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Summary
In this deliverable we describe the results of applying the RIAT+ IAM tool in two test cases: one for the Brussels Capital Region in Belgium and another for the region of Porto in the North of Portugal. The experience obtained through these two test cases will be used to further improve the Guidance Document that is the final output of the Work Package 4.

Version History

Version	Status	Date	Author(s)
0.1	First draft	01/04/2015	Peter Viaene, Pieter Valkering (VITO), Enrico Turrini (UNIBS)
1.0	First version	01/05/2015	Peter Viaene, Pieter Valkering (VITO), Ana Miranda, Hélder Relvas (UAVR), Claudio Carnevale, Enrico Turrini (UNIBS)
1.1	Final Version	27/5/2015	Peter Viaene (VITO), Ana Miranda (UAVR)), Enrico Turrini (UNIBS), Fabrizio Ferrari (Terraria)
1.2	Final Version revised	16/6/2015	Nadège Blond (CNRS), Philippe Thunis (JRC),Stijn Janssen (VITO)

Summary of Changes

Version	Section(s)	Synopsis of Change
0.1	All	First version: structure for the document
1.0	All	Contents for description RIAT+ and test cases for Porto and Brussels
1.1	Test cases Brussels/ Porto	Updates to the results for the test cases

Abbreviations

ANN	Artificial Neural Network
AQI	Air Quality index
AQP	Air Quality Plan
BCR	Brussels Capital Region
CLE	Current Legislation, used to indicate already adopted or planned (through legislation) policy
CNG	Compressed Natural Gas
CTM	Chemical Transport Model
IAM	Integrated Assessment Method
IAS	Integrated Assessment System
LEZ	Low Emission Zone
MFR	Maximum Feasible Reduction; used to indicate the maximum possible emission reduction taking into account technical constraints
NUTS	Nomenclature of Territorial Units for Statistics
YOLL	Years Of Life Lost

1. Introduction

The main objective of work package 4 is to deliver a state of the art guidance document on Integrated Assessment Methodology (IAM) that can be used by all stakeholders. The first draft version of the guidance document (D4.1) was written based on the insight gained during the extensive review process in work package 2 and the design for an IAM presented in work package 3 which focused on the Driver/ Pressure/ State/ Impact/ Response (DPSIR) scheme to describe an IAM.

In the second part of work package 4 the guidance put forward in D4.1 is evaluated using practical examples. In a first evaluation of the guidance document, existing air quality plans (AQPs) were used as test cases with the aim to identify which guidance was currently lacking and for which D4.1 should be further extended. In the second step, which is described in this document, this testing is extended by applying the RIAT+, as an example of IAM tool, to two test cases: one for the Brussels Capital Region in Belgium and the other to the region of Porto in the North of Portugal. The two cases are representative for the two options that are available for the decision pathway in the IAM framework (deliverable D3.1): the scenario calculation and the optimisation approach. Before we present the results obtained for the two test cases, this document first describes the RIAT+ IAM.

2 Description of the RIAT+ system

The RIAT+ system which was developed during the OPERA project (www.operatool.eu) is an IAM tool that was designed to help regional decision makers select optimal air pollution reduction policies that will improve the air quality at minimal costs. To achieve this the system incorporates explicitly the specific features of the area of interest with regional input datasets for the:

- precursor emissions of local and surrounding sources;
- abatement measures (technical and non-technical) described per activity sector and technology with information on application rates, emission removal efficiency factor and cost;
- the effect of meteorology and prevailing chemical regimes through the use of site specific source receptor functions.

The system runs as a stand-alone desktop application and can be downloaded from the project web-site (http://www.operatool.eu/download/). A personal, non-exclusive and royalty-free license is distributed by the RIAT+ Licensors (the OPERA partners and JRC – IES). RIAT+ has been applied in the Emilia-Romagna Region (IT) and in Alsace (FR) during the OPERA project.

In the next chapters we'll introduce two of the key concepts needed to understand what RIAT+ does as well give a brief description of how the system works in practice. For further details the interested reader is referred to OPERA (2013).

2.1 Decision pathways

The decision pathway is the procedure followed to decide on which abatement measures to select from a set of possible measures. The RIAT+ methodology (OPERA, 2013) implements two possible decision pathways as identified in the Appraisal IA framework (WP3), which can easily be interpreted in the light of the classical DPSIR (Drivers-Pressures-State-Impacts-Responses) scheme, adopted by the EU:

- **scenario analysis**. This is the approach mainly used nowadays to design "Plans and Programmes" at regional/local scale. Emission reduction measures (Policies) are selected on the basis of expert judgment or Source Apportionment and then they are tested through simulations of an air pollution model. This approach does not guarantee that the most Cost Effective measures are selected, and only allows for "ex-post evaluation" of costs and other impacts.
- **optimisation**. This pathway indicates the set of most Cost Effective measures for air quality improvement by solving an optimization problem. In other words, the approach allows for the computation of the efficient set of technical (end-of-pipe) and non-technical (energy efficiency) measures/policies to be encouraged and/or introduced to reduce pollution, explicitly considering their impacts and costs.

Both decision pathways are shown in Figure 1.

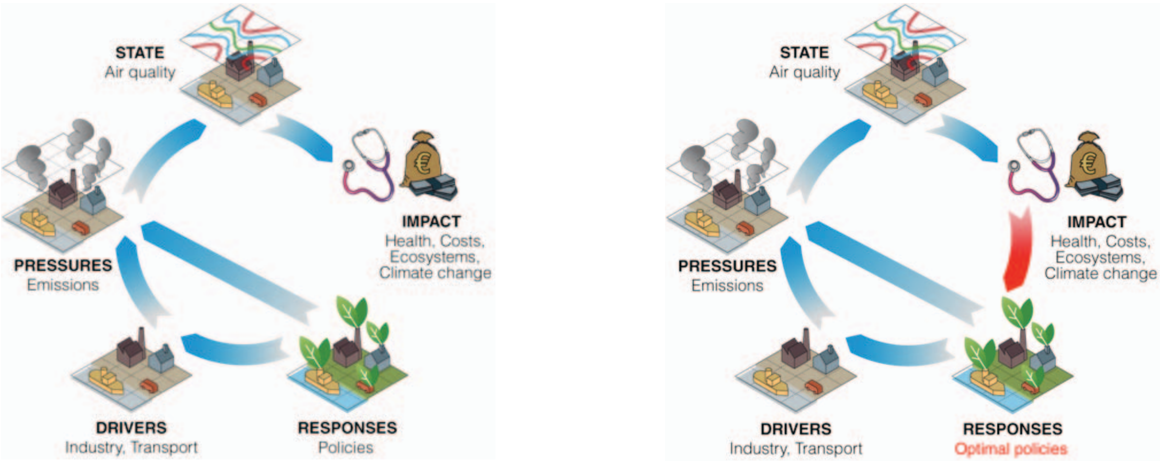


Figure 1: The scenario analysis (left) and optimisation (right) decision pathways.

More details and a formalisation of both these approaches can be found in Annex I and in the manual (OPERA, 2013).

2.2 Source receptor models

In an IAS a source receptor (S/R) model is used to relate emissions (pressure) to concentrations or an air quality indicator, AQI (state). A source receptor model can be as simple as a linear relationship between emission and concentration/AQI or as complex as a chemical transport model. In case optimisation is used, as described in 2.1 above, running a full blown CTM is due to the implied CPU time requirements impossible and the IAS will have to use simpler S/R models.

In RIAT+ the nonlinear relations between emissions and air quality indices are identified by means of Artificial Neural Networks (ANNs) tuned to replicate the results of deterministic air quality modelling system simulations. The reason for this choice is that ANNs are known to be suitable to describe a nonlinear relationship between data, such as those theoretically involved in the formation of air pollution. Given a class of surrogate models, the identification procedure requires two steps: 1) the definition of the specific structure, and 2) the calibration of the parameters to the specific application. These two steps, however, are not completely independent and the definition of the structure is often constrained by available data, while the output of the calibration step obviously depends on the structure adopted. Furthermore, the structure of the ANNs must be able to retain what are considered to be the essential features of the original model. So models formalized and identified in this work have to retain spatial information, linking emission values to local air quality indexes, that later could be processed to obtain a single global value.

As the value of an air quality index is not only dependent on the local precursor emissions but also on surrounding emissions the procedure needs to consider the influence of these surrounding emissions and the prevalent wind direction. This is achieved by considering a quadrant shape input configuration as shown in Figure 2 where the emissions are summed according to these quadrants.

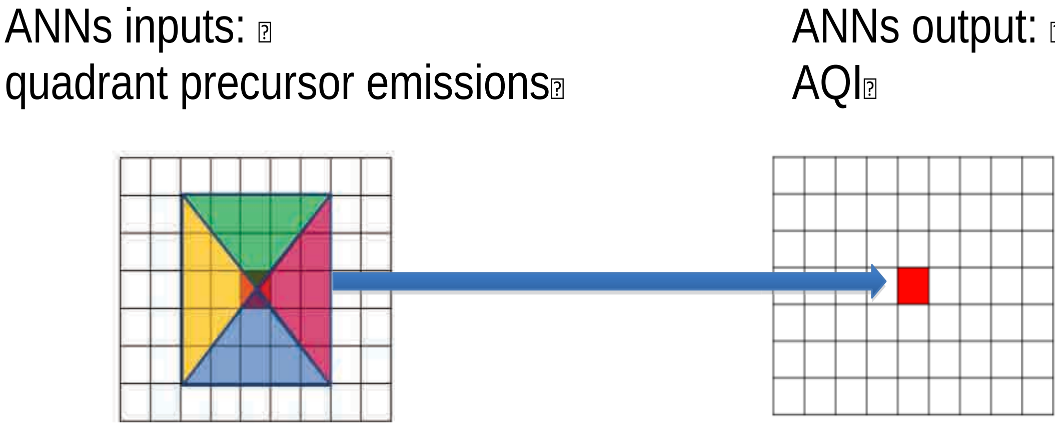


Figure 2: Quadrant shape input configuration.

An important aspect when setting up an ANN is the training of the ANN. For the training a set of CTM calculations is performed that are representative of the range of emissions/ concentrations (AQI) that can be encountered when applying the ANN. The process of selecting the configurations for the CTM will be run to produce the training data set is typically referred to as the 'Design of Experiment'. On the one hand these simulations have to be limited in number due to the deterministic model computational time, but on the other hand they must be able to represent as closely as possible the cause-effect relationship between precursor emissions and the various considered AQI.

2.3 RIAT+ in practice

Figure 3: Main window of the RIAT+ application

As can be seen in Figure 3 the main inputs for the RIAT+ are the emissions, a database containing details on the emission reduction efficiency and costs of available emission abatement measures and a S/R model that can calculate the effect of a set of selected abatement measures on an AQI.

After having input the necessary data to the system these data are validated and then pre-processed by RIAT+. This pre-processing is mainly done to allow for faster subsequent calculations with the system.

In the run settings (Figure 4) the user has to specify a number of options for running RIAT+:

- name for the run which is used to refer to the results of the run in the results panel;
- choice of decision approach (scenario or optimisation) Depending on this choice the user has to supply a number of additional inputs:
  - choice of AQI (‘objectives’) for PM, O_3 and NO_2
  - can some measures be replaced by others (technology replacement)
  - how to weight the individual objectives when combining them in the optimisation

- a ‘scenario’ in which the user specifies the application rates for individual abatement measures

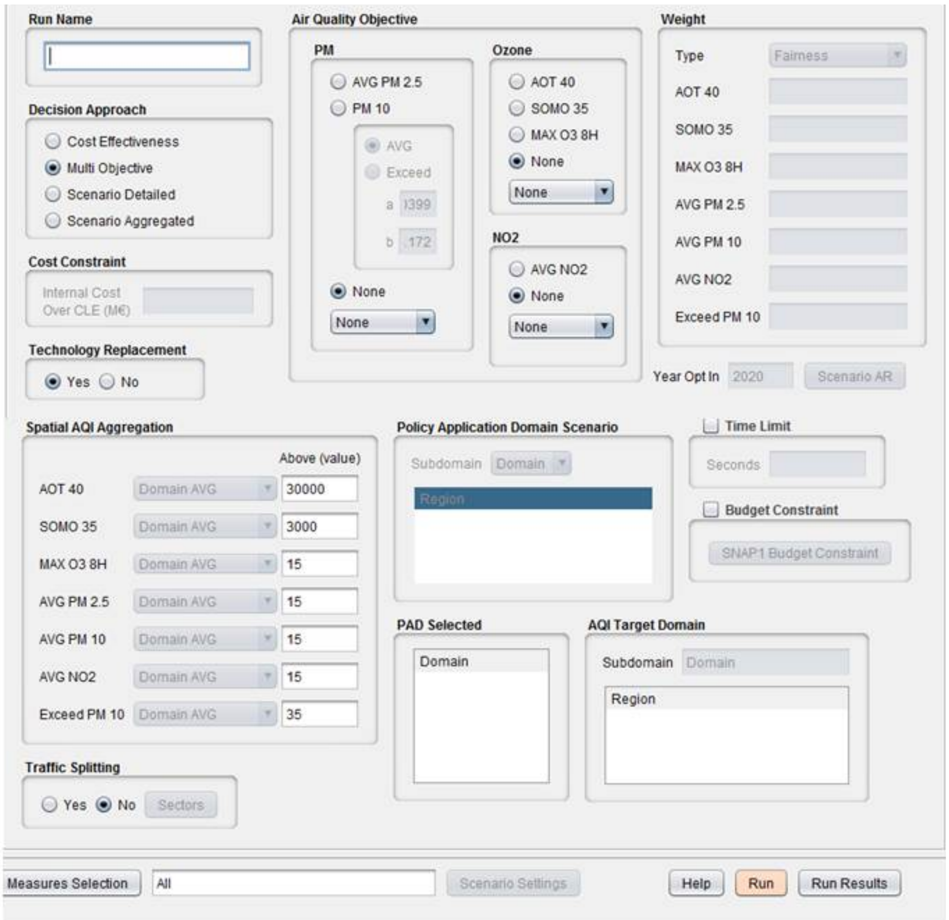


Figure 4: Run settings panel for the RIAT+ application

Once the system has run the user can select the run names from the results panel and visualize the results as maps or tables (Figure 5).

Figure 5: RIAT+ results functionality: A: main panel (selection of run), B: Summary results for selected run, C: Table with the application rates for the different measures, D: map of the yearly average PM10 concentration for the run.

3 Brussels Capital Region

3.1 Introduction

The Brussels Capital Region (BCR) has an area of 161 km^2 and is home to more than 1.1 million people. The region consists of 19 municipalities, one of which is the Brussels Municipality, the capital of Belgium. The location of the BCR in Belgium is shown in Figure 6.

Figure 6: Location of the BCR (red zone) in Belgium

For the BCR, Brussels Environment, BIM (http://www.ibgebim.be) is responsible for the study, monitoring and management of air, water, soil, waste, noise and nature (green space and biodiversity).

Within the APPRAISAL project, the RIAT+ system was setup for the BCR in order to test the potential of a more complex (Tier 2) management support tool such as RIAT+, to gain further insight in the requirements put forward by urban air quality managers such as Brussels Environment and to test and elaborate the Guidance document on Integrated assessment based on the insight gained from this application.

3.2 Proposed abatement measures for the BCR

3.2.1 INTRODUCTION

To set up the RIAT+ system for the BCR input is required on the costs of abatement measures and on their effects on emissions. BIM provided VITO with a list of 13 measures consisting of 9 traffic measures and 4 domestic heating measures that all have been approved by the Brussels authorities. For these abatement measures BIM provided order-of-magnitude estimations of the costs and emission reductions. These were first screened to determine the effect of the different measures. Where it was deemed necessary some corrections were made or cost estimates were provided (when available) where these were missing.

We stress that the proposed emission reduction and costs presented in this document are often only order-of-magnitude estimations based on rather bold assumptions. Therefore they only should be considered as indicative. The results are mainly intended to contribute to the development of new modelling methodologies (proof of concept) in APPRAISAL. To be able to draw definitive conclusions, a more thorough and detailed analysis should be made.

In the next sections, each of the proposed measures is briefly described. Most of the measures are contained in the Plan Air-Climat-Energie proposed by Brussels Environment. In this case, reference is made to the specific code for the measure in the Plan Air-Climat-Energie.

3.2.2 TRAFFIC 1: MEASURES INVOLVING A LOW EMISSION ZONE

3.2.2.1 Description

The legal basis for measures involving a low emission zone (LEZ) in the BCR is the measure with code 30.2 in the Plan Air-Climat-Energie. BIM considers 4 different possibilities for the implementation of a LEZ measure that differ in the extent of the zone that will be imposed and the types of vehicles involved. The implementation of the LEZ by the Brussels-Capital region (BCR) will be setup in collaboration with the communes

Two different zones are being considered for the LEZ: a more limited zone that coincides with the area within the boulevards of the inner ring roads (PEN) and a zone encompassing the whole Brussels capital region (BCR). Both zones are shown in Figure 7.

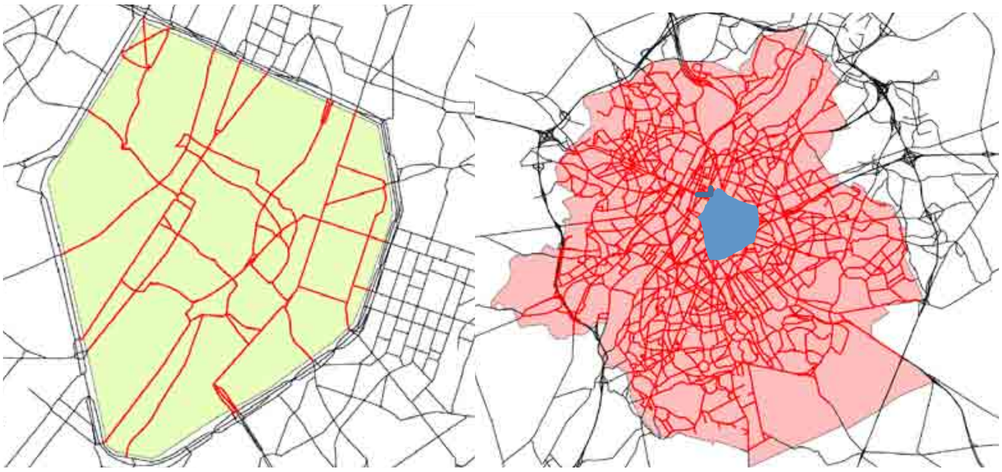


Figure 7: The 'PEN' (left) and 'BCR' (right, in red) zones. The PEN zone is coloured blue on the BCR map. The red lines correspond to roads within the LEZ.

Not only the zone considered for the LEZ is under scrutiny but also the targeted vehicles. Two scenarios are being considered in which vehicles are no longer allowed within the LEZ:

1. eVW: heavy duty vehicles (< EURO V)
2. PVW: both passenger cars (gasoline < EURO 2 & diesel: < EURO 5) and heavy duty vehicles (< EURO V).

This results in a total of four possible scenarios for the LEZ implementation which are listed in Table 1.

Table 1: The four scenarios considered for the LEZ.

	Geographical area restriction	
Vehicles affected	BCR	PEN
eVW: Only Trucks	TRAFFIC1.1	TRAFFIC1.3
PVW: Trucks & Passenger cars	TRAFFIC1.2	TRAFFIC1.4

These different options were elaborated in a study by TM-Leuven (2011) in which also the emission reductions and related costs were quantified.

3.2.2.2 Emission reductions

For the PEN scenarios, two variants were considered in the TM-Leuven (2011) study. One where transit traffic largely changes routes to comply with the LEZ restrictions, and one where transit traffic does not change significantly ('transit ongewijzigd') due to mobility restrictions. In what follows, we only consider the latter variant where transit traffic does not change significantly and the older diesel (< EURO 5/V) and gasoline (< EURO 2) vehicles are replaced by newer (≥ EURO 5) ones.

The emission reductions for a number of pollutants are listed in Table 2 both for the autonomous development (CLE), where the already planned measures but none of the extra measures is considered, as for the four LEZ emission scenario's that are considered. The percentages listed apply only to the emissions within the zone considered e.g. the 9% reduction in NOx for the traffic 1.3 scenario only applies to the emissions within the PEN zone.

Table 2: Percent emission reductions for the four LEZ scenarios that are considered (from TM-Leuven, 2011).

	autonomous		BCR-eVW (traffic 1.1)		BCR-PVW (traffic 1.2)		PEN-eVW (traffic 1.3)		PEN-PVW (traffic 1.4)	
	2015/2010	2020/2010	S2015/2015	S2020/2020	S2015/2015	S2020/2020	S2015/2015	S2020/2020	S2015/2015	S2020/2020
NOx	29	62	10	13	18	25	9	13	13	20
NO2	4	38	4	6	3	19	4	6	3	15
PM2.5	42	74	11	8	28	40	10	8	20	28
EC	43	79	10	10	30	60	9	11	20	42

It should be remarked that the estimates of pollution reduction for the autonomous development itself already include significant reductions.

3.2.2.3 Costs

The cost estimates in the TM-Leuven (2011) report only consider the costs of adapting the car fleet. Infrastructure costs are excluded in the estimates as they are too dependent on the approach taken. Estimates were only made for the larger Brussels area (BCR) based on the total car fleet registered in Brussels as specific information in the smaller area (PEN) is missing.

Table 3: Cost estimate in M€ for the two scenario's applied to the BCR zone.

	Vehicle type		
Scenario	Heavy duty vehicle	Passenger car	Total
evW (only heavy duty vehicles)	63	0.00	63
PVW (both trucks and cars)	63	621	684

For the PEN zone costs are “expected to be only a fraction of the costs for implementation in the entire BCR”. Here, we adopt the crude assumption that costs scale as the relative fraction of vehicle km in PEN compared to BCR. Taking the ratio of vehicle km between PEN (194,234 vkm/day) and BCR (7,269,200 vkm/day) as a rough indication of the cost difference, costs would amount to some 1.7 and 18 M€ respectively for the eVW and PVW scenario when implemented in the PEN zone only.

