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International review of the Air Quality Innovation Programme (IPL)

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Content

Executive summery

The Dutch Air Quality Innovation Programme (*Innovatieprogramma Luchtkwaliteit*; IPL) was established in 2005 with the purpose of identifying innovative measures which could be used locally to improve air quality alongside motorways in the Netherlands, and developing those measures that exhibited significant air quality benefits to a level suitable for network implementation.
This Report provides the main summary in English of the work undertaken within IPL, and presents the findings of an independent Scientific Board which was commissioned to provide advisory and reviewing functions, and to act as a conduit to and from the international research community.
The Report describes the background and rationale for the programme, the work conducted, and the findings of the Scientific Board.

This report has been issued and amended as follows:

Version	Date	Description	Editor	Technical referee
1.1	*19 June 2008*	*Scientific Board Strategy document*	*Theo Cornelissen, Paul Boulter and Ian McCrae*	*Ian McCrae*
1.2	*23 February 2009*	*Scientific Board Strategy document*	*Theo Cornelissen, Paul Boulter and Ian McCrae*	*Ian McCrae*
1.3	*24 November 2009*	*IPL Scientific Board Review*	*Paul Boulter and Ian McCrae*	*Ian McCrae*
Final	*10 December 2009*	*IPL Scientific Board Review*	*Ian McCrae*	*Paul Boulter*

1 Introduction

1.1 Overview

The Dutch Air Quality Innovation Programme (*Innovatieprogramma Luchtkwaliteit*; IPL) was established in 2005 with the purpose of identifying innovative measures which could be used locally to improve air quality alongside motorways in the Netherlands, and developing those measures that exhibited significant air quality benefits to a level suitable for network implementation.
This Report provides the main summary in English of the work undertaken within IPL, and presents the findings of an independent Scientific Board which was commissioned to provide advisory and reviewing functions, and to act as a conduit to and from the international research community.
This introductory part of the Report describes the background and rationale for the programme. The remainder of the Report is divided into two main Parts:
- Part B, which describes the work undertaken, and
- Part C, which contains the findings of the Scientific Board.

A glossary of acronyms and abbreviations used in the Report is provided in Appendix A.

1.2 Programme background and context

1.2.1 *Air quality standards in the Netherlands*

As with other Member States of the European Union, the Netherlands is subject to European air quality standards which have been established for specific pollutants. Directive 2008/50/EC on ambient air quality and cleaner air for Europe entered into force on 11 June 2008, and brought together most of the existing air quality legislation, including the air quality standards (as shown in Table 1).

Table 1
Air quality standards in the European Union.

Pollutant	Concentration	Averaging period	Legal nature	Permitted exceedences each year
PM_{10}	50 µg/m^3	24 hours	Limit value 1.1.2005	35
	40 µg/m^3	1 year	Limit value 1.1.2005	n/a
$PM_{2.5}$	25 µg/m^3	1 year	Target value 1.1.2010 Limit value 1.1.2015	n/a
SO_2	350 µg/m^3	1 hour	Limit value 1.1.2005	24
	125 µg/m^3	24 hours	Limit value 1.1.2005	3
NO_2	200 µg/m^3	1 hour	Limit value 1.1.2010	18
	40 µg/m^3	1 year	Limit value 1.1.2010	n/a
Lead	0.5 µg/m^3	1 year	Limit value 1.1.2005	n/a
CO	10 mg/m^3	Max. daily 8-h mean	Limit value 1.1.2005	n/a
Benzene	5 µg/m^3	1 year	Limit value 1.1.2010	n/a
Ozone	120 µg/m^3	Max. daily 8-h mean	Target value 1.1.2010	25 days averaged over 3 years
Arsenic	6 ng/m^3	1 year	Target value 1.1.2012	n/a

Pollutant	Concentration	Averaging period	Legal nature	Permitted exceedences each year
Cadmium	5 ng/m^3	1 year	Target value 1.1.2012	n/a
Nickel	20 ng/m^3	1 year	Target value 1.1.2012	n/a
PAH [(a)]	1 ng/m^3 [(b)]	1 year	Target value 1.1.2012	n/a

(a) Polycyclic aromatic hydrocarbons.

(b) Expressed as concentration of Benzo(a)pyrene.

In August 2005 an Air Quality Decree (*Besluit luchtkwaliteit*) was issued by the Dutch government. This transposed the existing European air quality law into Dutch law. The Decree established standards for sulphur dioxide (SO_2), nitrogen dioxide (NO_2), total oxides of nitrogen (NO_x), PM_{10}, lead, carbon monoxide (CO) and benzene. The Decree laid down the requirements regarding air quality management (monitoring programmes and calculation methods), administration (air quality reports and reviews) dissemination of data to the public and the action to be taken when standards are exceeded (air quality action plans).

The Decree also allowed development projects to be implemented in areas where the standards for particulate matter and NO_2 were already exceeded, as long as the projects did not cause any further deterioration of air quality. It also opened the way for projects that did have an adverse impact on local air quality, as long as steps were taken to substantially improve the air quality in another nearby area (within, or partly outside, the same municipality). This was referred to as the 'local no-net-impact' approach.

However, in recent years the Administrative Jurisdiction Department of the Council of State has annulled a number of planning approvals based on air quality, including the planning permission for a new football stadium in the Hague, the application for a commercial park at Hendrik-Ido-Ambacht, the Stationseiland railway terminal in Amsterdam, and the addition of rush-hour lanes to major roads such as the A2 motorway. The approvals were annulled either because the plans failed to conform to the standards of the Air Quality Decree, there were poor procedures, or because there was a potential deterioration in air quality.

In 2008 the Decree was superseded by the Environmental Management Act (*Wet Milieubeheer*). The limit values for air pollutants remained the same, but the national legal structure was modified. In accordance with the EU Directive, the limit values are now applicable at every location up to 10 m from the kerbside, but actual concentrations do need to be determined at locations where people do not live or do not have access. As a result, many plans no longer have to be assessed.

The possibility for projects that have no net local impact to be implemented still exists in the new law, but is hardly used in practice. There is a possibility for projects to be implemented if they do not contribute 'in significant amounts' to air pollution (if they do not increase the yearly averaged concentrations of PM_{10} or NO_2 by more than 1.2 $\mu g/m^3$).

The main feature of the new air quality law is the National Air Quality Cooperation Programme (*Nationaal Samenwerkingsprogramma Luchtkwaliteit*, NSL). This programme specifies the measures that must be taken in the near future to ensure that the Netherlands remains within the air pollution limits, and forms the basis of a request for the European Commission to grant the Netherlands an extension to the deadlines for compliance with the limits. The NSL comprises a quantified assessment (Saneringstool)[1], a list of spatial planning and infrastructure projects for the next five years, a range of measures and compulsory annual monitoring. From now on, spatial planning and infrastructure projects will no longer be assessed for air quality on an individual basis, but rather according to whether they are an integrated part of the NSL.

1.2.2 Air quality alongside Dutch motorways: the need for IPL

In the Netherlands the high population density and high levels of traffic mean that the European air quality standards are difficult to achieve. According to the National Institute for Public Health and the Environment (RIVM), levels of NO_2 and PM_{10} are highest in the Dutch coastal conurbation and lowest in the north-east of the country.

It is alongside the country's busiest roads where limit values are most often exceeded. In an attempt to tackle such pollution 'hotspots', in November, 2005 the government reduced the speed limit from 100 to 80 km/h on four motorway sections:

- A10 West, between Nieuwe Meer interchange and the Coen Tunnel.
- A20, between Kleinpolderplein interchange and Crooswijk junction.
- A12, between Oudenrijn and Lunetten interchanges, all lanes.
- A12, between Utrechtsebaan and Voorburg, both directions.

Another speed restriction (from 120 to 100 km/h) has also been introduced on the A13 between Berkel en Rodenrijs and Delft-North.

However, projections indicate that existing (source-based) policies will be inadequate for meeting the NO_2 (annual mean) and PM_{10} (24-hour) standards on large parts of the Dutch motorway network by 2010 and 2015 respectively. It appears that existing infrastructure measures will not ensure compliance with the air quality standards, and it is likely that a wider range of measures and policies will be required.

1.3 Control of NO_2 and PM_{10} near roads

When the concentration of an airborne pollutant is measured at a location near to a road, the measured value includes a component which is derived directly from the road traffic and a 'background' component which is derived from other sources further away. In addition, some 'primary' pollutants emitted in road vehicle exhaust are transformed in the atmosphere on the timescales involved, a notable example being the oxidation of nitric oxide (NO) to form NO_2. Although some NO_2 is emitted in vehicle exhaust[2], most is formed in the atmosphere (AQEG, 2007).
The situation regarding particulate matter is complex. The background concentration includes both primary and secondary particles. The latter are formed via are formed

[1] http://www.saneringstool.nl/saneringstool_ENG.html
[2] By convention, the sum of NO and NO_2 is termed 'NO_x'. NO_x emissions from traffic are decreasing with time. However, with the rapid dieselisation of the European fleet, the use of oxidation catalysts, and the implementation of specific types of particulate trap, the proportion of NO_2 in vehicle exhaust ('primary NO_2') from the European fleet has increased in recent years.

by reactions between gas-phase components, and are typically composed of inorganic compounds such as sulphates and nitrates. The particulate matter generated by road transport activity can be categorised according to its mechanism of formation. It is often assumed that diesel exhaust (*i.e.* combustion) is the main primary particle source. However, there are a number of non-exhaust processes – such as tyre wear and brake wear - which can also result in primary particles. Furthermore, material previously deposited on the road surface can be resuspended in the atmosphere as a result of tyre shear, vehicle-generated turbulence, and the action of the wind. Particle size is dependent on the process involved. In the case of road transport, it is commonly assumed that most primary fine particles ($PM_{2.5}$) are emitted from the exhaust, whereas many of the coarse particles ($PM_{2.5-10}$) are considered to originate from non-exhaust sources. However, there is evidence to suggest that non-exhaust particles contribute to both the fine and coarse modes (Boulter *et al.*, 2007).

The actual concentration of a given pollutant at a particular location near a road is dependent upon a number of factors. These include the following:

- The *background concentration*, which itself varies in time. For example, in the Netherlands the highest concentrations of particulate matter are measured in winter when the background air originates from the continent. For some pollutants (*e.g.* PM_{10}) the background component can represent a large fraction of the total concentration at roadside, whereas for others (*e.g.* CO) the primary traffic emission is the largest component.
- The *location and surroundings of the road*, which affect dispersion. In addition, the contribution of non-road activities will be different in urban and rural areas.
- The type of *road surface*. Roads may be paved or unpaved, and different surfaces have different characteristics.
- The nature of the *traffic* on the road (its volume, composition and speed), and its emission characteristics. In the case of particulate matter, different formation processes are relevant.
- The *distance* of the location from the road. As this distance increases the concentration decreases until it approaches the background concentration.
- The *meteorological conditions*, which affect the chemical transformation and dispersion of pollutants.
- The *time of year*. Winter maintenance activities can be a source of particulate matter.
- *Factors which affect the rates of chemical transformations*, such as the levels of oxidant and the light intensity.

Knowledge of the effectiveness of abatement strategies is needed to develop practical strategies for reducing ambient pollutant concentrations, and any control measures for air pollution must address one or more of factors listed above, where possible. In policy documents and papers from both the Dutch government and the European Union, a variety of policies have been proposed to satisfy the standards for specific air pollutants, However, with respect to the motorway network, relatively few measures have been available to reduce emissions and/or pollutant concentrations at roadside receptors.

Achieving compliance with the air quality standards for PM_{10} is rather complicated, as it requires control of both fine and coarse particles and different tyres of control are required (Boulter *et al.*, 2007).

Primary fine particles from combustion sources are subject to regulation. All new light-duty vehicle models and heavy-duty engine models sold in Europe must be approved with respect to exhaust emissions in accordance with European Union Directives. As a result, vehicle emissions in the Netherlands have decreased in recent years. Between 1990 and 2007, and emissions of PM decreased by 47%, and those of NO_x decreased by 45%. These reductions occurred despite a growth in traffic of 33%. However, emissions from other sectors - such as industry - are also decreasing, and road transport remains a significant source of NO_x ad PM_{10} (Netherlands Environment Assessment Agency, 2007). However, the regulation of exhaust emissions from new vehicles represents a national (or international) measure rather than a local one. Of course, some controls are possible at the regional or local levels, such as retrofitting programmes, traffic management and low-emission zones.

