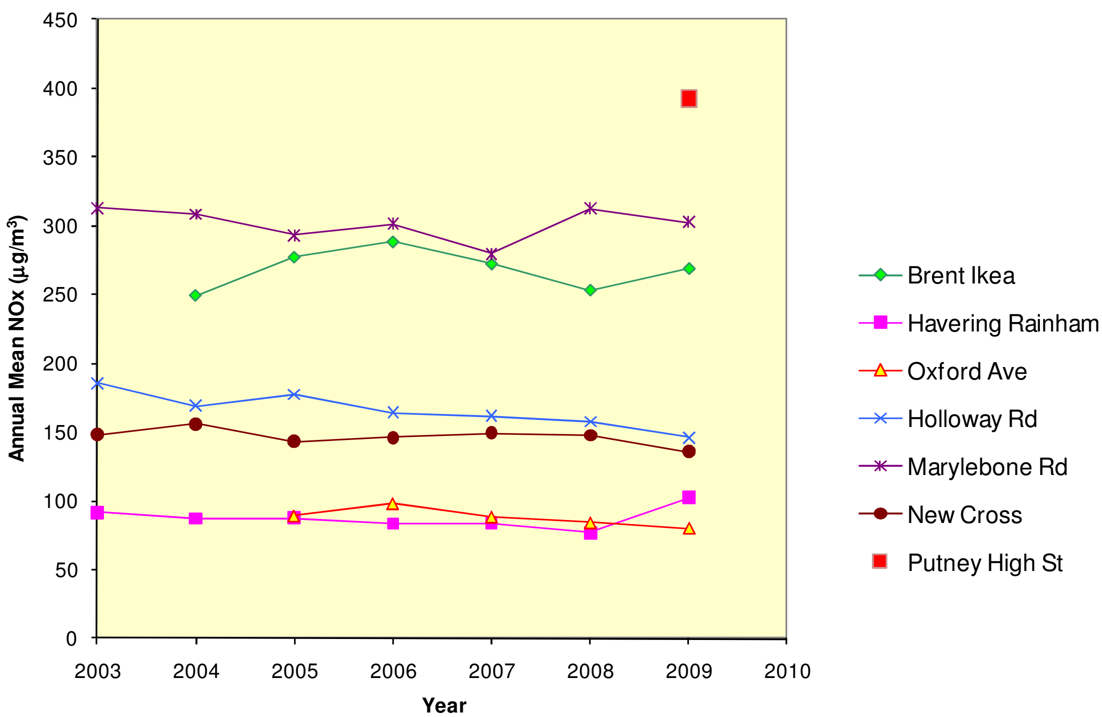

Figure 3: Trends in Measured Annual Mean NOx Concentrations. Data capture >75% except at Putney High Street, where the monitor was been in place for less than six months in 2009. Some of the 2009 data are provisional.

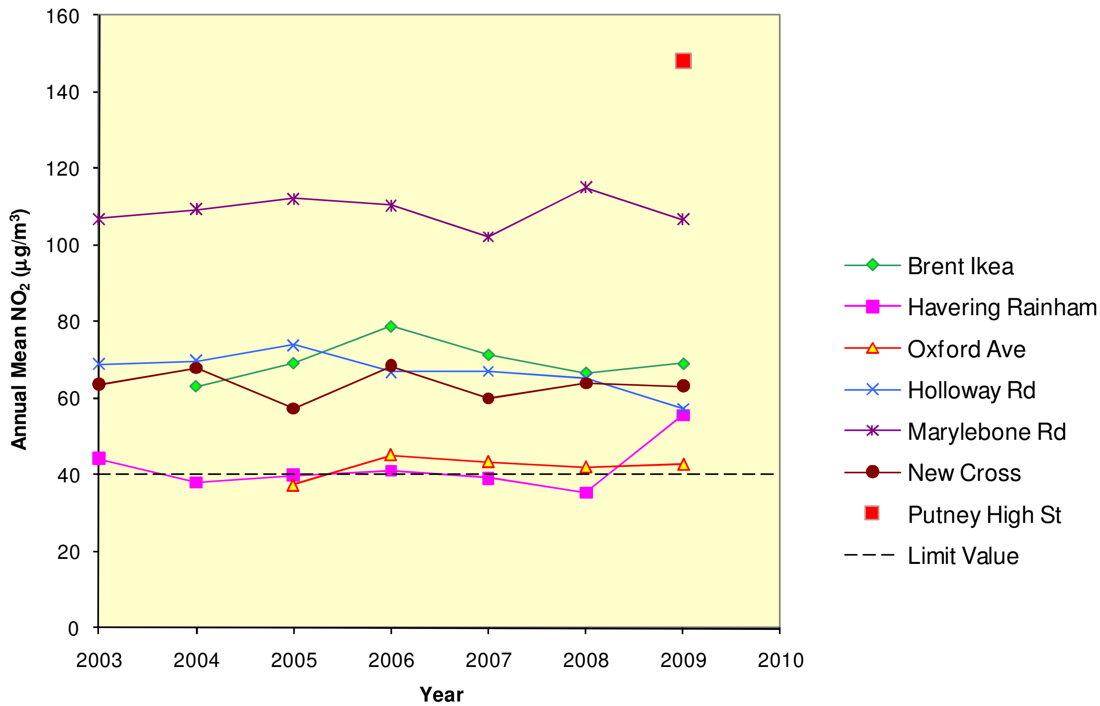

Figure 4: **Trends in Measured Annual Mean NO_2 Concentrations.** Data capture >75% except at Putney High Street, where the monitor was been in place for less than six months in 2009. Some of the 2009 data are provisional.

Source Contributions to NOx Emissions

2.15 Table 3 sets out the traffic flows on each of the seven identified locations (road links), together with the proportions of each vehicle type. These data were taken from the 2006 London Atmospheric Emissions Inventory (LAEI) (GLA, 2009b). The flows have been combined with Defra's new Emission Factor Toolkit (v4.1; published by Defra 2010) to calculate the contribution of each vehicle type to the total NOx emissions from the road. These data are also shown in Table 3 and indicate that while cars form the bulk of the traffic (64-84%), they contribute just 23-45% of the NOx emissions. On the other hand, HGVs contribute a relatively small amount to total flows (2-8%), but make a relatively large contribution to NOx emissions (25-57%).

Table 3: Average Traffic Flows and Fleet Compositions, and Relative Contribution of Each Vehicle Class to Local NOx Emissions at Each Site in 2009

		Brent IKEA	Rainham New Rd	Oxford Avenue	Holloway Road	Marylebone Road	New Cross	Putney High Street
	Vehicles per day	100,226	22,608	23,029	32,593	66,542	38,128	22,427
Petrol Cars	% Traffic	57%	54%	60%	51%	46%	47%	50%
	% Emissions	19%	13%	23%	15%	13%	11%	12%
Diesel Cars	% Traffic	22%	21%	24%	20%	18%	19%	20%
	% Emissions	17%	13%	22%	17%	15%	12%	17%
Taxis	% Traffic	0.9%	0.9%	0.9%	3.5%	10%	3.5%	3.4%
	% Emissions	1.0%	0.7%	1.2%	3.7%	11%	2.9%	3.4%
Petrol LGVs	% Traffic	1.4%	1.4%	0.7%	1.6%	1.4%	1.2%	1.2%
	% Emissions	0.9%	0.6%	0.5%	0.9%	0.7%	0.5%	0.6%
Diesel LGVs	% Traffic	12%	12%	6.0%	14%	12%	11%	11%
	% Emissions	15%	11%	8.9%	18%	15%	10%	13%
Rigid HGVs	% Traffic	3.5%	5.4%	2.0%	3.2%	3.1%	3.7%	2.6%
	% Emissions	24%	30%	18%	26%	25%	24%	21%
Articulated HGVs	% Traffic	1.7%	2.7%	0.3%	0.6%	0.4%	1.2%	0.2%
	% Emissions	21%	29%	4.9%	10%	5.7%	15%	3.6%
Buses and Coaches	% Traffic	0.5%	1.2%	5.0%	2.0%	3.4%	7.6%	6.5%
	% Emissions	1.6%	2.9%	20%	8.0%	14%	24%	28%
Motorcycles	% Traffic	1.2%	0.6%	1.1%	3.8%	5.5%	6.3%	6.2%
	% Emissions	0.4%	0.1%	0.4%	0.9%	1.2%	1.2%	1.2%

2.16 Concentrations of NOx and NO_2 are influenced by both local (in this case road traffic) and background sources. Background concentrations are influenced by emissions from the wider, local area, and by emissions transported from regional and transboundary sources. Local measures applied to traffic on individual roads will not affect these background contributions. Background concentrations during 2009 at each site have been derived from the national maps published by Defra, which cover the whole of the UK on a 1km x 1km grid (Defra, 2010).

2.17 The 2009 annual mean NOx concentrations measured at each of the seven monitoring sites have been source-apportioned by first subtracting the mapped background concentrations from the measured values to derive the local road contribution (termed "Road NOx"), and then by apportioning this road contribution using the data in Table 3. The results are presented in Figure 5 . It should be noted that whilst the data for most sites are based on a full calendar year, the data for Putney High St relate to only a six-month period.

2.18 Figure 5 shows the background contribution to vary between 32 μg/m³ and 72 μg/m³, with Marylebone Road having the highest background and Rainham New Road the lowest. In relative terms, the background contribution ranges between approximately 75% of the total NOx at the Oxford Avenue site (which is near to Heathrow Airport and some distance from the road), to 12% at Putney High Street. In terms of local traffic sources, passenger cars and HGVs are the largest contributors at all sites, with cars contributing a maximum of 98 μg/m³ to NOx at Putney High Street and a minimum of 9 μg/m³ at Oxford Avenue; HGVs contribute between 95 μg/m³ and 4 μg/m³. The contribution of bus emissions is substantial at Putney High Street, New Cross and Marylebone Road, but less so at the other sites. Similarly, the contribution of taxis at Putney High Street and Marylebone Road is appreciable, but relatively small at the other locations.

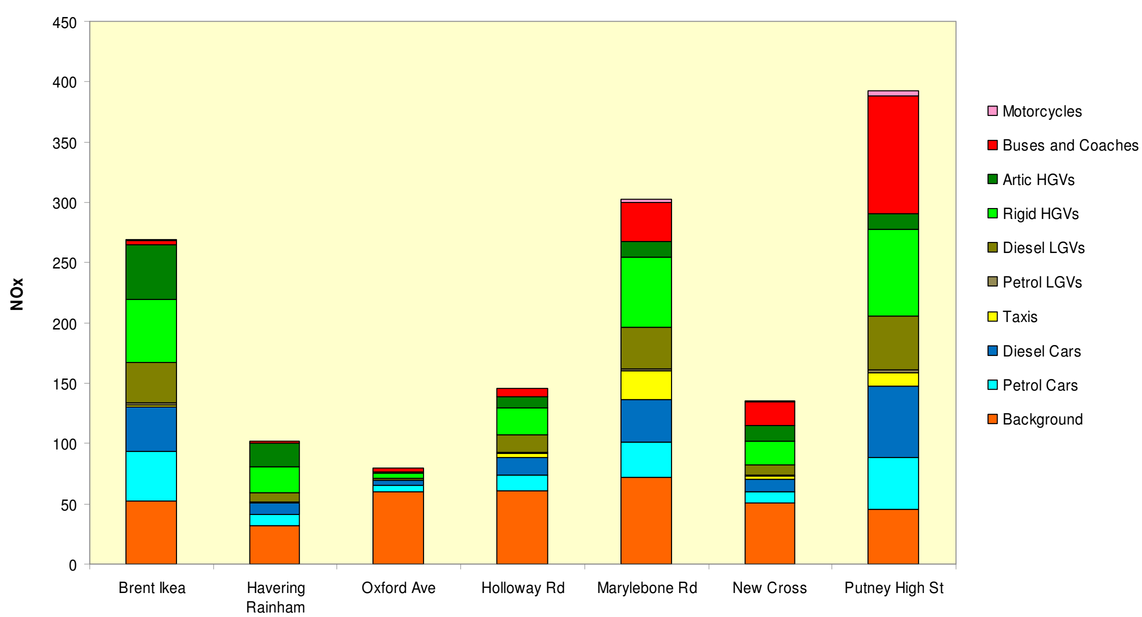

Figure 5: Source Apportioned Annual Mean NOx Concentrations in 2009 (μg/m³)

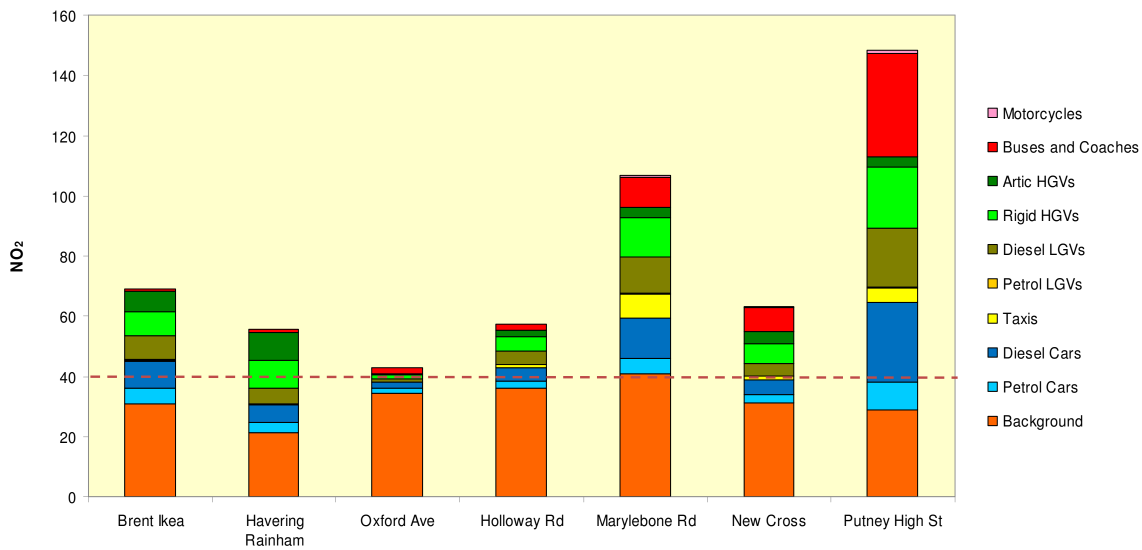

Figure 6: Source Apportioned Annual Mean NO_2 Concentrations in 2009 (µg/m^3)

2.19 Figure 6 provides similar estimates for source apportionment for NO_2 based on available emissions factors This allows for the varying contributions of primary NO_2 from the different vehicle types. It does this by in turn removing the NOx contribution from each vehicle type in turn and then recalculating the f-NO_2 for the remaining vehicle mix and using the NOx to NO_2 calculator (Defra 2010) to derive a new NO_2 concentration. The difference between this NO_2 concentration and the total NO_2 concentration derived from the calculator is then assigned to the vehicle type. The results for each vehicle type calculated in this way are then summed. This sum was then scaled to match the measured road NO_2 (total minus background) and this factor used to adjust the contribution from each vehicle type.