3.2.3 TRAFFIC2: CONSIDER THE COMMON ARTEMIS DRIVING CYCLES (CADC) AS THE BASIS FOR THE EUROPEAN STANDARD.

3.2.3.1 Description

The legal basis for this measure is chapter 2.3 of the Plan Air-Climat-Energie as well as European legislation concerning the EURO standards for vehicle emissions. The rationale behind this measure is in the apparent discrepancy between manufacturer quoted emissions and real world observed emissions. According to Weiss et al. (2011), "nitrogen oxides emissions of diesel vehicles (0.93 ± 0.39 grams per kilometre [g/km]), including modern EURO 5 diesel vehicles (0.62 ± 0.19 g/km), exceed emission limits by 320 ± 90%." Similar difference are reported in Hausberger (2010), where average emission levels for EURO 5 diesel cars range from 0,255 g/km (NEDC) to 0,89 g/km (CADC). These big discrepancies are observed for diesel cars and nitrogen oxides but are relatively minor for gasoline cars and other pollutants.

In this abatement measure BIM proposes replacing the test cycle that is now used as to ensure that real world vehicle emissions correspond to the car manufacturers claimed emissions. More specifically they propose to replace the current NEDC by the CADC test cycle. An obvious remark that can be made with respect to this abatement measure is that this measure can only be imposed by Europe and not by the Brussels Capital Region.

3.2.3.2 Emission reductions

Assumptions:

- Adopting CADC driving cycles decreases average NOx emissions with a factor 3 for all new diesel passenger cars as of 2015 (or a potential reduction factor of 33%).
- Evolution diesel passenger car fleet: ~3M cars in 2020 out of which ~2.4M EURO 5 (compared to 2.9M cars in 2015 out of which 1.5M EURO 5 in 2015) → 0.9M new EURO 5 cars in 2020, or 0.9/3 = 30% of the diesel passenger car fleet (see Figure 8).
- Current share of NOx emission in traffic originating from diesel passenger cars: ~50% (see Figure 9).

From these assumptions we can conclude that for this measure the overall reduction of NOx in traffic amounts to 0.33 * 0.3 * 0.5 ≈ 5% of total traffic emissions.

3.2.3.3 Costs

The manufacturers costs to reduce the engine emissions to be conform with what effectively would be a stricter EURO standard will most probably also result in higher vehicle prices for the consumer. In a report by the International Council on Clean Transportation (ICCT, 2012) the costs for emission reduction technology for diesel light duty vehicles are estimated to be respectively 927 US$ for EURO 5 and 1,398 US$ for EURO 6. Assuming that these costs are indicative a cost of 400 € per vehicle could be a rough estimate which would result in a total cost of 0.9 M vehicles* 400 €/vehicle = 360 M€ if this measure is applied to all new EURO 5 cars after 2015 in Belgium.

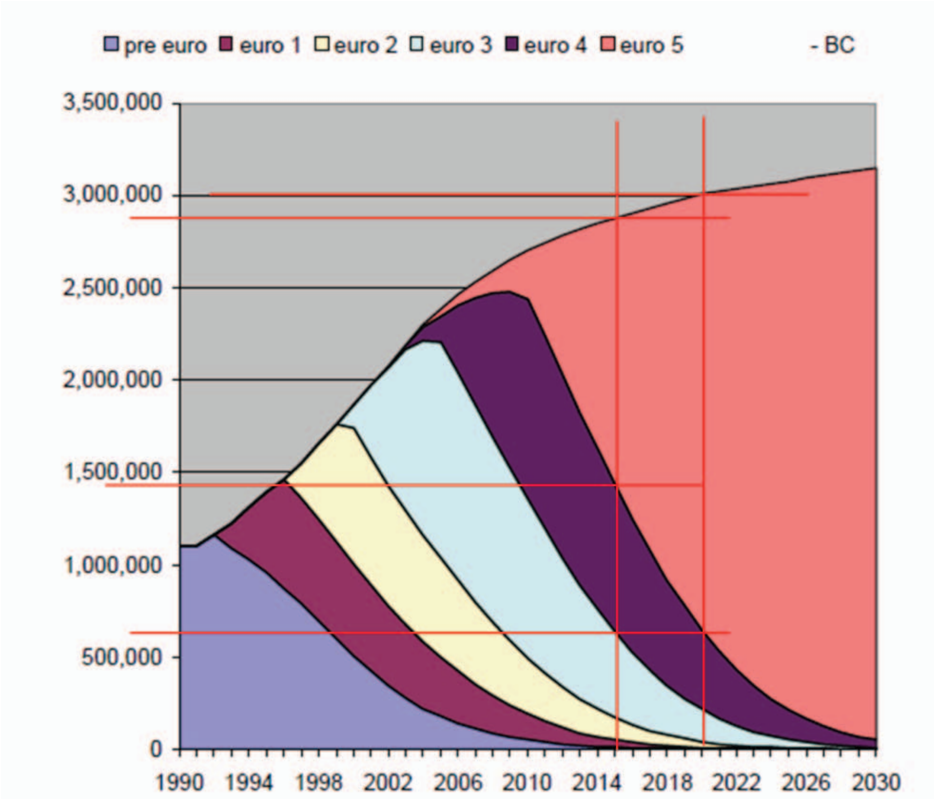


Figure 8: Penetration of emission standards in the fleet of diesel passenger cars (number of vehicles vs. year)

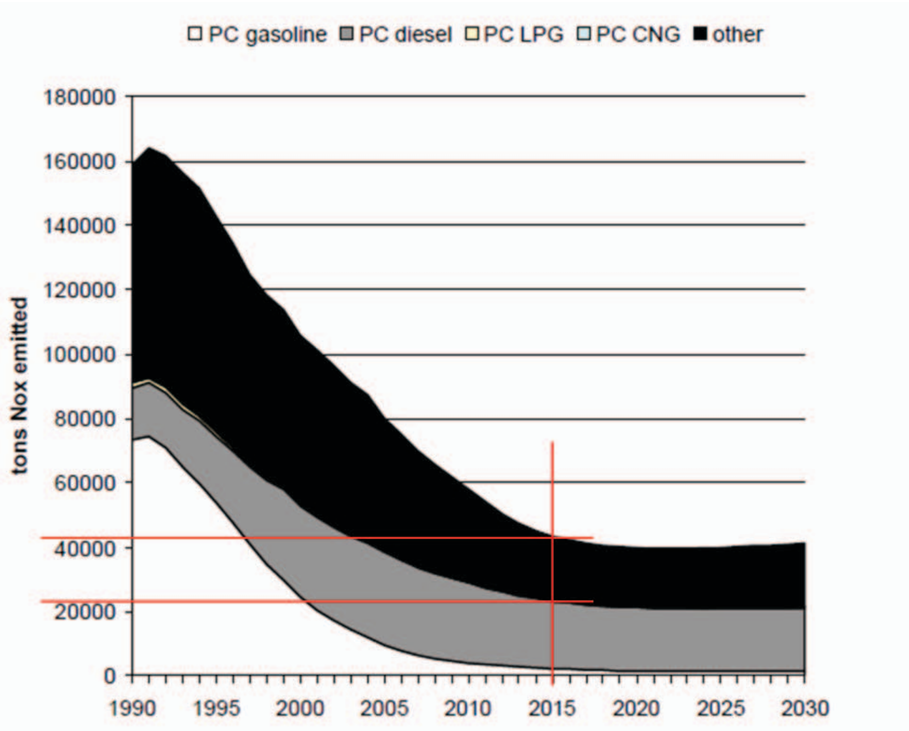


Figure 9: NOx emission from road traffic (TM-Leuven, 2006). The category other are mainly heavy duty vehicles.

3.2.4 TRAFFIC3: Reduce commuting traffic by reducing parking space

3.2.4.1 Description

The legal basis for this measure can be found in measure 27 of the Plan Air-Climat-Energie. The measure consists of reducing parking space with 25000 places.

3.2.4.2 Emission reductions

Each business day, there are (BIM/IBGE, 2012) 140,000 commuters entering Brussels and 225,000 Brussels residents who use their vehicles to get to work.

Average distances travelled (Beldam, 2012):

- A Brussels commuter: 8.7 km
- A Flemish commuter: 12.2 km
- A Walloon commuter: 13.4 km

Total passenger-car vehicle-km in Brussels (2011):

- 8564 M km (M&T, 2013)

Assumptions:

- Equal shares of Flemish and Walloon commuters, hence an average commuting distance of 12.8 km for commuters entering Brussels.
- Average (return) commuting trip = 2*(225,000*8.7+140,000*12.8)/365,000 = 20.55 km
- Avoided vehicle-km: 20.55*25,000=513,630 km / working day or 513,630*251 = 128.92 M km / year
- Emission reduction in 2011 : 128,92 M km / 8564 M km ≈ 1.5% for the sector passenger cars.

The related reductions in pollutant emissions are listed in Table 4 .

Table 4: reduction in pollutant emissions (%) for 2011 emissions

NOx	CO	VOC	PM10
0.8	1.2	0.8	1.1

3.2.4.3 Costs

The costs of reducing parking space are assumed to be zero.

3.2.5 TRAFFIC4: Reduce commuting traffic with a transport plan

3.2.5.1 Description

The legal basis for this measure is measure 29 of the Plan Air-Climat-Energie. ‘Plans de déplacements d’activités’ (PDA) or activity mobility plans are designed to focus on alternatives to the private car for travel related to cultural, commercial and sporting activities with more than 1000 participants. For the activities involving more than 6000 participants, additional measures are planned.

Two parties will be affected by this obligation:

- Managers of sites hosting more than 1000 people: they will have to implement structural measures so that the events/activities organized on their site have less impact on the environment.
- The organizers of events involving more than 1000 people: they must implement measures to encourage alternative travel modes to their event.

The approach used in a PDA, which has been implemented during several years for both companies (company transport plans) and schools, has proven its effectiveness. For example the share of private car usage in the commuting of companies who have implemented such a plan has decreased from 45% to 37% between 2004 and 2011, which corresponds to a decrease of 17%. This approach will therefore be pursued and extended.

3.2.5.2 Emission reductions

Assumptions:

- A further 17% reduction of car use for commuting traffic by 2020.
- Share of commuting traffic in passenger cars is [2*(8.7*225,000+12.8*140,000)*251] km / 8564 M km ≈ 22%
- Hence an emission reduction of 17%*22% = 3,7% for the traffic sector.

Table 5: reduction in pollutant emissions (%) due to implementing a transport plan

NOx	CO	VOC	PM10
1.9	3.0	1.9	2.6

3.2.5.3 Costs

The costs of a transport plan are assumed to be negligible.

3.2.6 TRAFFIC5: Reduce commuting traffic using a modal shift from car to bicycle

3.2.6.1 Description

The legal basis for this measure is measure 28 of the Plan Air-Climat-Energie. This measure intends to promote the use of the bicycle in order to achieve the objective of IRIS2 which is a 20% modal share for cycling in 2018. This mode-related investment is assumed to be highly effective. An English study showed that each new cyclist corresponds to a 500 € gain per year for society, mainly through the reduction of costs in health care (Cycling England 2007).

3.2.6.2 Emission reductions

Currently 1.9% of commuting trips is undertaken by bike. For this measure it is expected that an increase of the modal share of bikes in commuting traffic leads to a 20% reduction of vehicle-km for commuting traffic. In Flanders, the small trips < 5km feasible to undertake by bike only represent 2% of the total commuting km. A ceiling of e.g. 5% may therefore be more realistic to adopt instead of the 20%.

The travel back and forth from work to home correspond to 24% of the vehicle km in Brussels. If these are reduced by 20% an emission reduction of 20%*24% = 4.8% for the sector passenger cars can be expected. Estimated emission reductions for the sector passenger cars need to be translated to reductions for the transport sector overall. To this end, the estimated reduction is multiplied with the share of current total transport emissions (Table 6, state 2015) attributed to passenger cars (TM-Leuven 2006). Numbers are given in Table 7.

Table 6: Share (%) of the emissions that can be attributed to passenger cars for 2015.

Pollutant	NOx	PM10	CO	SO2	VOC
Share passenger cars	50%	70%	80%	0	50%

Table 7: Reduction in emissions due to a modal shift from passenger cars to bicycles (numbers for SO_2 and PM_{10} are missing in the report)

Pollutant	NOx	CO	VOC
Reduction [%]	2.4	3.8	2.4

3.2.6.3 Costs

The costs of the modal shift are assumed to be zero.

3.2.7 TRAFFIC6: URBAN TOLL

3.2.7.1 Description

The legal basis for this measure is measure 27 of the Plan Air-Climat-Energie. Pricing is probably the most powerful tool to control car usage. The IRIS2 plan defines the policy for mobility in the BCR for the period 2010-2018. The objective of IRIS2 is to reduce the traffic volume by 6 to 10% in 2015 and by 20% by 2018 compared to observed traffic in 2001. Preliminary studies to the IRIS2 plan have shown that imposing a toll on car use in itself would be enough to reach the objective of reducing the greenhouse gas and NOx emissions to which the BCR has committed itself. Three different possible payment schemes are considered:

- Scheme 1: Toll zone with 12 €/day for BCR
- Scheme 2: Toll zone with 3 €/day for RER (which includes BCR, see further)
- Scheme 3: KM-pricing in RER zone (0,07 €/km)

The details for these schemes are based on the STRATEC study (2014). In the toll zone schemes the car driver circulating in the specified zone has to pay a fixed amount while in the KM pricing scheme (aka intelligent pricing) the driver has to pay according to the distance travelled.

The toll zone scheme would be either applied to the BCR zone or be extended to the roads that are included in the Brussels Regional Express Network (RER) network. All traffic entering or leaving the zone or within the zone would be submitted to the toll. The driver will have to pay the toll before starting his journey for the day.
In the KM pricing scheme the car driver pays on average 0.07 € per km within the zone encompassing the RER.

3.2.7.2 Emission reductions

Effects on transport emissions are specified for zone BCR in Table 8. Relative figures are calculated compared to a baseline scenario that includes km-pricing for trucks (0.65 €/km).

Table 8: Emission reduction (%) relative to autonomous development in 2018.

Scheme	NOx	SO2	VOC	PM10
Toll zone 12€/day for BCR	18%	19%	23%	15%
Toll zone 3 €/day for RER	11%	12%	16%	11%
KM-pricing zone RER (0,07 €/km)	9%	9%	28%	9%

3.2.7.3 Costs

Regarding costs, we only consider the costs for implementing the system. The toll wages themselves are ambiguous; depending on the perspective taken they can be considered costs (for the users) or revenues (for the state), and are therefore discarded in the analysis. The costs involve a system of e-vignettes, including a system of cameras and number plate recognition. The cost for sub-region RER (scheme 2) is considered equal to the one for implementing the system only in BCR (scheme 1): for the full zone RER, no additional indication is given. Net present value consists of the total investment amount plus the yearly maintenance and operational costs discounted over a time period of 6 years (e.g. 2014 -

2020) on the basis of the given interest rate. The costs for the three possible schemes are listed in Table 9.

Table 9: Costs for the different car use schemes

scheme	Cost (M€)
Toll zone 12€/day for BCR	250
Toll zone 3€/day for RER	250
KM-pricing zone RER (0,07EU/km)	2474

3.2.8 TRAFFIC7: STIMULATING CNG USE AS CAR FUEL

3.2.8.1 Description

The legal basis for this measure is measure 33.3 in the Plan Air-Climat-Energie. In 2013 in Belgium only 216 passenger cars on a total of 5.392.908 run on Compressed Natural Gas (CNG). The two main reasons that CNG is not used more frequently as fuel are psychological and a lack of infrastructure. It is necessary to implement incentives and information campaigns and to increase the number of points of sale sufficiently to make CNG a viable alternative as in many other countries. Cooperation between regions will also be needed to assure a coordinated development in all three regions.

3.2.8.2 Emission reductions

According to FEBIAC (2013) in 2010 there were ~ 5.3 M passenger cars that drove a total of ~ 82 G km that year. This corresponds to an average of ~15,500 km/year per car. If the total NOx emission that can be attributed to passenger transport is ~28 KTon (TM-Leuven 2006), this corresponds to an average emission of ~ 340 mg/km.

Assumptions:

- 10% (or 540.000) off all vehicles run on CNG by 2020, instead of diesel (-10,1% or -6.3% share) and gasoline (-10,1% or -3,7 % share). This concerns:
  - (6.3/62.3)*3,358,900 = ~340,000 diesel cars
  - (3.7/36.5)*1,966,780 = ~200,000 gasoline cars
- The new CNG cars replace otherwise newly bought Euro5 diesel and gasoline cars. The assumed emission characteristics are given below (Table 10).

As emission reductions are only provided for all cases for NOx, only NOx is considered. For NOx we find that the average reduction in emissions would be -93% for diesel and -47% for gasoline cars or an overall average reduction of (340*40/600 + 200*40/75) / 540 = -76%, which when applied to 10% of the cars results in a reduction with -9.3% and -4.7% for respectively diesel and gasoline or an overall value of-7.6%.

Table 10: Emissions (mg/km) from Euro5 gasoline and diesel cars compared to CNG (TM-Leuven, 2006)

Emissions [mg/km]	NOx	PM10	VOC
Gasoline Euro5	75		60
Diesel Euro5	600	5	
CNG	40	n.a.	68

3.2.8.3 Costs

The cost for the measure is related to the premium of 2000 € that would be given to people buying a CNG car. The total cost would thus be 2000 * 540,000 = 1.080 billion €

3.2.9 TRAFFIC8: Eco-driving

3.2.9.1 Description

The legal basis for this measure is measure 32.1 in the Plan Air-Climat-Energie. To make eco-driving the standard on roads, these techniques should be in the first place taught during the various formations of the road users (driving license, taxi driver permit, training of bus and truck drivers, etc.). But we must also regularly sensitize drivers by information and awareness tools. In this regard, the training courses within the framework of the enterprise transport plans will be a primary place to recall the principles of eco-driving.

To fulfil their exemplary role, the administration in the region will ensure that their employees incorporate eco-driving techniques during their work. To this end, training and information campaigns will be organized on the subject especially in the context of their transport plans. The possibility to implement systems that help respect the rules of eco-driving should be considered when new vehicles are deployed.

3.2.9.2 Emission reductions

Following AIRPARIF (2012) it is assumed that about 25% of all drivers are susceptible to a more eco-driving style, implying 7% less fuel use, and hence (also assuming emissions to decrease proportionally with fuel use) a 1,7% reduction of emissions overall is estimated.

3.2.9.3 Costs

Indications of the costs of eco-driving campaigns can be found in ECODRIVEN (2008). Cost estimates for eco-driving activities range from low investment (0 – 20k€; e.g. implementing eco-driving in driving school curricula or tire pressure campaigns), to medium investment (25k€-100k€; e.g. eco-driving workshops and roadshows) to high investment (e.g. 2500k€ annually for the full scale national eco-driving program ‘het nieuwe rijden’ in The Netherlands).

For the BCR, we assume that a full scale eco-driving campaign similar to ‘het nieuwe rijden’ is appropriate, albeit for a much smaller target group (17 million inhabitants in the Netherlands compared to 1.2 million in Brussels). This results in a rough estimate of (1.2/17) * 2500 k€ = 180k€ annually. This implies a net present value discounted over a time period of 6 years (e.g. 2014 - 2020) on the basis of a 5.7% interest rate of about 1 M€.

3.2.10 TRAFFIC9: Reducing the speed limit

3.2.10.1 Description

The intention of this measure would be to reduce the speed limit to 30 km/h for the whole of the BCR.

3.2.10.2 Emission reductions

From literature (e.g. Int Panis et al. 2006) it is concluded that the effect of this measure is probably non-existent on pollutant emissions.

3.2.10.3 Costs

The costs for this measure are assumed to be negligible.

3.2.11 HEATING1: MAINTENANCE OF RESIDENTIAL HEATING APPLIANCES

3.2.11.1 Description

The legal basis for this measure is in the Code Bruxellois de l'air, du climat et de la maîtrise de l'énergie 'COBRACE' (articles 2.2.15 to 2.2.17 and 2.5.1 to 2.5.5) and the government decision of the Brussels Capital Region dated June 3, 2010 concerning the requirements for heating systems.

This measure consists of a periodic inspection which consists of a number of maintenance and monitoring requirements as listed in the PEB (Performance Energétique des Bâtiments) guidelines for boilers. This applies to the residential and tertiary sectors. However, in order to respect the principle of 'additionality' with the provisions imposed under Directive 2010/31/EU for boilers over 100kW, the measure will only take into account here the case of residential boilers, with a power in excess of 20kW which corresponds to 95% of all boilers in the residential sector.

Specifically, the periodic inspection of boilers consists of cleaning all components of the boiler and flue system, the burner setting and compliance verification requirements. Oil-fired boilers should be checked annually while natural gas boilers should be checked every 3 years.

3.2.11.2 Emission reductions

The emission reductions to be expected by imposing this measure are listed in Table 11.

Table 11: emission reduction (Ton)

Pollutant [Ton]	2012	2015	2020
NOx	18.90	47.44	72.08
CO	17.98	55.33	83.13
SOx	12.46	20.92	32.74
VOC	2.11	6.16	9.28
PM 2.5	1.07	1.95	3.03

3.2.11.3 Costs

In the BIM proposal costs are neglected and only the fine that is foreseen in the regulations for the owner who fails or refuses to periodically check the boiler is mentioned. In (VITO, 2011), the number of different types of boilers and their maintenance costs are given (p. 102 / p. 179). On this basis, total maintenance costs are estimated at some 37 M€. Assuming boldly that currently 50% of maintenance is carried out, the measure would imply a cost of some 18 M€ for the home owners in Brussels.