The control of coarse particles is less straightforward, as such particles arise from processes which are difficult to characterise (Harrison *et al*., 2001). There are also currently no legal requirements for the control of non-exhaust particles from road vehicles. According to a report by the Municipality of Nijmegen *et al.* (2007), resuspension is responsible for about 4 $\mu g/m^3$ (10%) of roadside PM_{10} in Nijmegen - this is a the maximum reduction that could be achieved in theory with local measures which are designed to reduce resuspension.

Research has identified long-range transport as a potentially important source of particulate matter in Europe (Borge *et al*., 2007). This is therefore a source that cannot be influenced by national or local policies.

1.4 Establishment of IPL

IPL was established in the spring of 2005 to identify measures which could be used locally to improve air quality alongside motorways in the Netherlands. IPL formally ends on 1 January 2010. Therefore, by the end of 2009 at the latest, IPL has to make policy and implementation recommendations on the potential and the limitations of the measures which have been identified.

IPL's mission
The aim of IPL was to identify, develop and test local measures that could contribute to improving air quality alongside motorways, to an extent which satisfied the standards for NO_2 and PM_{10} laid down in European Union Directives and Dutch air quality legislation.

The initiative for IPL was taken by the Dutch Ministry of Transport, Public Works and Water Management (V&W). IPL was designed and implemented jointly with the Ministry of Housing, Spatial Planning and the Environment (VROM). The programme was formally contracted to the Centre for Transport and Navigation (DVS)[3] of the Directorate-General for Public Works and Water Management (Rijkswaterstaat, RWS). The overall budget for IPL was €20 million.

[3] Formerly the Road and Hydraulic Engineering Division (DWW).

IPL was not concerned with generic measures (such as particulate traps on vehicles or fuel charges), nor with measures relating to non-trunk roads or the inner-city environment (such as urban traffic signals or parking charges)[4]. The focus of IPL was rather on developing existing ideas further and initiating innovative research.

In order to encourage innovative solutions the programme actively promoted exchanges between the private sector, universities and research institutes. Whilst this process encouraged openness, the award of contracts and funding of projects was undertaken in accordance with the European Directive on the coordination of procedures for the award of public works contracts, public supply contracts and public service contracts and, where relevant, similar national regulations.

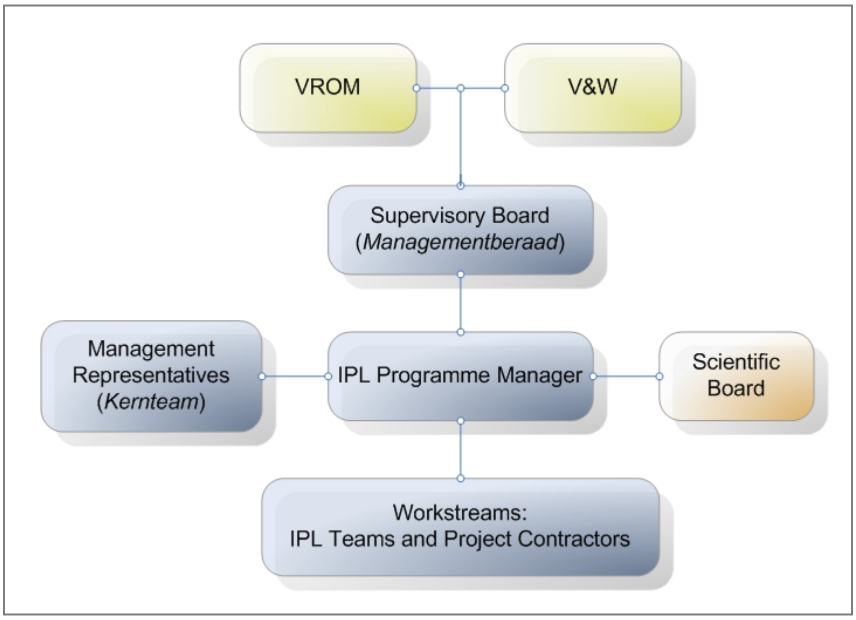
IPL was a results-oriented programme, and as long as it was running an exhaustive search was made of all measures that could potentially help achieve the stated aim. These measures were identified, their scope for improving air quality was assessed, and quantitative estimates were made of their likely contribution to the goal.

1.5 Operation of IPL

1.5.1 Structure

The organisation of IPL is illustrated in figure 1. Ultimate responsibility for IPL resided with the ministers of both **VROM** and **V&W**, whereas executive responsibility lay with the **Supervisory Board.** The Supervisory Board represented V&W and VROM, as well as the implementing agency *Rijkswaterstaat*. The members oversaw the implementation of the programme, and were responsible for any changes to standing arrangements.

Figure 1
Organisational structure of IPL.



[4] *Rijkswaterstaat* is responsible for the national (A) road network only. All other roads are the responsibility of the provinces or municipalities. The National Information and Technology Platform for Transport, Infrastructure and Public Space (CROW) is an advisory body for these parties.

An IPL Programme Team, headed by a **Programme Manager**, bore responsibility for the technical and strategic implementation of the programme within RWS. The **Management Representatives** (known in Dutch as the *Kernteam*) acted as advisors to the **IPL Programme Manager** with regard to the overall day-to-day management. Some of the Supervisory Board members were also members of the *Kernteam*. The actual scientific work on the projects within the IPL Workstreams was undertaken by external contractors.
It was important for IPL to be able to justify its budget and costs at a high level within the Dutch Government. In order to ensure high quality and relevant research within IPL, the managers of the programme established a **Scientific Board** to serve as an advisory panel (see Appendix B for board membership). A similar process had previously been used successfully within the Noise Innovation Programme (*Innovatie Programma Geluid* - IPG[5]). The role of the Scientific Board in IPL is explained in more detail in Part C of this Report.
Details of all Board members and the Programme Team are provided in Appendix B.

1.5.2 *Challenges and considerations*

The programme was confronted with various challenges and issues which had to be taken into consideration. Some of these are identified below.

1. The operating environment was extremely dynamic. For example:
    a. EU policy is continually being developed and amended. This is reflected, for example, in the recent introduction of exposure reduction targets for $PM_{2.5}$, and increasing emphasis on reducing carbon emissions.
    b. The Dutch road transport emission factors have been modified several times in recent years.
    c. The National Air Quality Cooperation Programme was established. This Programme is compiling all air quality knowledge and management under one regime.
2. There was a need to address pollution hot spots and - given the introduction of the new background exposure reduction objectives for $PM_{2.5}$ - a general improvement in background concentrations.
3. There were questions concerning the intrinsic technical and legal feasibility of mitigation measures, especially the most innovative.
4. Whilst reference methods existed for the measurement of PM_{10} and NO_2, guidance on equivalence to instrumentation (makes and models) routinely used in the field was far from definitive.
5. The resources required were highly uncertain.
6. It was questionable that the market-based strategy in IPL could deliver the envisaged innovations.
7. There was a need to avoid duplication between studies.

To manage issues such as these, the following general principles were established in IPL:

1. It was ensured that the basic constraints relating to innovations were transparent.
2. The programme focused on the IPL mission, and the goals were clearly defined.
3. The envisaged range of innovations was defined.
4. Measurement methods were standardised.

[5] http://www.innovatieprogrammageluid.nl/gbdefault.asp

5. It was ensured that there was clear communication between the IPL Programme Manager and project staff on efforts required, scheduled and expended. Consideration was given to the use of temporary contract staff for IPL support.
6. An IPL back office was established, and clear working arrangements were established with existing organisations for the input and exchange of knowledge.
7. Clear decision milestones were also defined (for potential impacts on other projects).

1.5.3 Project selection

In IPL projects were selected - following independent assessment by air quality experts - on the basis of a set of constraints and evaluation criteria, as described in the following sections.

Constraints

The aim of the assessment against the basic constraints was to filter out unrealistic proposals. Proposals failing to meet one or more of the constraints were generally rejected, although a degree of caution was exercised to ensure that proposals which were not feasible at the time of the assessment, but could become feasible in the future, were still retained 'on hold'.

The constraints were as follows:

- Reduction of NO_2 or PM_{10} concentrations. Proposals which would lead to no decrease in NO_2 and/or PM_{10} (but only CO_2 or SO_2, for example), or an increase in NO_2 and/or PM_{10}) were given a low score.
- Technical feasibility. Proposals which were obviously completely unrealistic in technical terms were rejected.
- Organisational feasibility and public acceptance. Proposals which were unlikely to gain government and/or public support - such as the closure of the motorway network - were rejected.
- Legal feasibility. Proposals that would require changes to the Constitution were rejected. Some which exhibited significant air quality improvements were placed 'on-hold'.

Assessment criteria

At the time a proposal was assessed, quantitative data were often unavailable. This made assessment a somewhat subjective process. To address this issue, several independent assessments were carried out:

- Impact on noise. Did the proposal generate noise or have an impact on local noise abatement measures?
- Impact on safety. This related to the safety of road users, local residents and road workers.
- Impact on traffic flow, travel time and access. Although these were three different concepts, they were combined to limit the number of criteria.
- Feasibility on motorways. The proposal was given a high or low score depending on the number of motorways where it could be implemented.
- Feasibility at other locations. The proposal was given a high or low score depending on the number of other locations (*e.g.* inner-city roads) where it could be implemented.
- Magnitude of NO_2 and/or PM_{10} reduction. The aim here was to assess how the proposal compared with other proposals; a reduction in concentration of 1 $\mu g/m^3$ was considered to be comparatively good, for example.

- Time required for implementation. Given the urgency of the problem, proposals needed to be assessed in terms of the speed of implementation.
- Stability of impact. Certain proposals (such as those to improve traffic flow) improve air quality but may also attract more traffic. There may also have been other considerations limiting ’sustainability'.
- Cost-effectiveness. There obviously needed to be an assessment of cost versus envisaged reductions in NO_2 and/or PM_{10}. Ratings on this point were limited to ‘very favourable’, ‘favourable’, ‘very unfavourable’ and ‘unfavourable’.
- Impact on climate. Did the proposal lead to an increase or decrease in CO_2 emissions? The weighting of this assessment was low, as any increase or decrease was small compared with total CO_2 emissions.

Project Workstreams
In a series of workshops at the start of IPL the independent assessments were compared and a number of promising measures were selected. This selection was also evaluated by the Management Representatives and officially approved by the Supervisory Board. The following IPL Project Workstreams were established:
- Workstream 1: Optimisation of noise barriers
- Workstream 2: Roadside vegetation
- Workstream 3: Road surface cleaning (and dust binders)
- Workstream 4: Canopies and air treatment
- Workstream 5: Catalytic coatings
- Workstream 6: Dynamic Traffic Management (DTM) and air quality forecasts.

A so-called ‘Competition Lite’ was also established in order to identify ideas which were not already being examined within the above Workstreams. One conclusion drawn from the Competition was that the additional innovative measures which were identified fitted well into the six existing Workstreams. In fact, the results from the Competition were incorporated mainly in Workstream 1, and to a lesser extent in Workstreams 3 and 4. As a consequence, the results from the Competition are not reported separately in Parts B and C of this Report.

Two projects - ‘optimisation of noise barriers’ and ‘catalytic coatings’ - were accepted by IPL at its inception. The other projects emerged fairly rapidly following a review of an extensive list of ideas and proposals. Any other ideas which subsequently showed potential were assigned as sub-projects within these existing projects.

The initial emphasis was on drawing up an international catalogue of known measures, complete with an indication of any gaps in the information. Complementing this was the generation of new ideas. An international survey of motorway air quality improvement measures was completed in 2006, and this served as the basis for a database that can be consulted on the IPL web site. Although this database is largely in English, access is presently only in Dutch.

Because of the growing need for IPL to deliver results in the short term, in 2006 an accelerated strategy was adopted, with the programme focusing even more on developing and testing local measures to improve air quality along motorways, and preparing them for implementation. Indeed, this was the main focus of IPL. In 2006 the research questions were defined in more detail, and national and international collaborations were strengthened.

The likely impacts and feasibility of the various measures became clearer as IPL progressed. This enabled more emphasis to be placed on addressing the potential of the developers of mitigation measures: what innovative methods and technologies were already available, and what could be developed and implemented in the short term?