2.20 Comparing Figure 5 with Figure 6 shows that the background contribution to be proportionally higher for NO_2. There is also a more dominant role for diesel cars and light goods vehicles. At Marylebone Road in 2009, the background contribution exceeded 40 µg/m^3 (the limit value), and was only marginally lower at Oxford Avenue and Holloway Road. The contribution of passenger cars to annual mean NO_2 concentrations in 2009 ranged from 4 µg/m^3 at Oxford Avenue, to 19 µg/m^3 at Marylebone Road and 36 µg/m^3 at Putney High Street. Taxis contributed 8 µg/m^3 of NO_2 at Marylebone Road and 5 µg/m^3 at Putney High Street, but less than 1 µg/m^3 at all other sites. Buses and coaches contributed 34 µg/m^3 to measured NO_2 concentrations at Putney High Street, 10 µg/m^3 at Marylebone Road and 8 µg/m^3 at Lewisham New Cross, then below 2 µg/m^3 at the other sites.

Improvements Required

2.21 The results presented in Figure 6 are informative, but are potentially misleading due to the non-linear nature of the NOx to NO_2 relationship. Thus, whilst the results show the relative contribution of each source to the total NO_2 concentration, it should be recognised that removing any one source would not bring about a proportional reduction in NO_2. For example, Figure 6 shows that HGV traffic contributed 24 $\mu g/m^3$ to the measured NO_2 concentrations at Putney High Street; the removal of all HGV traffic would not, however, reduce concentrations by this amount. This is because, for example, a 10% reduction in road NOx concentrations would not bring about a 10% reduction in road NO_2 concentrations.

2.22 Because of this, it is appropriate to investigate the reduction required to achieve the limit value in terms of NOx, rather than NO_2. On investigation, it was found that the method for calculating NO_2 from NOx provided by Defra (2010) does not describe some of the identified sites very well. Site-specific NOx to NO_2 relationships were thus calculated using the hour-by-hour NOx and NO_2 data from each monitoring site in 2009. These calculated relationships are set out below, and are also shown in Figure 7.

- New Cross NO_2 = Exp (-0.0567 x Ln NOx^2 + 1.2196 x NOx – 0.3945)
- Marylebone Road NO_2 = Exp (-0.0324 x Ln NOx^2 + 1.0033 x NOx + 0.0557)
- Putney High Street NO_2 = Exp (-0.0008 x Ln NOx^2 + 0.8177 x NOx + 0.1116)
- Holloway Road NO_2 = Exp (-0.0437 x Ln NOx^2 + 1.156 x NOx – 0.5797)
- Oxford Avenue NO_2 = Exp (-0.0468 x Ln NOx^2 + 1.1001 x NOx – 0.0847)
- Rainham New Rd NO_2 = Exp (-0.0134 x Ln NOx^3 + 0.0751 x NOx^2 + 0.819 NOx^2 + 0.0626)
- Brent Ikea NO_2 = Exp (0.6524 x NOx + 0.6149)

2.23 These site-specific NOx to NO_2 relationships have been used to calculate the annual mean NOx concentration that would correspond to an annual mean NO_2 concentration of 40 $\mu g/m^3$ at each site. Table 4 sets out the NOx concentration measured at each site in 2009, as well as the calculated road NOx component, the total NOx concentration estimated to be equivalent to the limit value (based on 2009 data), the NOx reduction required to meet the limit value (i.e. the total NOx minus the required NOx), and the reduction required as a percentage of the Road NOx. Whilst alternative methods could be used to calculate the level of reduction required, they are not expected to give significantly different results from these.

2.24 It is also important to note that the calculated reduction for NOx in Table 4 does not take account of any reduction in the background contribution: should background concentrations decline in future years in line with current Defra predictions (Defra, 2010) then the required improvement in 2015 would be lower than that shown in Table 4. However, as shown in Figure 3, there is little evidence to support declining NOx concentrations at any sites in London at present.

2.25 Table 4 indicates that even removing all traffic from Marylebone Road would not deliver compliance with the limit value unless accompanied by a reduction in local background concentrations, or other measures to address ambient NO_2. Substantial reductions in local traffic emissions are required at other sites e.g. approximately 90% at Putney High Street, 85% at New Cross, and more than 65% at all other locations[1].

Table 4: Reduction in NOx Concentrations Required to Meet the Limit Value Based on 2009 Data

Location	Total NOx (µg/m^3)	Road NOx (µg/m^3)	Required Total NOx (µg/m^3)[a]	Reduction Required (µg/m^3 NOx)[a]	Reduction Required as % of Road NOx
Brent Ikea	269	217	111	158	73%
Rainham New Rd	102	70	55	47	67%
Oxford Ave	80	20	65	15	77%
Holloway Rd	146	85	85	62	72%
Marylebone Rd	303	231	66	237	103%
Putney High St	393	347	81	312	90%
New Cross	136	85	64	72	85%

[a] The annual mean NOx concentration that would give an annual mean NO_2 concentration of 40 µg/m^3 at each site according to the calculated NOx to NO_2 relationships, and the reduction required to meet this NOx concentration

[1] This assumes that the NOx:NO_2 curves described in Figure 7 remain unchanged.

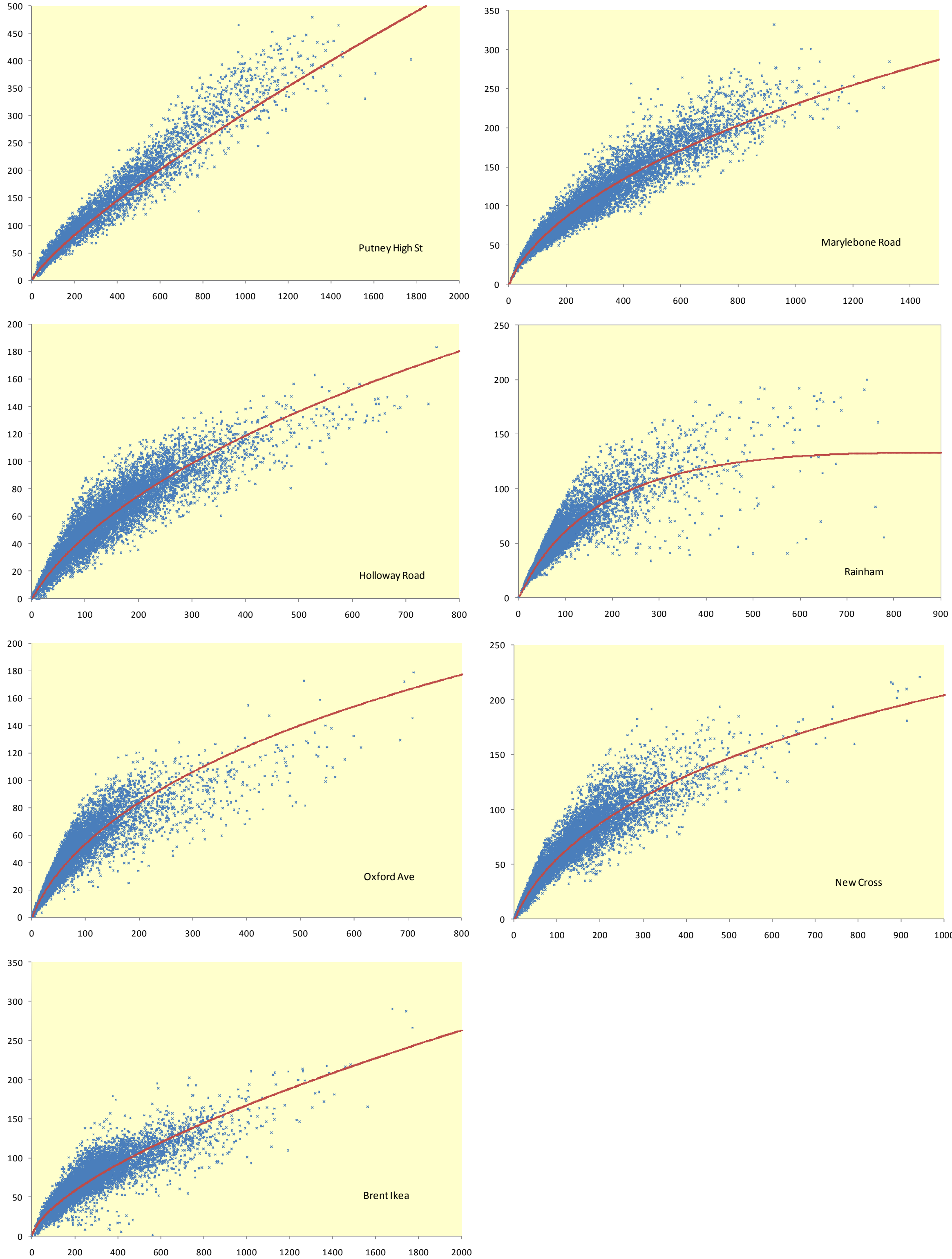

Figure 7: Hourly NOx (horizontal axis) vs NO_2 (vertical axis) Concentrations ($\mu g/m^3$) Measured in 2009 at Each Site with Best-fit Relationship Line Shown in Red.

3 Overview of Borough Action Plan Measures

3.1 This Chapter provides a brief overview of the measures included in borough Air Quality Actions Plans. The focus has been upon those boroughs within which the road links identified for this study are located. It is important to note that this information was derived from the database held by GLA, but no attempt was made to check on the status of implementation of the measures.

3.2 The intent of this exercise is to avoid duplication, i.e. if a measure is widely in use by the boroughs, or is intended to be introduced, there is little benefit in further proposals being submitted.

3.3 The analysis of borough measures has been carried out using the database maintained by GLA. The measures have been categorised, and are summarised in Table 5 below. A number of measures are consistent across boroughs, for example the promotion of walking and cycling campaigns, travel plans, parking management and charging. These measures were therefore not taken forward in this assessment, as they would represent a duplication of interventions that are already planned or underway. It is of interest to note that only one borough (Hillingdon) has directly identified the reduction of traffic flows as a measure within its Action Plan.

Table 5: Action Plan Measure Categories, by Borough

Measure	Brent	Havering	Hillingdon	Islington	Lewisham	Wandsworth	Westminster
Direct Traffic-Related							
Access Control/ Clear Zones	X			X	X		X
LEZ	X	X		X	X	X	X
Re-routing and road hierarchy		X			X		
Roadside Emissions Testing	X	X		X	X	X	
UTMC[a]	X						
Indirect Traffic-Related							
Airport			X				
Anti-idling		X					
Awareness		X	X				
Cleaner Fuelled Vehicles		X	X				
Congestion Charging				X			
Development of Cycling & Walking	X	X		X	X	X	X
Emissions from Other Forms of Transport			X				
Fleet Management and Clean Fuels	X	X		X	X	X	X
Freight Measures	X	X	X	X	X		

Measure	Brent	Havering	Hillingdon	Islington	Lewisham	Wandsworth	Westminster
Industrial	X	X	X		X		
Land Use Planning	X			X	X	X	X
Parking Management & Charging	X	X		X		X	X
Physical Traffic Management	X	X		X	X		X
Planning		X	X				
Promotion, Education and Awareness	X	X		X	X	X	X
Public Transport Initiatives - bus	X			X	X		X
Public Transport Initiatives - rail/ other	X	X		X	X	X	X
Reduce Need to Travel by Car			X				
Reduce Traffic Flows			X				
Travel Plans	X	X		X	X	X	X
Non-Traffic Related							
Buildings and Construction Sites		X	X				
Domestic			X	X	X	X	X
Monitoring & Modelling		X	X		X		X
General[b]			X				
Other[c]		X	X				

[a] UTMC – Urban Traffic Management and Control
[b] 'General' includes items such as Regional Air Quality Strategy development
[c] 'Other' includes Climate Change measures

4 Review of Abatement Measures

4.1 A detailed literature review of the potential measures for reducing PM_{10} concentrations in hotspots has previously been carried out (Moorcroft et al, 2009). For the present study this review has been examined again to identify measures that could also be applied to reduce NOx/NO_2 emissions and/or concentrations, e.g. shared spaces. Details of these measures are not however repeated, and reference should be made to the previous report (Moorcroft et al, 2009) Further work has, however, been carried out to identify the potential role of a number of measures that are specific to NOx/NO_2, and the findings of this additional literature review are summarised in this Chapter.

Pollution Reduction Measures

4.2 Various traffic-reduction measures, such as the introduction of access restrictions, use of shared spaces etc, were described in detail in the previous report to identify local measures for PM_{10} hotspots; information relating to these measures is not reproduced here. Subsequent parts of this Chapter focus on measures that have not been previously considered in any detail, or have a different emphasis for NOx/NO_2 reduction.

Photo-catalytic coatings

4.3 In recent years considerable efforts have been made to develop construction materials and coatings which have the potential for reducing levels of air pollution. A review of these materials by Gomez-Garcia et al. (2005) highlighted six NOx-removal materials utilising adsorption, absorption and/or solid-gas reactions. These were classified as metal oxides, spinels, perovskites, zeolites, carbonaceous materials and heteropolyacids. The de-polluting properties of these materials are often reliant upon photo-catalysis. One of the most commonly used photo-catalysts, particularly in relation to NOx generated by road traffic, is the compound titanium dioxide (TiO_2). Titanium dioxide acts as a catalyst to oxidise NO and NO_2 into nitrate (NO_3^-) in the presence of oxygen and ultraviolet radiation.

4.4 The effectiveness of TiO_2 coatings has been successfully demonstrated in laboratory trials, and has recently been investigated in the Dutch Air Quality Innovation Programme (Innovatie Programma Luchtkwaliteit - IPL)[2]. The main findings from IPL have been summarised by Kempenaar et al. (2010). Some of the work on IPL was also summarised in the earlier report for TfL on PM_{10} hot spots (Moorcroft et al., 2009). In a series of laboratory experiments TiO_2-coated materials were exposed to typical ambient levels of NOx and ultraviolet light. The experiments

[2] The aim of IPL was to identify, develop and test local measures that could contribute to improving air quality (NO_2 and PM_{10}) alongside motorways in the Netherlands. IPL made policy and implementation recommendations on the potential and the limitations of various measures.

were concerned solely with investigating the basic conversion efficiency of various coatings, and establishing how conversion was affected by factors such as light intensity, turbulence and humidity (Duyzer et al., 2007). It was concluded that conversion efficiency is highly dependent on UV light intensity. When this falls to a value below 5 W/m^2 the conversion drops by 50%. This light level is still attained each day (in the Netherlands) until the end of October. Relative humidity was found to have little impact on NOx adsorption in the range investigated: between 55% and 95%. In much drier atmospheres (like those in southern Europe) far greater NOx conversion levels might be achieved.

4.5 In addition, a CFD model was built to simulate the dispersion of motorway traffic emissions and their adsorption on a noise barrier coated with TiO_2 (Duyzer et al., 2007). The model calculations showed that under optimum conditions (high light intensity, very active barrier coating, wind perpendicular to barrier) up to 11% of the emitted NOx could be converted (no more than 11% of the emitted NOx actually reached the barrier, with the rest passing over it).