3.2.12 HEATING2: IMPROVING INSULATION OF BUILDINGS

3.2.12.1 Description

Since 2007, the Brussels-Capital launches almost every year a project call "Exemplary Buildings" ("BATEX") for the entire Brussels property market. The projects aims to stimulate the construction and building renovation programs by demonstrating that it is possible to achieve excellent energy and environmental performance while opting for economically justifiable solutions and promoting high architectural quality. It provides building owners the opportunity to be ambitious, and allows at the regional level to generate a number of exemplary buildings that have a lasting effect on the Brussels construction market through the experience obtained.

Selected projects must be outstanding according to the following 4 criteria:

1. Very High Energy Performance;
2. Very limited environmental impact;
3. Reproducibility of solutions at a reasonable economic cost;
4. Urban and architectural integration of the building.

Following six calls for proposals for projects launched between 2007 and 2013, 193 projects (29% collective housing, 28% private housing, 27% community facilities, 16% office and trade) were selected, representing no less than 520,000 m² in Brussels.

3.2.12.2 Emission reductions

The emission reductions to be expected by imposing this measure are listed in Table 12.

Table 12: emission reduction (Ton)

Pollutant [Ton]	2012	2015	2020
NOx	1.46	3.23	4.41
CO	2.34	5.17	7.06
SOx	-	-	-
VOC	0.24	0.54	0.74
PM 2.5	0.01	0.03	0.04

3.2.12.3 Costs

The selected projects receive financial aid (100 €/ m²) and are coached by an expert. A total budget of 28 million has been allocated over six years.

3.2.13 HEATING3: LOCAL ACTION PLAN FOR ENERGY MANAGEMENT

3.2.13.1 Description

The Local Action Plan for Energy Management (PLAGE) is mandated by the Brussels Code of Air, Climate and Energy Management (COBRACE - adopted May 2, 2013), section 2.2.21 to 2.2.24 and 2.4.313.

The plan which will be implemented from 2016 aims to ensure that managers of large real estate portfolios over a period of about 4 years will improve the energy management of their assets through:

- The establishment of an energy register for all the buildings the organization owns or occupies;
- The identification of buildings for which, following the completion of the energy register, an energy accounting system is most needed;
- Development and implementation of an action plan to reduce energy consumption: this plan will include actions related to the management and maintenance of building facilities and investments.

3.2.13.2 Emission reductions

The emission reductions to be expected by imposing this measure are listed in .
Table 13.

Table 13: emission reduction (Ton)

Pollutant [Ton]	2018	2022	2026	2030
NOx	4.91	9.82	14.73	19.64
CO	6.63	13.27	19.90	26.53
SOx	1.27	2.54	3.81	5.08
VOC	0.62	1.24	1.87	2.49
PM2.5	0.13	0.27	0.40	0.53

3.2.13.3 Costs

Costs for the measure are assumed to be zero since the PLAGE is an obligation contained in the Code Brussels Air, Climate and Energy Management (COBRACE - Chapter 4) which also details the procedures for penalties in case of failure.

3.2.14 HEATING4: ENERGY AUDITS

3.2.14.1 Description

The legal basis for this measure is the Decree of the Government of the Brussels-Capital dated December 15, 2011. The Decree requires an energy audit for all facilities that apply for renewal of an environmental permit when the facility consists of one or more buildings with a total area not used for housing of more than 3500 m². Permits will be granted on the condition that the owners implement the identified measures that have a payback period of less than 5 years within the 5 years following issuance of the permit. This measure has been in force since 2012.

3.2.14.2 Emission reductions

The emission reductions to be expected by imposing this measure are listed in Table 14.

Table 14: emission reduction (Ton)

	2012	2015	2020
NOx	3.53	13.94	30.84
CO	4.94	19.54	43.24
SOx	0.71	2.81	6.21
VOC	0.53	2.09	4.62
PM 2.5	0.09	0.34	0.75

3.2.14.3 Costs

Costs are again assumed to be zero. Costs for the owners of the buildings are neglected.

3.3 Application of RIAT+

3.3.1 TECHNOLOGY DATABASE

The RIAT+ database with abatement technologies that are available for the macro-sectors of interest - non-industrial combustion (2) and transport (7) – is the same as the one that was derived from GAINS Europe in the frame of the OPERA LIFE+ project. As the focus is on abatement measures for these two sectors only, no measures for any of the other macro-sectors are considered in this case study. The measures that are proposed by the BCR (§3.2) were added to this initial set based on GAINS as follows:

- the ‘low emission zone’ (LEZ, §3.2.2) was modelled in RIAT+ through changing the distribution of cars and trucks over EURO1 – EURO6 and it was assumed that the traffic volume would not change. The EURO classes are already available as technological measures in the GAINS database so no additional measures were needed to add this abatement measure to the database. As the effect of only implementing the LEZ within the inner ring road will be limited to only a few grid cells at the modelling scale of 1 km x 1km, it was decided to omit this option and to only consider the application of the LEZ on the whole BCR.
- Some of the measures proposed imply changes to emissions outside the BCR area, something that would also require extending the modelling setup that was taken for the chemical transport modelling and these were therefore not considered. For the urban toll measure (§0) we thus only considered the case where this measures is implemented in the BCR and not the alternatives in which the larger RER area is considered. Also the shift to CNG cars (§0) and the adoption of the Common Artemis Driving Cycle (§3.2.3) were not considered because of these measures relate to respectively the national and even European level.
- All other traffic and non-industrial combustion emission measures were added as non-technological measures to the database using the emission removal efficiencies that were presented in §3.2. For the traffic sector the measures were added in such a way that they will affect exhaust emissions for all fuel types as well as non-exhaust emissions (brake and tyre wear, ..). Also for the non-industrial sector, these measures were added in the data base to account for all fuel types (gas, petrol, …).
- An obvious problem is that not all reductions listed in §3.2 apply to the same reference year and time horizon. The reference year for which we’ll do the AQ model calculations and for which thus the emission inventory is available is 2009. Where available we have taken the reductions with respect to the 2010 emissions but for all other cases we have retained the reported percentages well knowing that these could therefore be an over or underestimation of the actual emission reduction effectiveness. For the heating appliance measures we have related the reported values to the emissions for 2009. For traffic and domestic heating the emissions for 2009 are listed in Table 15.
- For some measures costs provided seem rather unrealistic. Often only the direct costs for implementing an abatement measures is considered and costs affecting those that will have to comply to the measure (drivers, house owners, ..) are neglected. As it is not the intention to use RIAT+ in optimisation mode where costs are needed in the optimisation process, costs where neglected in this study. This implies that no results are provided for the costs of implementing the measures.

Table 15: Emissions (Ton/year) in the BCR for 2009 for the sectors domestic heating (SNAP2) and transport (SNAP7).

SNAP	NOx	CO	SOx	VOC	PM2.5
2	2266	3899	586	299	71
7	2026	1581	5	5	130

For the RIAT+, technology data base, 2010 has been chosen as the reference year which is closest to the year used for the regional emission inventory (2009). The GAINS database contains activity data for the years 2010, 2015, 2020 and 2025.

In the database of measures the CLE (Current Legislation Level) is the set of Application Rates or the degree of implementation of a technology that reflects the requirements of the current legislation. MFR (Maximum Feasible Reduction) is the set of Application Rates or the degree of implementation of a technology that reflects the maximum degree and physically plausible applicability of a technology. The GAINS database provides the degree of potential application (Potential Application Rate) used to compute the MFR scenario.

The final list of measures with their emission removal efficiency (2010) are shown in Table 16. The Low Emission Zone measures are omitted because these are modelled using the EURO parameters which are from the GAINS database.

Table 16: list of measures considered for the BCR with their removal efficiency as % of the 2010 emission.

Description	Emission reduction per compound (%)				
	NOx	SOx	VOC	PM2.5	PM10
Eco driving	1.7	1.7	1.7	1.7	1.7
Modal shift	2.4	0.0	2.4	3.4	3.4
Transport plans	1.9	0.0	1.9	2.6	2.6
Urban toll	18	19	23	15	15
Parking places	0.8	0.0	0.8	1.1	1.1
Boiler maintenance	3.2	5.6	3.1	4.2	4.2
Exemplary buildings	0.2	0.0	0.2	0.1	0.1
Energy efficiency large buildings	0.3	0.3	0.3	0.3	0.3
Energy audits	1.4	1.1	1.5	1.0	1.0

3.3.2 Chemical transport modelling

For air quality modelling of the Brussels capital region the AURORA chemical transport model was used (e.g. Mensink et al., 2001, Lauwaet et al., 2013). The air quality modelling system AURORA was designed to simulate the transport, chemical transformations and deposition of atmospheric constituents at the urban to regional scale. It can be applied both in hindcasting and forecasting mode and can evaluate the effects of emission reduction scenarios, scenarios related to spatial urban structure, mobility etc., on air quality. The

AURORA model consists of several modules. The emission generator calculates hourly pollutant emissions at the desired resolution, based on available emission data and proxy data to allow for proper downscaling of coarse data. The actual Chemistry Transport Model (CTM) then uses hourly meteorological input data and emission data to predict the dynamic behaviour of air pollutants in the model region. This results in hourly three-dimensional concentration and two- dimensional deposition fields for all species of interest.

For solving the advection, the AURORA model uses the Walcek (2000) scheme, which ensures monotonous advection in x, y and z directions. The model only accounts for vertical diffusion through turbulence using a solution based on the semi-implicit Crank-Nicholson diffusion scheme with damping of oscillations. The dry deposition which is solved together with the diffusion is parameterized as a downward flux. Wet deposition is modelled using species-dependent washout coefficients and allows for accumulation to saturation in the rain drops during the washout process. AURORA has a choice of three different chemical mechanisms for the gas phase: (1) the CB-IV-99 mechanism, which is an extension of the CB-IV (Gerry et al., 1989) mechanism with isoprene chemistry, (2) CB5 (Yarwood et al., 2005), which compared to the CB-IV-99 mechanism incorporates terpene oxidation and an improved description of the nitrate radical chemistry at night and (3) CB5 extended with oxidation reactions that result in the formation of semi-volatile organic compounds, which can condense to form secondary organic aerosols. Finally, for the formation of secondary inorganic aerosols the model uses the ISORROPIA model (Nenes et al.,1998) for calculating the equilibrium between the gas and aerosol phase for the inorganic compounds and a kinetic description of the desorption/adsorption process for the semi-volatile organic compounds.

For the Brussels Capital Region study AURORA was set up for a domain of 49 x 49 grid cells at 1 km resolution (Figure 10) for the year 2009. For the vertical discretisation 20 layers were used for a domain extending up to 5 km. The layer thickness increases from 27 m for the bottom layer to 743 m for the top layer. For the boundary conditions the results of an AURORA run for the same year was used for a domain covering Belgium at a resolution of 4 km. These same boundary conditions were used in all runs. For the meteorological inputs the ECMWF ERA INTERIM data with a resolution of 0.25° were used and interpolated to the model grid. The emissions are based on the CORINAIR emission inventory which were spatially disaggregated using the Emission MAPping tool (E-MAP) developed by VITO (Maes et al., 2009). This tool downscales national emission inventories using a set of proxy data, such as land use information or the road network. For the calculations the CB5 chemical mechanism was used.

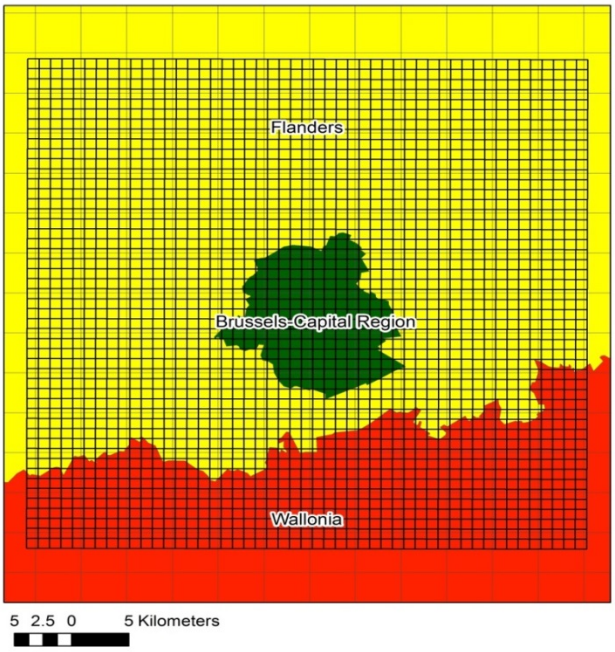


Figure 10: model grid used for the CTM calculations. Both the 1 km resolution grid and the lower (5 km) resolution grid are shown. The different colours correspond to the different regions (green: Brussels Capital Region, yellow: Flanders, red: Walloon)

The results of the 1 km resolution model setup were validated by comparison to the observed values at the measurement stations inside the model domain. For the validation the methodology proposed by FAIRMODE (http://fairmode.jrc.ec.europa.eu/) was adopted. Details on this methodology can be found in Thunis et al. (2012 and 2013) and Pernigotti et al. (2013). Briefly put, the methodology accounts for observation uncertainty in the evaluation of model results and proposes a model quality objective (MQO) to decide whether model results are acceptable.

In Figure 11 the target diagram for the NO_2 results is shown. The advantage of the target diagram is that it allows the user to see at a glance whether the model results are acceptable as the MQO requires the model results to lie within the circle with radius 1. In this sense evaluating a target diagram is much the same as looking at a darts board, the aim being to have all points as close to the centre as possible and at least within the circle with radius 1. In this case all station results comply to the MQO. Only for the single point corresponding to the station with code BETR002 that is classified as a suburban traffic station the underestimation of observed values (BIAS) is bigger although still within the acceptable range.

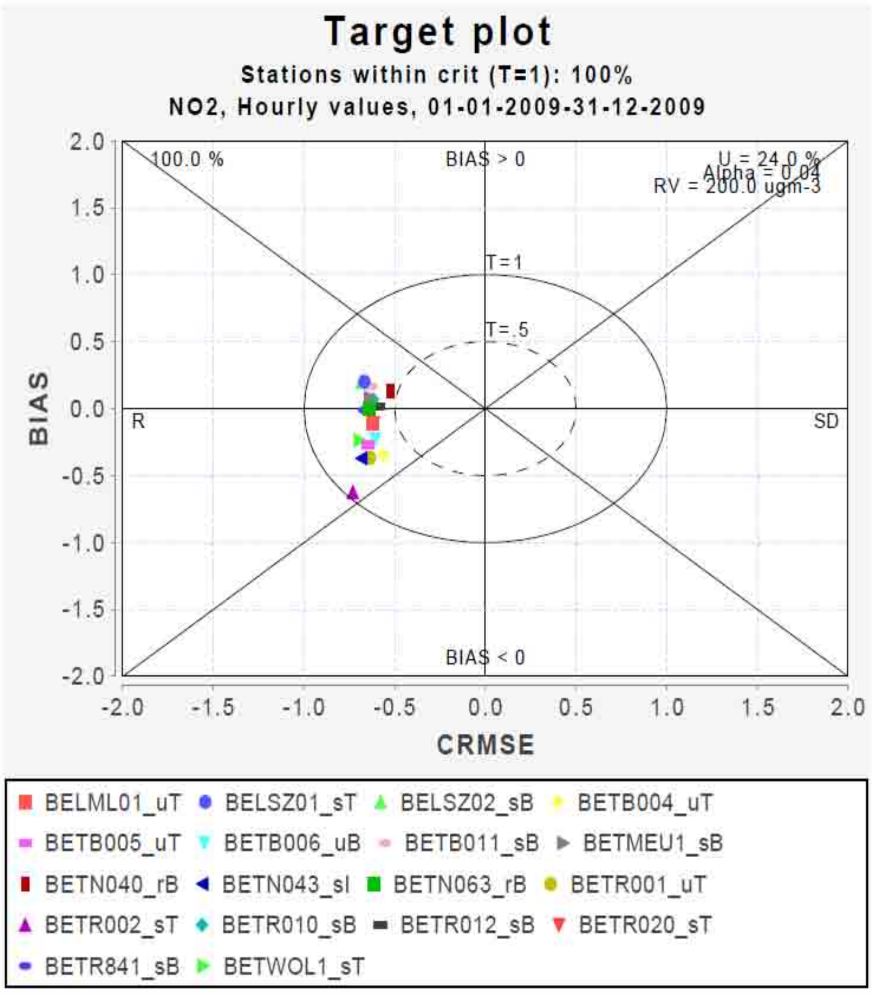


Figure 11: target diagram for the observation stations for NO_2 inside the model domain for 2009.

More details on individual station performance can be found in Table 26 in Annex II where we present the BIAS, RMSE and correlation (R) for NO_2 for the individual stations within the model domain. The worst model results are found, as also indicated by the target diagram, for station BETR002. At this traffic station the yearly average measured NO_2 is also highest.

As shown by the target diagram (Figure 12) for PM_{10} the model results are in less than half of the observation stations in accordance with the MQO requirement, i.e. the results are not within the circle with radius 1. The main problem is the large underestimation of observed values by the model. This negative bias is a general problem found with many of the current chemical transport models and is most likely due to missing primary emission sources in the model input. The bias is largest in the stations with the highest observed values as can be seen from the table statistics for the individual stations (Table 27 in Annex II).

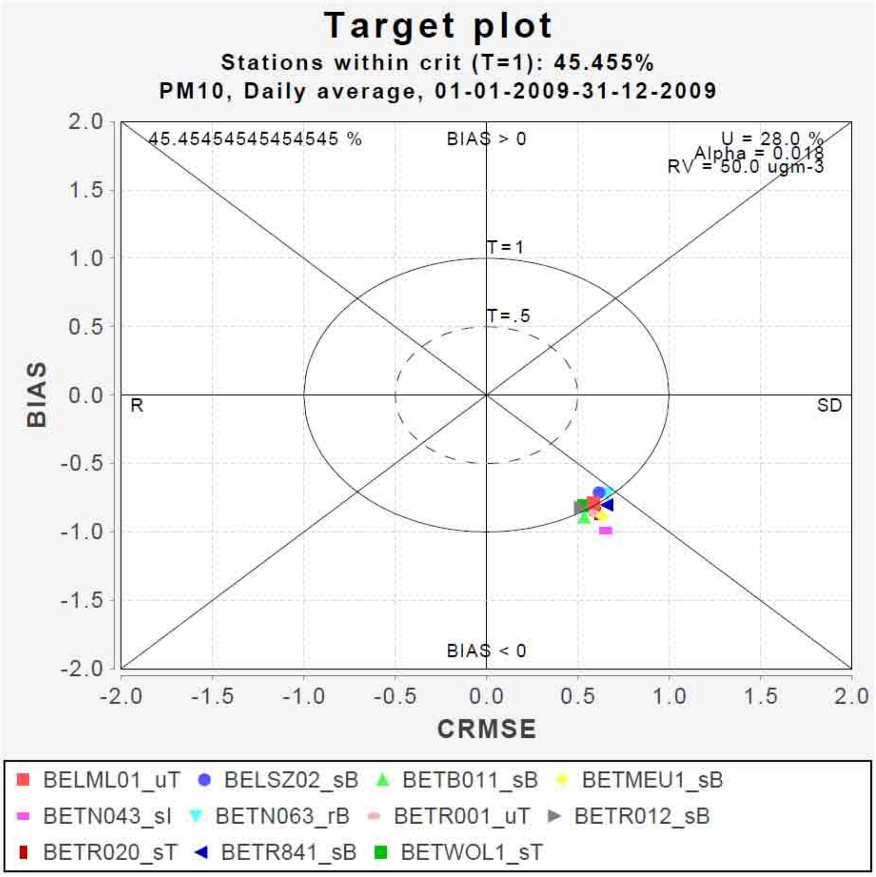
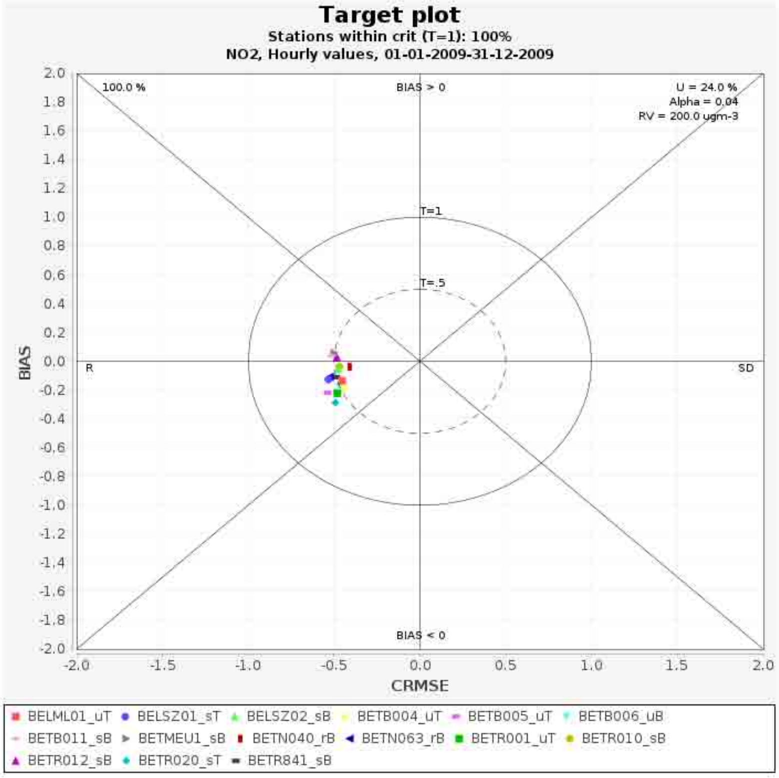


Figure 12: target diagram for the observation stations for PM_{10} inside the model domain for 2009

The proposed set of emission reduction measures is expected to have a limited effect on the concentrations due to the fact that the combined measures will only reduce the total emissions by 20 - 30% and only within the 'small' area of the BCR. While the model results for NO_2 are acceptable according to the validation procedure outlined above, for PM_{10} the model error is too large and this might well obscure the effect of the emission reduction measures. We would therefore like to improve the model results. For assessment, a better estimate of concentrations can be obtained using the RIO model (Janssen et al., 2008). RIO interpolates observed concentrations in an intelligent way by using CORINE land cover data as a spatial driver. To do this, long-term trends are determined between the observed concentrations at a given measurement station and the CORINE land cover in the surroundings of this station. Before interpolating by Ordinary Kriging, the concentrations at the measurement stations are 'de-trended'. This assures that all measurements are drawn from a distribution with a spatially independent mean and variance, a precondition to apply Ordinary Kriging. Afterwards, the observed trends are added again to the interpolated concentrations.