1.5.4 *Exploitation*

The core exploitation strategy was to take any promising results from pilot studies and practical trials within the IPL framework, using the following means:

- Completing the pilots and starting practical trials and/or implementation as soon as possible.
- The project *Big Steps, Rapid Progress*, which indicated which measures could be implemented in the short term (September 2006 onwards).
- Greater market involvement in implementing the programme, by means of the following strategy:
    - 'Cherry-picking': testing those products which were already physically available in order to demonstrate their effectiveness in field trials.
    - Open and closed 'competition'-type configurations, with the market (in the broad sense) being invited to come up with innovative products and proposals for product development.
    - On-going reviews of unsolicited proposals received by the Ministry of Transport, under the umbrella initiative *Idea V&W*. This resulted in one selected proposal – electrostatic pollution removal using technology proposed by Royal BAM Group and Delft University.
- Further measures taken in 2006 to strengthen project organisation and, in particular, a realignment of the management structure to facilitate quick and businesslike decision-making.

The implementation plan was structured around the specific air quality improvement measures selected at an earlier stage of the programme for study and/or development.

Several 'strategy sessions' were held at IPL to assign strategies to the various projects which had been selected. Certain strategies were found to be more or less suitable for specific projects. The criteria used were as follows:
- What results have the pilot studies yielded to date?
- To what extent are ideas from the market anticipated?
- How feasible are full-scale trials (costs, safety, acceptance, *etc*)?

1.5.5 *Communication*

In 2005 various communication activities were initiated to improve the 'brand recognition' and profile of IPL. Examples included fact sheets on the programme as a whole and on the individual pilot projects (in both Dutch and English), an electronic newsletter, a promotional film, articles in both internal and external publications, Dutch- and English-language websites[6], and an IPL representative at

[6] www.ipluchtkwaliteit.nl and www.ipl-airquality.nl

various external meetings on air quality (speaker, information resources and/or an IPL promotional display stand).

Naturally, there was also an exchange of knowledge between the different parties working on the various projects.
A full list of the publications produced during IPL is provided in Appendix C.

1.5.6 Relationships with other programmes

There was a clear link between IPL and the Noise Innovation Programme (IPG). On 1 March 2006 the two programmes were brought under single management at DVS. This represented an initial step towards integrating the two Programme Teams. Additionally, a Communications Coordinator and an Operations Manager (Deputy Programme Manager) were recruited for the two programmes jointly. Where possible, IPG and IPL participated jointly in congresses and similar events, such as the Dutch Noise, Vibration and Air Quality congress which is held each November. There was collaboration with IPG on the following specific activities:

- Noise barriers: The impact of motorway noise barriers (and innovative IPG designs such as 'T-top' barriers) on air quality was studied in a joint programme which involved wind tunnel trials.
- Road surface cleaning. IPL and IPG jointly researched preventative and curative cleaning of dual-layer porous asphalt concrete. A competition on this topic was jointly organised by IPG and IPL.

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2 Workstream 1: Optimisation of noise barriers

2.1 Overview

Although the many kilometres of noise barrier along Dutch motorways are intended primarily to reduce noise intrusion into local neighbourhoods, they can also enhance the dispersion of traffic emissions, thus potentially improving local air quality.
This Workstream investigated the degree to which noise barriers can improve air quality, and to what extent they can be further optimised for this purpose. The project was implemented in four phases, as described in the following Sections.

2.2 Phase 1: Literature review and initial wind tunnel studies

The likely effects of noise barriers on air quality were initially investigated in a literature review (Hofschreuder *et al.*, 2005), from which it was concluded that the introduction of a roadside barrier leads to an increase in pollutant concentrations over the road and in its direct vicinity as a result of a reduction in wind speed. However, barriers can also enhance local turbulence (mixing and dilution) and induce vertical movement of the plume, leading in turn to a decrease in pollutant concentrations further away from the road. Further reductions can be achieved by increasing the height of a noise barriers and/or planting tall trees immediately behind it. What also emerged was that the following basic strategies are available for barrier optimisation:

- porous barriers
- barriers with vegetation
- draught-assisted barriers (with an upward draught over the barrier face)
- modification of barrier height and shape
- catalytically active barriers (to reduce NO_2 concentrations)

Fourteen different barrier configurations were then tested in wind tunnel experiments using scale models (Bouter and Koopmans, 2006). Various parameters were modified, including barrier height, barrier shape (straight/vertical or 'T-top'), the position of the barrier relative to the road, and the number of barriers. Different types of environment were also considered (*e.g.* 'few structures', 'highly urbanised'). For each barrier a value was derived for the reduction in the road traffic contribution to pollutant concentrations relative to the situation without a barrier. For the highly urbanised environment the effect of additional turbulence due to the barrier was less pronounced, as there was already a substantial amount of turbulence due to buildings. The vertical movement of the plume was the more important factor affecting pollutant dispersion. In environments with fewer structures both effects were important, and consequently a noise barrier should have a relatively greater impact on air quality.

2.3 Phase 2: Cherry-picking strategy

Phase 2, which was conducted between 2006 and 2008, consisted of three parallel sub-projects:

– *'Cherry-picking the market'*: Starting in August 2007, practical measurements were performed on existing barriers and on innovative barriers which were expected to have an additional positive impact on air quality.
– *Further wind tunnel study*: This sub-project investigated the extent to which wind tunnel studies constitute a reliable method for predicting a noise barrier's air-quality impact.
– *Computational Fluid Dynamic (CFD) modelling study*: This sub-project investigated the extent to which CFD studies constitute a reliable method for predicting the impacts of barriers on local air quality.

The practical trials were conducted at a dedicated IPL test site along the A28 motorway near Putten. The impacts of eight different optimised barriers were measured between 2006 and 2009. The site was equipped with 100-m sections of reference and test barriers. Thirteen different measurement points were used for NO_2, NO_X, PM_{10} and $PM_{2.5}$ (plus O_3), with measurements at a range of distances behind the barrier (5 m, 10 m and 30 m). Meteorological conditions and traffic intensity were also recorded. The monitoring was undertaken for five three-month periods. The experimental design included measurements both with and without a 'standard' barrier. All of the measurements were defined in a measurement plan, which was peer-reviewed by a range of specialists in advance of the field work. The measurements were undertaken by air quality specialists. A detailed statistical analysis was undertaken to evaluate the effects of the different barriers and the uncertainty in the results.

The results from wind tunnel and field measurement campaigns were subsequently compared with a selection of CFD-based modelling approaches.

2.4 Phase 3: Competition

Following the completion of Phase 2(i), May 2007 saw the launch of a competition in which companies were invited to come up with innovative designs for optimised noise barriers to assist in the improvement of roadside air quality. The competition comprised two 'Lots'. In Lot 1 four innovative barriers were tested for their effectiveness at the IPL test site. In Lot 2 the four innovative barriers were subjected to laboratory testing.

The first trials began in mid-March 2008. In August 2008 the first series of winning barriers from the competition were exchanged for the second, which were tested through to December 2008. One of the two barriers tested in the first round of measurements was a seven-metre-high structure. In December 2008 this was reinstalled at the IPL test site for three more months of trials. Further work was conducted in 2009. During a three-month period four test conditions were investigated: (i) no barrier, (ii) reference 4 m barrier, (iii) no barrier and (iv) 7 m barrier. At the end of March 2009 all the barriers and measuring equipment were cleared from the test site, and the site was returned to its original state.

2.5 Phase 4: Implementation

Based on the results of the entire project, in this phase recommendations on implementation were established. This phase is scheduled for completion as one of the final tasks of the IPL programme, towards the end of 2009. The implementation strategy will be dedicated to the Dutch environment and will support the development of the NSL.

3 Workstream 2: Roadside vegetation

3.1 Overview

Through a combination of filtration and uplift, roadside trees and shrubs can reduce concentrations of NO_2 and airborne particulate matter. The effectiveness of vegetation depends on a number of factors.
A set of criteria had already been developed in the Netherlands for this purpose prior to IPL (species, planting scheme, maintenance requirements, *etc*.). However, there was still insufficient understanding of how different types of vegetation perform in practice, and thus a series of practical trials was conducted.

This Workstream therefore addressed two main questions:
- To what extent does vegetation (trees and shrubs) improve roadside air quality?
- Can the air-cleaning action of vegetation be optimised by means of a dedicated planting scheme?

The project was implemented in five phases, as summarised below.

3.2 Phase 1: Literature study

The literature on the effects of vegetation on air quality was initially reviewed by Peutz Consultants (Hesen and Koopmans, 2006). It was 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, and there are different mechanisms of capturing PM and nitrogen oxides. It was found that:
- Deciduous trees are most effective for reducing NO_2; modelling studies indicated a 10% reduction.
- Coniferous trees are most effective for reducing PM_{10}; modelling studies indicated a 15 to 20% reduction.

3.3 Phase 2: First practical measurements

On the basis of the review it was considered appropriate for IPL to conduct its own 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 2006 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 situation 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. The PM_{10} levels with vegetation were approximately the same as in the control situation with no vegetation.
This work yielded a dataset which was used to validate subsequent modelling studies. Promising results were achieved in this pilot study, and thus the next research step was to assess the influence of the planting scheme (vegetation design). The measurements were restricted to a relatively short monitoring period. Air pollution modelling was therefore also undertaken using the ENVI-met model. However, as with the barrier optimisation project, it is evident from the modelling studies that the roadside vegetation increased pollution concentrations within the roadway area.
This phase has been completed and the report is available via the IPL website.

3.4 Phase 3: Market-based strategy

In the third subproject a workshop on vegetation and air quality was organised to engage companies, research institutes and other organisations dealing with landscaping and associated sectors. This resulted in a report on vegetation and air quality, setting out all the available knowledge on vegetation, modelling, air quality measurement and constraints. A dedicated technical review group was also established.

3.5 Phase 4: Competition

The results from the first three phases were used to define an international competition to demonstrate the effectiveness of various types of vegetation (coniferous versus deciduous) in improving air quality along motorways.

In Lot 1 of the competition companies were invited to submit ideas for conducting measurements and modelling on an existing strip of vegetation. The winner of Lot 1 was a consortium comprising ECN, TNO Built Environment and Geosciences and Plant Research International BV. This study involved an air quality measurement campaign along an existing strip of vegetation on the A50 at Vaassen (the location was the same as that used in Phase 2). These measurements began in March 2008 and were completed in mid-2009.

Lot 2 involved testing ideas on the design and implementation of an ideal vegetation structure, and the subsequent measurement and modelling of its impacts on local air quality. The winner of Lot 2 was the consortium comprising Arnhem-Nijmegen City Region, Wageningen University and Research Centre (Alterra, Animal Science Group, Meteorology and Air Quality), KEMA and Integralis PP. The consortium created two strips of trial vegetation along the A50 near Valburg (Meilanden service area). These trials constituted the Flora project, part of the Eureka environment programme being implemented by Arnhem-Nijmegen City Region. The new strips involved the introduction of additional top soil and the planting of around 500 trees (between 4m and 5m high), including separate stretches with coniferous and deciduous trees. The test section was approximately 300m long, with a 100m stand of coniferous trees, 100m of deciduous trees and bramble, and a further 100m of grass. The monitoring began in March 2008, and the results will be available later in 2009.

As the existing strip of vegetation at Vaassen was deciduous, both summer and winter conditions were investigated. The situation was also investigated using the ENVI-met model developed by the Flemish Institute for Technological Research in Belgium (VITO). This micro-scale model can be used to calculate the impact of vegetation elements on motorway air quality. The PANAIR model was also employed to model roadside air quality (Vermeulen *et al*., 2009). For both the model and measurements the effects on concentrations were 0-26% for NO_2 and <5% for PM_{10}. For particles <1 µm the filtering effect was negligible. Overall, the effect of the vegetation was, at best, 10-31% of the traffic contribution. This was just due to the turbulence induced by the vegetation, and only in summer. For NO_2 there was only a reduction at distances of more than 90 m from the road.

The results of the measurements on both strips will be used as input to a model for future prediction of air quality enhancement by vegetation.

3.6 Phase 5: Implementation

Based on the results of the previous 4 phases, this phase focused on developing recommendations on practical implementation.

4 Workstream 3: Road surface cleaning

4.1 Overview

The problem of road dust resuspension from motorways can be tackled by the wet-sweeping of road surfaces or through the application of dust binders, such as calcium chloride (road salt). If a motorway road surface is swept or sprayed with water, less particulate matter can be suspended. In Trondheim (Norway) and Düsseldorf (Germany) positive results have been achieved with wet-cleaning. In this pilot study, this method was evaluated in practical trials in the Netherlands.