4.6 However, De Boer (2005) noted that although their effectiveness had been demonstrated under controlled laboratory conditions, there were few reliable data on how photo-catalytic materials performed in practice. This is partly because it is difficult to distinguish the impact of chemical conversion on the catalyst surface from fluctuations in concentrations due to, say, meteorology.

4.7 Concrete panels coated with TiO_2 paint were therefore tested on an existing noise barrier along the A1 motorway at Terschuur (Duyzer et al., 2007). Several other coatings were also exposed for reference. Between August and December 2006 the precipitation running off the panels was collected, and its nitrate content determined (this is a good indicator of the quantity of NOx adsorbed). The amount of NOx converted by the panels was compared with the estimated emission of NOx from the traffic during the measuring period. In practice, the coatings proved to be ineffective. On average, only a small fraction of the NOx emitted per metre of motorway was converted. The maximum value recorded was 0.04% of the emission. Therefore, conversion at the monitoring site was also calculated by two other means: one based on the CFD calculations and one based on locally measured NOx concentrations. The adsorption estimates obtained by these two methods were both higher than the value recorded in the field, but remained low (between 0.1 and 0.2%). However, there were long periods of low conversion due to low UV light intensity, the wrong wind direction, periods of rain, etc. The exposed panels were therefore subjected to several more laboratory tests, and indeed under certain conditions they showed very low adsorption. In particular, it was found that when the panels had been wetted by rain they were far less active for a period of several days while they were drying. In damp climates this effect will lead to a large decrease in the efficiency of these particular coatings, although the effect is probably less pronounced for more hydrophobic coatings. With extremely active coatings, the conversion could be up to 1% of the amount of NOx emitted by the traffic. With realistic values for conversion efficiency, pollutant conversion by the barrier could be between 0.1 and 0.3%.

4.8 Photo-catalytic materials have also been investigated in the joint EU and JRC project PICADA3 (photo-catalytic innovation coverings applications for de-pollution assessment). The main objectives of this project were to improve the understanding of the processes and chemical mechanisms involved, to assess the cost and durability performances of different coverings, and to develop and market products. Within the PICADA study various coatings have been tested in an exposure chamber, confirming their potential to reduce pollutants such as NOx. Field trials have already been conducted in Milan on a coated-road surface. In 2002, after 7000 square metres of road surface were covered with a photo-catalytic cement-like material, there was up to 60% reduction in the concentration of NOx at street level.

4.9 The effectiveness of a 'NOxer' noise barrier on air quality near the M60 motorway was assessed on behalf of the UK Highways Agency by Atkins (2009). The site selected was on the eastern side of the M60 between Junctions 13 and 14 near Swinton. The barrier, which is impregnated with TiO_2, was designed and patented by Eurovia in France. The titanium dioxide was incorporated into cement-coated woodchip. Laboratory trials had shown that the NOxer material was capable of removing up to 80% of NOx from the air. The technology had been previously trialled in the Netherlands, France and elsewhere in the UK, though no results existed for a NOxer barrier under typical British meteorological conditions. According to the manufacturer the NOxer barrier section needed a minimum surface area of 200 m^2 in order to have an effect on pollutant concentrations. The NOxer section used during the trial was approximately 350 m in length, and 3 m high. The NOxer barrier section was corrugated to provide a greater surface area and hence reaction surface (see Figure 8). The active surface of the NOxer barrier faced the M60. The entire rear length of the barrier was clad in plastic with wooden uprights as described above, and was not active.

Figure 8: NOxer Barrier Section (Atkins, 2009).

3 www.picada-project.com/domino/SitePicada/Picada.nsf?OpenDataBase

4.10 A monitoring regime was implemented to establish baseline conditions (concentrations of ambient NOx at fixed positions at or near the fence) with the original barrier in place. Once the new barrier had been installed, monitoring recommenced to allow comparison of pre- and post-installation results. Data were collected simultaneously at the barrier face of both the NOxer section and the standard untreated sections. Duplicate monitoring took place a few metres behind the barrier as a measure of the potential effects on air quality at actual exposure locations (e.g. residential properties)

4.11 The results at the NOxer barrier face were generally lower than at the control barrier. There was no distinct pattern of reduction, but a set of 'optimum' conditions generally gave the largest decreases in NO_2 concentration. The effect was influenced by wind speed, solar intensity, temperature, and (especially) wind direction. Winds perpendicular to the barrier face resulted in lower concentrations of NO_2 (by 5.1 $\mu g/m^3$) at the NOxer barrier but higher NO concentrations (by 7.9 $\mu g/m^3$) than at the standard barrier. However, the barrier could not have been functioning during many of these hours due to darkness, low temperatures or a damp surface. When only optimal conditions were analysed, concentrations of NO_2 were much lower, (by 20.1 $\mu g/m^3$) and NO concentrations were only slightly higher (by 4.6 $\mu g/m^3$) at the NOxer barrier. Due to the orientation of the barrier, optimal conditions with a perpendicular wind direction occurred for only 0.4% of the monitoring period.

4.12 Long-term average NO and NO_2 concentrations were higher behind the NOxer barrier than behind the standard barrier. However, it is likely that wind direction had a significant effect in determining these concentrations. Winds perpendicular to the barrier face resulted in higher NO_2 (by 6.9 $\mu g/m^3$) concentrations behind NOxer barrier site and lower NO concentrations (by 7.2 $\mu g/m^3$) than at the site behind the standard barrier. However, the barrier could not have been functioning during many of these hours due to darkness, low temperatures or a damp surface. When only optimal conditions were analysed, lower concentrations of NO_2 (by 11.6 $\mu g/m^3$) and NO (by 16.3 $\mu g/m^3$) were observed behind the NOxer barrier site than the site behind the standard barrier.

4.13 TiO_2 coatings have also been investigated by Cheshire East Council in Congleton. A solution containing TiO_2 was applied to various surfaces near residential properties, including 200 m^2 of paving, the properties themselves, garden walls, street lamps and road signs. A feature of the trial is that the properties formed a terrace only a few metres from the road and created a canyon like setting. It was reported that the coating would need to be reapplied regularly. The interim results of the trial led to a substantial reduction in the concentration of NO_2 (over 10 $\mu g/m^3$ measured using diffusion tubes) (Pointon, 2009). However, a report of this study was not available at the time of writing.

4.14 In the earlier report for TfL on PM_{10} hot spots, Moorcroft et al. (2009) described a product from Shell Bitumen known as 'Active Asphalt'. Shell Bitumen has also been working on an asphalt solution for reducing NOx. This also involves the use of TiO_2. No results appear to be available at present, but full-scale trials are planned (Taylor, 2009).

4.15 A recent article published by the Royal Society for Chemistry[4] suggests that there may be grounds for caution in using TiO_2 coatings, as the reaction of NO_2 produces nitrous acid (HONO), which may have health consequences and is also an important gas in the atmospheric photochemical cycle. This is a matter that requires further investigation.

4.16 The overall picture for the use of TiO_2 coatings is rather confusing, with some studies suggesting no significant impact and one incomplete study suggesting a substantial impact. The Congleton study would suggest that there may be benefits for more canyon-like settings, such as Putney High Street. There would also be advantages in a rigorous and carefully planned study within a typical urban setting, to help determine the true benefits of TiO_2 coatings.

Denitrification Systems

4.17 Denitrification systems or processes are designed to remove NO_2, and other oxides or nitrogen, from road tunnel air, but a number of alternative systems are available; most work by either a chemical absorption or catalytic process. For example, potassium hydroxide can be used to absorb NO_2, and metal catalysts such as platinum initiate the conversion of contaminant gases to less harmful gases. An electrostatic precipitator may be required upstream of the denitrification system to remove particles that would otherwise foul the catalyst and render it ineffective.

4.18 As of 2004, it appeared that the operational use of denitrification technology had been rather limited. A system was installed in the Laerdal tunnel in Norway, but its performance has been difficult to assess because traffic volumes in the tunnel are low, and the pollution levels within the tunnel are lower than those required to trigger the use of the denitrification system. However, tests have indicated that the system may remove as much as 85-90% of NO_2. A removal efficiency of 90% for NO_2 has also been claimed for a German system (Child & Associates, 2004).

4.19 Willoughby et al. (2004) described the experimental trial of denitrification in Japan. The experiment, which was being conducted at the Keihinjima Ventilation Station in Tokyo, involved parallel tests with air first passing through an ESP and then denitrification equipment. One test involved removing NO_2 by absorption using Matsushita equipment and the other using equipment manufactured by Kawasaki. Information provided by Matsushita and Kawasaki indicated a removal efficiency (for both systems) of 90% for NO_2.

4.20 Three NO_2-removal systems have been installed in tunnels as part of the Calle 30 project in Madrid, but as before there is little information in the literature on their effectiveness.

4.21 The application of denitrification systems at open roadside locations does not appear to have been reported, and the application of these systems on wide-scale basis in London is considered to be impractical at present.

4 www.rsc.org/chemistryworld/news/2009/august/11080902.asp

Bio-filtration

4.22 Bio-filtration is a general term used to describe processes in which contaminated air is passed over or through some medium containing micro-organisms capable of consuming, converting or otherwise removing some or all of the harmful pollutants present. Again, such systems are being considered for use in road tunnels. Child and Associates (2004) noted that the application of bio-filtration processes to emission treatment in road tunnels involves a conflict between the need to move large volumes of air relatively quickly and the need for air to have relatively long exposures or residence times for the biological processes to be effective. In road tunnel applications, relatively large volumes of 'bio-reactor' space would need to be created, so that the contaminated road tunnel air could be 'slowed' enough for the respective bioprocesses to be effective. The same authors describe bio-filtration systems manufactured by Fijita, in which polluted air is passed through an aeration layer into one or two soil beds, each 50 cm thick. The removal efficiency for NO_2 was claimed to be 91%. However, bio-filtration remains an unproven technology, even for road tunnels, and its application to open roads seems rather impractical at present.

Scrubbing

4.23 Scrubbing describes a range of processes in which contaminated air is passed through a wash liquid, and pollutants are either entrained or dissolved in the liquid. The effectiveness of the process relies on the removal of pollutants by either solution or physical entrainment in the washing or scrubbing medium. Scrubbing is a well-established treatment technology in a number of industrial process applications, but these generally involve more heavily polluted air streams than are experienced at roadside locations. Again, this approach is likely to be impractical and ineffective at roadside locations.

Vegetation

4.24 In IPL, a review by Hesen and Koopmans (2006) concluded that although vegetation can have a positive impact on air quality in the vicinity of roads, few studies have permitted unambiguous interpretation. The height, width, type and porosity (leaf density) of the vegetation appear to be important. The effects of vegetation on particulate matter were reviewed by Moorcroft et al. (2009), but there are different mechanisms of capturing PM and NOx.

4.25 IPL conducted measurements to assess the impacts of vegetation on concentrations of $PM_{2.5}$, PM_{10} and NO_2 (Weijers et al., 2007). The measurements took place in the summer of 2007 alongside the A50 motorway near Vaassen. It was found that near to the vegetation the net impact of deposition or absorption via stomata (lowering concentrations) and hampered dilution due to obstruction (increasing concentrations) resulted in no net improvement in air quality relative to a control without vegetation. NO_2 concentrations were higher with the vegetation between around 10 and 30 m from the road. However, measurements further away from the road (45-90 m) indicated that the NO_2 concentration was 20% lower than the control. One possible explanation may be that the vegetation gives rise to a wave of turbulence downwind, and this may introduce cleaner air.

4.26 Further measurements were then conducted throughout 2008 at Valburg, as well as at Vaassen. As the existing strip of vegetation at Vaassen lost its leaves in winter, both summer and winter conditions were investigated. In addition, the situation was also investigated using a CFD model (PanAir) (Vermeulen et al., 2009). For both the model and measurements the effects on concentrations were relatively low for NO_2 (0-26%), and there was only a reduction at distances of more than 90 m from the road.

4.27 The potential use of “nitrogen-philic” plants, which can grow with NO_2 as their sole nitrogen source has been investigated by Morikawa et al, 2003; specific consideration was given to covering the vertical surfaces of buildings and highway corridors with NO_2-philic plants. It is claimed that a “hypothetical petunia wall” could remove about 15,000 tonnes of NO_2 per year, but the precise details of the required coverage are not provided.

5 Local Measures for NO_2 Hotspots in London

5.1 The potential measures for NO_2 hotspots in London are identified in this Chapter, drawing on the findings for the PM_{10} study (Moorcroft et al, 2009) and the literature review set out in Chapter 4. Where appropriate, measures to reduce PM_{10} concentrations will be complementary to those designed to reduce NO_2 concentrations and *vice versa*, and for the majority of measures this is expected to be the case. However, there is an important distinction between local measures that are targeted at achieving the limit values for PM_{10} and those targeted at NO_2. In the case of PM_{10}, the principal focus is on exceedences of the daily-mean concentrations, as these are at greatest risk of exceeding the limit value. It is therefore appropriate to focus local measures for PM_{10} on "short-term" or "occasional interventions", particularly if they can be targeted at "exceedence days". For NO_2, on the other hand, the principal focus is on annual mean concentrations as these are at greatest risk of exceeding the limit value. In this case, short-term or occasional measures would have a much reduced impact. This distinction has been taken into account in putting together the local measures for NO_2.

5.2 A further consideration is that the extent of exceedences of the NO_2 limit value is so widespread that measures targeted at small sections of road (for example, the use of tunnels or canopies) could not feasibly be implemented. For this reason, such measures have been discounted in most cases.

5.3 As set out in Chapter 2, the required reduction in NOx emissions at some of the road links identified is substantial. Furthermore, the technological fixes relied upon to date (e.g. increasingly stringent emissions standards for road vehicles) have so far proven unable to deliver the necessary improvements for some vehicle types, and there is continuing concern that they may continue to fail to deliver in the short to medium term that is the focus of this report. For this reason, it is believed that measures that can deliver substantial reductions in traffic volume may be most successful in working towards achievement of the annual mean limit value by 2015, and such measures are assigned priority in the subsequent assessments, although over the timescales considered a combination of different measures would need to be considered.

Site categorisation

5.4 As noted in Chapter 1, the approach taken in this report has been to focus on seven specific locations in London, with the intent that measures for these locations could be readily transferred to other parts of London with similar characteristics and conditions. To aid this approach, the seven "hotspot" locations have been assigned into four different categories, "A" to "D", based on their physical and pollutant source characteristics, as shown in Table 6.

Table 6: Categorisation of Site Types

Type	Site	Number of Lanes	Built up (i.e. canyon-like even if not canyon)	AADT	% buses	% HGVs	Speed (kph)	Annual Mean NO_2 (2009) $\mu g/m^3$
A	Brent Ikea	6	N	100,226	1%	5%	60	69
B	Havering Rainham	6 (at junction)	N	22,608	1%	8%	45	56
	Oxford Ave	4	N	23,029	5%	2%	43	43
C	Holloway Road	4 or 5	Y	32,593	2%	4%	29	57
	Marylebone Road	6 or 7	Y	66,542	3%	4%	25	107
D	New Cross	4	Y	38,128	8%	5%	29	63
	Putney High Street	2	Y	22,427	7%	3%	18	148

Potential Measures

5.5 A range of potential measures for application within the hotspots have been identified[5]. They are principally designed to reduce emissions of NOx/NO_2.