Based on the target diagram (Figure 13) it can be seen that the RIO results for PM_{10} are much better than those for AURORA. When points are located within the circle with radius 0.5 in the Target diagram this means that the model results are within the range of observation uncertainty and it is not possible to assess whether further improvements to the model are closer to the true value based on the available measurements. For NO_2 the improvement is less impressive but model results are still better than those for AURORA. As RIO is based on observations this is off course not so surprising. Because observations are used in the model, it should be remarked that for the validation the RIO results were obtained by a 'leaving one approach' in which the RIO interpolation is applied for a single station based on all data except the data of the station itself. In this way, an independent validation of the RIO model is performed.



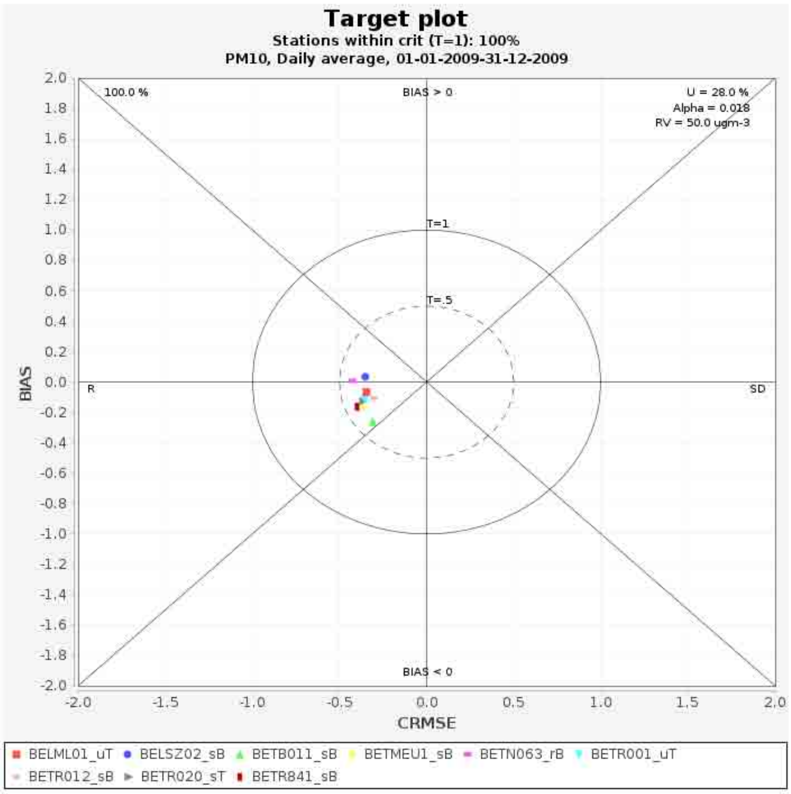


Figure 13: target diagrams for the RIO results for NO_2 (top) and PM_{10} (bottom) for the observation stations within the AURORA model area covering the BCR.

The RIO results are clearly more reliable than those for AURORA but are off course not available for future years and/or emission scenarios. To take advantage of the RIO results a procedure was used in which the RIO time series in individual model grid cells were combined with the concentration change due to applying a specific scenario. This procedure is depicted in Figure 14. As shown in this figure, in a first step regression relations are determined for the individual model grid cells based on the chemical transport model result time series for the reference and the emission scenario. These regressions relations are then used on the same grid cells of the reference time series for RIO to derive a new time series for the scenario.

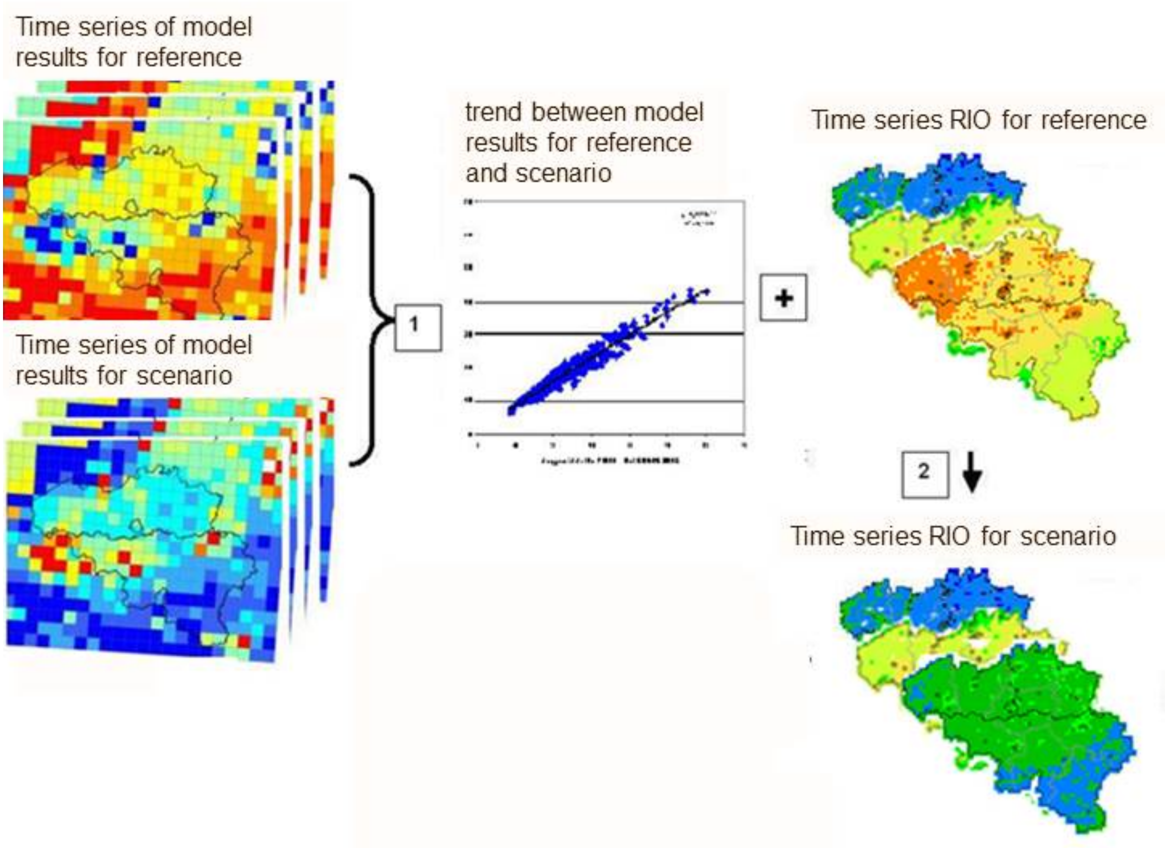


Figure 14: procedure used to combine AURORA and RIO results.

3.3.3 Design of Experiment

For the Design of Experiment phase three levels of emission application levels were distinguished: base case (B), high emission reductions (H) and low emission reductions (L). These three levels are applied to the cells inside the Brussels Capital Region (BCR) domain (the green area in Figure 10). In particular these levels correspond to the following cases:

- The B emission level corresponds to the CLE2020 emissions, increased by 20%. To derive the CLE2020 emissions starting from the 2009 regional emission inventory, rescaling factors were derived using RIAT+ based on the Activity Level and Technology Application Rates taken from the IIASA website. After the CLE2020 emissions computation, these emission levels are increased by 20% to make sure that the emissions for which the ANN will be applied are smaller.

- The H level (high emission reductions) is obtained by projecting the 2009 regional emission inventory to 2020, using the RIAT pre-processor taking into account the potential technology application rates for 2020 found on the IIASA website.
- The L level (low emission reductions) is obtained as the average between B and H levels.

The emission levels for the model grid cells outside the BCR were also changed according to the changes inside the BCR. For these outside cells the three levels were determined as an average scaling factor, for each pollutant and macro-sector, based on the emission variations inside the BCR domain with respect to the 2009 inventory emissions.

The last step, was to estimate an emission projection to CLE2020 for the cells outside the 49 x 49 km domain in order to obtain CLE2020 boundary conditions. To do this, the average emission variation from the 2009 inventory projected to CLE2020 of the BCR domain cells was applied to the emission inventory covering the Belgian domain. The results of the CTM runs for this 4 km resolution outer domain will provide the boundary conditions for the 1 km resolution runs covering the BCR. These CLE2020 results on the 4 km resolution domain were used for all scenario runs on the 1 km resolution domain.

In order to determine the emission reduction scenarios for the ANN training, the three levels B, H, L were combined to produce the 14 emission scenarios listed in Table 17. These scenarios are applied to the emissions both in - and outside the policy application domain (PAD). The PAD is in this case the BCR.

Table 17: Description of the 14 emission reduction scenarios obtained combining B, H, L scenarios in and outside the policy application domain (PAD). The policy application domain is in this case the BCR.

Scenarios	NOXa	VOCa	NH3a	PM_{10}a	$PM_{2.5}$a	SO2a
1	B	B	B	B	B	B
2	L	L	L	L	L	L
3	H	H	H	H	H	H
4	H	B	B	B	B	B
5	B	H	B	B	B	B
6	B	B	H	B	B	B
7	B	B	B	H	H	B
8	B	B	B	B	B	H
9	H	H	L	L	L	L
10	H	L	H	H	H	H
11	H	L	H	L	L	L
12	H	L	H	L	L	H
13	L	L	L	L	L	H
14	H	L	H	L	L	H

3.3.4 Identifying the source-receptor models

The AURORA model was run using the 14 scenario emission inputs described above and the resulting outputs were combined with the AURORA results for the reference year 2009 and the RIO results for 2009 as described in 3.3.2 to generate a training dataset for the

Artificial Neural Networks (ANNs) that will be used as a surrogate model in the RIAT+. In this study, the Air Quality Indexes (AQIs) that are related to emissions by the ANNs are:

- PM_{10}: yearly average of PM_{10} concentrations;
- NO_2: yearly average of NO_2 concentrations.

For the ANN, emissions surrounding individual model grid cells are aggregated according to 4 quadrants (see Figure 2). Several tests were done to identify the best radius of influence to aggregate emissions. From these tests it was decided to take a quadrant dimension of 14 cells for PM10 and of 20 cells for NO_2.

Tests were also done to identify the best transfer functions to be used in these ANNs. The choice of the best transfer function (Table 18) depends on the pollutant considered.

Table 18: Activation functions for the best ANNs, for each of the AQI considered.

AQI	Functions	Radius (# cells)
PM10	Tansig-tansig	14
NO2	Tansig-purelin	20

3.3.5 VALIDATION OF THE ANN.

To validate the results from the ANN, output values are compared to the results calculated by the CTM. In Figure 15 the results are shown when the comparison is done for an independent validation data set which consists of a random selection of 20% of the grid cells and for which the CTM results were not used in the training of the ANN.

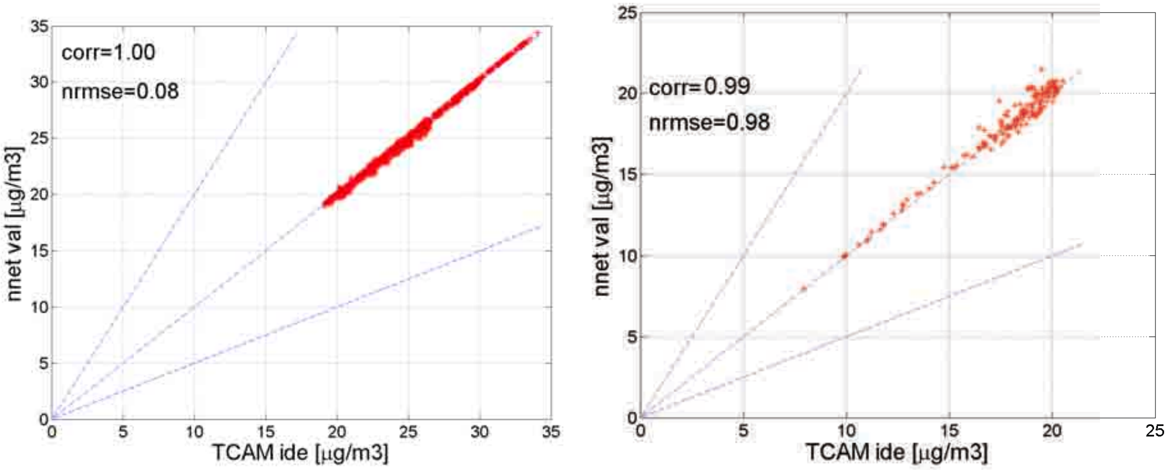


Figure 15: NO_2 (left) and PM_{10} scatter plots for the validation of the concentrations ANN vs the AURORA (X-axis, here referred to as 'TCAM') model.

As can be seen from these scatter plots (Figure 15) the ANN is able to reproduce the modelled concentrations for both NO_2 and PM_{10} albeit the results for NO_2 are somewhat better.

As we want to use the ANN in scenario calculations we also checked whether the ANN is capable of reproducing the dynamic behaviour of the CTM.

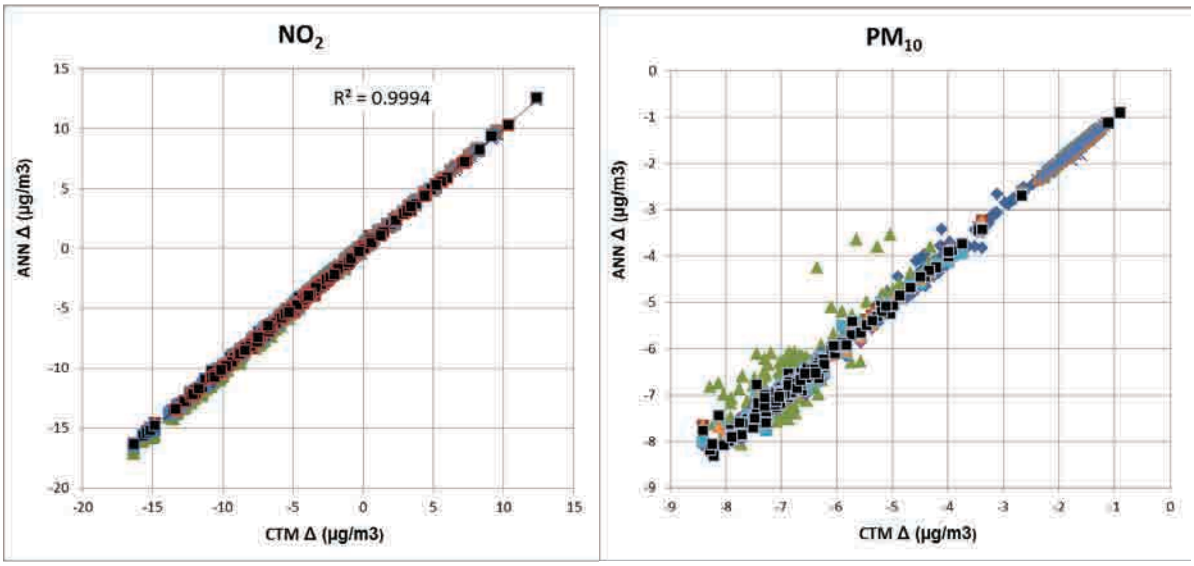


Figure 16: Scatter plots for the concentration changes (Δ) for the scenarios 2 – 15 of the training dataset calculated by the ANN vs. CTM (AURORA) (scenario 4=).

The concentration changes were calculated by subtracting scenario2 from each of the other scenarios. As can be seen in Figure 16 the ANN is well capable of reproducing the CTM behaviour for NO_2 but has more difficulties with reproducing the PM_{10} concentration changes. This is especially true for scenario 4 in which only the NOx emissions are changed and for which the results are shown as small green triangles in the figure. For this last case the average normalised bias amounts to 3.6 % with extreme values of up to 33% whereas for all the other scenarios the average normalised bias is less than 0.25%. More details on some statistics for the difference in concentration changes calculated by the CTM and the ANN for different scenarios relative to scenario 1 are presented in Table 19.

Table 19 correlation (R), Normalised absolute average bias, NBIAS(%) and normalised root mean square error, NRMSE(%) for the changes in PM10 with respect to scenario 1 ('base case').

scenario	R	NBIAS	NRMSE
2	0.98	0.37%	3.44%
3	0.99	0.15%	1.82%
4	0.90	3.62%	7.29%
5	1.00	0.29%	1.48%
6	1.00	0.31%	0.37%
7	1.00	0.27%	0.56%
8	1.00	0.04%	0.15%
9	0.99	0.45%	2.02%
10	0.99	0.18%	2.06%
11	0.99	0.35%	2.20%
12	0.99	0.18%	2.00%
13	0.99	0.15%	1.82%
14	0.99	0.18%	2.06%

Because of the problems with scenario 4 this scenario was omitted from the training data set for the PM_{10} ANN. The results shown are for the ANN trained without scenario 4.

3.3.6 RESULTS OBTAINED WITH RIAT+

Once the ANNs have been trained these can be used in RIAT+ to test the different scenarios. The RIAT+ was run for the year 2020. In

Besides tabular output of statistics RIAT+ also produces a number of maps for both the emissions, the AQI and other derived quantities such as the Years of Life Lost (YOLL). On the following pages examples are shown of these RIAT+ outputs.

The spatial distribution for the emissions obtained using EMAP (Maes et al. 2009) can be seen in Figure 17. The non-industrial combustion emissions have been distributed according to a population density map while the traffic emissions are mainly assigned to the highways. Although this distribution between road types is in accordance with COPERT, one can wonder whether this is realistic. Road type also doesn't always reflect actual traffic volumes. While the ring road in Brussels goes all around the city, due to a code change it now seems part of the ring road is missing in the South eastern part of the domain.

In Table 20 the percent changes in emissions with respect to CLE 2020 are presented for the different abatement measures considered. As can be seen from this table the emission changes are rather limited even if all measures are applied. As the costs for implementing measures are provided in the RIAT+ input database, the IAM also calculates the internal costs that can be attributed to implementing these measures. However due to the rather weak premises on which many of these cost estimates were based it was decided to drop these all together (3.3.1) and so no costs are shown.

As the emission changes are limited, unsurprisingly, the concentration changes are also limited as can be seen from the average concentrations for NO_2 and PM_{10} that are listed in Table 20. The average concentration changes for PM10 are for most measures less than 0.1 $\mu g/m^3$. This is in the range of the values found for RMSE of the ANN so these results should therefore be considered with caution. In what follows we have decided to drop results showing the changes in PM_{10}. Results for the external costs are also calculated by RIAT+ as the Years of Life Lost, YOLL (M€/year). As YOLL are mainly dependent on PM_{10} concentration these numbers should again be interpreted cautiously due to the low accuracy of the ANN result for PM10 concentration changes. These results are here mainly included to emphasise that a full-fledged IAM should not stop at determining pollutant concentrations but should also quantify health impacts.

Looking at individual measures the 'toll' measure seems most effective. The low effect of the LEZ measure is due to the fact that in 2020 a large part of the vehicles of type EURO 1 – EURO 4 will already have been replaced by newer types in the CLE case.

Besides tabular output of statistics RIAT+ also produces a number of maps for both the emissions, the AQI and other derived quantities such as the Years of Life Lost (YOLL). On the following pages examples are shown of these RIAT+ outputs.

The spatial distribution for the emissions obtained using EMAP (Maes et al. 2009) can be seen in Figure 17. The non-industrial combustion emissions have been distributed according to a population density map while the traffic emissions are mainly assigned to the highways. Although this distribution between road types is in accordance with COPERT, one can wonder whether this is realistic. Road type also doesn't always reflect actual traffic volumes.

While the ring road in Brussels goes all around the city, due to a code change it now seems part of the ring road is missing in the South eastern part of the domain.

Table 20: The emission reductions for 2020 emissions relative to the CLE emissions and the values for the average NO2 and PM10 concentrations (µg/m³) and the Years of Life Lost, YOLL (M€/year) due to these emission changes
Σtraffic = 1+2+3+4+5 +7 | Σheating = 8+9+10+11 | all =Σ traffic + Σheating

	measures	Emission reduction relative to CLE (%)					NO2 µg/m³	PM10 µg/m³	YOLL (M€/yr)
		NOx	VOC	PM10	PM2.5	SO2			
0	reference	0	0	0	0	0	28.6	22.1	314
1	Eco driving	0.62	0.12	2.31	2.43	0	28.6	22.1	309
2	Modal Shift	0.62	0.12	3.47	3.64	0	28.6	22.1	308
3	Traffic plan	0.62	0.12	3.47	3.64	0	28.6	22.1	308
4	Toll	5.61	1.35	17.36	18.22	0.04	28.2	21.0	285
5	Parking	0.31	0.06	1.16	1.21	0	28.6	22.1	312
6	LEZ_HDV	0.40	0.10	1.20	2.4	0	28.6	22.0	313
7	LEZ_ALL	2.00	0.20	19.40	17.2	0	28.6	22.0	308
	Σ Traffic	9.78	1.97	47.17	46.34	0.04	27.8	20.7	280
8	Boiler maintenance	2.2	0.19	2.25	2.5	1.51	28.6	22.0	312
9	Exemplary building	0.14	0.01	0.05	0.06	0	28.6	22.1	314
10	Energy efficiency of buildings	0.21	0.02	0.16	0.18	0.08	28.6	22.0	314
11	Energy audits	0.96	0.09	0.54	0.6	0.30	28.6	22.0	313
	Σ Heating	3.51	0.31	3.00	3.34	1.89	28.6	21.9	311
	All	13.29	2.28	50.17	49.68	1.93	27.7	20.6	279

In the reference case (Figure 18) we see that the highest concentrations occur in the centre and the North of the domain while in the South East where the Sonian Forest and more residential areas are located the concentrations tend to be lower. Notice that the spatial distribution of the YOLL map is in this case identical to the PM10 map. This is because due to time constraints the population was distributed evenly over the model domain. As most of the population is in reality living in the centre and the North of the domain where the highest concentrations occur, YOLL are probably higher than what is currently estimated using the current input.