The overall objective of this Workstream was to identify measures which could be used to reduce the traffic contribution to PM_{10} by reducing resuspension. The initial emphasis was on wet cleaning. Further work addressed dry cleaning, dust suppressants/binders, and the effects of different pavement surfaces. The specific objectives were as follows:
- To review and disseminate the available knowledge and products.
- To review the current understanding of the mechanisms for targeting improvements in ambient PM concentrations.
- To establish, through practical trials, whether resuspension of PM can be reduced.
- To undertake preliminary work on the revision of the Dutch Measurement and Calculation Regulations as an instrument to maintain PM concentrations within legislative limits.

4.2 Phase 1: Exploratory study

The experience in other countries – notably Germany, Scandinavia, USA, Canada and the Netherlands - was summarised in a literature review (Hooghwerff and Verstappen, 2005). The review showed that the principles of wet-sweeping and spraying are widely used in certain specific environments (*e.g.* industrial activities where there is pronounced generation of particles) and can be implemented in a variety of ways. In Trondheim and Düsseldorf some positive results have been achieved with wet-cleaning.

A number of studies have shown that a significant fraction of PM_{10} alongside roads and motorways may be attributed to resuspension, consisting mainly of coarse particles within the size range 2.5 to 10 microns ($PM_{2.5}$ to PM_{10}). Most of this 'road dust' is derived from the wear and tear of tyres, brake linings and road surfaces, as well as other natural sources (*e.g*. clay particles) and debris on the road. The fine fraction (less than $PM_{2.5}$) is largely associated with exhaust particles.

Measurements performed in 2006 in the Dutch city of Nijmegen showed that the coarser fraction contributes most to ambient concentrations, and is also subject to greater local variation. It was also found that PM_{10} levels decrease substantially following rainfall: by as much as 4-5 $\mu g/m^3$ (rain not only cleans the road surface, but also the air itself). In July 2005 it was recommended trials should be conducted in the Netherlands to establish the feasibility of wet cleaning of road surfaces as a strategy to reduce PM concentrations.

4.3 Phase 2: Nijmegen trials

Air quality measurements were conducted in Nijmegen during the summer of 2006 to assess the effects of different spraying and cleaning approaches (Claessen and Vrins, 2006). The effectiveness of wetting and cleaning of both porous asphalt concrete (PAC) and dense asphalt concrete (DAC) was examined.

Owing to local sources of particulate matter within the vicinity of the trials, some of the measurements were difficult to explain. It was also found that the effect of rain on PM_{10} concentrations was much greater than that achieved with wet-cleaning. This is because rain washes out not only the particles associated with the road but also those from all other local sources. It also influences background concentrations. Nevertheless, the following preliminary conclusions were drawn:

- The PM_{10} concentration alongside the section with a (new) PAC surface was lower (by 8 $\mu g/m^3$ at a point 10 m from the road) than alongside the section with an (old) DAC surface.
- Cleaning the PAC with a 'PAC cleaner' had a positive impact on particulate emissions.
- Spraying water on the DAC surface had a beneficial impact on particulate emissions. If the entire road were treated in a similar manner there would be an estimated reduction in PM_{10} of 4 $\mu g/m^3$ immediately after spraying.

It should be noted that the weather was dry and hot during the trials, and by no means representative of an entire year. Given the limited nature of these trials, no conclusions could be drawn regarding the impact on annual average concentrations. However, the results were seen as strong evidence that the use of PAC surfaces and road-cleaning both have a positive effect.

4.4 Phase 3: 'Cleaner, quieter and more homogenous asphalt'

Because of the high speed of motorway traffic, wet or dry cleaning of these road surfaces presents a greater practical challenge than its application to local roads. A competition was organised in which companies were invited to come up with innovative ways of cleaning motorway surfaces.

Various ideas were submitted to IPL. Three of these were assessed in field trials: spraying with calcium chloride ($CaCl_2$) binder and two dry vacuum methods (Hooghwerff and van Beers, 2006). A new on-road measurement method was also developed in collaboration with Delft Technological University. With this method it was possible to measure the resuspended particulate material after the passage of each individual vehicle.

On 24 April 2008 a concluding workshop was held with all those involved in this project. This was not only retrospective, but also looked to the future and what still needed to be done before wet cleaning could be implemented as an effective means of improving air quality.

4.5 Phase 4: Trials with calcium chloride

Following the successful outcome of Phase 3 it was decided to go ahead with a fourth phase, in which the strategy of wet-cleaning with $CaCl_2$ was further investigated. The effects of $CaCl_2$ on PM_{10} concentrations were investigated on the A73 motorway near Maastricht between December 2008 and March 2009, and in Rotterdam in the autumn of 2009. The preliminary conclusion from the experiments on the A73 was that the application of $CaCl_2$ led to a reduction in the PM_{10} concentration of around 12%.

5 Workstream 4: Canopies and air treatment

5.1 Overview

By covering a motorway section with a canopy made of plastic or another lightweight material, vehicle-derived air pollutants can be prevented from reaching the immediate surroundings and sensitive locations. The main objective of this Workstream was to assess the impacts lightweight canopies on air pollution.

However, as pollutant levels at the 'portals' of what are effectively tunnels are generally high, in this pilot IPL was also looking to combine the canopy with a suitable air filtration system.
Two research questions were addressed:
- Can light-weight canopies be designed to be strong and durable, and at the same time safe and economically viable?
- What technologies are available for treating the polluted air and what are the associated costs? The amount of pollution being released from the portals or ventilation stacks of canopies (or tunnels) can potentially be reduced using various air treatment technologies (electrostatic precipitators, filters, wet scrubbers, *etc.*), and the second main objective of this Workstream was to investigate such technologies.

The project was implemented in four phases, as described below.

5.2 Phase 1: Information gathering

An initial review of existing and new concepts (Cornelissen, 2007) found that if a roadway is to be covered for air quality reasons a lightweight canopy can be used, resulting in substantial cost savings compared with a heavier traditional structure. However, the costs of these canopies were very high - estimated to be between €6 million and €66 million per km (for 2x3 lanes, not including preparatory work). The wide range is due to the various construction materials which are available, and different aesthetic requirements. Where air quality considerations already indicate a need for very high roadside barriers, it may be an option to use a lightweight canopy instead. The safety requirements laid down in the Dutch Tunnel Act will, in all likelihood, be satisfied by a lightweight canopy, assuming that the safety provisions are well thought out.

Three companies were then commissioned to develop an engineering structure satisfying all relevant safety requirements as well as requirements regarding visual impact, recycling, air quality within the canopy, *etc*. In addition, several firms contacted IPL proposing existing engineering solutions and plans.

To address the second research question, a review was undertaken of the technologies currently in use across the world for treating tunnel air. One element was an examination of patents relating to tunnel air treatment (regardless of whether or not they have been applied). The patents were assessed in terms of relevance and feasibility.

In September 2005 a number of market parties developed ideas at an 'Innovation Workshop'. One supplier of air filtration equipment that employs filter mats made a cost calculation for a canopy unit based on their technology. IPL collaborated with the Netherlands Centre for Underground Construction (COB) on developing knowledge on air treatment in tunnels and indoor car parks.

With respect to safety there were consultations with the Tunnel Safety Support Unit (part of the Rijkswaterstaat Engineering department) and with those responsible for drawing up the existing Dutch Tunnel Act, the terms of which would also apply to the safety requirements pertaining to 'motorway canopies'.

Phase 1 was rounded off with a report on the knowledge gathered to date.

5.3 Phase 2: Creation of decision matrix and cherry-picking strategy

This phase began February 2007. To take account of the vast diversity of possible situations and approaches an evaluation matrix was developed. The matrix covered four different environments: (i) inner city (multiple obstacles to air circulation, moderate dispersion), (ii) rural (open fields, good dispersion), (iii) sunken geometry (poor dispersion), and (iv) tunnel portal (high concentration). It also included different types of canopy (fully enclosed; with apertures and slots in the roof; with different numbers of stacks; with systems for capturing NO_2 and PM_{10}). Consideration was given to cost (building and operation), the effect on air quality, and the safety aspects (Muntinga and Sluis, 2007).

The work yielded insights into the canopy configurations which could be applied to certain air quality problems. The results indicated that a canopy will have a substantial impact on local air quality, with NO_2 and PM_{10} levels falling to the background concentration. At the tunnel portals, on the other hand (and particularly in inner-city situations with sunken geometry), there may be a major increase in local peak concentrations. The quantity of polluted air leaving the canopy is a major determinant of ultimate impact, and it makes little difference how the ventilation is achieved (slotted roof, one or more stacks). Additional measures, such as taller stacks and lower exit velocities, also make little difference to the results.

5.4 Phase 3: Practical trials

Phase 3 of the Workstream, which commenced in January 2008, involved the investigation of novel concepts for reducing PM concentrations. Initial laboratory-based testing showed very beneficial results. The most promising technique was found to be a system (CleanAIR) - developed by BAM and the Technical University of Delft - which is based upon a set of electrically-charged wires (high voltage and low current) mounted on the tunnel wall. The resulting electric field charges the particles in the tunnel air, and the charged particles are then caught by another part of the system - a set of electrically grounded metal screens mounted on the opposite wall.

The CleanAIR system was tested in full-scale experiments in the Thomassentunnel (on the A15 motorway) in the Rotterdam industrial area (TNO, 2009). Measurements were conducted at four locations (three inside and one outside the tunnel) between June and September of 2009. The parameters measured included PM_{10}, NO_x, air temperature, humidity and wind speed. The reduction effect of the CLeanAIR system on the PM_{10} concentration during the test in the Thomassentunnel was of the order of 10%. It is recognised that there are a number of ways in which the system can be improved, and therefore higher PM_{10} removal efficiencies are anticipated in the future.

5.5 Phase 4: Implementation

In this phase recommendations on implementation will be provided, based on the results of the Workstream.

6 Workstream 5: Catalytic coatings

6.1 Overview

Recent studies have described attempts to reduce roadside pollution levels by applying photocatalytic coatings of titanium dioxide (TiO_2) to buildings and other surfaces (De Boer, 2005). TiO_2 applied to buildings, road surfaces or noise barriers can help break down the NO_2 associated with vehicle exhaust in the presence of sunlight to relatively harmless nitrate. This catalytic process has already been demonstrated in laboratory trials in Greece, Japan and Belgium.

The impacts on local air quality of using TiO_2 were evaluated in this Workstream. The aim of the research was to establish whether coatings of photocatalytic TiO_2 applied to noise barriers or other structures could effectively scavenge NO_x from the air alongside busy motorways.

6.2 Phase 1: Literature study

In 2005 a literature review was undertaken to examine existing knowledge and research findings. It was noted that although their effectiveness has been demonstrated under controlled laboratory conditions, there are few reliable data on how these materials perform 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

6.3 Phase 2: Laboratory study and small-scale practical trials

In a series of laboratory experiments TiO_2-coated materials were exposed to realistic levels of NO_x and ultraviolet light in a stirred glass reactor. The experiments were concerned solely with investigating the basic conversion efficiency of various coatings, and establishing how conversion is 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 attained each day in the Netherlands until the end of October. Relative humidity was found to have little impact on NO_x adsorption in the range investigated: between 55% and

almost 95% (normal values for the Netherlands). In much drier atmospheres (like those in southern Europe) far greater NO_x conversion levels might be achieved.
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 NO_x could be converted (no more than 11% of the emitted NO_x actually reached the barrier, with the rest passing over it).

Next, TNO carried a series of modest outdoor trials on a rig comprising several different panels and measuring several square metres. In these controlled experiments TiO_2 coatings from various manufacturers were applied to the test panels. Measurements were carried out under different weather conditions in terms of wind speed and direction, turbulence, temperature and light intensity. From these initial results, conclusions were drawn as to the conversion efficiency for NO and NO_2.
August 2006 saw the start of small-scale practical trials in which four panels with different types of TiO_2 coating were fitted to existing noise barriers along the A1 motorway at Terschuur. Several other coatings were also exposed as reference. During a period of almost five months (August to December 2006) the precipitation running off the panels was collected and its nitrate content determined (this is a good indicator of the quantity of NO_x adsorbed). The amount of NO_x converted by the panels was compared with the estimated emission of NO_x from the traffic during the measuring period.