5.6 The various measures have then been tentatively rated according to a series of factors, using the same approach as applied to the rating of measures for PM_{10} hotspots (Moorcroft et al, 2009). This follows on from the assessments provided by Boulter et al. (2007a) and Reeves et al. (2008). The results of this evaluation are provided in Table 7.

5.7 Consideration has been given to the magnitude of the reduction in NOx/NO_2 emissions/concentrations that the measure could be expected to achieve, and how long the reduction could last. The full list of factors which have been taken into account in the evaluation is:

- The potential size of the reduction in NOx/NO_2 emissions/concentrations that the measure might achieve;
- How long the impact on NO_2 concentrations might last;

[5] London-wide measures are not included within this review, even though they would contribute to improving air quality within the hotspots.

- Technical feasibility;
- Timescale for implementation;
- Relative Cost;
- Any other environmental impacts, either positive or negative (e.g. noise, greenhouse gas emissions);
- Road safety;
- Potential Impact on travel times;
- Public appeal;
- Political/public acceptability (based on subjective evaluation).

5.8 For each measure an indication of its general suitability for application at hotspots in London, based on the criteria above, is provided by colour-coding in Table 7 as follows:

- Dark Green – likely to be very suitable;
- Light Green – likely to be suitable;
- Orange – potentially suitable;
- Red – likely to be unsuitable (for a variety of possible reasons).

5.9 Where possible, quantitative evidence of the effects of these measures has been provided. However, the data are rather limited. Furthermore, the reported effects are likely to be rather site-specific, and may not be directly transferable to other locations. Consequently, based on current information and understanding, this assessment is largely subjective. The findings of the review, and the scores in the evaluation, are summarised below.

Recommended Measures

5.10 Based on the review and evaluation presented here, potential measures are proposed for consideration at each of the identified "road categories". The measures are outlined below and their application to the four road categories is summarised in Table 8:

- *Adjustment or removal of traffic lights.* Simple cost-effective measures that can effectively smooth the traffic flow and reduce congestion including average speed enforcement cameras or the programming of responsive traffic light systems such as SCOOT to smooth flow along the hotspot roads, or even the removal of traffic lights in some situations, would be suitable for a number of the hotspot locations in central London. This would be consistent with the commitment in the draft MAQS to smooth traffic flows through better traffic management.

- *Shared spaces.* This is a measure which is potentially attractive for hotspot areas which are sensitive to infrastructure changes, or where there are significant pedestrian shopping areas. Whilst unproven in terms of NOx reduction, shared space schemes potentially offer other environmental and amenity benefits.

- *Access restrictions.* Measures to control and/or limit access to and from sections of main road (e.g. by closure of side roads) could also be effective in relieving congestion, although care would need to be taken to ensure that congestion was not increased in other areas.

- *Effective policing of red routes:* Red routes are implemented to reduce congestion along main arterial routes. Effective policing would enforce this benefit.

- *Deployment of cleaner buses:* Buses make a substantial contribution to NOx emissions along some sections of road and deployment of new hybrid buses along these road links would be beneficial. This measure has been identified within the draft MAQS.

- *Reducing idling.* The assignment of hotspot areas as priority locations for the enforcement of existing powers to limit idling, and to be taken forwards in new measures established by the Mayor would be beneficial.

- *Toll roads.* The introduction of toll road charges to specific road links could be beneficial in reducing traffic volumes, although care would need to be taken to ensure that traffic is not simply diverted onto other sections of road, thereby increasing problems at other locations. Toll prices could be adjusted (or even removed) at different times of day, or at weekends, to most effectively target periods of substantial congestion;

- *Restrictions on car parking.* Substantial local restrictions on car parking availability could reduce traffic volumes as use of the private car in many cases would be obviated if there was nowhere to park at the journey end;

- *Vegetation.* The use of green ("living") walls may be effective in street canyons by reducing NO_2 concentrations in recirculated air. It would be necessary to identify "nitrophilic" species that would be capable of growing in polluted environments.

5.11 In addition to the above measures, consideration has also been given to measures that would apply more widely across all hotspots. These do not fall within the definition of "local" interventions, and are therefore not strictly within the remit of this project. They are included in recognition of the important role of cars and HGVs at all seven of the sites.

- *Extension of Freight Operator Recognition Scheme:* The Freight Operator Recognition Scheme (FORS)6 established by TfL is designed to make the freight industry safer and more environmentally friendly. It includes benchmarking of operator performance in terms of CO_2

6 See www.tfl.gov.uk/microsites/fors

emissions. Consideration should be given to extending this scheme to nitrogen oxides emissions. This measure also relates to eco-driving approach covered in the next Chapter.

- *Modification of the Low Emission Zone:* The current London Low Emission Zone (LEZ) is targeted at introducing cleaner vehicles into areas of poor air quality. The existing LEZ is focussed on reducing emissions of PM from lorries, buses and coaches. Modification of the LEZ to introduce restrictions related to NOx emissions across a wider range of vehicles could provide significant improvements across the road network. Potentially, a “dual-zone” LEZ could be implemented, with the stricter controls applied to a “central zone”.

- *Road-user charging.* Introduction of a ‘charge per kilometre’ system could potentially deliver substantially reduced NOx emissions across London. Such a system is to be introduced in the Netherlands, where it is anticipated that vehicle-kilometres could be reduced by 15%. Whilst the base tariff is dependant upon the vehicle category (related to CO_2 emissions), but would also reflect emissions of NOx.

.

Table 7: Assessment of Potential Measures to Reduce NO_2 Concentrations in Hotspots.

Category	Measure	NOx		Technical feasibility	Timescale to implement measure	Cost	Other environmental impacts	Road safety impacts	Impact on travel times	Public appeal	Acceptability
		Impact	Duration of impact								
A, B, C, D	Adjusting or removing traffic lights	✓	Years	Depends on scheme	*T*	Low	Smoothing of traffic should reduce fuel consumption and noise	Ought to be beneficial, but may not be significant.	Probably small.	Should be positive if reduces stop-start driving	High, if reduces congestion and/or stop-start driving
D	Shared space	✓	Years	✓✓	*T*	Medium-high	Smoothing of traffic should reduce fuel consumption and noise	Should be beneficial	Potential increase if speeds are low and diversions are common	Good public visibility. Should create a more pleasant environment for pedestrians and cyclists	Medium, although potential objections form visually impaired groups
C, D	Access restrictions	✓✓/x	As and when required	✓✓	*T*	Medium	Generally positive inside zone. May lead to increased emissions outside the restricted zone	Should be beneficial	Depend on scheme	Good public visibility, but unlikely to be popular with motorists and some businesses	Medium
A, B, C, D	Effective policing of red routes	✓	Years	✓✓✓	*T*	Low	Limited	Should be beneficial	Should be beneficial	Good public visibility,	High
A, B, C, D	Modification of LEZ	✓✓	Several years	✓	*TT*	Medium	Generally positive inside zone. May lead to increased emissions outside the restricted zone	Should be beneficial	May increase journey times outside of zone	Unlikely to be popular with motorists and some businesses	Medium
B, D	Deployment of cleaner buses	✓	Years	✓✓✓	*T*	Low	Limited	N/A	N/A	No specific issues	High
A, B	Toll roads	✓✓	Years	✓✓	*TT*	Medium	Generally positive alongside toll road. May lead to increased emissions outside the restricted zone	Limited	May increase journey times on other roads	Unlikely to be popular with motorists and some businesses	Medium
A, B, C, D	Road user charging	✓	Years	✓	*TTT*	Medium	Depends on extent of road charging scheme	Limited	Should be beneficial	Unlikely to be popular with motorists and some businesses	Low
C, D	Car parking restrictions	✓✓	Years	✓✓	*TT*	Medium	Depends on extent of restrictions	Limited	Should be beneficial	Unlikely to be popular with motorists and some businesses	Medium
C, D	Engine switch-off	✓	Years	✓✓✓	*T*	Low-medium	Beneficial for CO_2	Limited	Limited	Has promotional value, but can be difficult to enforce	Medium
D	Photo-catalytic coatings	✓	N/A	✓	*T*	Medium	N/A	N/A	None	Has promotional value	Medium
C, D	Green walls	✓	Years	✓	*TT*	Low-medium	Absorb CO_2 while growing	None	No effect	High	Medium-high. Highly visual. Improved street environment
C, D	Freight Operator Recognition Scheme	✓	Years	✓	*T*	Low-medium	Beneficial for CO_2	Should be beneficial	No effect	Neutral for public beneficial for freight operators	High
N/A	Denitrification systems	✓	Years	✓	*T*	Low-medium	N/A	None	No effect	No specific issues	Medium
N/A	Bio-filtration	✓	Years	✓	*T*	Low-medium	N/A	None	No effect	No specific issues	Medium
N/A	Scrubbing	✓	Years	✓	*T*	Low-medium	N/A	None	No effect	No specific issues	Medium

Key

Impact on NO_2

x slight increase in NO_2 possible
xx substantial increase in NO_2 possible
✓ slight reduction in NO_2 possible
✓✓ substantial reduction in NO_2 possible

Technical feasibility

× Unlikely to be feasible
✓ Feasible but difficult
✓✓ Intermediate
✓✓✓ Straightforward

Timescale

T Short-term
TT Medium-term
TTT Long-term

Green	**Likely to be very suitable**
Light green	**Likely to be suitable**
Orange	**Potentially suitable**
Red	**Unlikely to be suitable**

Notes

The evaluation of Cost is based on a relative assessment between the various measures.

The evaluation of Acceptability is based on professional judgement of the potential overall political and public reaction to each measure; no opinion surveys were carried out

Table 8: Summary of Potential Hotspot Measures for NO_2

Category of Road		Potential Measures
A	Very high flow dual carriageway >60,000 veh/day – open setting (e.g. the North Circular)	Adjusting/removing traffic lights Effective policing of red routes Modification of LEZ Toll roads Road user charging
B	Moderate flow dual carriageway 20,000-40,000 veh/day – open setting, outer London (e.g. the A4 in Hillingdon)	Adjusting/removing traffic lights Effective policing of red routes Modification of LEZ Deployment of cleaner buses Toll roads Road user charging
C	High flow single/dual carriageway 30,000-60,000 veh/day – built up area, central London (e.g. the Marylebone Road)	Adjusting/removing traffic lights Access restrictions Effective policing of red routes Modification of LEZ Road user charging Car parking restrictions Engine switch-off Green walls
D	Moderate flow single carriageway 20,000-40,000 veh/day – built up area, congested, high bus flow (e.g. the Putney High Street)	Adjusting/removing traffic lights Shared space Access restrictions Effective policing of red routes Modification of LEZ Deployment of cleaner buses Road user charging Car parking restrictions Engine switch-off Photo-catalytic coatings Green walls

6 Eco-Driving

6.1 This Chapter provides a summary of the potential benefits in NOx reduction that could be achieved from so-called “Eco-driving” measures, and draws upon the detailed study that is provided in Appendix 1 to this document.

6.2 Eco-driving measures include a wide range of actions including:

- Vehicle purchase;
- Vehicle use;
- Driving style;
- Travel and transport planning.

6.3 The focus of the term eco-driving is often on driving style, which has led to initiatives for driver training.

6.4 The principal focus of eco-driving measures has been on reducing fuel consumption, and thus emissions of CO_2. In the context of this review, it is important to understand how emissions of NOx might also be affected. However, there are fewer data on the impact of driving style on NOx emissions, the tests are frequently restricted to certain classes or types of vehicle (e.g. Euro 4 petrol cars) and the results of studies are somewhat variable. In particular, there seems to be no information relating to the potential benefits to NOx emission of applying eco-driving principles to LGV and HGV vehicles.

6.5 Eco-driving measures promote responsible and more educated driving styles, for example:

- Maintaining steady speeds
- Avoiding unnecessary braking and acceleration
- Sensible use of gears
- Avoiding unnecessary engine idling

6.6 The general adoption of “driving style”-related eco-driving principles appears able to give rise to a reduction in fuel consumption of the order of 5 to 10%, although the precise effects are very dependant upon the road type and the level of traffic. In London, where the roads are frequently congested and traffic speeds are low, the fuel efficiency benefits are more likely to be towards the lower end of this range. For modern petrol-driven cars, the evidence seems to suggest that NOx emissions are slightly lower when eco-driving principles are applied in urban conditions. However, for diesel cars, some studies have shown that eco-driving principles and the use of a gear-shift indicator can lead to increases in NOx emissions during urban driving. This latter effect is thought to be related to the eco-driving advice to change up gears at lower speeds. This detrimental effect could potentially be avoided if the advice were to be reformulated, but cautions against the widespread use of eco-driving measures until the advice is amended to cover both CO_2 and NOx.

6.7 In terms of engine switch-off, this measure appears to be beneficial in terms of both fuel consumption and NOx emissions, particularly for modern diesel cars. For petrol cars there is also a fuel consumption benefit, but little effect on NOx.

6.8 A more complete summary, and specific recommendations to TfL regarding eco-driving measures, can be found in Appendix 1.

7 References

Atkins (2009). Assessment of the Effect of a NOxer© Barrier on Air Quality. Final draft Oct09.

AQEG (2007). Air Quality Expert Group, Trends in Primary Nitrogen Dioxide in the UK. London. HMSO.

Boulter P G and Barlow T J (2009). Emission factors 2009: Report 3 - exhaust emission factors for road vehicles in the United Kingdom (2009). TRL Report PPR356. TRL Limited, Wokingham.

Beevers S, Carslaw D, Westmoreland E and Mittal H (2009). Air pollution and emission trends in London. King's College, London.

Carslaw D C (2005). Evidence of an increasing NO_2/NO_x emissions ratio from road traffic emissions. *Atmospheric Environment*, Volume 39, pp. 4793–4802.

Child & Associates (2004). M5 East Freeway: A review of emission treatment technologies, systems and applications. Review undertaken by Child & Associates for the Roads and Traffic Authority of NSW.
http://www.rta.nsw.gov.au/constructionmaintenance/downloads/2004_10_childrepfiltration.pdf

De Boer E (2005). 'Katalytische afbraak van NO_x met TiO_2' (Catalytic breakdown of NO_x using TiO_2). IPL Report.

Defra, 2010. Air Quality Archive at http://www.airquality.co.uk

Duyzer, J., Voogt, M., Weststrate, H. and van der Welle, R. (2007). 'Toetsing van de werking van TiO¬2 coatings om NOx concentraties langs wegen te verlagen in de praktijk'. Report number 2006-A-R0359/B. TNO, Apeldoorn. IPL Report.