When it comes to explaining the spatial pattern seen for the concentration changes due to the emission abatement measure (Figure 19, Figure 20 and Figure 21) we see that there still is a problem with the ANN results. There seems to be almost no relationship with the emission distribution and we are unable to relate the emission changes to concentration changes.

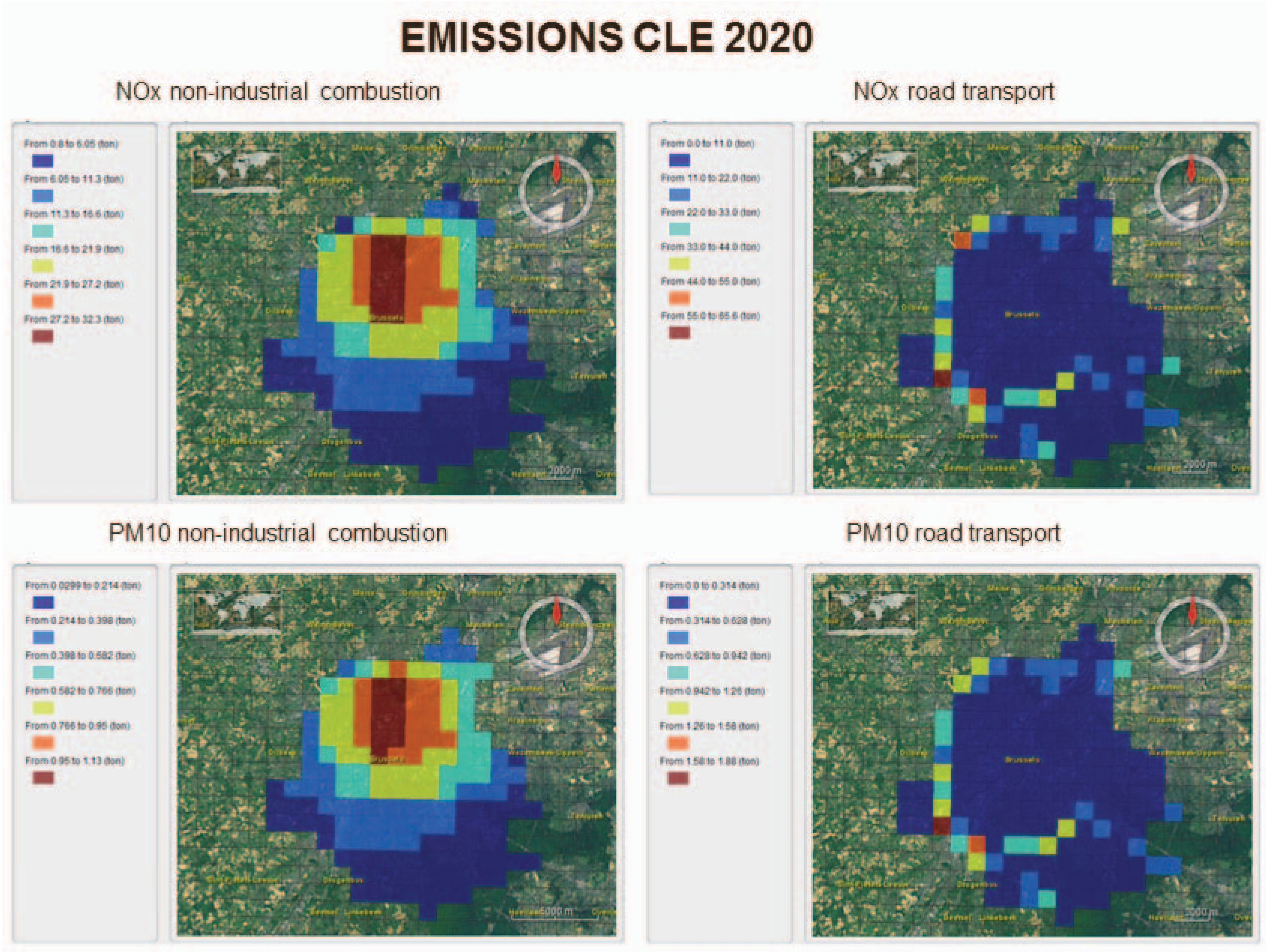


Figure 17: emissions for NOx and PM10 for the two sectors, non-industrial combustion and road transport, to which the abatement measures that are considered in the BCR apply.

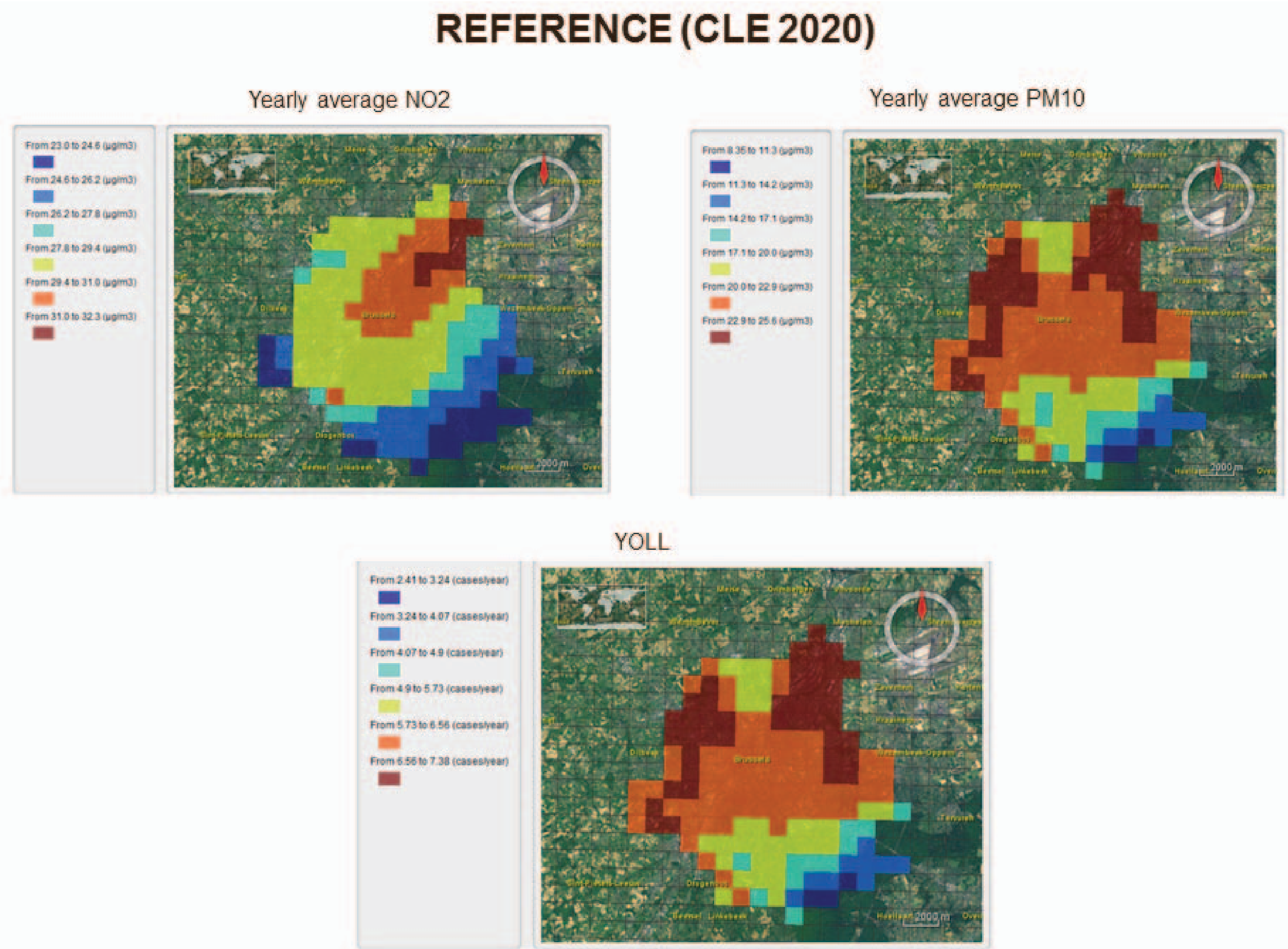


Figure 18: Yearly average NO_2 and PM10 concentrations ($\mu g/m^3$) and the Years of Life Lost, YOLL(M€/year) for the reference case (CLE 2020).

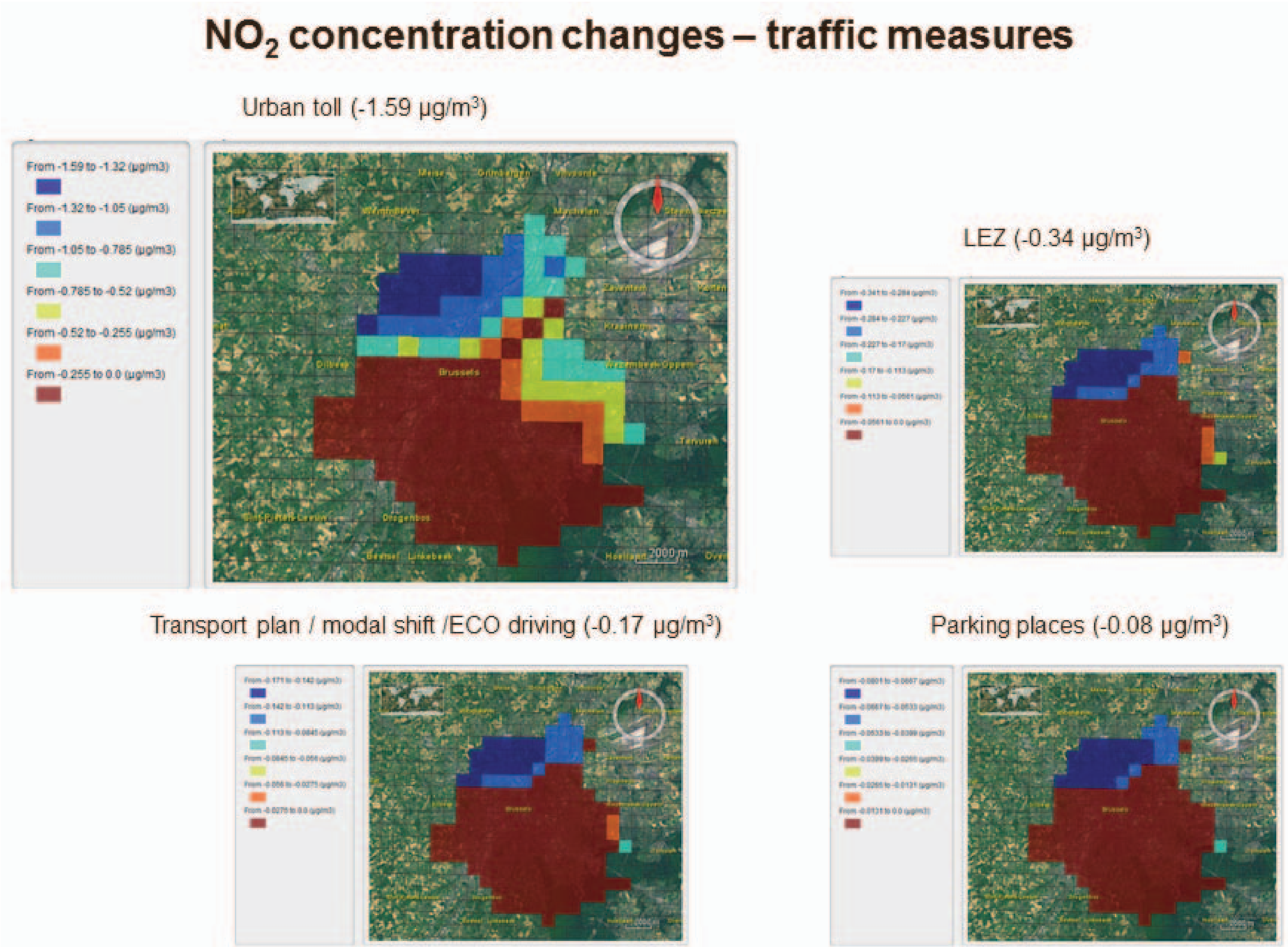


Figure 19: Yearly average NO_2 concentration changes ($\mu g/m^3$) for the different traffic measures in 2020 compared to the reference (CLE 2020). The number in parentheses is the maximum concentration change.

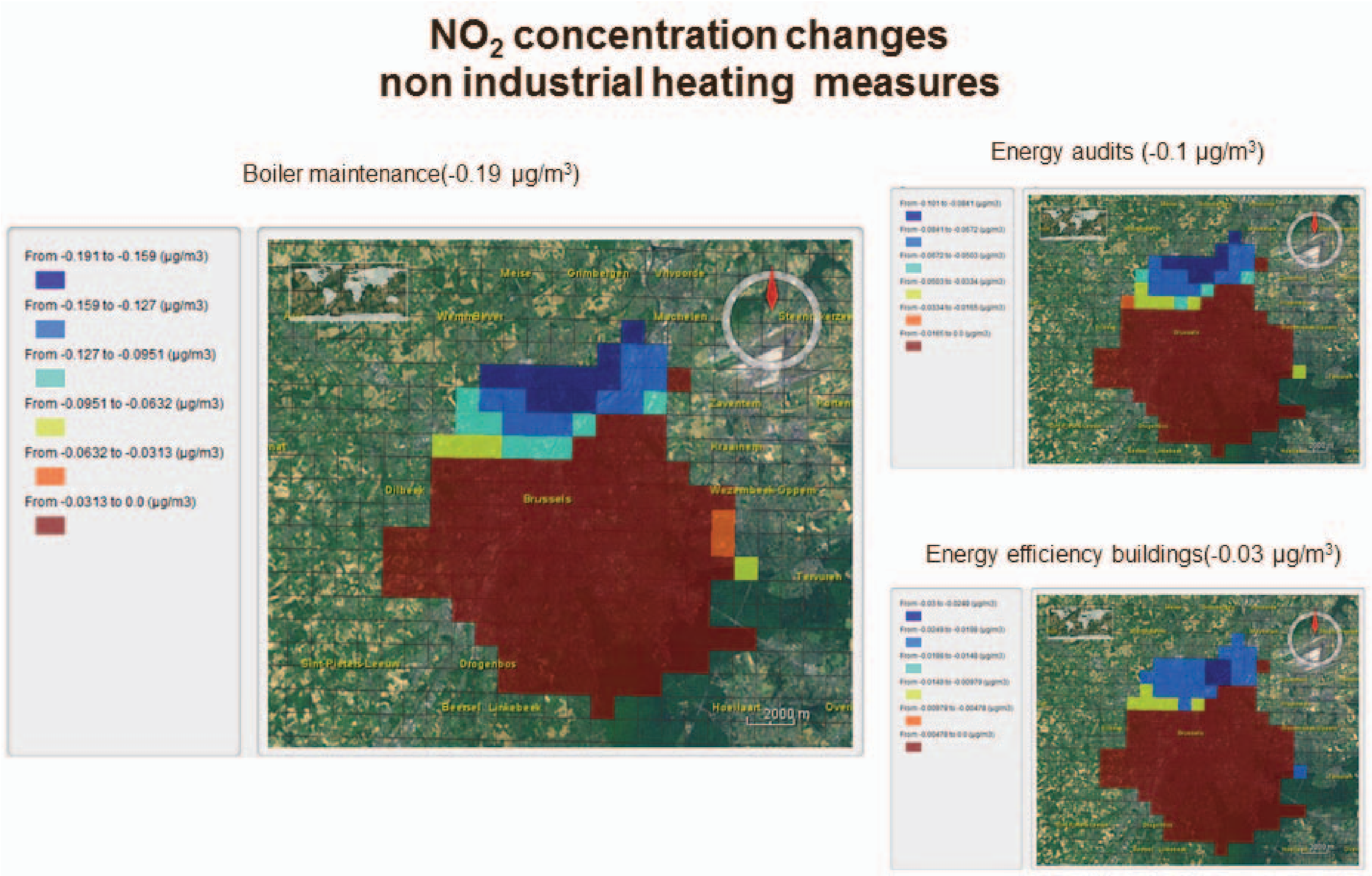


Figure 20: Yearly average NO_2 concentration changes (µg/m^3) for the different non-industrial heating measures in 2020 compared to the reference (CLE 2020). The number in parentheses is the maximum concentration change.

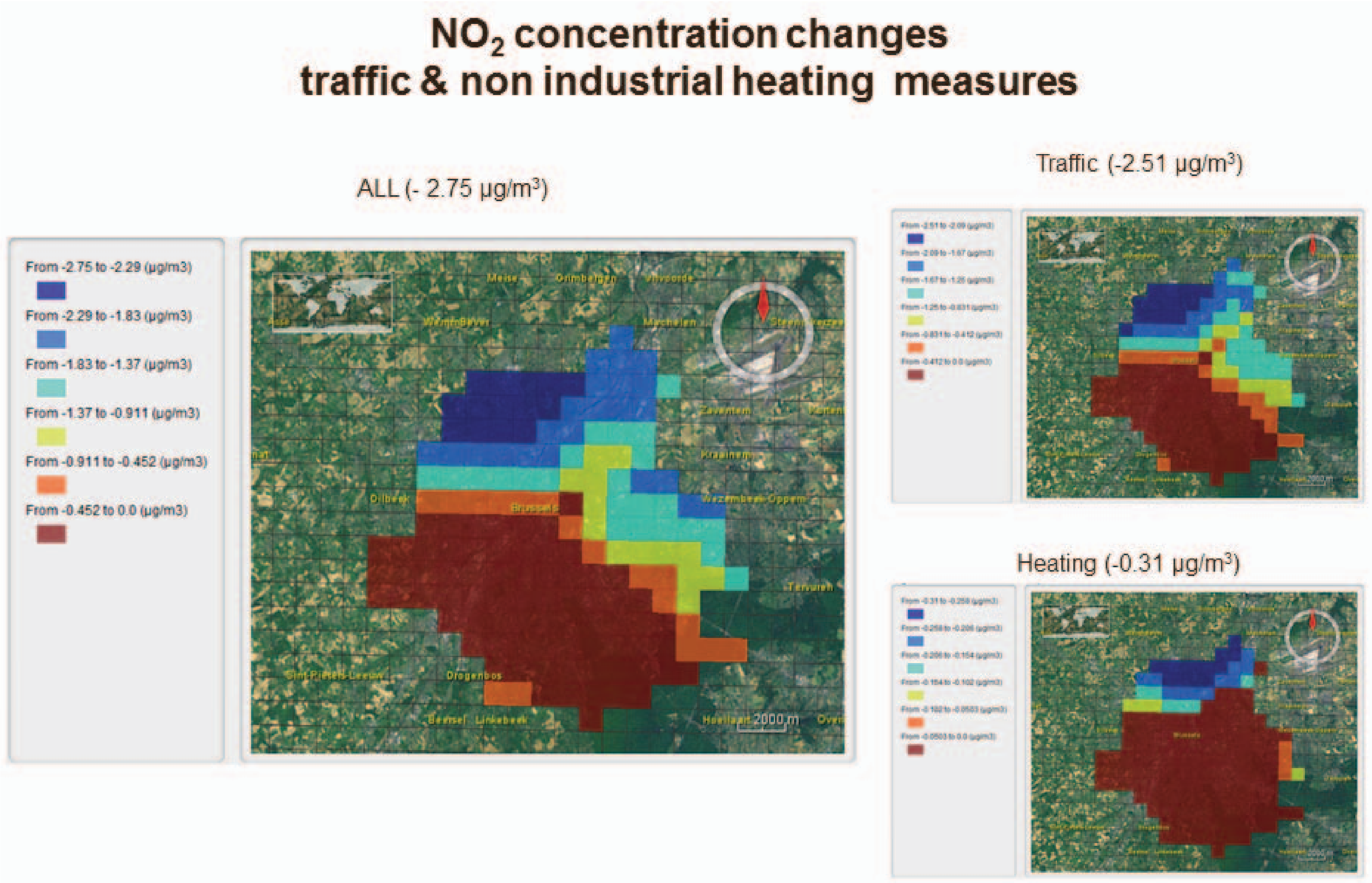


Figure 21: Yearly average NO_2 concentration changes (µg/m³) for all traffic and all non-industrial heating measures as well as for the combination of these two in 2020 compared to the reference (CLE 2020). The number in parentheses is the maximum concentration change.

3.4 Lessons learned

The application for Brussels was limited to a few abatement measures applied to a small application domain. While this reflects the real needs of the administration of Brussels – they can only impose measures within their own region that are deemed politically acceptable - during the implementation of the IAM it was from the onset clear that this would limit the applicability of a system such as RIAT+. It was therefore decided to only attempt a scenario mode calculation with the system. While for the Brussels case the focus is therefore only on those non-technical measures requested by the administration, in Porto, the next test case (paragraph 4), the whole database of technical measures as provided by IIASA will be considered.

The application revealed that one of the main points to be taken into account is the design of the experiments needed to define a consistent set of simulations for the source receptor model identification. In particular, such scenario simulations have to be defined in order to give precursor emission perturbation strong enough to excite the CTM model dynamics for the AQI under study;

Even though the resolution of the modelling is already high (1km) for an operational CTM, it is questionable if the concentrations changes calculated by the CTM can be considered representative of the actual street level concentration changes to be expected from changes in traffic volumes. As actual exposure and thus health impact should be assessed at the street level the resolution of the CTM should be increased even further so that it can be used to quantify effects at the local scale.

Although half the time in setting up the application was spent to quantify the costs and emission removal efficiency for the proposed abatement measures there is still a lot of improvement possible for the abatement measures database. Especially the costs incurred by implementing the measures proposed by the Brussels administration are disputable and were therefore here also neglected in the end. Better estimates for these costs however require the contribution from experts who are often not even involved in air quality studies.