The most striking result was that the coatings were considerably less effective in the practical motorway trials than in the laboratory setting. On average, only a small fraction of the NO_x 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 NO_x 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%). The main reason for this was found to be that the contact time between the polluted air and the coating was too short under practical conditions for a significant effect to be observable. There were also 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 the damp Dutch climate this effect will lead to a stark 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 NO_x emitted by the traffic. With realistic values for conversion efficiency, pollutant conversion by the barrier could be between 0.1 and 0.3%. This probably means that these coatings will only have a real impact in situations with high NO_x concentrations or restricted air circulation.

It was considered that another possible cause of these disappointing results in a practical setting might lie in the use of a less-than-satisfactory measurement method. It was therefore decided to measure coating performance once again at the IPL test site using a range of different measurement methods.

The use of TiO_2 in pavement and road surfaces was also considered. However, a Dutch study on treated paving surfaces noted the effects on friction and rolling resistance. The issue of safety was considered to be a major drawback in implementing test sections in the Netherlands. Therefore, this was excluded from future work.

6.4 Phase 3: Studies to determine coating performance

The aims of this phase were to establish a suitable measurement method for catalytically coated barriers with a rough surface (and also for appraising similar innovations), and to subsequently conduct both laboratory and outdoor trials to assess coated barrier performance.

Coating effectiveness was determined for both NO_x and NO_2. The measurement method was developed and applied to a 'Durisol' barrier. In this test, TiO_2 was found to have only a minimal impact on NO_x conversion. Recommendations are currently being drawn up on the use of TiO_2 coatings as a means of improving motorway air quality. Perhaps other applications are possible, such as in tunnels or on road surfaces, where TiO_2 coatings may well have a greater impact because of the potentially longer contact time with pollutants.

6.5 Phase 4: Implementation

In this phase recommendations on implementation were developed, based on the results from the Workstream. A complete review of IPL publications is provided on the IPL website.

7 Workstream 6: DTM and air quality forecasts

Dynamic traffic management, or DTM, is a form of ‘intelligent’ traffic control that is already employed in the Netherlands to combat congestion. However, it could also be used to improve air quality, given that emissions may be optimised with smoother-flowing traffic. When poor air quality is forecast, the highway authority could introduce short-term measures such as lower speed limits, banning certain vehicle categories or closing lanes, to be supplemented by other measures if air quality deteriorates further.

In this Workstream pollution-responsive traffic management was investigated. The aim was to determine the additional environmental benefits that could be achieved through the encouragement of smoother driving and more even traffic flows. The Workstream was concerned largely with the reduction of PM_{10} through DTM. This was because DTM could conceivably be used to reduce individual 24-hour averages, rather than annual averages, and thus equates better to the daily mean exceedences associated with PM_{10}. Because of the relatively short duration of DTM measures, they will have limited influence on the annual average concentration.

Seven measures were evaluated: 3 dynamic routing variants (local route advice, regional route advice, motorway exit closure), 3 regulated access variants (regulated access to motorways, regulated access to main roads, lane closure), and ‘clean freight’ on bus lanes.

This project addressed the following research questions:
- To what percentage reduction in PM_{10} could the implementation of a given DTM measure lead?
- How many days a year can PM_{10} be kept within 50 $\mu g/m^3$ by means of DTM measures, when this limit would otherwise have been exceeded?
- What are the conditions for, and constraints on, introducing DTM measures?
- Is introduction by 1 January 2010 feasible?

To address the first two of these questions the effectiveness of the measures was initially assessed through the modelling of roads around Rotterdam. The results from this study were developed into a decision matrix (Ludeking *et al*. 2008).

The impacts achieved depended very much on the local traffic situation - in other words the traffic volume and the amount of congestion at the location concerned. However, implementing the measures on high-speed roads would lead to only a limited reduction in the roadside PM_{10} concentration (0.1 or 0.2 μg/m^3). With these measures the number of days on which the PM_{10} limits are exceeded alongside high-speed roads would be reduced by just 1 day. In terms of scale and duration, the impact on traffic would be so limited that over a 24-hour period there would be no marked reduction in the daily average PM_{10} concentration. However, relatively little congestion occurred during the study, and larger reductions might be possible where the traffic is more congested.

In addition, the traffic and air quality models used were not particularly detailed. To gain a better idea of the decrease in intensity and improvement of traffic flow achievable, the effects of the DTM measures would have to be modelled for a variety of traffic situations, and the effect of traffic flow smoothing would have to be based on models which allow changes in driving dynamics to be addressed.

A robust PM_{10} predictor is also essential. Furthermore it is important to establish how far in advance PM_{10} episodes can be accurately forecast, and the required accuracy for this purpose, in terms of absolute concentration, location and time. A PM_{10} predictor has already been developed within the framework of road speed policy (Manders *et al*. 2008). However, it can only predict the PM_{10} concentration one day in advance, and its reliability is questionable. It was therefore not considered suitable in the context of IPL. The Royal Netherlands Meteorological Institute (KNMI) has also worked on a PM_{10} forecasting system in the context of road speed policy. The National Institute for Public Health and the Environment (RIVM) also has a model for predicting PM_{10} levels. The results from these were evaluated as part of IPL

For the third question the conditions and constraints on the introduction of the six measures were assessed. An attempt was also made to establish the feasibility of implementing potential measures by 1 January 2010. To establish the constraints and conditions on introduction and application of DTM measures, in August and September 2007 a number of experts were interviewed, and a list of constraints and the initial modelling results were discussed.

In the Netherlands there are regulations governing the introduction of DTM. Consequently, the use of DTM to address air quality - via some form of Traffic Decree - should not be a problem. However, before implementing DTM measures for air quality improvement current control scenarios will have to be reconsidered. Furthermore, the impacts of the measures at network level will need to be addressed, and the information structure underpinning DTM implementation must be developed. The required infrastructure is probably already in place at those locations potentially amenable to air quality improvement by means of DTM. If this proves not to be the case, the costs are likely to be high.

A preliminary study was undertaken to assess the practical implications of introducing a system for forecasting air quality at a particular location several days in advance so that timely measures can be taken (*e.g.* road-cleaning, different speed limits).

Finally, IPL assessed the potential for designing an ‘air quality bulletin’ based on the system for reporting icy roads (with 320 monitoring points) operated by the Rijkswaterstaat Centre for Traffic and Navigation. It was found that the system for reporting icy roads was inadequate for forecasting PM_{10} concentrations.

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9 Scientific Board Review

9.1 Background

9.1.1 Composition of the Scientific Board

The Scientific Board was organised by FEHRL (the Forum of European National Highways Research Laboratories), and was composed of experts from several road research institutes (see Appendix B). The Board was supported by a secretary, who was responsible for providing all the required briefing and background material through liaison with the IPL Programme Team at DVS.

9.1.2 Role and functioning of the Scientific Board

The Scientific Board was established to help ensure that the research conducted within IPL was appropriate, of high quality, clearly reported, and effectively disseminated. The main emphasis was on the provision of an impartial assessment of the technical aspects of the programme. The Board acted in an independent advisory capacity within IPL, and was not required to provide specific technical guidance on individual aspects unless requested to do so by the Programme Team – it did not act in a steering capacity. The experts, who were neither involved in the selection nor directly involved in the execution of IPL projects, had extensive experience in the subject areas covered by IPL. In this sense IPL was different to other large government-funded research projects, in which an international panel has to review and evaluate the project applications.
The role of the Scientific Board within the strategy evolution process of IPL is shown in figure 2. The 'PLAN' activity was taken as being the starting point for the evolution of each project. The Scientific Board was involved directly in the 'CHECK' activity.

The Scientific Board met periodically to discuss progress and strategic issues of relevance to IPL activities during the preceding period. The meetings were held on the following dates:

- Meeting 1: 24/25 June 2008
- Meeting 2: 26/27 November 2008
- Meeting 3: 4/5 March 2009
- Meeting 4: 7/8 October 2009

There was also a special meeting on noise barriers on 19 June 2009 with focused discussions on the provisional data recorded at the IPL test site summarised in the topic report by Hooghwerff and Tollenaar (2009).

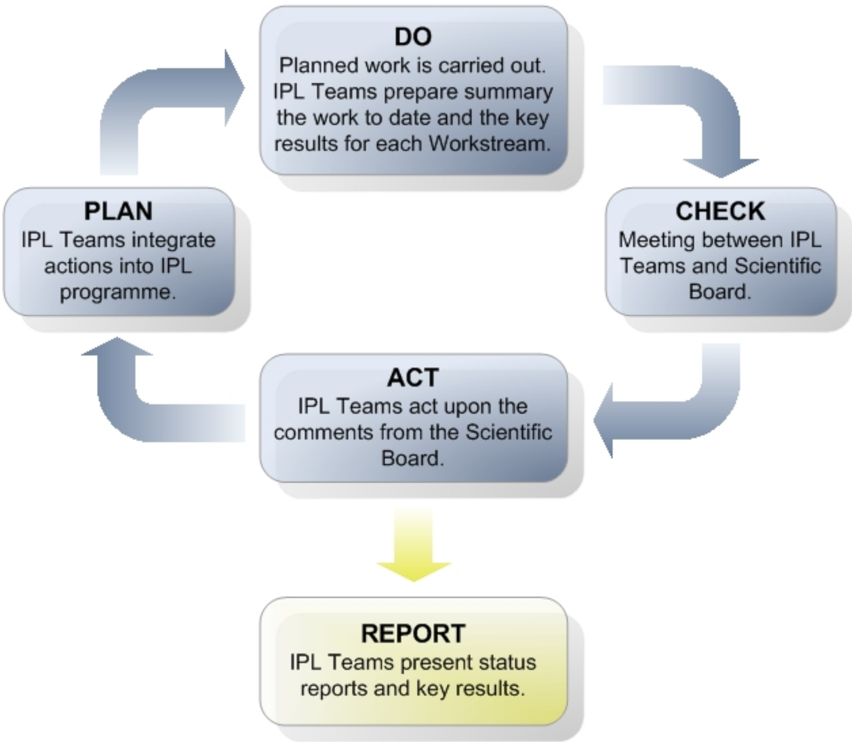
At each meeting the Board was requested to assess the validity of existing and planned activities within each of the Workstreams, confirming that the activities and approaches were scientifically robust. The assessment of activities was achieved via responses to specific questions provided in the agenda for each meeting. As far as possible, the discussions and deliberations of the Board were restricted to these questions.

Prior to each Scientific Board meeting the IPL Programme Team presented a number of questions for discussion. As input to the ongoing development and focussing of IPL, detailed minutes of these discussions were recorded.

A Scientific Strategy document was compiled in order to track progress on the various Workstreams, and this contained the following information:
– A description of the rationale underlying the sub-projects within each IPL Workstream.
– A summary of progress on each project.
– Issues raised by the IPL Teams.
– Questions and actions arising from the Scientific Board meetings.
– Responses received from the IPL Teams and the Scientific Board members.

The Scientific Strategy formed the link between the 'DO' and 'CHECK' activities in figure 2, as well as providing input to the 'REPORT' activity.

Figure 2
Evolution of Scientific Strategy within IPL.



The Scientific Board was also requested to advise IPL on similar international projects, and to thereby facility an exchange of information. This was achieved primarily through summary presentations and the exchange of technical reports.

In addition, the members of the Board were involved in the dissemination of IPL activities, including oral and poster presentations at conferences and meetings.

9.1.3 *Compilation of the Scientific Board Review*

The views of the Scientific Board were noted in the minutes of each meeting, as well as in the Scientific Strategy document. Often, these notes related to specific technical points and went into some detail. However, the IPL Programme Team also wished to capture the more general views of the Board on the success of the both the programme as a whole and the individual Workstreams. The Programme Team therefore posed a short number of additional questions to the Scientific Board members towards the end of IPL, and these questions are given below.

For the programme as a whole:

Question 1: *What are the Scientific Board's views on the general scientific aspects of the programme?*

Question 2: *What is the opinion of the Scientific Board with regard to the accessibility of the data and results from IPL?*

Question 3: *Are results available from (non-IPL) completed or on-going studies in other countries which are relevant to the improvement of air quality near roads?*

For the individual Workstreams:

Question 1: *In the view of the Scientific Board, has the research in the Workstream contributed significantly to the understanding of measures for improving air quality alongside roads?*

Question 2: *What are the strengths and the weaknesses of the research presented in the Workstream?*

Question 3: *Can the Scientific Board provide any recommendations for those who will use the results from IPL in the future?*

For each question the Board members were asked to support their responses using examples where possible. The Scientific Board was also asked to make recommendations for further research.