Gomez-Garcia M A, Pitchon V and Kiennemann A (2005). Pollution by nitrogen oxides: an approach to NO_X abatement by using sorbing catalytic materials. *Environment International*. Vol. 31, pp. 445-467.

Greater London Authority (2009a). Clearing the Air: The Mayor's draft Air Quality Strategy for consultation with London Assembly and functional bodies.

Greater London Authority, (2009b). London Atmospheric Emissions Inventory, 2006.

Hesen, J. J. G. and Koopmans, J. F. W. (2006). 'Actualisatie literatuuronderzoek "Beplanting en luchtwaliteit"'. (Update of literature review – vegetation and air quality), *Report number FL 17485-1*. Peutz B.V. IPL Report.

Kempenaar C, Cornelissen T, Boulter P and McCrae I (2010). Results from the Dutch Air Quality Innovation Programme (IPL). Paper presented at the Transport Research Arena Europe 2010 conference, Brussels.

Ligterink N, de Lange R, Vermeulen R and Dekker H (2009). On-road NO_x emissions of Euro-V trucks. TNO report MON-RPT-033-DTS-2009-03840. TNO Science and Industry, Delft.

Moorcroft S, McCrae I, Boulter P, Savage A and Laxen D (2009). Local Measures for PM_{10} Hotspots in London. Air Quality Consultants, Bristol.

Morikawa H, Takahashi M, Hakata M and Sakamoto A (2003). Screening and genetic manipulation of plants for decontamination of pollutants from the environment. *Biotechnology Advances*, 22, 9-15.

Pointon R (2009). Investigation of the Effectiveness of Titanium Dioxide Paint in reducing ambient NO_2 concentrations. Presentation at Investigation of Air Pollution Standing Conference (IAPSC), June 2009.

Rexeis R and Hausberger S (2009). Trend of vehicle emission levels until 2020 – Prognosis based on current vehicle measurements and future emission legislation. *Atmospheric Environment*, Volume 43, pp. 4689–4698.

Taylor R (2009). Personal communication to Ian McCrae at TRL.

Vermeulen, A. T., Kraai, A., Duyzer, J. H., Klok, E. J. and Pronk, A.A. (2009). Vegetatie voor een betere luchtkwaliteit Prijsvraag "Meten is weten" Perceel 1: A50 Vaassen De invloed van vegetatie langs (snel) wegen op de luchtkwaliteit. Eindrapport Rapportnummer DVS-2009-012. IPL Report.

Weijers, E. P., Kos, G. P. A., van den Bulk, W. C. M. and Vermeulen, A. T. (2007). 'Onderzoek naar de luchtkwaliteit rondom een vegetatiestrook langs de snelweg' (Study of air quality around a strip of roadside vegetation). *Report number E--07-011*. ECN. IPL Report.

Willoughby P, Stricker J and Humphrey G (2004). Electrostatic precipitators and ventilation in road tunnels in Japan. Report of a visit by a delegation from the NSW Roads and Traffic Authority to Japan from 30 September – 10 October 2003. New South Wales Roads and Traffic Authority, February.

8 Glossary

Standards	A nationally defined set of concentrations for nine pollutants below which health effects do not occur or are minimal.
Objectives	A nationally defined set of health-based concentrations for nine pollutants, seven of which are incorporated in Regulations, setting out the extent to which the standards should be achieved by a defined date. There are also vegetation-based objectives for sulphur dioxide and nitrogen oxides.
Exceedence	A period of time when the concentration of a pollutant is greater than the appropriate air quality objective. This applies to specified locations.
AQMA	Air Quality Management Area
PM_{10}	Small airborne particles, more specifically particulate matter less than 10 micrometers in aerodynamic diameter.
NO_2	Nitrogen dioxide.
NO	Nitric oxide.
NOx	Nitrogen oxides (taken to be NO_2 + NO).
$\mu g/m^3$	Microgrammes per cubic metre.
HDV	Heavy Duty Vehicles (> 3.5 tonnes)
LDV	Light Duty Vehicles (<3.5 tonnes)

A1 Appendix 1 – The effects of eco-driving on fuel consumption and exhaust emissions

A1.1 'Eco-driving'[7] has been widely publicised as a means of reducing fuel consumption and emissions of air pollutants. It is also claimed that eco-driving improves road safety, reduces noise, and reduces driver stress. It is aimed at both private motorists and fleet operators, and typically involves either a simple set of 'rules' to be followed or a programme of training. Various organisations provide advice on eco-driving, including Transport for London (TfL) itself via its 'Smarter Driving' web page[8].

A1.2 The eco-driving advice which is provided by different organisations varies considerably in terms of the level of detail, but it generally features a number of common actions. Some examples of these are listed in

A1.3 Table 1: Examples of eco-driving actions.

Theme	Action
Vehicle purchase	Purchase a vehicle with a low environmental impact
Vehicle maintenance	Keep the vehicle well maintained
	Follow the servicing schedule
	Keep the tyres at the correct pressure
Vehicle use	Reduce the vehicle weight
	Reduce the aerodynamic drag of the vehicle
	Turn off air ancillary devices
Driving style	Drive off as soon as the engine has been started
	Adopt a responsible driving style
	Anticipate the road ahead
	Choose an appropriate speed
	Avoid sharp acceleration and heavy braking
	Use coasting techniques
	Use gears sensibly
	Drive in the highest gear

7 Various synonyms are used in the literature, including 'eco-friendly driving, 'ecological driving', 'smart driving', and 'environmentally-aware driving', but the meaning is generally quite consistent. In this report, the term 'eco-driving' is used throughout.

8 www.tfl.gov.uk/roadusers/smarterdriving/5564.aspx

In-vehicle devices	Change up gear at lower engine speed
	Avoid unnecessary engine idling
	Use the vehicle instruments and navigation devices
Travel and transport planning	Limit private car use
	Plan journeys
	Combine journeys
	Share trips
	Avoid cities
	Avoid short journeys

A1.4 . These actions have been grouped according to themes, though there is some overlap between these themes. The advice is sometimes contradictory, such as ‘avoiding use of ancillary equipment’ and ‘using route-guidance devices’. Moreover, some of the actions (*e.g.* checking tyre pressure) are also clearly more practical than others (*e.g.* avoiding cities). An additional action, which is not mentioned in the Table, is to actually monitor fuel consumption.

A1.5 The effects of the various eco-driving actions have been reviewed, where information exists, in Section A1.6 of this Report. Average overall reductions in fuel consumption of around 5-10% are typically reported for eco-driving[9]. Although such claims appear to make sense when one considers the types of action involved, there is relatively little evidence in the peer-reviewed scientific literature to support them, especially in relation to real-world driving conditions. Much of the information that is available comes from projects, national programmes, initiatives and commercial activities. Examples of these include the following:

- The EU ECODRIVEN[10] project.
- The EU TREATISE[11] Project.
- The ‘New Driving Style’ programme in the Netherlands[12].
- The Eco-driving Quality Alliance in Switzerland[13].
- Germany’s ‘Drive and Save safely’ (Fahr und Spar) programme.
- The UK Safe and Fuel Efficient Driving (SAFED) programme.

9 www.ecodrive.org/What-is-ecodriving.228.0.html

10 www.ecodrive.org/. The UK Energy Saving Trust has participated in the ECODRIVEN project.

11 TREATISE = Training programme for local energy agencies & actors in transport & sustainable energy actions. No functioning web site for the project was available at the time of writing.

12 www.hetnieuwerijden.nl/

13 www.eco-drive.ch

Table 1: Examples of eco-driving actions.

Theme	Action
Vehicle purchase	Purchase a vehicle with a low environmental impact
Vehicle maintenance	Keep the vehicle well maintained
	Follow the servicing schedule
	Keep the tyres at the correct pressure
Vehicle use	Reduce the vehicle weight
	Reduce the aerodynamic drag of the vehicle
	Turn off air ancillary devices
Driving style	Drive off as soon as the engine has been started
	Adopt a responsible driving style
	Anticipate the road ahead
	Choose an appropriate speed
	Avoid sharp acceleration and heavy braking
	Use coasting techniques
	Use gears sensibly
	Drive in the highest gear
	Change up gear at lower engine speed
	Avoid unnecessary engine idling
In-vehicle devices	Use the vehicle instruments and navigation devices
Travel and transport planning	Limit private car use
	Plan journeys
	Combine journeys
	Share trips
	Avoid cities
	Avoid short journeys

A1.6 It is also worth noting that the effects of eco-driving are dependent upon both the driver (*i.e.* the extent to which the advice/training is acted upon, and how long the actions are retained) and the vehicle (*i.e.* the extent to which any changes in operation affect emissions). Although eco-driving has the potential to reduce fuel consumption and emissions in the short term, the effects may diminish in the longer term. However, it may be difficult to measure the true long-term impact of eco driving, as there is the potential for people to forget the eco-driving techniques over time (Avery *et al.*, 2009).

A1.7 In the context of this work, an important consideration is the effectiveness of eco-driving for vehicles being used in London. Little of the literature appears to refer specifically to London, and so it has been assumed that the most relevant findings are those which relate to nominal 'urban' driving conditions, rather than 'rural' or 'motorway' driving.

Effects of eco-driving actions

Vehicle purchase

A1.8 Unsurprisingly, eco-driving guidance advises that individuals should choose a car with a low impact on the environment, taking into account the type of vehicle needed, and the purposes for which it will be used. The EU energy label – which covers CO_2 emissions and fuel consumption - is a useful indicator when choosing a new car. Some web sites offer more detailed criteria concerning the environmental score of vehicles.

Vehicle maintenance

A1.9 A car which is not properly maintained will generally have higher fuel consumption than an equivalent well-maintained vehicle. Most emission-related maintenance issues should be addressed during the regular service. A typical issue which is highlighted in eco-driving programmes is that of tyre pressure. If tyre pressure is too low, this increases rolling resistance fuel consumption, and also affects the handling of the vehicle. According to SenterNovem (2005), a tyre looses 0.1 bar of pressure each month. A vehicle with a tyre pressure which is 25% too low has an increase in rolling resistance of 10% and an increase in fuel consumption of 2%. It is therefore recommended that the tyre pressure is checked regularly (*e.g.* monthly), and tyre pressure monitoring systems are available to make this task easier. Such systems are now often fitted to new cars, and can be retrofitted to older cars, and their mandatory fitting is currently being considered by the European Commission.

Vehicle use

Reducing vehicle weight

A1.10 The lighter the vehicle load, the lower the fuel consumption and emissions. An additional load of 100 kg on a medium-class vehicle of 1,500 kg results in an increase in consumption of about 6.7% (SenterNovem, 2005). Drivers or operators should remove any unnecessary weight from the vehicle, including loads within the boot. This also applies to fuel. However, the advantages of using a partly fuelled tank could be offset if there is a need to drive long distances to filling stations, although this is unlikely in most parts of the UK.

Reducing aerodynamic drag

A1.11 Most externally mounted equipment attached to a vehicle – such as roof racks, bicycle racks, ski racks or luggage racks - will introduce sharp discontinuities in a vehicle's frontal profile, increasing the frontal area and the drag coefficient. The overall result is an increase in aerodynamic air resistance, especially at high speeds, and fuel consumption. Furthermore, such devices will add weight, thereby increasing rolling resistance. SenterNovem (2005) state that at a speed of 120 km/h a roof rack can cause at least a 20% increase in fuel consumption. The use of such obstacles to the air flow should therefore be minimised. However, for low-speed driving the use of a roof rack on a small car may be more fuel efficient than using a larger vehicle. Similarly, there is no significant benefit in retrofitting spoilers to most modern vehicles, since most cars will already have been optimised within their basic size and shape constraints for reduced aerodynamic drag and optimum grip. Drivers should also close windows, especially at high speeds, as open windows also increase drag.

A1.12 The majority of information regarding the effects of external attachments to cars on fuel consumption and exhaust emissions is qualitative. This problem is compounded by the diverse range of equipment which can be attached to cars; these will be of varying sizes and shapes and therefore difficult to categorise. The tests which have been conducted, particularly the road tests, tend to focus on fuel consumption rather than emissions

A1.13 Lenner (1998) examined the influence of roof-mounted items and towed trailers on fuel consumption and NO_x using on-board measuring apparatus installed in a 1992 petrol car with a three-way catalyst). The car was driven at various constant speeds (70, 80 and 90 km/h) whilst the fuel consumption and emissions were constantly measured. Fuel consumption increased by 1-3% following the installation of a roof rack, 10% for a ski box (which was placed on top of the roof rack), 30-50% for a towed trailer and 60-80% for a towed trailer with a raised cover. These add-on devices also appeared to increase the sensitivity of fuel consumption to increases in speed. Increasing speed between 70 to 90 km/h led to an increase in fuel consumption of 13% without add-ons, but an increase of 25% with a covered trailer and load. The main conclusion of this study was that increased air resistance rather than the extra weight of the add-on devices generally has the greater effect on fuel consumption. NO_x emissions did not correlate in any systematic manner with either speed or the use of add-on equipment.

A1.14 Hammarstrom (1999) reported fuel consumption and NO_x measurements for a catalyst-equipped petrol car towing a caravan. The car was driven over several test cycles on the road and on a chassis dynamometer, both with and without the caravan, at various constant speeds (50, 80 and 110 km/h), and over the type approval cycle. With the caravan attached, fuel consumption increased by 30-40% over the 50-80 km/h range compared with driving without a caravan. For the car on its own, NO_x increased when the speed was increased from 50 to 80 km/h, and dropped considerably when speed was increased from 80 to 110 km/h. With the caravan attached NO_x emissions increased by 50% over the 50-80 km/h range.

Minimising the use of ancillary devices

A1.15 Ancillary devices such as the rear window defroster, fog lights, air conditioning, radios, CD players, *etc.* result in increased fuel consumption and should therefore be used as sparingly as possible. The use of air conditioning is however, quite problematic. It is likely that opening windows would be more fuel efficient than switching on the air conditioning at lower speeds, although this may be impractical if the outside temperature and humidity is uncomfortably high. In addition, having the windows open has a similar effect on fuel consumption when driving at higher speeds (above 60 km/h) because of the increase in air resistance. At higher speeds it is better to use the air vents without air conditioning. Van Mieghem and Gense (2005) showed that driving with the windows open can add 10% to total fuel consumption, compared with 18% for air conditioning.

Driving style

Driving off as soon as the engine has been started

A1.16 Eco-driving guidance states that a trip should begin as soon as the engine has been switched on. Clearly, any unnecessary time spent with the engine running at idle will waste fuel. However, the vehicle should be driven gently until the engine has reached its normal operating temperature. This action has the additional advantage of reducing low-frequency noise especially, from diesel engines.

Adopting a responsible driving style

A1.17 Eco-driving programmes generally encourage the adoption of a 'responsible' driving style. The main elements of this include:

- Maintaining a steady speed. The most fuel-efficient speed is typically around 45-50 mph. Lower constant speeds using high gears will generally result in lower fuel consumption (and possibly lower emissions as well), since the power required to travel at higher speeds increases non-linearly due to air resistance.
- Anticipation. In order to drive at a steady speed it is important to anticipate traffic situations to avoid unnecessary braking and acceleration. When approaching an obstacle or crossroads, the accelerator pedal should be released with the car in gear. The driver should stay in the same gear, and change only when there is a need to accelerate.
- Reducing speed on motorways. At high speeds the impact of air resistance on fuel consumption increases exponentially.
- Applying light throttle and avoiding heavy braking. These actions will reduce fuel consumption as well as wear.