In this specific case the impact of the selected abatement measures on air quality is clearly limited due to both the small number of measures and the size of the domain. A first screening step (e.g. . a simple scenario to check the importance of the impacts) before using a complex methodology would therefore be advisable. This could then possibly lead to the conclusion that there is in this case no need to apply a more complex IAM.

The health impact assessment is in the test case limited to the calculation of YOLL. This could be extended to other health indicators. It would also certainly be worthwhile, given that a better population density is available for Brussels, to improve the exposure calculation by replacing the uniform population density distribution map.

4 Porto

4.1 Introduction

The Great Porto Area is a Portuguese NUTS3 (Nomenclature of Territorial Units for Statistics) sub region involving 11 municipalities. It covers a total area of 1024 km^2 with a total population of more than 1.2 million inhabitants. Figure 22 shows the location of the Greater Porto Area in Portugal and in the northern region of Portugal.

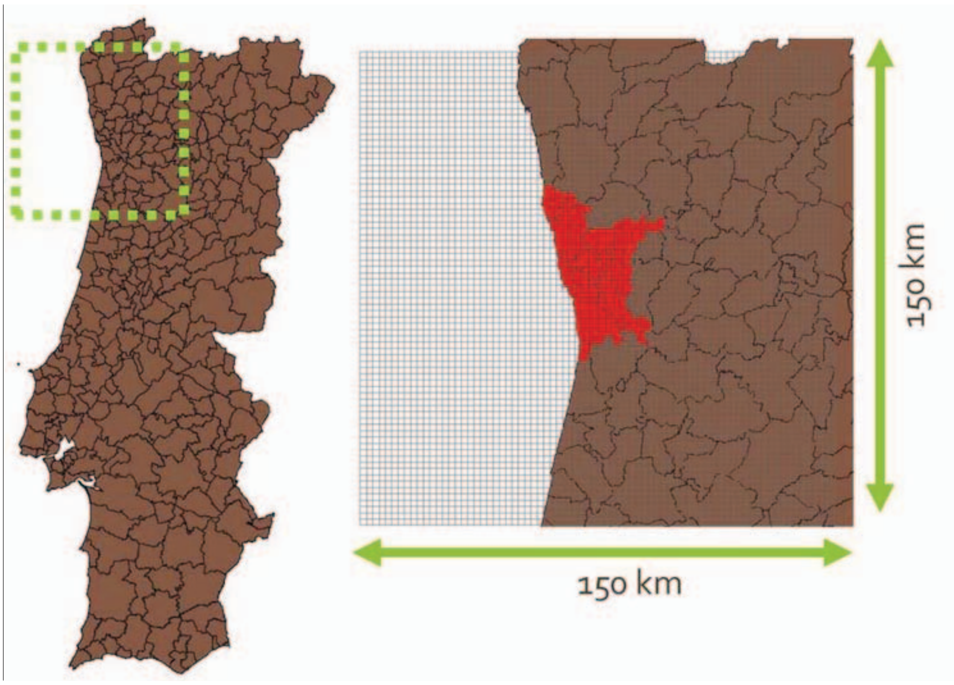


Figure 22: Location of the Great Porto Area in Portugal and in the Northern Region of Portugal.

This region of Portugal is one of the several EU zones that had to develop and implement an air quality plan (AQP) to reduce PM10. AQP were initially designed based on a scenario approach and using an air quality model, the TAPM model, which was applied over the study region for the reference situation with the current PM10 emissions, and for a reduction scenario with PM10 emissions re-estimated considering the implementation of abatement measures (Borrego *et al.*, 2011, 2012). The most relevant identified emission sectors were industrial combustion, residential combustion and road traffic.

The RIAT+ IAM is now applied in the optimization mode aiming to contribute to a better definition of air quality improvement measures.

4.2 Proposed abatement measures

We decided to use the GAINS database (technology database), which contains a large data set collected for Portugal by IIASA (http://www.iiasa.ac.at). The most relevant local measures proposed in the Porto's AQP were identified in the GAINS-Portugal measures database, namely concerning: new/improved fireplaces (SNAP2), efficient dedusters (SNAP3 and SNAP4), and low-emission vehicles (SNAP7).

Moreover, we checked that all possible Portuguese measures were included in the GAINS-Portugal database and these were then selected to be used in the Greater Porto Area according to its main characteristics and needs. There are some macro sectors which were not considered for the Great Porto Area, in particular the Extraction and distribution of fossil fuels and geothermal energy (SNAP 5), the Waste treatment and disposal (SNAP 9) and the Agriculture (SNAP 10).

Selected measures are presented by CORINAIR macro-sector (SNAP code) including technologies and removal efficiencies for different pollutants. Each technology is related to a specific sector (see Annex III) and activity (see Annex IV). For each technology the associated costs per activity unit (M€/Activity Unit) could be found on the IIASA website. A list of measures and their removal efficiency can be found in Annex V. Residential wood and manufacturing industry (small and medium scale industries) combustion are main contributors to PM levels in the Great Porto Area. Emission reductions to be expected by imposing technologies are listed in Table 31 and Table 32 in Annex V.

4.3 Application of RIAT+

4.3.1 TECHNOLOGY DATABASE

To set up the RIAT+ system for the Great Porto Area a list of abatement measures, including costs and emissions effects is required. As previously mentioned the GAINS database for Portugal was used. This database includes different types of data: activity details (unabated emission factor, activity level…) and technology details (removal efficiency, CLE and potential application rate, unit cost…). The technology database contains data for the years 2010, 2015, 2020 and 2025. The reference scenario «TSAP» of March 2013 was considered and 111«triplets» (sector-activity-technology) were linked to an emission inventory. Technologies for food and drink industry production processes and for construction activities are not available in the GAINS database. Therefore, only other types of processes were selected. Road transport significantly contributes to air pollution in the Great Porto Area. The old vehicle technologies (EURO 1, EURO 2, and EURO 3) can be replaced by new technologies.

4.3.2 CHEMICAL TRANSPORT MODELLING

The Air Pollution Model (TAPM) (Hurley et al., 2005) was used for the simulation of different mitigation scenarios. It is a 3-D Eulerian model with nesting capabilities, which predicts meteorology and air pollution concentrations delivering results on a Graphical User Interface. It simulates the transport, dispersion and chemistry of atmospheric pollutants, at both local and regional scale, and it is suitable for long term simulations (e.g. a full year) since it is not strongly time-demanding in terms of computational efforts. Point, line and area/volume source emissions are considered and a nesting mode can be used to improve efficiency and resolution.

The model has two components: the meteorological prognostic, and the air pollution concentrations component. The meteorological module of TAPM is an incompressible, optionally non-hydrostatic, primitive equation model with terrain-following coordinates for 3D simulations. The results from the meteorological module are one of the inputs to the air pollution component. The gas-phase chemistry mode of TAPM was used, which is based on the semi-empirical mechanism entitled the Generic Reaction Set (GRS), including also the reactions of SO_2 and PM, having 10 reactions for 13 species.

The TAPM model was applied to the Great Porto Area (150 km x 150 km) for one entire reference year (2012) with a 2 km by 2 km spatial resolution (see Figure 22) using disaggregated emissions from the Portuguese 2009 emission inventory, which is the most recent available inventory.

Notwithstanding a previous evaluation of the model for the Great Porto Area (Borrego et al., 2012), the results of the 2 km^2 resolution TAPM current simulation were compared to the measured values at the monitoring stations inside the model domain. As in Brussels case, we used the methodology proposed by FAIRMODE (http://fairmode.jrc.ec.europa.eu/) for the validation.

In Figure 23 the target diagram for PM10 results is shown. In this case modelling results at 66% of the monitoring stations comply with the MQO.

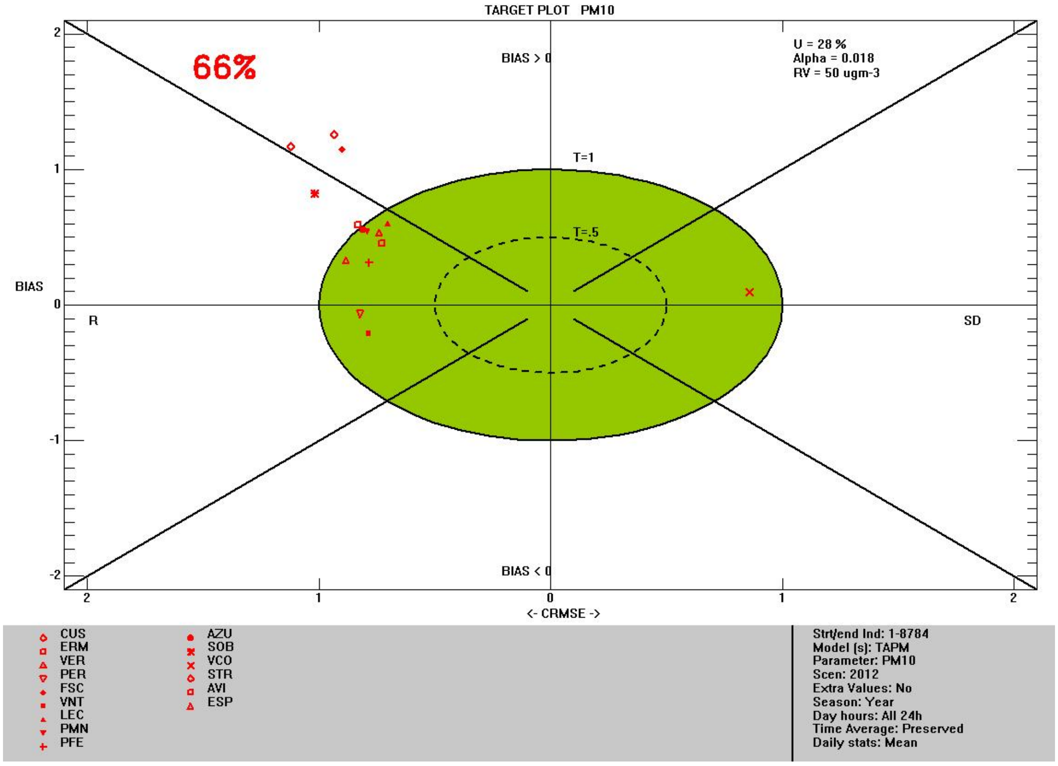


Figure 23: Target diagram for the observation stations for PM10 inside the model domain for 2012

To better understand the non-complying results, more details on performance on individual station can be found in Table 29 in Annex II where the BIAS, RMSE and correlation coefficient (R) are presented.

The 4 non-complying stations (SRT, CUS, FSC and SOB) monitoring stations) have high values of BIAS and RMSE. In fact, the estimated BIAS for the majority of the monitoring stations is larger than zero, indicating an overestimation of PM10, which could be related to an overestimation of provided background values.

The target diagram (Figure 24) for NO_2 shows that model results for most stations are in accordance with the MQO requirement, i.e. the results are within the circle with radius 1, with exception of 4 stations (AZU,LEC,FSC,STR).

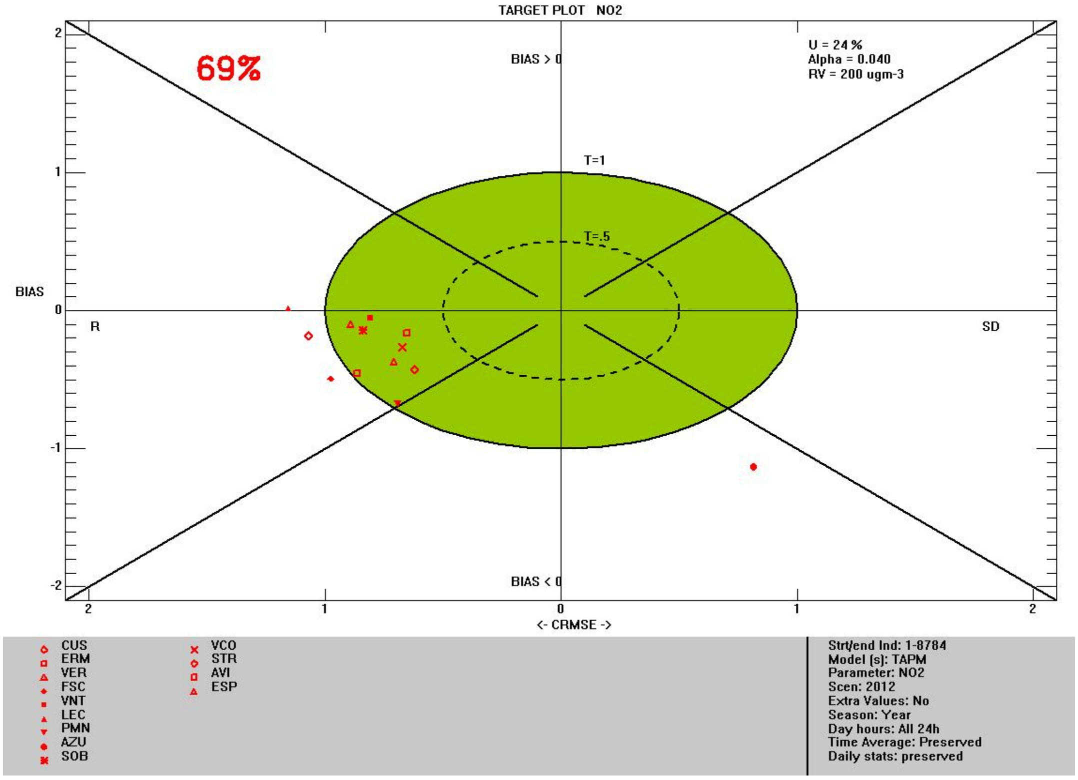


Figure 24: Target diagram for the observation stations for NO_2 inside the model domain for 2012.

The correlation coefficient is generally smaller for NO_2 when compared to PM10 (see Annex II). The time profile of NO_2 concentration values is related to road traffic behaviour and some limitations to reproduce this behaviour could be the reason for this result. Contrary to what happens in the PM10 case, for NO_2 the BIAS is negative in almost all stations, and is largest in the stations with the highest observed values. Table 28 in Annex II contains the performance estimated indicators per monitoring station.

Even knowing that simulation results for some monitoring stations do not fulfil the model quality objectives, we decided to proceed with the RIAT+ application so that we could test the guidance document on integrated assessment methodologies. The ideal procedure would have been to carefully assess the monitored data and the simulations results, and to perform data fusion, if needed. However, taking into consideration the main purpose of the case study, simulation results were still considered to be included in the integrated assessment. In case of a real assessment, with policy support objectives, it is recommended to fully accomplish the model quality objectives (the target)."

4.3.3 Design of Experiment

The Design of the Experiment aims to define the scenarios to be simulated by TAPM in order to define the identification and validation dataset for source-receptor models. Due to computational time constraints the minimum set of scenarios needed to train RIAT+ Artificial Neural Networks was the basis for the modelling activities. This minimum number of scenarios has to contain all possible relationships between precursor emissions and the various considered air quality indices. Table 21 presents the list of used scenarios to train the RIAT+ Artificial Neural Networks for the Great Porto Area. In this case less scenarios were run than for Brussels. Ideally, the number of scenarios is determined by checking the incremental improvements to the ANN results of adding additional scenarios to the training dataset. In this case the number was limited due to time constraints.

Table 21: List of the 10 emission reduction scenarios simulated with the TAPM model.

	PAD emissions			
Scenarios	NO_X	VOC	PM	SO_2
0	B	B	B	B
1	L	L	L	L
2	H	H	H	H
3	H	L	L	L
4	L	H	L	L
5	L	L	H	L
6	L	L	L	H
7	H	H	L	L
8	H	L	H	H
9	H	L	L	H

Starting from the 2009 Portuguese emission inventory, three different emission levels were considered to establish scenarios inside the Great Porto Area Policy Application Domain (PAD): B (base case), L (low emission reductions) and H (high emission reductions).

The B (base) case considers the evolution of 2009 emissions taking into account the fulfilment of CLE2020 increased by 15% to increase the identification bounds for Artificial Neural Networks guarantying the correct identification of source-receptor models.

The H (high reduction) case is associated to the Maximum Feasible Reduction of emissions at 2020 (MFR2020), decreased by 15%. The MFR2020 emissions were estimated using rescaling factors found on the IIASA website applied to the 2020 CLE projected emissions. The L (low reduction) scenario results from averaging B and H emission scenarios values.

4.3.4 IDENTIFYING THE SOURCE-RECEPTOR MODELS

Deterministic models (as TAPM) (describing the non-linear dynamics linking precursor emissions to air pollutant concentrations) cannot be embedded and run in real time within the RIAT+ optimization procedure because of computational requirements. For this reason in the proposed procedure, that needs to process hundreds of model runs to find the optimal solution ANNs (instead of TAPM) have to be used. The procedure to implement these source-receptor models requires two steps. Because in the context of neural networks it is impossible to know a priori which ANNs structure produces the best results in the first step the best ANNs structures were chosen on the basis of maximum correlation and minimum RMSE, considering a series of different possible configurations (i.e. different network structure, activation function and number of cells). Then, in a second step the best structure was applied to the whole domain. The identification and validation data series were selected processing the TAPM simulation results obtained considering CLE and MFR scenarios. Each TAPM simulation is a full year simulation. Meteorology is not used in the ANNs identification, because the final purpose of the source-relationship models is to create a direct link between emissions (control variables) and concentrations. The target considered in this application was the PM10 annual mean. Table 22 presents the best ANNs parameters selected for the annual PM10 concentration value.

Table 22: ANNs best parameters, for PM10 annual mean index.

ANNs features	Value
Nodes in the input layer	16
Hidden layer transfer function	Log-Sigmoid
Nodes of the hidden layer	20
Output layer transfer function	Linear
Nodes in the output layer	1
Training function	Levenberg-Marquardt backpropagation
Radius of influence (nº of cells)	4
Training set (nº of cells)	6784
Validation set (nº of cells)	1696

4.3.5 VALIDATION OF THE ANN.

To validate the results from the ANN, output values are compared to the results calculated by the CTM. In Figure 25 results are shown when the comparison is done for an independent validation data set which consists of 20% of the available grid cells and for which the ANN was not trained. The scatter plot (Figure 25) shows the good performance of the ANNs, with a Normalised Root Mean Square Error (RMSE) of 0.35 and a correlation coefficient of 0.95, and confirms that the ANNs system has the capability to simulate the nonlinear source–receptor relationship between PM10 mean concentration and the emission of its precursors.

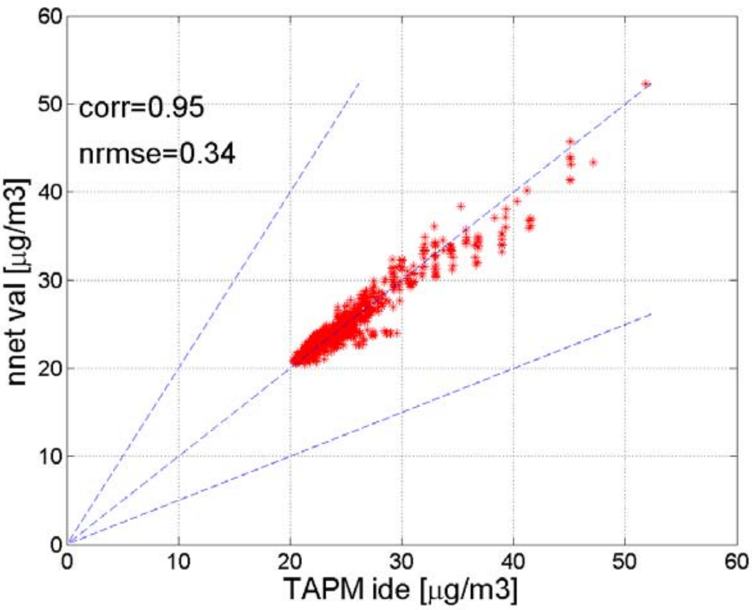


Figure 25: ANNs system performances evaluated in terms of scatter plot between ANNs and TAPM results for PM10.

We also checked to what extend the ANN is able to reproduce the concentration changes of TAPM (Figure 26).

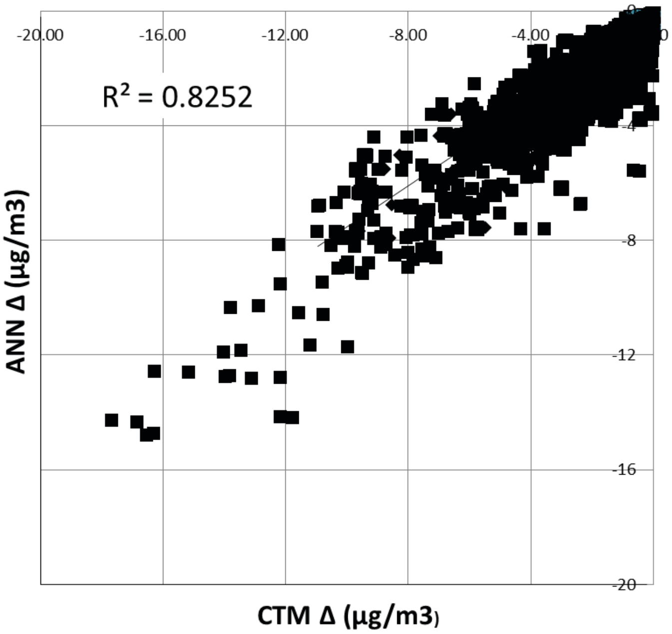


Figure 26: ANNs system performances evaluated in terms of scatter plot between the concentration changes calculated by the ANNs and TAPM for PM10.