The information from the aforementioned documents and the responses to the questions was assembled, and are presented here as the combined views of the Scientific Board. Section C2 presents the views of the Board on the programme as a whole, and Sections C3 to C8 cover the individual Workstreams.

The following should be noted:

- Because there was some overlap in the questions posed by the IPL Programme Team in relation to the individual Workstreams (Sections C3 to C8), and indeed in the responses, within each of these Sections the responses to the three questions have been combined.
- Clearly it was not possible for the Scientific Board to cover *all* technical aspects of IPL in the same level of detail (see Section C1.2).
- There is a certain bias in the way in which the views of the Scientific Board are presented here. The views are, on balance, more negative than positive. This is largely because (i) it is much easier to focus on the shortcomings of research rather than work which is conducted logically or correctly, and (ii) it is not practical (or indeed particularly interesting) to identify all the aspects or procedures which could not be faulted. In addition, in many cases the questions posed by the Scientific Board to the researchers were countered with reasonable responses or arguments.

9.1.4 *Review of overall programme*

Some comments received from the Scientific Board members fell outside the scope of the specific questions posed by IPL, and mainly concerned the role and influence of the Board within IPL. These comments were, however, still considered to be important because they effectively defined the context within which other responses were made.

The Board members were initially optimistic that IPL would provide greatly needed information on the effects of air pollution prevention and mitigation measures. For example, the results of the research in IPL could be used to allow an improved consideration of mitigation techniques in other countries, as the effects of measures are generally not well quantified. The inclusion of the 'Competition Lite' was also seen by the Scientific Board as a useful way of capturing any additional ideas.

However, the Scientific Board members considered the design and functioning of IPL to be rather unconventional. From the perspective of the Scientific Board one of the main problems in IPL was the timing of activities. The Board was not appointed until all of the research projects had started, and this was clearly too late for it to radically influence any of the projects. Some of the information for the Board meetings was received too late for it to be properly reviewed before the meeting, and some of it was in Dutch. Some of the initial results were not well written up, making it difficult to follow what had happened and what the results meant, and this then made it difficult for the Board to provide advice. Moreover, at the end of IPL there was very little time for the Scientific Board to discuss the results of the work and to suggest how they could be used. The results from the Workstreams had not been fully written up by the time of the last Board meeting, and it was therefore difficult for the Board to fully evaluate (and promote) the work.

However, with respect to the overall IPL programme, it was generally agreed by all of the Scientific Board that it had provided a relatively unique platform for innovation, research and implementation into various air pollution mitigation strategies. This type of integrated multidisciplinary approach was recommended to other highway authorities. However, significant and additional benefits could have been achieved through the formal links with similar programmes being undertaken in the urban environment.

The answers to the specific questions posed by IPL are provided below.

> ***Question 1****: What are the Scientific Board's views on the general scientific aspects of the programme?*

On the whole, the Scientific Board considered IPL to have been a worthwhile exercise which was highly relevant to air quality problems, and one which has produced some interesting and valuable results. However, there were serious concerns about the scientific quality of some of the work.

The specific comments received from the Scientific Board can be summarised as follows:

1. The Scientific Board would like to have been involved in the initial selection of the Workstreams. Whilst this may not have changed the decision to investigate the chosen Workstreams, it would have ensured an early exchange of international experience, experimental designs and assessment techniques.
2. IPL was effective at targeting the most relevant technical measures which are currently available for improving air quality. However, the programme did omit some aspects that might be as important, such as policies and measures which deal with travel demand and behaviour.
3. IPL intentionally focused on mitigation measures to be applied once pollutants had been released. It would also have been useful to compare the magnitude of any improvements observed in IPL with those associated with other emission-reduction strategies in urban areas, and the technical measures for emission-reduction from individual vehicles. This would have provided additional information regarding the relative costs and benefits of the IPL strategies recommended for implementation. It is accepted, however, that technical measures and urban environments were being introduced and investigated in other research programmes.
4. The focus of IPL was on NO_2 and PM_{10}, and the Board considered this to be appropriate as the EU limit values for these pollutants are often breached near busy roads. It was noted by the Scientific Board that the IPL mission did not cover $PM_{2.5}$. However, it was also recognised that IPL was established before the introduction of the $PM_{2.5}$ standard, and that $PM_{2.5}$ was included within some of the IPL projects. Nevertheless, it was felt that it would have been more far-sighted to have included $PM_{2.5}$ in the original IPL mission.
5. The Scientific Board expressed concern about the low weighting given to CO_2 within the programme. CO_2 should now be considered as the main pollutant associated with transport. There was general agreement from the Scientific Board members that the interactions between strategies for local air quality improvement and regional CO_2 must be considered together (AQEG, 2007; FEHRL, 2008). If a mitigation measure is expected to increase energy consumption and hence carbon emissions, then this should also be quantified. According to the Programme Team, CO_2 was outside the scope of IPL, and the issue of CO_2 emissions from transport was being investigated by other teams and government departments.
6. The Scientific Board identified some weaknesses in terms of the current and future source apportionment of air pollution – in particular the road traffic contribution and therefore the effectiveness of mitigation measures. For example, the use of diesel particulate filters will increase the relative importance of non-exhaust PM emissions (not addressed in any detail). This has significant implications for future air pollution control strategies. It was felt that this issue should have been treated in more depth in IPL.
7. The tendering process within IPL (calls for ideas, for example) sometimes hindered the research and affected the quality of the scientific work. Tenders were often directed at consultants (sometimes non-specialists) rather than, say, academic institutions. Some members of the Scientific Board felt that this had the following negative effects:
    a. It led to a number of unoriginal proposals to investigate aspects of air pollution which had already been the subject of detailed investigation in the past.

b. In some cases it resulted in weak experimental design.
c. The state-of-the art reviews within some projects were rather weak and not comprehensive.

Such problems might have been avoided through the earlier involvement of the Scientific Board, or with higher demands being placed upon the scientific competence of the contractors. It was felt in some cases the consultants did not understand the criticisms of the Scientific Board, and that the effectiveness of the overall programme suffered as a result.

8. It would have been helpful - both for the Scientific Board and for IPL - if the researchers who had actually conducted the IPL research had been invited to present their findings at the Scientific Board meetings. This may have prevented many of the misunderstandings and unclear points from the start.
9. A frequent issue within several Workstreams was the suitability and reliability of the instrumentation and analytical techniques used by the contractors. In some cases the type of instrument being used had to change in the middle of an experiment, and this led to increased uncertainty and loss of data. However, the Board also recognised that in research the most suitable approach is not always the one which is adopted first.
10. In some cases attempts were made to use statistical analyses to overcome the weaknesses in the measurements. However, the use of low-quality data is a fundamental problem, and cannot be masked by such analyses.
11. Emissions from traffic were only estimated approximately using relatively old emission factors.
12. Experiments and calculations were sometimes poorly validated.
13. Measurements of ambient concentrations (in relation to limit values) are not a direct measure of exposure (and thus health impact), but an indicator. This could have been clearly highlighted.
14. Insight into the local transport of pollutants was limited.
15. The reporting in Dutch appeared to be comprehensive and of a relatively high standard. However, because the results are of international interest allowance should have been made for the publication of more documents in English. Not only would this have assisted the work of the Scientific Board, it would also have allowed a wider review of the results and outcomes of IPL by external interested organisations.
16. The Board considered it useful that some of the air pollution measurements in IPL were being undertaken in combination with the noise measurements in IPG programme.
17. Better use could have been made of more advanced statistical tools. Knowledge within the air pollution community of data analysis and data mining appears limited. Indeed, a common criticism of the air pollution community is that significant effort is invested in air pollution monitoring, and less resources placed on data analysis and data mining.
18. Any new infrastructure should be subject to life cycle assessment – covering both the build and maintenance phases.
19. There was also general support from the Board members that IPL should seek collaboration with those who are looking at ways of influencing travel behaviour. The use of behaviour change (reducing the need or changing travel mode) rather than infrastructure changes should be supported, although it is recognised that this was not a core stream within IPL.
20. The possible benefits of IPL presenting its work via publicity campaigns could have been investigated.

***Question 2**: What is the opinion of the Scientific Board with regard to the accessibility of the data and results from IPL?*

A number of IPL dissemination activities were viewed positively by the Scientific Board:

1. The publication of a series of public-friendly advisory notes was considered to be useful. The Board emphasised the need to maintain public acceptability when introducing pollution-reduction strategies that affect the individual.
2. The IPL web site was considered to be informative and well structured. However, the site is probably not visited frequently by non-Dutch people (IPL could produce some statistics), and so further publicity will be needed to raise awareness of the work. The Board also considered it important to ensure that the IPL web site had a life after the end of the programme (the results from IPL will actually be used to compile a web site containing guidance).
3. The IPL measurement database was considered to be a good example of a way in which information from IPL can be made available to any interested parties. However, it is important that potential users of the data are made aware of their limitations and usability. In practice it is likely that it will be difficult for others to use the data. Firstly, any user of the data will effectively have to understand the measurement campaigns to the same level of detail as the original authors. Secondly, the aim of the new user will usually be different to the aim of the original experiment; the experiments were designed to answer specific questions, and the data will not normally be useful for answering other questions.

Other aspects were viewed less favourably:

4. The results from an initial international survey of all existing pollution-reduction measures were compiled into a database of ideas. This was considered to be of Europe-wide interest, and would be beneficial to both IPL and other communities. However, this was not subsequently updated. There was general agreement from the Scientific Board members that whilst ideas continued to be identified during the programme, the work of IPL would have been strengthened by the periodic updating of this database.
5. It is understood that all the data and results from the research reports will be posted in Dutch on the IPL web site. Summaries of each research project will also be presented in English on the web site. However, if the full research reports are not translated, then some of the detail will be lost to the non-Dutch. Some very interesting results have been produced by this work, so it does need to be promoted outside Holland. Some of the Scientific Board members would be willing to write papers or give presentations in their own countries. This should be facilitated.
6. The Scientific Board was critical of the knowledge of, and involvement in, dissemination events on the part of the IPL Teams and contractors. The profile at international conferences has been low. The IPL Programme Team attributed this to the fact that not all IPL project leaders were air quality specialists, but were specialist project managers.
7. Few papers appeared to have been published in the scientific literature, and this does not appear to have been a priority of IPL. Again, a possible reason for this is that the results are presented in the reports of consultants, and are mainly in Dutch rather than in English. Considering the amount of research performed in

IPL, there should have been many more opportunities for publications, presentations and dissemination of various kinds. The Scientific Board hopes that *Rijkswaterstaat* (or the contractors) will be active in ensuring that the results from IPL are disseminated more effectively in the future.

***Question 3**: Are results available from (non-IPL) completed or on-going studies which are relevant to the improvement of air quality near roads?*

IPL requested the views of the Scientific Board concerning other measures which IPL ought to have been investigated during the programme. The Scientific Board was asked to ensure that IPL captured any new developments in air pollution mitigation.

Although it was not possible for the Scientific Board to review all the IPL work and to identify specific gaps in the understanding, the activities listed below were noted by the Scientific Board members as being relevant, and could be used to support the Dutch guidance at a later date. Some specific references are presented at the end of the Chapter.

Barriers
- Wind tunnel tests were performed in Europe during the 1990s in order to investigate the effects of different shapes of barrier and openings in cut-and-cover tunnel sections. Field experiments were performed at various locations.
- The EU-LIFE project 'Sound and particle absorbing systems' (SPAS)[7] investigated the use of PM filter elements on sound barriers. A series of laboratory tests was undertaken, followed by two field trials. The project has been running since October 2006, and is due to complete by the end of 2009.

Vegetation
The UK Highways Agency carried out research into the effectiveness of vegetation in the 1990s, and concluded that it was not especially effective at reducing concentrations.

Road surface cleaning
- There is some experience in this area in Sweden and also some studies from Spain, China and Germany. However, the negative results from earlier trials in Sweden led to a shift in attention away from this type of measure.
- In Norway a number of studies have been undertaken, including tunnel-based studies.

Dust binders and road surface issues
The Scientific Board noted that research into the effects of tyres, road pavements, dust binders and air quality is being conducted in several countries, and the resulting data might complement or fill gaps in the IPL findings. Some examples include the following:
- Evidence from Australia has shown that dust suppressants are effective at reducing PM_{10} concentrations.

[7] Further details may be found at www.life-spas.at.