- Coasting. When slowing down or coming to a stop, this uses the momentum of the vehicle to maintain forward motion. This is promoted in the media campaigns for the 'New Driving Style' in the Netherlands. No pressure is placed on the accelerator, the clutch is not engaged, and the car is still in gear. The clutch should be engaged if the engine speed falls below about 1,000 rpm (depending on the car). Coasting in neutral allows the car to role further than when it is in gear and the braking action of the engine is used. According to CIECA (2007), most countries would appear to prefer stipulating that the car should remain in gear, but deceleration should not involve changing down through the gears.

A1.18 Due to the confounding effects of different parameters, and effects which are difficult to control in real-world driving situations, the results of studies have been somewhat variable.

A1.19 Using an on-board measurement system, De Vlieger (1997) compared the effects on emissions and fuel consumption of 'calm' (anticipating other motorist's movements and avoiding sudden acceleration), 'normal', and 'aggressive' (sudden acceleration and heavy braking) driving behaviour. Six three-way catalyst petrol cars and one carburetted non-catalyst petrol car were used. Emissions associated with aggressive driving in urban and rural traffic were up to four times higher than those associated with normal driving, and fuel consumption increased by 30-40%. Calm driving generally resulted in decreases in emissions (except for NO_x) and fuel consumption compared with normal driving. Using a similar approach but different vehicles, De Vlieger *et al.* (2000) observed slightly different results. Depending on road type and vehicle technology, fuel consumption was observed to increase by 12 to 40% for aggressive driving compared to normal driving (and emissions increased by up to a factor of 8). However, calm driving compared to normal driving only produced a 5% decrease in fuel consumption.

A1.20 Latham *et al.* (2000) reviewed the influence of driving style on emissions and fuel consumption, and possible methods of providing feedback to the driver on how to reduce these. It was found that the potential for reducing CO, HC and possibly NO_X by changing driving style using a Euro 4 petrol vehicle was high, since only a small proportion of the driving time was responsible for most of the emissions. These periods usually coincided with prolonged states of high throttle use during which time the fuel air mixture became non-stoichiometric and the catalyst functioned less effectively.

A1.21 An eco-driving study was conducted between 2000 and 2002 by the Swedish National Road Administration (Johansson *et al*., 2003). In the study 86 drivers were used, with half of these having been trained in eco-driving. The drivers followed a route in real-world traffic using two instrumented cars. The cars were both petrol-fuelled and of the model year 2000. One of the cars was compliant with the Euro 4 emission standard, and the other with the Euro 3 standard. Driving patterns and fuel consumption were measured on-board, and emissions were measured by repeating the measured driving patterns on a chassis dynamometer. For the two vehicles tested, eco-driving was found to have no significant effect on emissions of NO_x and HC. For one of the cars the fuel consumption of eco-drivers was 8% lower than that of untrained drivers, but for the other car there was no difference in fuel consumption.

A1.22 Parkes and Reed (2005) used a heavy vehicle driving simulator to compare almost 300 drivers before and after an eco-drive training session (an instructional video). In the after-training simulator drive, there was a 7% reduction in circuit completion time, a 13% decrease in the number of gear changes used, and a 3% reduction in fuel consumption. However, Symmons *et al.* (2009) noted that no control group was used in the study.

A1.23 The effects of different measures to reduce exhaust emissions from passenger cars were measured by Vermeulen (2006). For the measurement programme 28 cars were selected. These included petrol and diesel cars, divided equally between the Euro 3 and Euro 4 emission standards. To determine the effects of eco-driving, urban and rural driving cycles were developed using real-world data recorded in an earlier project entitled 'Interpretation of driving style tips' (Van de Burgwal and Gense, 2002). The gear-shift strategies which were typical for both a moderate Dutch driver (already considered to be quite 'calm') as well as the Dutch eco-driver were also derived from this data. The eco-driving rules were:

- Shift up as soon as possible to a gear as high as possible, and at a maximum of 2,500 rpm (petrol) or 2,000 rpm (diesel).
- Keep the speed steady, driving at low engine speeds in the highest gear as possible.
- Look ahead as much as possible and anticipate other traffic.
- When decelerating or stopping, depress the throttle and coast the vehicle with a gear engaged.
- Stop the engine, even for short stops. Start again without pressing the throttle.
- Check tyre pressure monthly.
- Use in-car instruments like the rev counter, cruise control and trip/fuel meter.

A1.24 The driving cycles and the gear change strategies were investigated using a chassis dynamometer in an emission-testing laboratory. It was found that applying the eco-driving tips under average Dutch urban and rural traffic conditions led to a significant decrease in CO_2 emissions (Figure 1). For the petrol cars the reduction was around 7%, and for diesel cars the reduction was around 8-10%. For a reference situation with less 'passive' driving the beneficial effects on CO_2 and fuel consumption would be larger. For the petrol Euro 3 and Euro 4 cars eco-driving resulted in lower CO, HC and NO_x emissions for rural driving (although the differences for Euro 4 were not significant). For the diesel cars eco-driving resulted in an increase in NO_x emissions during urban driving, whereas for rural driving it resulted in a decrease in NO_x emissions (Figure 2). According to Vermeulen (2006) this may be explained by a combination of two effects: on the one hand changing gear at lower engine speed increases the NO_x emission, whilst on the other hand the stable driving with fewer accelerations and thus a lower overall engine load, may generally result in lower NO_x emissions. For urban driving the first situation prevails, whereas for rural driving the second situation prevails. The effects of eco-driving on PM emissions of diesel cars with or without a particle filter (Figure 3) were variable and not significant.

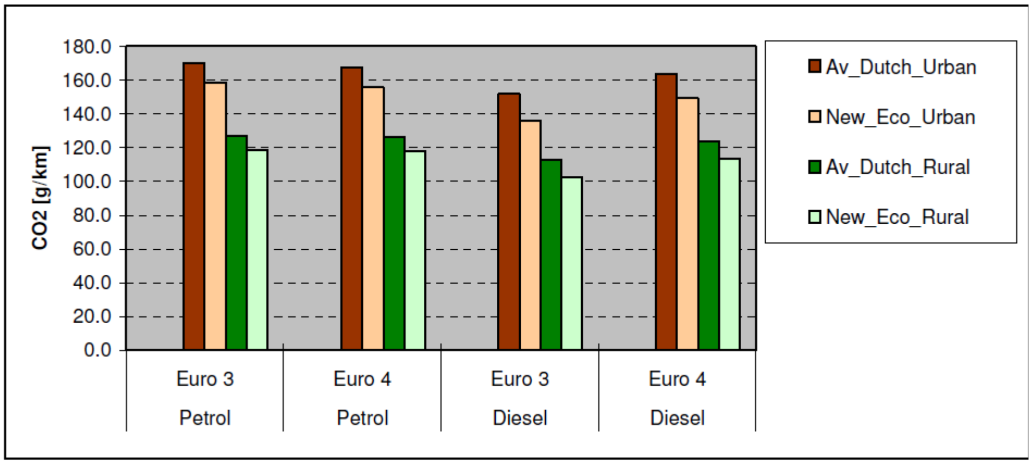

Figure 1: Average CO_2 emissions for average Dutch driving and eco-driving (Vermeulen, 2006).

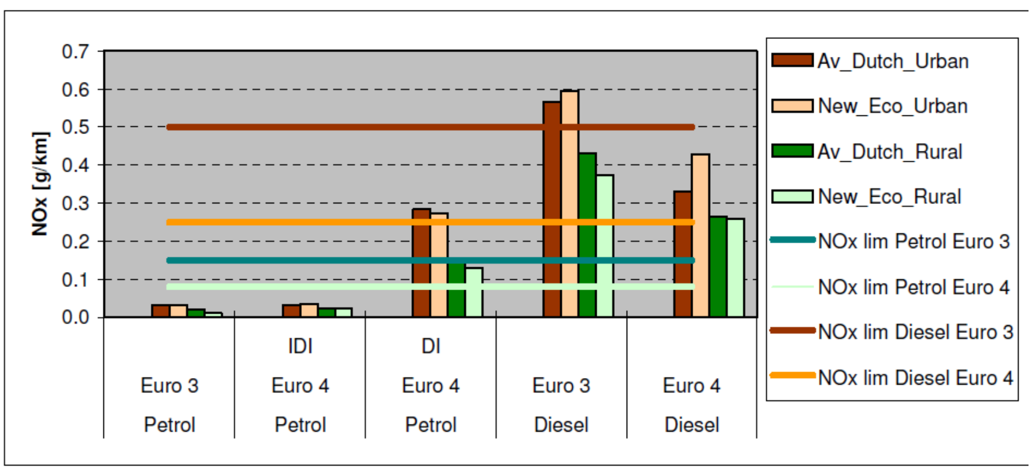

Figure 2: Average NO_x emissions for average Dutch driving and eco-driving. The EU NO_x emission limits are also shown (IDI = indirect injection, DI = direct injection) (Vermeulen, 2006).

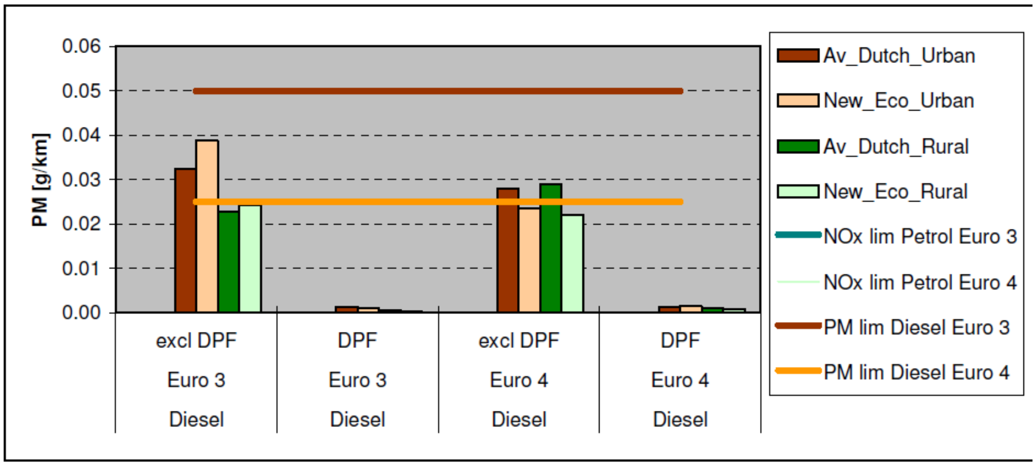

Figure 3: Average PM emissions for average Dutch driving and eco-driving. The EU PM emission limits are also shown, and vehicles with and without a DPF are presented separately (Vermeulen, 2006).

A1.25 It was concluded that the advice for gear shifting should be reformulated in such a way that the risk of an increase in NO_x emissions from diesel cars under urban driving conditions is minimised. Increasing the shifting speed to somewhere between 2,000 and 2,500 rpm will probably result in a smaller increase in NO_x, albeit with a reduced decrease in CO_2 (Vermeulen, 2006).

A1.26 Within the TNO eco-driving study driving cycles were also developed to assess the effects of acceleration behaviour on fuel consumption and emissions (Vermeulen, 2006). In these cycles the vehicle was accelerated from rest to 100 km/h in different ways, keeping the overall distance travelled constant. Three typical acceleration strategies were examined:

- 'Alternative 50%', with a moderate (50%) throttle position and low engine speeds for gear changes (2,000 and 3,000 rpm for diesel cars, and 2,500 and 3500 rpm for petrol cars).
- 'Alternative 90%', with a deep (90%) throttle position and low engine speeds for gear changes.
- 'Reference 50%' (applying a moderate throttle position at a high shifting speed).

A1.27 For both petrol and diesel cars the 'Alternative 50%' strategy resulted in the lowest fuel consumption and emissions, with the exception of NO_x for diesel cars which proved to be the highest for this strategy. The observed increase in NO_x was thought to be linked to the fuel efficiency; lower fuel consumption (increased efficiency) can be accompanied by an increase in NO_x emissions.

A1.28 In the 'Alternative 90%' strategy for petrol vehicles fuel enrichment resulted from the increased engine loads to increase driveability, engine power and to provide additional engine cooling. As a consequence, the 'Alternative 90%' strategy led to high fuel consumption, in spite of having the highest engine efficiency in theory.

A1.29 In general, the acceleration strategy with a moderate throttle position and a low shifting speed led to the lowest fuel consumption and emissions, with the exception of NO_x for diesel cars, which was the highest for this strategy.

A1.30 In a study in Greece, Zarkadoula *et al.* (2007) collected in-service driving and fuel consumption data for three bus drivers before and after eco-driving training. Two of the drivers reduced their fuel consumption and driving time by an average of 16% and 6% respectively. The third driver, who demonstrated the best pre-training levels for both fuel consumption and circuit time, recorded an increase in fuel consumption of 2%. The authors were also criticised by Symmons *et al*. (2009) for not determining whether the improvement for the two drivers (and deterioration for the third driver) was consistent over time, and explanations for the deterioration are not proposed.

Sensible use of gears

A1.31 A key part of eco-driving involves using gears effectively. The most fuel-efficient area of the engine map usually lies at low-to-mid engine speeds and high engine loads. For a given speed a higher gear is usually more economical than a lower gear (Figure 4). Hence, driving in the highest gear possible for a given speed, and at a low engine speed but without labouring the engine, is generally the most fuel-efficient way of driving. The ideal moment to change gears depends on the individual car and whether it is running on petrol or diesel. Changing-up gear before 1,800-2,500 rpm (petrol) and 1,500-2,000 rpm (diesel) is generally advisable. However, the guidance varies from country to country (CIECA, 2007). The guidance provided in the EU TREATISE project also notes that when driving uphill the most efficient approach is to use the highest gear possible with a deep accelerator position, and that a high gear should be used when negotiating bends (when safe and practical to do so).

A1.32 Laboratory experiments were performed as part of the Swiss Quality Alliance Eco-Drive programme by Weilenmann (2002). Three test cycles, representing 99% of urban driving conditions in Switzerland were used. Normal and eco-driving styles were represented using two gear-change strategies: 'Normal3000' and 'Eco2000'. 'Normal3000' was defined as changing up gear at 3,000 rpm, and changing down 3 km/h below the changing up speeds. 'Eco2000' was defined as changing up gear at 2,000 rpm during accelerations. During cruise modes the highest possible gear was used, and during decelerations no changes down in gear took place. The 10 vehicles tested showed a decrease in fuel consumption of 17.6% for the Eco2000 gear-shift strategy, which was due primarily to the periods of cruising at nearly constant velocity in a high gear Emissions of NO_x also decreased by 50%, but CO emissions increased by 190% and HC emissions increased by 60% for the whole cycle.