Table 23 correlation (R), Normalised absolute average bias, NBIAS(%) and normalised root mean square error, NRMSE(%) for the changes in PM10 with respect to scenario 1 ('base case').

scenario	R	NBIAS	NRMSE
2	0.94	18.51%	51.76%
3	0.96	22.19%	38.82%
4	0.92	14.60%	62.31%
5	0.89	32.96%	66.82%
6	0.96	17.21%	36.97%
7	0.91	22.01%	64.08%
8	0.90	28.81%	63.38%
9	0.96	14.36%	40.48%
10	0.91	18.59%	63.97%

4.3.6 RESULTS OBTAINED WITH RIAT+

RIAT+ was applied in the optimization mode and Figure 27 shows efficient solutions after optimization over the Great Porto domain. On the horizontal axis of the figure there are internal costs, considered over CLE and expressed in M€, and on the vertical axis there is the averaged AQI value (for this particular case, PM10 annual average) estimated for the entire study area.

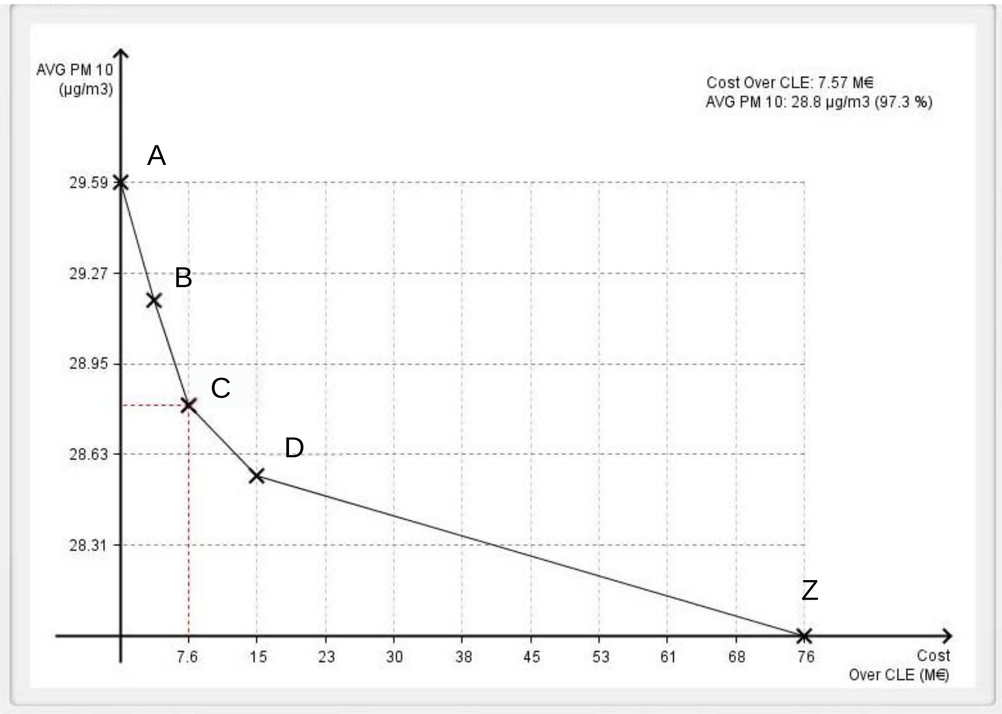


Figure 27: Pareto curve for the optimization of PM10 yearly mean concentrations.

The Pareto Curve (a curve providing the optimal solutions ranked by costs) shows that a PM10 mean concentration of 28.8 µg/m^3 can be reached by adopting emission reduction technologies costing around 7.6 Million € per year (point C). While points A and Z represent extreme cases, no actions or maximum effective reductions, respectively, are implemented, the other points of the Pareto Curve are intermediate solutions (possible combinations of reduction measures and their cost and AQI).

For the point C of the Pareto Curve, Figure 28 presents the emission reduction by CORINAIR macro sector and for the different considered pollutants

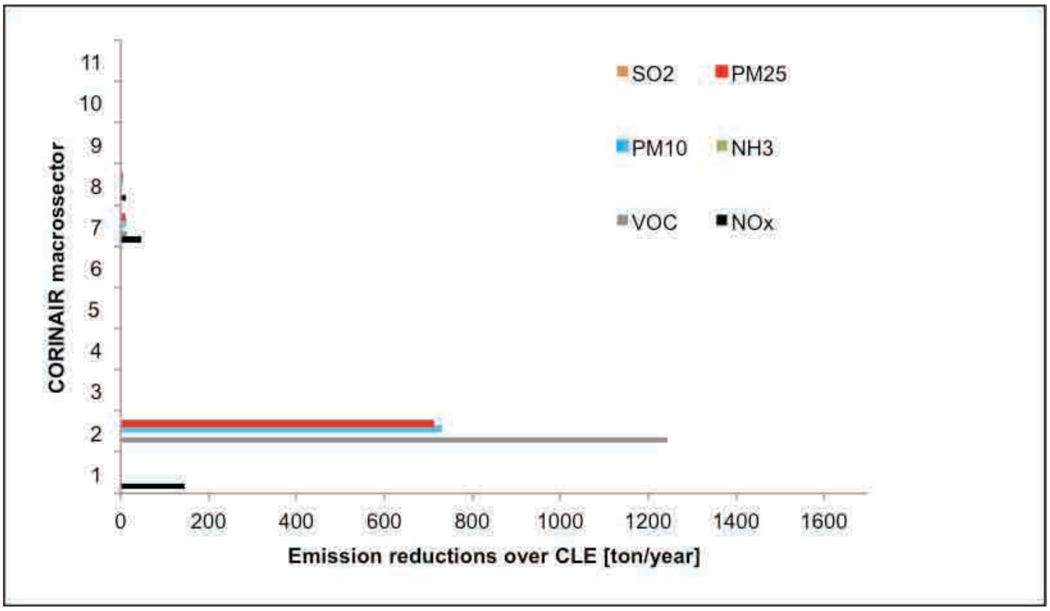


Figure 28: RIAT+ emission reductions (ton/year), by CORINAIR macro sector corresponding to point C of the Pareto curve.

PM emission reductions, for point C, would be reached mainly acting on non-industrial sector activities (SNAP 2). Road transport (SNAP 7) and other mobile sources and machinery (SNAP 8) could also contribute to this reduction of PM emissions.

Table 24 contains all the measures involved in the optimization process, including their application rate, those highlighted in blue have been optimized and their application rate is above CLE. For each optimized technology, it is possible to assess the PM10 emission reduction (ton/year) and the correspondent cost over CLE.

Table 24: List of measures involved in the optimization of PM10.

Measures List

SNAP 1	Sector	Activity	Technology	Application Rate...	CLE AR	OPT AR	EmiRedPm10[ton]	EmiRedNox[ton]
2	Residential-Commercial: Fireplaces	Fuelwood direct	Fireplace improved		15.0	79.8	728.1	0.0
7	Light duty vehicles: cars and small buses ...	Medium distillates ...	EURO 4 on light duty diesel road vehicles		16.2	19.7	30.1	27.7
7	Light duty vehicles: light commercial trucks...	Medium distillates ...	EURO 5 on light duty diesel road vehicles		47.1	51.1	22.1	76.3
7	Light duty vehicles: cars and small buses ...	Medium distillates ...	EURO 5 on light duty diesel road vehicles		37.4	38.4	11.0	12.6
7	Light duty vehicles: light commercial trucks...	Medium distillates ...	EURO 4 on light duty diesel road vehicles		15.1	15.7	2.5	11.4
8	Other transport: agriculture and forestry	Medium distillates ...	Stage 1 control on construction and agriculture mobile so...		7.2	22.9	1.7	12.5
2	Residential-Commercial: Heating stoves	Fuelwood direct	Biomass stove improved		40.0	41.4	0.1	0.0
1	Oth. En. Sect.: combustion	Gas	Combustion modification on oil and gas industrial boilers ...		20.0	20.1	0.0	0.0
1	Oth. En. Sect.: combustion	Heavy fuel oil	Good housekeeping: industrial oil boilers		100.0	100.0	0.0	0.0
1	Oth. En. Sect.: combustion	Heavy fuel oil	Low sulphur fuel oil (0.6 %S)		76.0	76.0	0.0	0.0
1	Oth. En. Sect.: combustion	Medium distillates ...	Good housekeeping: industrial oil boilers		100.0	100.0	0.0	0.0
1	Oth. En. Sect.: combustion	Medium distillates ...	Low sulphur diesel oil - stage 1 (0.2 % S)		40.0	40.0	0.0	0.0

Optimized Measures: Optimized AR over CLE; Optimized AR below CLE

Application Rate: Optimized; Over CLE; CLE; Potential

EmiRed = Emi Reduced (respect CLE)

According to the optimal solution determined by RIAT+ almost all the money should be spend in technologies related to macro sector 2 (new and improved fireplaces). These results are consistent with the ones obtained by Borrego et al. (2012) : in Portugal 18% of PM10 emissions are due to residential wood combustion, which may deeply impact the PM10 levels in the atmosphere. According to the Portuguese emission inventory this macro sector is the second most important in terms of PM10 emissions, after macro sector 4 (industrial processes), in the Great Porto Urban area.

Figure 29 presents the spatial distribution of the expected reductions of PM10 emissions and concentration levels, for the Point C of the Pareto curve.

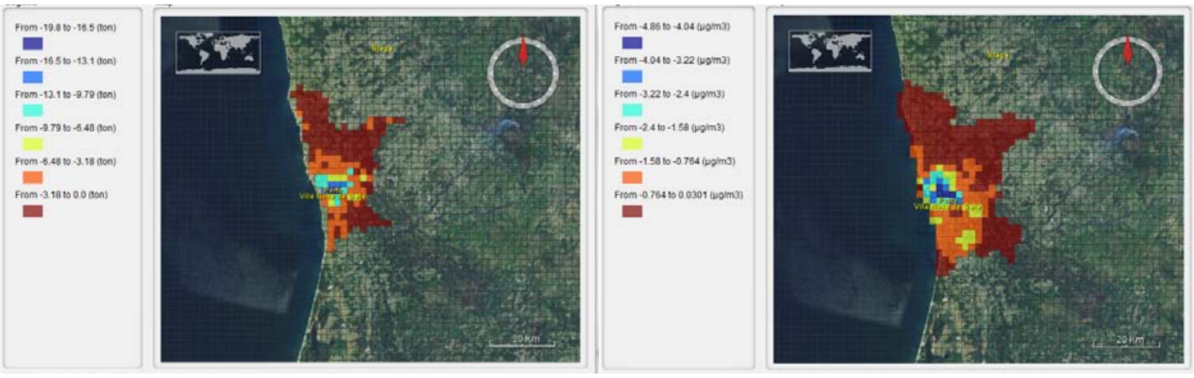


Figure 29: RIAT+ emission (ton/year) and concentration (µg.m^{-3}) reductions for the point C of the Pareto curve.

Larger reduction of PM10 emissions and concentration levels are expected over the Porto municipality where the population density is higher.

Figure 30 shows the spatial distribution of PM10 annual concentration values for the selected point of the Pareto curve.

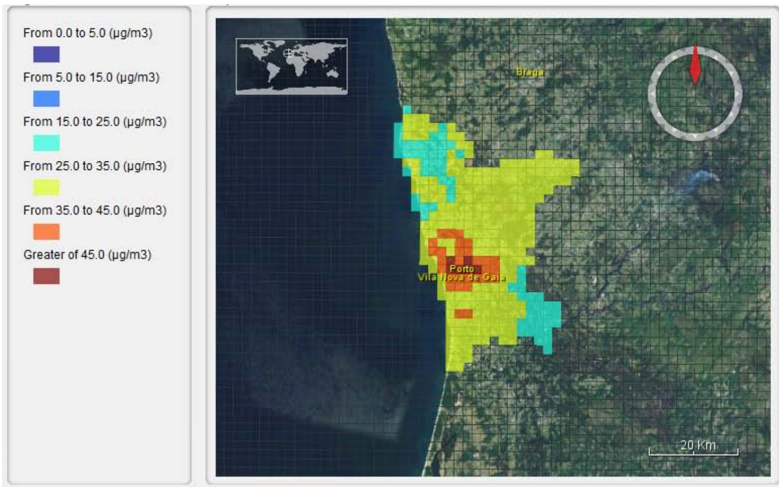


Figure 30: Mean PM10 concentrations resulting in RIAT+ (point C of the Pareto curve).

It is possible to observe that for this selected point, which implies spending around 7.6 M€, some areas with values exceeding the PM10 annual limit value (40 µg/m^3) can still be expected.

Finally, Figure 31 presents the relation between internal investment cost and external cost (benefit) as estimated by the optimization process. The ratio between external and internal costs significantly decreases when Point B is reached. In other words, the additional gain in health benefit I smaller per additional € invested. However, as can be seen from this figure, investment costs are always lower than the external costs (i.e. below the Y=X line) until the point Z. This indicates that acting on emission control to reduce PM10 concentrations is greatly beneficial from a socio-economic point of view.

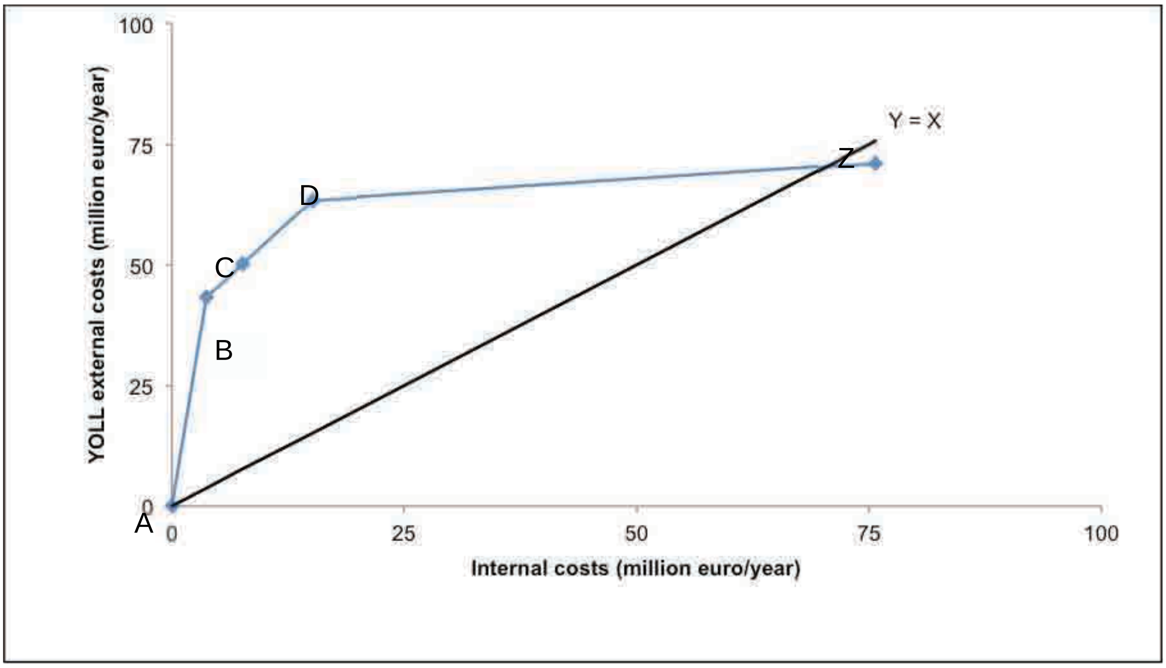


Figure 31: Cost-Benefit Analysis (external costs and internal costs)

4.4 Lessons learned

It is very important to have an emission inventory with a high detail (spatially and temporally) to better reproduce the mitigation measures, namely the technology based.

Using the list of available technologies from a previous database allows you to identify the sectors where to focus the mitigation activities and to estimate associated costs, but a more concrete list of measured has to be decided and discussed with stakeholders and policy makers.

ANNs avoid a lot of computational efforts, but their training is a crucial stage of the process in order to guarantee the right results.

One main advantage of the RIAT+ system is the speed of the optimization process, which allows quickly testing multiple options during the decision making process.

5 Conclusions

In this document we have presented the implementation of an existing comprehensive IAM system (RIAT+) for two different test cases, the Porto Region and Brussels Capital Region. The main aim of these applications was to confront the practical application of such a system with the guidance set out in previous deliverables for work package 4. The following are the main conclusions we can draw:

- In practice, the list of options for abatement measures is restricted not only by what is technically and economically feasible but possibly even more by political and social acceptance. IAM tools should therefore be extended to allow their users to take into account the implications of political and social acceptance in an early stage of the decision process.

- The applications demonstrate that tools exist which can be practically applied in an integrated assessment of air quality that does not only consider compliance of concentration to limit values but also efficiently takes into account internal and external costs (*e.g.* health impact) of different available abatement options.

- The biggest task when implementing such a comprehensive IAM is - as is also the case in regular air quality modelling applications – to obtain high quality input data *i.c.* information on local emissions and the cost and effectiveness of possible abatement measures. When such data is lacking you can still rely on existing European inventories and databases with data on abatement measures such as EMEP and GAINS well keeping in mind the assumed validity of such data for the region of interest and the implications for the results obtained using the IAM.

- If an IAM system uses source receptor relationships (artificial neural networks, linear regression, …) to relate emission changes to concentration changes, such relationships should be carefully tested to ensure that they not only correctly replicate the concentration values obtained through more complex modelling tools (e.g. CTMs) but also capture the dynamics i.e. the concentration changes calculated by the model for which they are a surrogate.

In the Brussels case a lot of time was put into estimating precise measures while the impact on air quality of these measures is rather limited due to the dimension of the area selected. A first screening step such as a simple scenario to check the importance of the impacts should be done before using a complex methodology as the latter has limited added value in such cases.

In the Porto case a list of available technologies from an existing database was used and the main sectors were selected and identified. Nevertheless a more local list of measures needs to be decided and discussed with stakeholders and policy makers. With the optimization approach it was possible to have a first idea of the optimal investment costs and benefits to achieve a given PM10 air quality objective.

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7 Annex I: RIAT+ background information

7.1 SCENARIO ANALYSIS

The scenario analysis case allows to assess the variations of the air quality indexes due to the application of a set of policies chosen a priori by the user. The problem can be formalized as follows:

$$AQI_n = f\big(E(\theta)\big) \; with \; n = 1,..,N$$

where:
E represents the precursor emissions;
$AQI_n\big(E(\theta)\big)$ are the Air Quality Indexes concerning different pollutants. Each Index depends on precursor emissions through emission reductions;
θ is the decision variable set constrained to assume values in the feasible set. The decision variable set includes:

- for the *detailed approach*, the application rates for each reduction measure. They are constrained to assume values between CLE and MFR values. In this case the AQI computation is similar to an evaluation of the objective function performed during the optimization procedure (see the following section);
- for the *lumped approach*, the emission reductions for each pollutant in each macro sector. These variables are constrained to assume values in the emission range of the surrogate emission models.

For the detailed approach, the scenario analysis can also estimate the costs associated to the application of the selected reduction measures and, for both approaches, the population exposure costs.

7.2 OPTIMIZATION APPROACH

In this section the Multi Objective optimization methodology is formalized. The Cost Effectiveness case is a particular case of the Multi Objective optimization, in which a unique point of the Pareto curve, given a budget for technologies application, is computed; for this reason, it does not deserve a separate formalization.

DECISION PROBLEM

A **Multi Objective** problem consists of a number of objectives to be simultaneously optimized while applying a set of constraints. The problem can be formalized as follows:

$$\min_{\theta}[f_o(\theta)], \qquad with \; o = 1, \dots, O_{obj}$$

subject to: $\theta \epsilon \Theta$

where f_o is the *o*-th objective function,
O_{obj} is the number of the objectives,

θ is the decision variable set (namely the emission reduction measures) constrained to assume values in Θ (the feasible decision variable set).
The target of this problem is to control (secondary) pollution at ground level. The solutions of the Multi Objective problem are the efficient emission control policies in terms of air quality and emission reduction costs. The problem can be formalized as follows:

$$\min_{\theta} J\big(E(\theta)\big) = \min_{\theta}\big[AQI_n\big(E(\theta)\big)\ inC(E(\theta))\big], \qquad with\ n = 1, \dots, N$$

E represents the precursor emissions;
$AQI_n\big(E(\theta)\big)$ are (maximum *N*) Air Quality Indexes concerning different pollutants;
$inC\big(E(\theta)\big)$ represents the internal (emission reduction) costs.
All the objectives depend on precursor emissions through, as already said, emission reductions. The decision problem complexity can then be reduced to two objectives, considering just a single Air Quality Index (AQI) obtained as a linear combination of the various Air Quality Indexes AQI_n (plus the Cost index). These various AQIs can be aggregated through linear combination of normalized AQIs, using these two configurations:

- with “user-defined” weights (the user defines the relative importance of the AQIs, providing weight values between 0 and 1 for each AQI);
- with the so-called “fairness” approach (an automatic approach that balances the relative importance of the AQIs).

Normalization is performed by applying the following equation: $\frac{\mathrm{AQI}-\mathrm{AQI}_{\mathrm{mfr}}}{\mathrm{AQI}_{\mathrm{cle}}-\mathrm{AQI}_{\mathrm{mfr}}}$, in which $\mathrm{AQI}_{\mathrm{cle}}$ and $\mathrm{AQI}_{\mathrm{mfr}}$ represent, respectively, the AQI at Current Legislation and Maximum Feasible Reduction levels. The linear combination of normalized AQIs is then re-written to simplify the denominator, that can give rise to computational problems during the optimization phase.

Finally, the previous equation can be re-written as:

$$\min_{x\in X} J(x) = \min_{x\in X}[AQI(x)\ inC(x)]$$

where *x* is a vector containing the application rates of the reduction measures, constrained to be included in the feasible set X. The Multi Objective optimization problem is solved following the ε-*Constraint Method*: just the Air Quality objective is minimized, while the Internal Cost objective is included in the set of constraints. In this configuration, the Multi Objective approach has the same features of the *Cost Effectiveness analysis,* where the Figure of Merit is:

$$\min_{x\in X} J(x) = \min_{x\in X} AQI(x)$$

and the second objective is included in the constraints:

$$inC(x) \leq L \quad 0 \leq L \leq \bar{L}$$

where L can assume different values in the defined range. In this way a set of effective solutions is computed and a Pareto curve can be drawn.
The **Cost Effectiveness** approach is thus the solution of the above problem for a specific value of L.