– A Swedish report which evaluates four different dust suppressants (see references).
– In Sweden, Norway and Finland a lot of research has dealt with road dust issues due to the relatively high road surface wear rates associated with the use of studded tyres.
– The EU Life project KAPA-GS[8] dealt extensively with the effects of CMA as a dust binder. This issue is also covered within the EU Life project CMA+[9].

Canopies/tunnels and air treatment

– The use of lightweight canopies is topic of investigation in several countries. In Austria the safety and operational aspects (cleaning) are the main subjects of these investigations. Glass has been almost excluded due to cleaning problems (soot), and plastic material has been omitted for safety reasons.
– The Austrian highway operator ASFINAG has commissioned an investigation of lightweight canopies to reduce noise. The safety and operational aspect (cleaning) is the main subject of the investigation. Glass has been effectively excluded due to cleaning problems (soot), and plastic material has been omitted for safety reasons.
– The results of Norwegian work are available on a web site. This includes guidance on environmental tunnel construction and measurement strategies.
– There have been various studies using different materials for canopy construction.
– This issue of canopies was investigated in the UK approximately 15 years ago, and at that time it was not considered a viable option due to costs and the limitations in the control of portal emissions.
– A good description of the standard ESP systems is available in the PIARC report (covering PM and NO_2 mitigation) 'Road Tunnels: A Guide to Optimising the Air Quality Impact upon the Environment'[10].
– ESP techniques have been investigated around the world, notably in Norway, Japan and Spain.
– The new ring road round around Madrid has 35 ESP and 3-5 NO_2 systems. At the moment not all of these systems are operational, and thus there is limited real world data on their effectiveness and durability. Systems are also installed in Norway and Austria. From world wide tunnels, data are available for the effectiveness of PM_{10} remediation, but very limited similar data are available for NO_2.
– There is a large body of literature on the measurement of air pollution in road tunnels. The Scientific Board suggests a review of the PIARC homepage, as well as work conducted by organisations such as the Desert Research Institute in the United States, TUG in Austria, ETHZ in Switzerland, IVL in Sweden and TRL in the UK.

Catalytic coatings

– In the UK the Highways Agency has undertaken a field trial on a TiO_2-impregnated concrete noise barrier on the M60 (70 m long by 3 m high). This included measurements of NO_X and NO_2 at various distances from the barrier, and the collection and analysis of surface wash water samples. A report describing the

[8] Further details may be found at www.feinstaubfrei.at.
[9] Further details may be found at www.life-cma.at.
[10] http://publications.piarc.org/en/search/detail.htm?catalog&catalog-topic=5&catalog-offset=2&publication=2247

work will be published on the HA website[11]. Preliminary results indicated that the effectivenes of NO_2 reduction was dependent on the ocurrence of some key envirionmental conditions – (temperatures > 10 ^oC, wind speed < 3 m/s, no rain, perpendicular wind direction (relative to the barrier face) and solar radiation > 5 w/m^2). These conditions occurred at the monitoring site for less than 1% of the hours, over the monitoring duration. This may in part explain the more optimistic performance recorded from field trials undertaken in Southern Europe.

- TiO_2 has been used in pavements and building facades in London (London Borough of Camden and City of London and Congleton Borough Council), but no peer reviewed reports appeared to be available at the time of writing.
- Other studies have been undertaken Italy at Cesena and Segrate (Milan), and at Shanghai in China.
- The European project PICADA has also involved the evaluation of TiO_2[12].
- There was a small scale pilot project in Antwerp.
- A common feature of the international pilot TiO_2 applications is that results from the various campaigns are poorly reported, and are routinely not subject to peer review. This lack of traceability and audit limits the authority of these studies.

Dynamic Traffic Management (DTM) and air quality forecasts
During the last five years a large volume of work on controlled motorways has been undertaken in the UK, including variable speed limits, access management, hard shoulder running, dedicated lanes *etc*[13]. Various tools have been developed to assist in the assessment of such schemes. Various traffic modelling tools are routinely used to investigate the impacts on traffic flows and journey times, including SISTM, PARAMICS and VISSIM.
DTM is applied in NO_2 non-attainment regions in Austria (Tyrol, Upper Austria, Salzburg). They use a combination of monitoring and empirical modelling. Applications for PM_{10} (Styria) are based on a combination of emission and dispersion models. A legislative framework for the use of DTM for air quality purposes in Austria has recently received approval. For NO_2 (violation of annual mean value) a variable speed limit helps. For PM_{10} (violation of 24-hr value), however, the effects are very limited.
Pollution-responsive systems have been used in Norway since 1999. This includes a dynamic air pollution forecast for 1-day ahead, with information available via a web site. The system is evaluated on a yearly basis. Forecasting beyond 3 days into the future remains unreliable. Modelling is undertaken using the NILU AirQUIS model.
In the UK a trial is planned on the M20 (London to Dover) motorway, whereby a range of different triggers will be investigated to trigger traffic management regimes. One of these will be a pollution-responsive trigger. This scheme will also include automatic number plate recognition so that individual vehicles may be tracked through the scheme. Air pollution measurements will be undertaken within the boundary of the controlled area.

[11] See the research compendium at http://www.ha-research.gov.uk/projects/index.php?id=1142
[12] http://www.picada-project.com/domino/SitePicada/Picada.nsf?OpenDataBase
[13] A report of work on the M42 motorway can be found at http://www.dft.gov.uk/pgr/roads/tpm/m42activetrafficmanagement/M424LVMSLPerf1.pdf

It was also noted by the Board that the 6FP project FUMAPEX examined the linking of different models, and the experiences from this project might be of use in this context.

General
Some research programmes have investigated different aspects of mitigation, including the following:

- The EU-LIFE project – KAPA-GS (Klagenfurt's Anti-PM_{10} Action Programme with Graz and South Tyrol)[14] – considered a variety of PM-reduction measures from a range of sources, including domestic heating systems and non-exhaust PM. Various investigations of wet road cleaning, CMA (calcium magnesia acetate), binders, various cleaning sequences, *etc.* have been conducted, and a very dense PM monitoring network was used. Reductions in PM concentrations were evident with the use of CMA. However, CMA represents an additional cost over existing winter maintenance techniques, and is also associated with a reduced skidding resistance – which can influence road safety. The main impact on road safety was interpreted as being a result of drivers passing from dry road surfaces (without CMA) to wet surfaces (with CMA). A follow-up EU-LIFE project on CMA application[15] started in 2009, and is looking into this issue of reduced friction.
- The AQUELLA project[16] sampled PM_{10} in 3 different cities/regions in Austria over more than 3 years. The aim was to fine fingerprints for different sources. The results of detailed chemical analyses are available, although not everything has been published.

9.2 Workstream 1: Optimisation of noise barriers

The Scientific Board considered the barrier concepts which were investigated in IPL to be very innovative and unique, and that the Workstream had definitely contributed to the understanding of how barriers affect air quality, including the influence (or lack of influence) of optimised barriers compared with standard barriers.

A weakness of this study was the use test sections which were close together and relatively short (only 100m in length). This was perhaps one of the reasons for the difficulties encountered in the evaluation.
The experimental work commenced in 2006 with the deployment of four different noise barriers at the IPL test site, and the monitoring was undertaken for three months. The Scientific Board members concluded that this 3-month monitoring period was adequate given that relative differences were being investigated. However, the Board felt that it would have been better to have undertaken this work over a longer period (6-12 months).

The noise barriers were also tested in rural areas, where the local topography was rather simple. The application of the findings to more complex urban areas was therefore uncertain. Within IPL it was envisaged that the translation of these

[14] Further details may be found at www.kapags.at and www.feinstaubfrei.at.
[15] Further details can be found at www.life-cma.at.
[16] http://www.feinstaubfrei.at/htm/abschlusskongress_r_puxbaum.pdf

barriers to urban locations would only be done after proving their effectiveness using computational fluid dynamics (CFD) modelling tools.

However, the Scientific Board considered the CFD modelling undertaken in this Workstream to be one of the weaker aspects of IPL. This part of the Workstream lacked in a clear structure and a clear protocol to be followed by the participants. The initial results indicated large discrepancies between CFD results and the measurements, which supported the suggestion that CFD may not have been an appropriate method, especially as CFD models are not capable of complying with atmospheric dispersion situations associated with road environments. They are generally valid when applied to neutral stability/dispersion conditions, but these are only one part of dispersion situations associated with the roadside environment. CFD might be appropriate for the close proximity of the barriers, but at distances of ~>25 m special precautions have to be take for the turbulence model. For local range applications in most cases a combination of a wind field model (Eulerian model) with a particle model (Lagrangian model) is used for the dispersion process. This two-stage approach (model combination), which takes a very different approach to turbulence, is now gaining greater acceptance.

The wind tunnel tests performed within the framework of this Workstream did not come up with generally usable and accepted results.

Concentrations inside the road boundary were not measured, and therefore it was not known whether the exposure of drivers to air pollution had increased due to restricted dispersion effects of the barriers. A side effect of this strategy could actually be an increase in the overall level of exposure.

In the view of the Scientific Board it will be rather difficult for air quality practitioners to use the results from this Workstream, as the questions posed at the outset do not appear to have been answered in full. For example:

- What is the precise effect of a noise barrier in a particular situation?
- What are the effects of the receptor position, road profile, traffic volume, position relative to the wind direction, barrier height and position, whether the road is at level grade or not, on an embankment or at tunnel portal?
- What is the scope for further optimising this type of barrier?

A number of optimisation strategies have been identified: catalytic layer, vegetation, barrier shape and porosity, and ‘dedicated pollution barrier’, but no guidance is provided.

The results which indicated that optimised (and expensive) barriers had no effect on air quality suggest a need for further tests. Following work might focus on, for example, the effects of barrier height, barrier top construction, or the materials used in standard barriers.

The issue of barrier durability was not addressed in IPL. Information would be needed on the long-term efficiency of porous barriers.

9.3 Workstream 2: Roadside vegetation

The Board members considered this Workstream to be very ambitious, with interesting experimental set-ups and large amounts of data being collected.

The problems and disagreements which arose between the IPL Programme Team and the contractors conducting the Valburg experiments seriously affected the work. The Scientific Board felt that these issues were attributable to the organisation of projects within IPL (see general comments).

Even though the effects of vegetation on air pollution were rather disappointing, the work highlighted the difficulties in evaluating such effects, even in geographically rather simple environments. This is something from which future trials can learn. This Workstream has also emphasised the need for suitable instrumentation for accurate evaluation.

For the first practical trials the Board questioned why the monitoring was restricted to two six-week periods, when measurements over the whole 12-months would have been beneficial. Indeed, this would also have potentially highlighted the influence of seasonal leaf growth and loss, with different levels of rainfall and sunlight.

The use of tracer gases to investigate dispersion characteristics would have been beneficial.

There were some concerns that PM ($PM_{2.5}$ and $PM_{1.0}$) concentrations appeared to increase with vegetation.

The automatic traffic counter sites gave only a relatively poor resolution for traffic data. It was noted by the Board that an improvement in the fleet characterisation will undoubtedly improve the estimation of the emission source strength, and this could have been achieved using additional techniques (radar, video, *etc.*).

Scanning electron microscopy would be a good method to determine deposition on leaf surfaces.

Little or no information was provided on how the selected species fit in with local biodiversity requirements.

The results from this IPL Workstream will provide a useful input to follow-up programmes all over the world (*e.g.* Norway's proposed project on vegetation barrier optimisation).

9.4 Workstream 3: Road surface cleaning

The final results from this Workstream were not available at the time of writing, but the Board considered this Workstream to be of great interest as it focused on the suspension or resuspension of wear particles which contribute to high PM_{10} levels in many countries. The influence of pavement and sweeping/dust binding on air quality is very poorly understood, and therefore, despite some problems, the results for IPL are unique and interesting.

In the opinion of the Board the Workstream could have benefited more from the experience gained in other projects elsewhere. In particular, the design of experiments could have been better, and some problems could have been avoided or resolved more quickly (*e.g.* smearing of $CaCl_2$, optimal application time for evaluation).

When using dust binders consideration must be given to dose, concentration of the solution, when and how often to apply them, how long lasting the effect is, and interactions with the weather. The use of these binders can have a number of knock-on effects on corrosion, wider environmental impacts (ecosystems) associated with the fate of these products and the overall impact on road surface friction and thus accident rates. The Board recommended that these issues are carefully considered before commencing on any further trials.

Road cleaning had been shown to lead to reductions PM_{10} and $PM_{2.5}$ concentrations. The lack of an investigation into the effects on $PM_{2.5}$ was a clear weakness of this Workstream.