A1.33 The driver can be assisted in his or her choice of gear by a gear-shift indicator (GSI). A GSI advises the driver about when to change up or down by means of an indicator light/symbol (one for changing up and one for changing down) or a number on the dashboard indicating the preferred gear. GSIs are based on the same basic principles as eco-driving. When strong accelerations are required, however, a GSI will probably not advise the driver to shift up early at a low engine speed (Vermeulen, 2006). GSI strategies vary in complexity. Some strategies simply define limiting engine speeds for specific gear changes, whereas in others the exact gear shift required is computed from a combination of parameters. Some GSIs may have ‘adaptive’ or ‘sport’ modes which are unlikely to result in reductions in CO_2 emissions. The fitting of gear-shift indicators will become mandatory through the Regulation for General Vehicle Safety (Regulation EC No 661/2009). This calls for all relevant[14] vehicles which are fitted with a manual gearbox to be equipped with a GSI.

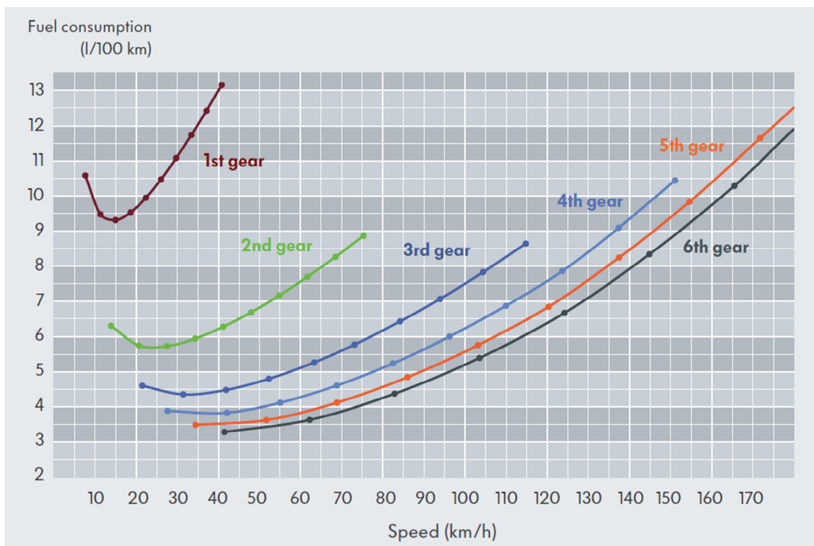

Figure 4: Fuel consumption curves in each of the six gears for 90 kW Volkswagen Golf 1.4 TSI, at 20°C ambient temperature[15].

A1.34 As part of the TNO study described earlier (Vermeulen, 2006), the effects of using a GSI were determined using the standard legislative European driving cycle, as well as the real-world urban and rural driving cycles developed in the EC ARTEMIS project. The standard gear-change points of the cycles were used as a reference. The adapted gear-change points were mainly provided by the vehicle manufacturers whose cars were used in the test programme. Over the legislative cycle the effect of the GSI on fuel consumption was found to be significant, with a reduction of 3-5%. The

[14] Vehicles of category M1 with a reference mass not exceeding 2,610 kg and vehicles to which type-approval is extended in accordance with Regulation (EC) No 715/2007 - specifically those vehicles first type approved after 1 November 2012, and all vehicles registered from 1 November 2014.

[15] Source: Volkswagen promotional brochure: Save as you drive – background information for expert fuel savers.

largest effect was observed during the urban part of the cycle, because during the extra-urban (higher speed) part there is not much room for optimising gear-changing (the car is driven for most of the time in its highest gear). For petrol cars there was also a reduction of 7% over the real-world urban cycle and 11% over the real-world rural cycle. For the diesel cars the reductions over the urban and rural cycles were 4% and 6% respectively. The effect for diesel cars was lower than for petrol cars because in the real-world cycles the gear shifts for diesel cars are already at substantial lower engine speeds. NO_x emissions from the diesel cars were found to increase (by 15-30%) when a GSI was used. PM emissions from diesel cars without DPFs also increased (by 15-50%) when a GSI was used. For the Euro 3 petrol cars a significant decrease in NO_x was observed over the urban part of the standard cycle and over the urban real-world cycle. A possible cause of the decreased NO_x emission may have been fuel enrichment caused by the deeper throttle positions and the resulting higher engine loads. The Euro 4 cars responded differently. They showed an increase in NO_x emissions with the GSI, but the increase was only significant over the real-world urban cycle. However, in absolute terms the emission levels were very low (Vermeulen, 2006).

A1.35 In a study by Fontaras *et al.* (2008) the standard gear-change points of the ARTEMIS driving cycle were replaced by points defined by a GSI. For a Honda Civic IMA[16] vehicle the gearshift indicator improved fuel consumption by between 1% and 6%.

Avoiding unnecessary engine idling

A1.36 In some traffic situations vehicles are idling for a large share of their time. Examples of these traffic situations include the following (Vermeulen, 2006):

- Traffic jams
- Rail crossings
- Traffic lights
- Taxi stands
- Distribution vans loading/unloading
- Short-term parking (e.g. near schools were parents drop off or pick-up their children)

A1.37 Whenever it is safe to do so, switching off the engine can reduce fuel consumption. Indeed, in some modern vehicles the engine switches itself off automatically under such conditions. Where the engine is to be switched off manually, some anticipation on the part of the driver is required. For example, the engine should be switched off if a stop of several minutes or more is anticipated.

[16] IMA = Integrated Motor Assist, a hybrid petrol-electric system.

A1.38 When switching on a modern fuel injected engine the accelerator pedal should not be pressed. The electronic engine management system takes care of a correct start and amount of injected fuel based on various parameters (SenterNovem, 2005).

A1.39 It is noted by CIECA (2007) that there are differences between individual cars with respect to when to switch off the engine from an emissions perspective. For some cars, it makes sense to turn off the engine at stops of only 10 seconds; for others the emissions are greater if you switch off the engine before 8 minutes have elapsed.

A1.40 In the UK, Rule 123 of the Highway Code sates that 'If the vehicle is stationary and likely to remain so for more than a couple of minutes, you should switch off the engine to reduce emissions…'. The Dutch national eco-driving programme suggests a period of 1 minute. Germany's 'Drive and Save safely' programme advises drivers to turning off the engine at stops lasting longer than 40 seconds. It also notes that the accelerator should not be used when starting the car. In Switzerland, as in Holland, candidates are – or will soon be - expected to turn off their engine at red traffic lights, provided they are a few cars back from the front of the queue.

A1.41 However, CIECA (2007) also identified a number of potential problems with this action, including the following:

- Learning to switch off the engine regularly at traffic lights can be rather stressful for a learner driver, particularly in terms of having to switch the engine back on and move away quickly once the lights go green.
- Learner drivers may have difficulty estimating the waiting time during a stop, and therefore whether or not to switch off the engine.
- In traffic jams at junctions, applying this rule could mean switching on and off the engine a number of times before passing through the traffic lights.
- The significant variation between individual car brands and models in terms of when it is best to switch off the engine means that it is difficult to establish a simple yet accurate rule.

A1.42 Another issue to consider is the extent to which repeated switching-off affects the service life of the starter motor and battery.

A1.43 Turning off a vehicle's engine when the vehicle is stationary for extended periods may reduce fuel consumption and pollutant emissions, but the literature is quite limited.

A1.44 The fuel consumption (or mass of pollutant emitted) during the period of time between when the vehicle stops and when it starts to move away needs to be considered and there two basic operational scenarios to compare:

- The engine is left running at natural idle, with a fairly constant emission rate.

- The engine is turned off as soon as the vehicle stops, and the emission rate drops to zero. The engine is turned on immediately before the vehicle moves away, and there is an additional fuel consumption associated with the engine start. However, the additional fuel consumption is mainly for older petrol cars with a carburettor.

A1.45 Any advantage offered by the latter scenario depends upon whether the mass of pollutant emitted during the emission peak is less than the mass emitted at natural idle during the switch-off period. This will obviously depend on the duration of the switch-off period. For a very short switch-off there will probably be a net increase in emissions, but for long switch-off periods there should be a net decrease. However, the problem is not straightforward, partly because the size of the emission peak will increase with time as the engine or catalyst cools, and also because both the idle emission rate and the emission peak will vary considerably from vehicle to vehicle, and will be dependent upon many factors, including pollutant, engine/fuel type, driving time/distance (*i.e.* there may be a 'cold start' effect), and ambient temperature. Vehicle age and technology (*e.g* catalyst/non-catalyst) are also important considerations. For example, with new cars the engine should re-start quite readily, but with older cars the driver may need to apply the accelerator pedal, and this will heighten the emission peak.

A1.46 According to an early study (Degobert, 1995), switching-off the engine had little effect on catalyst-equipped petrol vehicles, since the switch-off time would generally be insufficient to cool the catalyst.

A1.47 In Japan, Motoda and Taniguchi (2003) undertook a questionnaire survey which revealed that more than 80% of respondents switched off the engine of their vehicle when it was parked, but only 4% switched off the engine during stops when driving. The main reason why drivers did not stop the engine when driving was to avoid a starting time lag. A field test was carried out with three (undefined) vehicles that were driven about 3,700 km total. Two of the vehicles were equipped with an engine switch-off support system. The system resulted in a reduction in fuel consumption of 6% overall, and 13% on urban roads.

A1.48 More recently, and again as part of the TNO study described earlier, to determine the effects of 'stopping and restarting' and 'idling' petrol car engines, Vermeulen (2006) developed a special start and stop cycle with 'engine off ' times of respectively 1, 2 and 5 minutes and an idling period (5 minutes) serving as a reference. All emissions were measured second by second, so that the emissions over each typical situation could be determined individually. For the comparison with the reference (idle) situation, it was assumed that each engine stop would be preceded by an idle period of 10 seconds. This was to simulate the time a driver takes to make the decision to stop the engine. Every restart was followed by an idle period of 10 seconds to simulate the time a driver would restart his engine before driving. For diesel cars a cycle was used with a stop time of 1 minute. This cycle was performed 5 times and was measured as one sample. The following conclusions were drawn from this work:

- While idling, the emissions of NOx, PM and CO_2 from diesel cars, and the emissions of CO_2 from petrol cars are substantial, and are so high compared to the restart emissions that stopping the engine almost directly (after not more than 10 to 20 seconds) leads to a benefit.
- For CO and HC emissions from petrol and diesel cars, and NOx emissions from petrol cars, leaving the engine at idle would result in lower emissions than a restart, except for extremely long stops (probably more than one hour).
- Taking account of the level of the effects, the largest benefit can be obtained by directly stopping the engine. This leads lower NOx and PM emissions from diesel cars, and to lower CO_2 emissions from both petrol and diesel cars.

In-vehicle devices

A1.49 Various in-car devices encourage eco-driving and fuel saving, such as the rev counter, cruise control, on-board computers and satellite navigation systems. A rev counter or onboard computer can help the driver to choose an appropriate speed. Cruise control is a useful aid for smooth and steady driving. Satellite navigation systems are useful for avoid unnecessary mileage as well as avoiding congested traffic. Fleet operators should equip vehicles with satellite navigation. However, they should only be used when needed.

A1.50 According to SenterNovem (2005), in several field tests devices such as econometers, on-board computers, cruise controls and speed and revolution limiters drivers were able to save 5% fuel on average. Individual savings sometimes exceeded 10%. Field tests with more sophisticated experimental feedback instruments resulted in fuel-efficiency improvements of even up to 20%.

Travel and transport planning

A1.51 There is an argument that, by adopting eco-driving advice, motorists feel more comfortable about the environmental consequences of their actions, rather than feeling the need to modify their travel habits. Fuel consumption can be reduced by avoiding car travel altogether where possible and walking, cycling or taking public transport. Car sharing is also beneficial. Some eco-driving programmes advise that driving in cities should be avoided. Cities often have congested traffic, but also good public transport links. Fleet operators should use logistical routing packages that minimise distances travelled and encourage passenger sharing (Latham *et al.*, 2008).

Eco-driving programmes

A1.52 Several eco-driving initiatives, publications (including web sites) and training programmes have been introduced. Some examples of these are summarised in this Section of the Report. It was noted by CIECA (2007) that the various descriptions of eco-driving actions appear to largely repeat themselves. However, the precise wording and structure of these descriptions may have an impact on how well they are implemented on the ground.

ECODRIVEN

A1.53 The ECODRIVEN (European Campaign On improving DRIVing behaviour, ENergy-efficiency and traffic safety) project involved a Europe-wide eco-driving campaign aiming at drivers of passenger cars, delivery vans, lorries and buses. The ECODRIVEN campaign ran from January 2006 to December 2008 and covered nine countries: the United Kingdom, France, The Netherlands, Belgium, Finland, Austria, Poland, the Czech Republic and Greece.

A1.54 The activities were organised in collaboration with car dealers, fuel stations, touring clubs, drivers' associations and driving schools, as well as local authorities, businesses and hauliers. More detailed information about ECODRIVEN, end the results from specific case studies, can be found on the website (noted earlier). It is claimed that more than 20 million licensed drivers received the eco-driving message, and that ECODRIVEN resulted in the avoidance of 1 Mton of CO_2 emissions between 2006 and 2010.

TREATISE

A1.55 Treatise was an EC project which ran from January 2005 to June 2007, and provided free training on sustainable transport subjects. One of the subjects covered was eco-driving. The project was conducted by a consortium of seven European national energy agencies A web-based training tool was designed and built, and advice was disseminated via a series of training workshops. At the time of writing the website of the project (www.treatise.eu.com) could not be accessed.

A1.56 For TREATISE, EST (2005) provides brief summaries of the results eco-driving initiatives in several countries. It mentions trials conducted in 2004 by the UK Driving Standards Agency, in which the fuel consumption of drivers over a set course was measured before and after they had received 2 hours of eco-driving training. The trials demonstrated an average fuel saving of 8.5%. EST also mention a 2002 Dutch study in which private motorists were divided into eco-drivers and non-eco-drivers, based on self-reported behaviour . Over the one-year duration of the study the eco-drivers consumed 7% less fuel per km than the non-eco-drivers. A separate trial conducted in the Netherlands during the period 1995-2003 revealed a 2.1% reduction in fuel consumption associated with eco-driving. Similarly, a large-scale trial in Spain in 2003 demonstrated average fuel savings of 13.4% when drivers adopted eco-driving techniques, and in Hamburg in the same year 91 delivery van drivers consumed around 6% less fuel during the 6 months following eco-driving training.

Quality Alliance Eco-Drive (Switzerland)

A1.57 A summary of evaluation work undertaken for the Swiss Quality Alliance Eco-Drive programme was produced by Hornung (2004). Various types of evaluation, using a range of subjects, were described. It was concluded that in comparison with conventional driving techniques, with Eco-driving it is possible to reduce fuel consumption by about 10-15% without having to drive more slowly. However, the tests have been criticised by Symmons *et al.* (2009), as factors such as gender, driving experience, infringement history and other variables that might affect driving behaviour, as well as the lack of controls, were not adequately taken into account.

SAFED

A1.58 In the UK the Department for Transport (DfT) operates a Safe and Efficient Driving (SAFED) training programme. This has been developed to enable both vehicle operators and training providers to implement driver training and development for existing HGV drivers within the road freight industry. Various case studies were briefly described by DfT (2006). The evidence provided suggests that reductions in fuel consumption have been achieved, but is largely anecdotal.

ECO Stars

A1.59 In January 2009 Care4Air launched the ECO Stars Fleet Recognition Scheme - the first of its kind in the UK. The free, voluntary South Yorkshire-wide scheme encourages commercial operators of buses, coaches, HGVs and LGVs to implement operational best practice in fleet management. This is supported by tailored recommendations on how to reduce fuel consumption and lower vehicle emissions. Over 3200 vehicles across the region are currently signed up to the scheme.

A1.60 ECO Stars rates individual vehicles and fleet operation using a star rating system. By implementing the key measures in the ECO Stars Scheme a typical HGV operator could reduce fuel consumption by a minimum of 5% in the first year. Based on 80,000 miles per year at 8 mpg and an average of £1 per litre of diesel, there would be a saving of the equivalent of 10,000 gallons of fuel. For an operator with 10 vehicles this equates to a saving of £2,300 per vehicle[17].

Summary and recommendations

Summary

A1.61 The eco-driving advice which is provided by different organisations varies considerably in terms of the level of detail, but it generally features a number of common actions. However, it is rather

[17] Figures from Department For Transport Freight Best Practise Programme

difficult to separate the effects of these different actions, as they have often been examined in combination, or in the absence of controls.

A1.62 Eco-driving programmes generally encourage the adoption of a 'responsible' driving style. Due to the confounding effects of different parameters, and effects which are difficult to control in real-world driving situations, the results of studies have been somewhat variable. It appears that the general adoption of the 'driving-related' eco-driving principles can lead to a reduction in fuel consumption of the order of 5-15%, though the actual effect will depend upon the road type and the level of traffic. It is likely that for the traffic conditions in London – which are often congested and otherwise restricted (*e.g.* by traffic lights), the benefits are likely to be towards the lower end of the range. The use of gears in line with eco-driving rules may be responsible for a significant fraction of the overall reduction in fuel consumption. For modern vehicles the evidence indicates that NO_x emissions are slightly lower when eco-driving is used, with the exception of emissions from diesel vehicles under urban driving conditions, which appear to increase. Switching off the engine when a vehicle is stationary in traffic does appear to reduce fuel consumption and emissions, and is one measure that could be used to greater effect in congested London traffic. However, any reductions will be highly dependent upon the traffic conditions and the type and length of the journey.

A1.63 Other actions, which are not related to the actual driving, can also reduce fuel consumption. Ensuring that tyres are at the correct pressure (or even slightly overinflated) can lead to reductions in fuel consumption of a few percent. Where possible, reducing the vehicle weight, aerodynamic drag and the use of ancillaries can generally have a larger impact on fuel consumption (up to 20%).

Recommendations

Values to be used in TfL modelling exercises

A1.64 The questions to be addressed here include:

1. Which pollutants should be included?

   Fuel consumption/CO_2, NO_x and PM.

2. Which aspects of eco-driving can be included? Can the various elements be treated separately, or must they be treated in combination?

   At present the available literature does not permit the modelling of different aspects of eco-driving which relate to the actual driving. It is therefore recommended that a simpler approach is used, whereby it is assumed that the effects of these aspects are quantified in combination. Other actions, such as reducing vehicle weight, or reducing the use of ancillaries can be treated separately, but the problem here is the absence of real-world data.

3. What values should be used to show the benefits (or otherwise) of eco-driving for the different vehicle categories in the TfL fleet (*e.g.* buses, taxis, dial-a-ride vehicles, *etc.*)?

   The actual answers to these questions are going to be rather specific to the vehicles and drivers in the various fleets. It is recommended that experimental data be collected to determine the size of effects and the extent of their application (see Section 0).

4. What values should be used for private vehicles?

   Where private vehicles are included in TfL modelling exercises, it is recommended that conservative estimates are made of the effect of eco-driving (say, a 5% reduction in fuel consumption) and the extent and duration of the uptake.

5. How valid are the data for the driving conditions, and the drivers, in London?

   Few experimental data appear to exist for London driving conditions. Where there is reliance on data in the literature for modelling, the results for urban driving should be used.

6. What is the level of uptake?

   This is rather difficult to estimate for private vehicles, but at present the level of uptake of eco-driving principles is likely to be low. Higher levels of uptake can be assumed for TfL fleets where the extent of driver training is known.

7. How long do the effects of eco-driving training last?

   This is currently an area of research. It is not straightforward to determine how long, say, eco-driving training has an effect on driver behaviour and fuel consumption. It does not even appear to be known in any detail how the baseline driver behaviour (i.e. in the absence of any training) changes with time, either in the short term or the long term.

Design of test programme for evaluating eco-driving

Overview

A1.65 Ideally, the effects of eco-driving (or driver training) should be measured directly under real-world operational conditions. These effects include not only the changes in fuel consumption and emissions per vehicle, but also the level of uptake, the duration of the effect, and activity data relating to, for example, the use of ancillary devices, changes in vehicle weight, *etc.*

A1.66 In this Section of the Report some considerations are noted for the design of a suitable test - or programme of tests - for evaluating the effects of eco-driving, in this case within the TfL fleet, and only the driving-related aspects. The different aspects of eco-driving (*e.g.* avoiding sharp accelerations, driving in the highest gear, using coasting) would not be addressed separately.

A1.67 The questions which need to be answered include:

(i) Does driver training have a statistically significant effect on average vehicle fuel consumption?

(ii) What is the magnitude of the effect, and what are the confidence intervals on the estimate?

(iii) If there is a significant effect, how long does it last?

A1.68 As an example, it is proposed that an experiment could be conducted to investigate the effects of eco-driving training on the fuel consumption of buses[18] in the TfL fleet.

A1.69 Two groups of drivers will be investigated in the experiment:

- Group A: A target group, which will undergo driver training.
- Group B: A control group, which will not undergo driver training.

A1.70 It is essential that those selected for training are done so using a randomised process (albeit perhaps still stratified to achieve a balance of sexes, routes and bus types).

A1.71 The fuel consumption of the buses driven by both groups of drivers will be recorded continuously before and after driver training. In all cases, it is desirable that the drivers are not aware that they are participating in the experiment.

A1.72 However, there are likely to be a number of confounding factors which could affect the results of such an experiment. Such factors might include, for example:

- The varying response of different drivers to the training (driver effects).
- The varying response of different buses to changes in vehicle operation (bus effects).
- The possibility that the effect might be influenced by the general type of bus operation, such as low-speed or high-speed driving (route effects).
- The possibility that any observed effect is not related to the driver training, but occurs for other reasons (e.g. changes in traffic conditions).
- The fact that drivers do not always use the same bus (or drive the same route).

A1.73 Such effects will be controlled in the experimental design and/or the analysis of the data. Conditions during each run should be recorded, *i.e.* weather, traffic (light/med/heavy), delays, number of stops, *etc*.

Statistical considerations

Dependent variables

A1.74 The main dependent variable which will be measured (or noted) throughout the trial will be the vehicle fuel consumption (litres/100km), which will be determined from the fuel used and the distance driven during a particular period. However, a number of other variables, which may offer some insight into the reasons for any changes in fuel consumption, are also of interest. These

[18] The buses are equipped with automatic transmission, so gear-change behaviour is not relevant.

include, for example, vehicle speed, average acceleration, average deceleration, engine speed, and so forth.

Independent variables

A1.75 Independent variables are those that are manipulated in an experiment. In this case, these are likely to include things like driver gender, bus type and route. The combination of independent variables determines the number of experimental conditions to be investigated.

Sample size

A1.76 Sample size is an important element of experimental design. Samples that are too large may waste time, resources and money, while samples that are too small may lead to inaccurate conclusions because of not being able to detect an effect size that was of interest at the appropriate level of statistical significance. The minimum number of observations required to give statistically significant results can be estimated from the associated standard error of the fuel consumption measure and the accuracy required.

A1.77 The vehicle sample size required for the trial has been calculated using the equation:

$$n = \left[\frac{z_{\alpha/2}\sigma}{E} \right]^2$$

Where:

n is the sample size
$Z_{\alpha/2}$ is known as the 'critical value' (1.96 for 95% confidence)
σ is the population standard deviation
E is the acceptable margin of error

The population standard deviation and the acceptable margin of error would be assumed.

Experimental method – real-world driving

A1.78 The proposal here is to stratify the sample to include the two bus types and two driver types across a variety of routes (3-4) and use as large a sample as possible. There will also be time of day, weather and other factors – all of which should be recorded. The analysis would also control for the route type, bus type and driver type factors.

A1.79 The routes to be driven would be identified by TfL. The buses should be used across a variety of routes (3-4) which are broadly representative of the whole.

A1.80 There would be a number of options for data collection, such as:

- Option 1: Reporting of data by bus operators. This is the approach currently being used by TfL in its evaluation of the hybrid bus programme. However, there are some concerns about the reliability of the data, and this approach will not provide any detailed information on vehicle operation (only the route) or emissions (only fuel consumption).

- Option 2: Use of existing TfL fleet management systems. TfL is already monitoring the performance of its bus fleet, and is also in the process of integrating the CAN-bus interface with i-bus. These systems could potentially be used to provide the relevant data on distance and fuel use, and possibly detail on other aspects of operation (speed and acceleration, for example). It is not yet clear how much information on emissions would be available.
- Option 3: Vehicles instrumented by a third party. This could be rather expensive for large sample size.

A1.81 The monitoring will be conducted for a period of two months before the driver training, and again six and twelve months after the training so that the durability of any effect can be assessed. Data will be collected on a daily basis.

Experimental method – laboratory measurements

A1.82 Any effect of eco-driving training on fuel consumption would be due to a combination of factors, such as:

- Lower rates of acceleration and deceleration
- Lower engine speeds
- Switching off the engine
- Turning off auxiliaries

A1.83 Laboratory tests could be conducted to determine the relative contributions of such factors to the overall impact (but not the impact itself, as the laboratory tests will not replicate real-world driving conditions, and the driver will be aware of the purpose of the experiment). Firstly, a HDV driving simulator would be used to record the driving patterns of drivers before and after driver training. These driving patterns would then be used in experiments on a chassis dynamometer. During the tests, information on vehicle operation and fuel consumption would be recorded continuously, and a modal analysis approach will be used to estimate fuel consumption for different driving modes.

References (Eco-driving)

Avery K L, Myers D N, Cordell B and Harris B J (2009). Evaluating the Sustainability of Passenger Cars: Interventions and Trade-offs: A report to the Department for Environment, Food and Rural Affairs. TRL Limited. Defra, London.

CIECA (2007). Internal project on 'Eco-driving' in category B driver training & the driving test - Final Report (05-11-07). www.cieca.be

Degobert P (1995). Automobiles and pollution. SAE R-150. ISBN 2-7108-0676-2.

De Vlieger I (1997). On-board emission and fuel consumption measurement campaign on petrol-driven passenger cars. *Atmospheric Environment*, Vol. 31, pp. 3753-3761.

De Vlieger I D, De Keukeleere D and Kretzschmar J G (2000). Environmental effects of driving behaviour and congestion related to passenger cars. *Atmospheric Environment*, Vol. 34 (27), pp. 4649-4655.

DfT (2006). Companies and Drivers Benefit from SAFED for HGVs - A Selection of Case Studies. HMSO.

EST (2005). Ecodriving: Smart, efficient driving techniques. Energy Saving Trust London.

Fontaras G, Pistikopoulos P and Samaras Z (2008). Experimental evaluation of hybrid vehicle fuel economy and pollutant emissions over real-world simulation driving cycles). *Atmospheric Environment*, Vol. 42, pp.4023–4035.

Hammarstrom U (1999). Measurement and simulation of vehicle exhaust - driving with and without a caravan in different test cycles. Swedish National Road and Transport Research Institute (VTI). SE-581 95, Linkoping, Sweden.

Hornung W (2004). Summary: Evaluations of Eco-Drive Training courses. Quality Alliance Eco-Drive and Swiss Energy report. Bern, Switzerland. eco-drive.ch/download/sum_evaluationen.pdf

Johansson H, Gustafsson P, Henke M and Rosengren M (2003). Impact of EcoDriving on emissions. Transport and Air Pollution. *Proceedings from the 12th Symposium*, Avignon 16-18 June 2003

Latham S, Smith L and Harris G (2000). Behaviour change and environmental impact. TRL Report PR SE/165/2000. TRL Limited, Crowthorne.

Latham S, Boulter P, McCrae I and Turpin K (2008). A best practice guide for reducing emissions from taxis in London. TRL Report PPR349. Transport Research Laboratory, Wokingham.

Lenner M (1998). Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden. BIBLIOGRAPHIC NOTES: Reprint from SAE technical paper series SP-1335, paper 980682, pp 285-289 (International Congress and Exposition, Detroit, USA, February 1998).

Motoda Y and Taniguchi M (2003). A study on saving fuel by idling stops while driving vehicles. Proceedings of the Eastern Asia Society for Transportation Studies, Vol.4, October, 2003.

Parkes A M and Reed N (2005). Fuel efficiency training in a full-mission truck simulator. In *Behavioural Research in Road Safety 2005*: Fifteenth Seminar, pp. 135-146.

SenterNovem (2005). Ecodriving - The smart driving style. Produced by SenterNovem, Utrecht for the EC TREATISE project, September 2005.

Symmons M, Rose G and Van Doorn G (2009). Ecodrive as a road safety tool for Australian conditions. Road Safety Grant Report No. 2009-004. Department of Infrastructure, Transport, Regional Development and Local Government, Canberra, Australia.

Van de Burgwal H C and Gense N L J (2002). Interpretation of driving style tips: Application of the major driving style tips of 'New Style Driving' by passenger car drivers and the effects on fuel consumption and tailpipe emissions, TNO-report 02.OR.VM.004.1/HVDB, February 2002. TNO Science and Industry, Delft.

Van Mieghem R and Gense R (2005). Extra brandstofverbruik door gebruik van accessoires in personenauto's. TNO report 05.OR.VM.066.1/RvM. TNO Science and Industry, Delft.

Vermeulen R J (2006). The effects of a range of measures to reduce the tail pipe emissions and/or the fuel consumption of modern passenger cars on petrol and diesel. TNO report IS-RPT-033-DTS-2006-01695. TNO Science and Industry, Delft.

Weilenmann M (2002). Emissions and fuel consumption with Eco Drive - English summary. Report number 201209e. EMPA, Dübendorf, Switzerland.

Zarkadoula M, Zoidis G and Tritopoulou E (2007). Training urban bus drivers to promote smart driving: A note on a Greek eco-driving pilot program. *Transportation Research Part D: Transport and Environment*, Vol. 12 (6), pp. 449-451. Cited in Symmons *et al.* (2009).