In addition the Board recommended that a certification scheme for street sweepers should be considered, as the effectiveness of sweeping systems varied considerably with respect to the removal of small particles.

On the whole, the Board felt that IPL needed to show a better understanding of abrasion and resuspension processes in order to characterise the sources of PM. It was noted that resuspended can contribute substantially to PM_{10} concentrations, but the contribution is very dependent on the location. In addition, because a proportion of PM_{10} is secondary in nature, reductions through road surface cleaning could have a reduced effectiveness during periods when this secondary component is large. Such effects need to be considered when designing experiments and cleaning programmes.

The Board noted that the source apportionment of PM_{10} remains uncertain, particularly when allocating various abrasion sources and resuspension. To further define these sources, more work is required on the tracers associated with each source, and the size distribution associated with each of these sources. Recommendations from the Board for IPL to undertake source apportionment studies were not taken forwards.

The important contributions to road surface dusts from agricultural machinery, vehicles at waste transfer stations and construction activities are also worthy of note, and the Dutch literature review considered such issues.

It was generally agreed that specific tyre and brake wear emission factors by different surface types were not available. The influence of other parameters like winter service, humidity and local aspects is usually too great to allow pavement-specific emission factors for various asphalt pavements to be determined.

9.5 Workstream 4: Canopies and air treatment

The Workstream involved three key aspects. A literature review of technologies and concepts was initially compiled. Whilst this was considered comprehensive, it was difficult to identify which concepts might be the most effective for specific situations. Therefore, a spreadsheet-based matrix was devised to identify the benefits of a combination of canopies and air treatment systems. The third aspect involved the investigation of electrostatic systems to reduce PM concentrations.

The Scientific Board generally agreed that the project would have benefited from a revision to this initial state-of-the-art review. Closer interaction with the national bodies for tunnels and PIARC was also suggested, as new data on in-tunnel air quality would be of interest to the wider community.

Concerning light-weight canopies, tunnel operators/designers would be cautious about using glass due to cleaning issues and plastic due to its ability to withstand tunnel fires. Therefore, they are not currently used inside tunnel environments. There is no written guidance in this specific issue, but is a commonly held belief by designers and architects. In addition when glass is combined with concrete, there is a problem with shadows. Therefore this forces the use of more lighting, and hence higher energy costs. The Board also felt that safety should have been given a higher priority. It was also noted that the Dutch were pushing rather more than other member states for higher levels of tunnel safety. In addition, it was recommended that IPL re-engage with the Dutch tunnel authorities to ensure that the application of light-weight canopies are not prevented due to their potential failure to comply with the existing road tunnel fire regulations.

The Board noted that the spreadsheet (matrix) was very good, and could be a useful tool in early decision making. The Scientific Board found that the first version of the matrix was difficult to use and contained some obvious errors and inconsistencies. The revised matrix re-ordered the material, focused on the traffic contribution only (as the inclusion of total environmental concentration limits would limit its generic application), and incorporated a graphical interface.

However, some significant questions remain over the robustness of some of the data in the tables of the matrix. The Board raised the issue that the matrix was suggesting high levels of accuracy and precision, which may not be justified by the input data. The issue of uncertainty needs to be highlighted in the outputs from the matrix. In addition, a thorough investigation of feasibility and other important items like safety was missing. In addition, the current version of the matrix tool is written in Dutch, and a translation into English would be beneficial

The Board felt that the most interesting and promising aspect of this Workstream was the electrostatic concept developed by BAM. The results from the initial trials were impressive, and further, more extensive trials would be of great interest. The technique - provided it is safe[17] and not too expensive and energy-intensive when applied on a larger scale - is promising for air quality improvements in tunnels and canopies. Although the principle of the BAM technology is quite old, its application in

[17] Some recent work has highlighted that charged particles may be more readily deposited in the lung. Therefore it is important that before any wide scale implementation of this technique, that possible health effects are investigated.

road tunnels has largely been neglected until now due to concerns of shifting the pollution problem from the air to the installations within the tunnel. This work contributed a great deal to the implementation of new technology by addressing these aspects.

The Board noted that one of the main problems with existing ESPs is that the air must be extracted from the tunnel and passed it through the ESP. The problem here is that the extraction of the air requires a lot of energy. Once the air has been passed through the ESP, it is either passed back into the tunnel or vented outside. Therefore, if the BAM concept does not require the air to be extracted then this could be very beneficial. It was noted by the Board, however, that the effectiveness of the electrostatic technique was very dependent on the length of the tunnel section. Important information on the effects of the BAM technology on maintenance and durability of in tunnel equipment (fans, sensors, *etc*.) and eventually the shortened cleaning periods of the tunnel could not be investigated until now.

Similar electrostatic techniques to the one developed by BAM have been investigated in the past. However, in Norway it was found that for the efficient collection of fine particulate matter a much higher voltage was required (60,000 V). The use of 20,000 V would be sufficient for the attraction of the coarse fraction, with experimental studies showing 80-90% reductions in this coarse fraction. The cost of these electrostatic systems was high, primarily due to the costs associated with providing high levels of safety to tunnel users. For a 1 to 2 km section of tunnel, costs of this system were quoted at €5m for the infrastructure supply and installation. Some further experience from Norway had also shown that the use of high voltage cabling in tunnel roofs was very expensive and had been associated with fires. This was due to the particulate matter igniting on the cabling due to the high voltage. These systems were now not being used.

A comprehensive PIARC report[18] describes the possibilities for tunnel air after-treatment systems, including their usability and effectiveness. The BAM technology could be added to the list of systems described in the PIARC report.
As a more general point, it was felt by the Scientific Board that more work could also have been conducted in this Workstream on the air quality impacts of tunnels on the surroundings.

9.6 Workstream 5: Catalytic coatings

Catalytic coatings have been identified as a promising technique for NO_x-reduction, but few detailed studies have been reported in the literature. Consequently, this Workstream was welcome. However, the disappointing results from the initial field trials - and the resulting cancellation of continued work within IPL - were major setbacks. Nevertheless, the results were informative, showing that the catalytic coating effect is very dependent upon the environment in which it is used. The results were more or less confirmed by the results from trials in the UK.

It was suggested within IPL that catalytic coatings could be used inside road tunnels (with a supply of artificial light). The Board noted that the use of TiO_2 in tunnels might be problematic, as it would require extensive tunnel closures to install the

[18] http://publications.piarc.org/en/search/detail.htm?catalog&catalog-topic=5&catalog-offset=2&publication=2247

treated surfaces, and until this technology is proven it is unlikely that permission to close tunnels would be granted for this purpose. The issue of cleaning was also mentioned. The cleaning regime of TiO_2 is not known, and could require investment in new cleaning systems.

IPL already advises road managers in the Netherlands not to use TiO_2 as a cost effective mitigation strategy. This strategy ought to be reconsidered, given the lack of evidence relating to effectiveness under real-world conditions.

Nevertheless, there is still an interest in TiO_2. An EU-project called 'Nanocrete' is evaluating different TiO_2 concrete materials, and the city of Malmö in Sweden has announced that it will be testing these materials in streets. A further in-tunnel TiO_2 application is to be tested by a Dutch Municipality during 2010.

Finally the Scientific Board recommended that further checks were made on the environmental and health effects (including bioavailability) of the TiO_2 used either within coatings or impregnated within barrier materials.

9.7 Workstream 6: DTM and air quality forecasts

In the Netherlands DTM is undertaken through a series of well defined scenarios. If air quality is to be included then these scenarios would need to be changed, and the IPL Programme Team considered this to be a complex procedure. The Scientific Board noted that it was odd that the Dutch Ministry of Transport held the belief that enforcement and control scenario changes were very complex. Speed limit changes (from 10 km/h up to 30 km/h) are frequently used in response to air quality pollution episodes (*e.g.* France, Austria and Switzerland).

The Board felt that consideration could have been given to road charging during periods of high pollution. However, there is currently a large investigation into road tolling in the Netherlands, so links with this programme could be beneficial.

The Board considered the issue of forecasting to be important. It was noted that it is very difficult to forecast PM_{10}. Furthermore, pollution-responsive DTM would normally be introduced when dispersion conditions are poor. Under these conditions air pollution modelling is also relatively difficult. It might therefore be simpler to use meteorology to trigger the DTM. This is because pollution episodes are not produced by changes in emissions, but largely by changes in meteorology.

The Scientific Board also noted that it was important to encourage behaviour change in response to DTM, such as reducing the need to travel.

Enforcement of regulations is an important issue. In the UK there is a lot of experience on variable speed limits. Once drivers became familiar with these, enforcement was undertaken through speed cameras and automatic number plate recognition systems combined with fines.

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Appendix A: Glossary

Acronym/ abbreviation	Description
BAM	Company name: Royal BAM Group nv, Bunnik
CFD	Computational Fluid Dynamics
CMA	Calcium magnesium acetate
$CaCl_2$	Calcium chloride
CO	Carbon monoxide
CO_2	Carbon dioxide
DAC	Dense asphalt concrete
DTM	Dynamic Traffic Management
DVS	In 2007, DWW changed its name to the Centre for Transport and Navigation - *Dienst Verkeer en Scheepvaart* (DVS)
DWW	*Dienst Weg- en Waterbouwkunde* (Road and Hydraulic Engineering Institute) *Rijkswaterstaat*, The Netherlands
ESP	Electrostatic precipitation
FEHRL	Forum of European National Highway Research Laboratories
IPG	Project acronym: *Innovatieprogramma Geluid* (Dutch Noise Innovation Programme)
IPL	Project acronym: *Innovatieprogramma Luchtkwaliteit* (Dutch Innovation Programme for Air Quality)
$MgCl_2$	Magnesium chloride
M+P	Company name: M+P Raadgevende Ingenieurs bv, The Netherlands
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Total oxides of nitrogen
NSL	*Nationaal Samenwerkingsverband Luchtwaliteit* - A Dutch National Air Quality Cooperation Programme
PAC	Porous Asphalt Concrete
PAH	Polycyclic aromatic hydrocarbons

PM_X	Particulate matter passing a sampling inlet with a 50% efficiency cut-off at x μm aerodynamic diameter and which transmits particles of below this size.
RIVM	Dutch National Institute for Public Health and the Environment
RWS	*Rijkswaterstaat* (Directorate-General for Public Works and Water Management, The Netherlands)
SO_2	Sulphur dioxide
TiO_2	Titanium dioxide
TNO	*Toegepast Natuurwetenschappelijk Onderzoek* (Netherlands Organisation for Applied Science Research)
V&W	Dutch Ministry of Transport, Public Works and Water Management
VROM	Dutch Ministry of Housing, Spatial Planning and the Environment

Appendix B: IPL board members and programme team

Supervisory Board members

H van Hoorn	Ministry of Transport (chairman)
Drs R J J van Winden	Rijkswaterstaat
Mw M Philippsen	Ministry of Environment
Drs L J T C Lantain	Ministry of Transport
Drs ing A L J Sprangers	Rijkswaterstaat
Mw ir C Kempenaar	Rijkswaterstaat

Management Representatives (Kernteam)

Drs L J T C Lantain	Ministry of Transport (chairman)
Drs R J J van Winden	Rijkswaterstaat
Dr ir J P L Vermeulen	Ministry of Environment
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Programme team
The overall management of the program was undertaken by Christa Kempenaar, who was responsible for the contracts with the Dutch government, the financial planning and all aspects of the IPL team. She was assisted by Lotje van Ooststroom.

The IPL research programme will close at the end of 2009. All subsequent enquiries should be made to:

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Appendix C: List of IPL publications

IPL-1a Invloed schermen op de luchtkwaliteit

IPL-1b Toepassingsadvies schermen

IPL-2a Invloed vegetatie op de luchtkwaliteit

IPL-2b Toepassingsadvies vegetatie

IPL-3a Invloed wegdekken op de luchtkwaliteit

IPL-3b Toepassingsadvies wegdekken

IPL-4a Invloed TiO2 op de luchtkwaliteit

IPL-4b Toepassingsadvies TiO2

IPL-5a Invloed overkappingen&luchtreiniging op de luchtkwaliteit

IPL-5b Toepassingsadvies overkappingen&luchtreiniging

IPL-6a Invloed DVM op de luchtkwaliteit

IPL-6b Toepassingsadvies DVM

IPL-7 Database

IPL-8 International scientific report

IPL-9 Lessons Learned: Lucht meten en rekenen