AIR QUALITY OBJECTIVE

The Air Quality objective may consider several indexes, that can be computed over different domains, and can be related to yearly, winter or summer periods. The indexes are :

- mean PM10 concentration;
- mean PM2.5 concentration;
- SOMO35: ozone concentrations accumulated dose over a threshold of 35 ppb;
- AOT40: ozone concentrations accumulated dose over a threshold of 40 ppb;
- MAX8H: maximum 8-hour running average ozone concentrations;
- mean NO_2 concentration;
- number of times that PM10 daily threshold is exceeded (this index is computed applying a linear relation that transforms the “PM10 yearly average” in “daily number of exceedances”).

The relationship between the decision variables and the indexes is modelled by linear models or Artificial Neural Networks – ANNs (except for the “number of times that PM10 daily threshold is exceeded”), identified processing long-term simulations of a CTM model. Starting from the local value, computed cell by cell, an aggregation function is applied, to get the scalar variable (AQI) that has to be optimized. Such an aggregation function has to be selected among the following:

- spatial average;
- population weighted average;
- number of cells over threshold.

EMISSION REDUCTION COSTS

The emission reduction costs are calculated first for each sector-activity:

$$C_{k,f} = \sum_{t \in T_{k,f}} C_{k,f,t} \cdot A_{k,f} \cdot X_{k,f,t}$$

where:

- $C_{k,f,t}$ are the technology unit costs [M€/year] for sector, activity, technology *k,f,t*;
- $C_{k,f}$ are the total cost [M€/year] for sector, activity *k,f*;
- $A_{k,f}$ is the activity level for the defined sector-activity;
- $T_{k,f}$ are the technologies that can be applied in a defined sector activity;
- $X_{k,f,t}$ are the application rates of the technologies acting in the sector-activity *k,f*.

Then, the total internal costs [M€/year] is computed as:

- $C = \sum_{k,f} C_{k,f}$

DECISION VARIABLES

The decision variables are the application rates of the emission reduction measures. In particular, the two possible decision variables considered in this formalization are technical measures (e.g. end-of-pipe technologies) and efficiency/non-technical measures (e.g. behavioural changes).
More in detail, the following definitions (for technical and non-technical measures) are adopted:

- technical measures are the so-called "**end-of-pipe-technologies**", i.e. filters that are applied to power plant emissions, to cars, etc.. These measures neither modify the driving forces of emissions nor change the structural composition of energy systems or agricultural activities, but are applied to reduce emissions before being released in the atmosphere;
- non-technical measures or **energy efficiency measures** are measures that reduce anthropogenic driving forces that generate pollution. Such measures can be related to people behavioural changes (for instance the use of bicycle instead of cars for personal mobility, the reduction of temperature in buildings) or to technologies that aim to reduce the energy demand (urban/regional structural planning like densification, road management, building renovation), or to abate the fuel consumption (for instance: the use of high efficiency boilers, of building thermal insulating coats).

Applying these measures, the reduced emissions are computed as follows:

$$E_{k,f,p} = \sum_{t \in T_{k,f}} (A_{k,f} \cdot ef_{k,f}^{p}) X_{k,f,t} \cdot eff_{k,f,t}^{p} + \sum_{t \in Z_{k,f}} (A_{k,f} \cdot ef_{k,f}^{p}) Z_{k,f,t} \cdot eff_{k,f,t}^{p}$$

where:

- variable $X_{k,f,t}$: is the application rate (bounded in $[\bar{X}_{k,f,t}; \underline{X}_{k,f,t}]$) of technical measure *t* to sector *k* and activity *f;*
- variable $Z_{k,f,t}$: is the application rate (bounded in $[\bar{Z}_{k,f,t}; \underline{Z}_{k,f,t}]$) of non-technical measure *t* to sector *k* and activity *f;*
- $A_{k,f} \cdot ef_{k,f}^{p}$: is the pollutant *p* emission due to sector *k* and activity *f*;
- $X_{k,f,t} \cdot eff_{k,f,t}^{p}$: is the overall technical measure *t* removal factor with respect to sector *k*, activity *f* and pollutant *p*;
- $Z_{k,f,t} \cdot eff_{k,f,t}^{p}$: is the overall non-technical measure *t* removal factor with respect to sector *k*, activity *f* and pollutant *p*.

The total emission reduction for a pollutant *p*, due to the application of a set of measures, can be calculated as the sum of the emission reductions over all the <sector-activity> pairs:

$$E_p = \sum_{k,f} E_{k,f,p}$$

The Air Quality objective is a function of the emission reductions and, thus, of the technical and non-technical measure application rates.
The emission reductions are computed beyond the CLE scenario. It is important to note that the CLE scenario is estimated starting from the emissions at an initial year if no technology

had been applied. Such “no technology” scenario is defined in this report as "virtual emissions”.
The selection of the technologies to be optimized is done through a dedicated flag (for each technology, in fact, the user can select if they must be kept fixed at the Current Legislation level, or if they can be optimized). Furthermore, to speed up the computations, “not efficient” technologies are automatically excluded by the optimization, and kept fixed to CLE. Technologies are defined as “not efficient”: a) when the maximum feasible emission reduction associated to a technology is less than 10^{-6} tons; b) when CLE and MFR for that technology assume the same value.

CONSTRAINTS

The first constraint concerns the internal cost (for emission reduction implementation), which cannot be greater than the available budget *L*.
The Internal Cost objective is the total cost to apply the selected measures at the selected rates. As previously introduced, $c_{k,f,t}$ is the internal cost of applying measure $t \in T_{kf} \cup NT_{kf}$ to a unit of sector-activity *k*, *f*. The total units of activity to which technology *t* can be applied is given by $A_{k,f}\, X_{k,f,t}$ and $A_{k,f}\, Z_{k,f,t}$ for technical and non-technical measures, respectively.
Thus, the internal costs [M€/year] are calculated as:

$$inC(X,Z) = \sum_{k\in K}\sum_{f\in F_k}\sum_{t\in T_{k,f}} (X_{k,f,t}A_{k,f})c_{k,f,t} + \sum_{k\in K}\sum_{f\in F_k}\sum_{t\in NT_{k,f}} (Z_{k,f,t}A_{k,f})c_{k,f,t}$$

The constraint is thus the following:

$$inC(X_{k,f,t}; Z_{k,f,t}) \leq L$$

The following constraints hold for technical measures.

1. When **no technological substitution** is admitted, the following constraints are defined:

   - to ensure the application feasibility:

$$X^{CLE}_{k,f,t} \leq X_{k,f,t} \leq \bar{X}_{k,f,t} \;\; \forall\, k \in K, f \in F_k, t \in T_{k,f};$$

   - to ensure the mutual exclusion of the technical measures application (for each activity and each primary pollutant, i.e. for each activity and each precursor, the sum of all the application rates must be less than one):

$$\sum_{t\in T_{k,f}: eff^{p}_{kft}>0} X_{k,f,t} \leq 1 \;\; \forall\, k \in K, f \in F_k, p \in P\,;$$

   - it is worth observing that these constraints imply the so called “conservation of mass” associated with the application of the technical measures (for each activity and each primary pollutant, i.e. for each activity and each precursor):

$$\sum_{t\in T_{k,f}: eff^{p}_{kft}>0} X_{k,f,t}\, eff^{p}_{kft} \leq 1 \;\; \forall\, k \in K, f \in F_k, p \in P\,.$$

2. When **technological substitution** is admitted, the following constraints are applied:

   - to ensure the application feasibility:

$0 \leq X_{k,f,t} \leq \bar{X}_{k,f,t} \ \ \forall \ k \in K, f \in F_k, t \in T_{k,f};$

- to ensure the mutual exclusion of technical measures application (for each activity and each primary pollutant, i.e. for each activity and each precursor):

$\sum_{t \in T_{k,f}: eff_{kft}^{p} > 0} X_{k,f,t} \leq 1 \ \ \forall \ k \in K, f \in F_k \ , p \in P;$

to ensure that the emission reduction achieved according to the optimal solution are at least those guaranteed by the application of the technologies imposed by the Current Legislation, CLE (for each activity and each primary pollutant):

$$\sum_{t \in T_{k,f}: eff_{kft}^{p} > 0} X_{k,f,t} \cdot eff_{k,f,t}^{p} \geq \sum_{t \in T_{k,f}: eff_{kft}^{p} > 0} X_{k,f,t}^{CLE} \cdot eff_{k,f,t}^{p}$$

$\forall \ k \in K, f \in F_k, \mathrm{p} \in \mathrm{P};$

- to ensure that the emissions controlled according to the optimal solution are at least those controlled applying the technologies at the lower bounds imposed by the Current Legislation:

$\sum_{t \in T_{k,f}: eff_{kft}^{p} > 0} X_{k,f,t} \geq \ \sum_{t \in T_{k,f}: eff_{kft}^{p} > 0} X_{k,f,t}^{CLE} \ \ \forall \ k \in K, f \in F_k, \mathrm{p} \in \mathrm{P};$

Concerning non-technical measures:

- to ensure the application feasibility:

$Z_{k,f,t}^{CLE} \leq Z_{k,f,t} \leq \bar{Z}_{k,f,t} \ \ \forall \ k \in K, f \in F_k, t \in NT_{k,f};$

Moreover, when both technical and non-technical measures are applied, the global conservation of mass constraints have to be stated explicitly (for each activity and each primary pollutant):

$$\sum_{t \in T_{k,f}: eff_{kft}^{p} > 0} X_{k,f,t} \, eff_{kft}^{p} + \sum_{t \in NT_{k,f}: eff_{kft}^{p} > 0} Z_{k,f,t} eff_{kft}^{p} \ \leq 1$$
$$\forall k \in K, f \in F_k, \mathrm{p} \in \mathrm{P}$$

When required, additional constraints are added to manage macro sector budget constraints, and to keep consistency for traffic measures applied to different road types (highway, extra urban, urban).
When macro sector budget constraints have to be imposed, the following inequalities are added to the model:

$$inC(X_{k,f,t}^{i}; Z_{k,f,t}^{i}) - inC(X_{k,f,t}^{CLE,i}; Z_{k,f,t}^{CLE,i}) \leq \phi_i (inC(X_{k,f,t}; Z_{k,f,t}) - inC(X_{k,f,t}^{CLE}; Z_{k,f,t}^{CLE})) \quad i \in \tilde{M},$$

Where
M = {1,…,μ} is the index set for the macro sectors, and
$\tilde{M} \subseteq M$ identifies the macro sectors whose budgets have to be bounded.

In order to keep consistency for traffic measures applied to different road types (highway, extra urban, urban) the following constraints are imposed:

$X_{k',f,t} = X_{k'',f,t} \qquad k' = H, k'' = E, f \in F_{k'} \cup F_{k''}, t \in T_{k',f} \cup T_{k'',f}$

$X_{k',f,t} = X_{k'',f,t} \qquad k' = E, k'' = U, f \in F_{k'} \cup F_{k''}, t \in T_{k',f} \cup T_{k'',f}$

$$X_{k',f,t} = X_{k'',f,t} \qquad k' = H, k'' = U, f \in F_{k'} \cup F_{k''}, t \in T_{k',f} \cup T_{k'',f}$$

where *H, E, U* are the identifiers of the highway, extra urban and urban sectors, respectively. In this way, the values of the variables $X_{k,f,t}$ must be the same when these variables are associated with the same technical measure *t*, applied to the same activity *k*, which is performed in at least two sectors among highway, extra urban and urban.

7.3 Ex-post analysis

EXTERNAL COST COMPUTATION

The ExternE approach **(**Bickel et al., 2005) has been applied to compute health impacts and external costs, due to PM10 exposure. More in detail, considering the PM10 maps resulting from optimal air quality policies, the following health impacts/external costs have been considered:

- Asthmatic adults and children
  - Bronchodilator usage
  - Cough
  - Respiratory problems
- Over 65 years-old
  - heart attack
- Children
  - chronic cough
- Adults
  - reduced activity
  - chronic bronchitis
- Total population
  - chronic mortality
  - hospital admission for respiratory problems
  - hospital admission for cardiovascular problems
- Over 30 years
  - Years of life lost

The equation to compute impacts is as follows:

$$h^m = \sum_{x,y} \gamma^m \cdot P_{x,y} \cdot \chi_{x,y}$$

where:

- h^m is the morbidity indicator (m) cost;
- γ^m is the incidence of the indicator m;
- $P_{x,y}$ is the population exposed to PM10 pollution (population of children, adults …, depending on the selected health impact), at cell x, y;

- $\chi_{x,y}$ indicates the mean PM10 concentrations, at cell x, y.

Coefficients used to compute impacts and related economic values are shown in Table 25. The outputs produced by this ex-post analysis are (for each point of the Pareto curve):

- maps of impacts (years of life lost);
- total cost (over the domain) computed separately for morbidity and mortality.

Table 25: Data used to compute health impacts and related economic costs

receptors	impact indicator	pollutant	impact coefficient		economic value	
ASTHMATIC						
Adults						
	Bronchodilator usage	PM 10	0.163	cases/(year*person*mg/m3)	40	euro2000/case
	cough	PM 10	0.335	cases/(year*person*mg/m3)	45	euro2000/case
	Respiratory problems	PM 10	0.061	cases/(year*person*mg/m3)	8	euro2000/case
Children						
	Bronchodilator usage	PM 10	0.078	cases/(year*person*mg/m3)	40	euro2000/case
	cough	PM 10	0.267	cases/(year*person*mg/m3)	45	euro2000/case
	Respiratory problems	PM 10	0.103	cases/(year*person*mg/m3)	8	euro2000/case
OVER 65						
	heart attack	PM 10	1.85E-05	cases/(year*person*mg/m3)	3260	euro2000/case
CHILDREN						
	chronic cough	PM 10	0.00207	cases/(year*person*mg/m3)	240	euro2000/case
ADULTS						
	reduced activity	PM 10	0.025	cases/(year*person*mg/m3)	110	euro2000/case
	chronic bronchitis	PM 10	0.000049	cases/(year*person*mg/m3)	169330	euro2000/case
TOTAL POPULATION						
	chronic mortality	PM 10	0.26	[% of change in yearly mortality ratedi/(µg/m3)]		
	hospital admission for respiratory problems	PM 10	2.07E-06	cases/(year*person*mg/m3)	4320	euro2000/case
	hospital admission for cardiovasculary problems	PM 10	5.04E-06	cases/(year*person*mg/m3)	16730	euro2000/case
OVER 30						
	years of lost life	PM 10	0.0004	Years Of Life Lost (YOLL)	50000	euro2000/case

EX-POST ANALYSIS: GREENHOUSE GASES COMPUTATION

Also the GHG budget is computed ex-post, as a result of the optimal Air Quality policies application. Starting from the optimal application rates of emission reduction measures and from the activity level for each sector-activity, reduced GHG (beyond CLE) are computed. The GHG considered are the Kyoto protocol regulated ones, that is to say: CO_2, CH_4, N_20, Fgas.
Starting from estimated activity level (*A*) for each sector-activity (*k,f*) the removed GHG emissions (g), due to optimal air quality policies, are computed as:

$$GHG_{k,f,g} = \sum_{t\in T_{k,f}} (A_{k,f} \cdot ef^{g}_{k,f}) \cdot X_{k,f,t} \cdot eff^{g}_{k,f,t}$$

where all the various equation ingredients have already been explained. Finally, the total GHG reduced emissions (for GHG emission *g*) are defined as:

$$GHG_{g} = \sum_{k,f} GHG_{k,f,g}$$

8 Annex II: Validation results for individual stations

Table 26: Mean bias (BIAS), Root Mean Square Error (RMSE) and correlation (R) for the individual stations where NO_2 is measured in the model domain for BCR.

station code	station type	Average observed (µg/m^3)	BIAS (µg/m^3)	RMSE (µg/m^3)	R (-)
BELML01_uT	urban transport	33.36	-2.78	16.57	0.64
BELSZ01_sT	suburban transport	30.85	5.19	17.99	0.63
BELSZ02_sB	suburban background	28.70	4.93	17.76	0.61
BETB004_uT	urban transport	42.67	-10.10	19.43	0.69
BETB005_uT	urban transport	38.66	-7.64	20.01	0.64
BETB006_uB	urban background	38.44	-6.47	18.38	0.66
BETB011_sB	suburban background	28.32	4.26	16.52	0.72
BETMEU1_sB	suburban background	33.93	2.23	17.34	0.68
BETN040_rB	rural background	19.28	2.91	12.08	0.74
BETN043_sI	suburban industry	47.27	-11.76	24.65	0.58
BETN063_rB	rural background	22.13	0.10	15.00	0.59
BETR001_uT	urban transport	42.79	-10.94	21.84	0.62
BETR002_sT	suburban transport	51.57	-20.69	31.85	0.43
BETR010_sB	suburban background	30.85	1.81	16.09	0.69
BETR012_sB	suburban background	27.81	0.45	14.77	0.71
BETR020_sT	suburban transport	34.72	-3.05	16.84	0.67
BETR841_sB	suburban background	32.34	-0.28	17.49	0.61
BETWOL1_sT	suburban transport	39.23	-6.74	20.99	0.58

Table 27: Mean bias (BIAS), Root Mean Square Error (RMSE) and correlation (R) for the individual stations where PM_{10} is measured in the model domain in BCR.

station code	station type	Average observed (µg/m^3)	BIAS (µg/m^3)	RMSE (µg/m^3)	R (-)
BELML01_uT	urban transport	23.41	-8.49	9.72	0.40
BELSZ02_sB	Suburban background	19.44	-5.00	7.23	0.47
BETB011_sB	suburban background	21.22	-6.15	7.27	0.55
BETMEU1_sB	suburban background	21.05	-5.69	7.63	0.58
BETN043_sI	suburban industry	20.61	-5.58	7.88	0.12
BETN063_rB	rural background	17.14	-4.53	6.64	0.74
BETR001_uT	urban transport	19.77	-5.25	7.06	0.52
BETR010_sB	suburban background	19.42	-5.61	6.33	0.64
BETR020_sT	suburban transport	21.15	-6.48	8.24	0.69
BETR841_sB	suburban background	21.80	-6.82	9.20	0.49
BETWOL1_sT	suburban transport	19.51	-5.05	6.31	0.60

Table 28: Mean bias (BIAS), Root Mean Square Error (RMSE) and correlation (R) for the individual stations where NO_2 is measured in the model domain.

Station code	station type	Average observed (µg/m3)	BIAS (µg/m3)	RMSE (µg/m3)	R (-)
AVI	urban background	21.67	-3.81	15.63	0.58
AZU	urban traffic	40.98	-33.59	41.43	0.32
CUS	suburban background	34.03	-5.23	31.51	0.34
ERM	urban background	28.16	-11.80	25.23	0.36
ESP	suburban background	21.60	-8.58	18.61	0.48
FSC	urban traffic	44.78	-15.58	34.60	0.30
LEC	suburban background	26.07	0.53	31.04	0.28
PMN	urban traffic	28.13	-16.95	24.26	0.46
SOB	urban background	26.46	-3.57	21.18	0.50
STR	urban background	17.93	-9.34	16.49	0.14
VCO	suburban background	15.87	-5.78	15.81	0.46
VER	urban traffic	26.77	-2.44	22.33	0.38
VNT	suburban background	18.21	-1.25	18.06	0.36

Table 29: Mean bias (BIAS), Root Mean Square Error (RMSE) and correlation coefficient (R) for the individual stations where PM10 is measured in the model domain.

Station code	station type	Average observed (µg/m3)	BIAS (µg/m3)	RMSE (µg/m3)	R (-)
AVI	urban background	23.34	9.61	16.53	0.56
AZU	urban traffic	19.01	7.15	12.64	0.42
CUS	suburban background	20.02	16.68	23.13	0.35
ERM	urban background	25.41	7.56	14.34	0.55
ESP	suburban background	23.29	8.41	14.37	0.60
FSC	urban traffic	26.59	20.02	25.45	0.58
LEC	suburban background	25.64	10.28	15.80	0.65
PER	suburban industry	31.17	-1.37	16.78	0.43
PFE	urban background	22.53	4.64	12.52	0.39
PMN	urban traffic	19.70	7.13	12.63	0.39
SOB	urban background	27.44	15.20	24.23	0.57
STR	urban background	12.73	12.11	15.10	0.37
VCO	suburban background	24.03	1.61	14.37	0.58
VER	urban traffic	28.69	6.76	19.36	0.58
VNT	suburban background	33.26	-4.42	17.36	0.39

9 Annex III: Sectors considered for the Porto Region

ID	Sector
1	Agriculture: Ploughing, tilling, harvesting, Arable agricultural land in temporal and subboreal climate
2	Agriculture: Livestock - other cattle
3	Agriculture: Livestock - dairy cattle
4	Agriculture: Livestock - other animals (sheep, horses)
5	Agriculture: Livestock - pigs
6	Agriculture: Livestock - poultry
7	Manufacture of automobiles
8	Manufacture of automobiles (new installations)
9	Coil coating (coating of aluminum and steel)
10	Oth. En. Sect.: combustion
11	En. Sect. - own use and loss
12	Construction activities
13	Milk yield over 3000 kg/animal treshold
14	Gasoline distribution - service stations
15	Gasoline distribution - transport and depots (used in mobile sources)
16	Gasoline distribution - transport and depots (used in stationary sources)
17	Decorative paints
18	Degreasing
19	Degreasing (new installations)
20	Residential, commercial, services, agriculture, etc.
21	Residential-Commercial: Fireplaces
22	Residential-Commercial: Medium boilers (<50MW) - automatic
23	Residential-Commercial: Medium boilers (<1MW) - manual
24	Domestic use of solvents (other than paint)
25	Residential-Commercial: Single house boilers (<50 kW) - automatic
26	Residential-Commercial: Single house boilers (<50 kW) - manual
27	Residential-Commercial: Heating stoves
28	Dry cleaning
29	Dry cleaning (new installations)
30	Extraction, proc. and distribution of gaseous fuels
31	Distribution of gaseous fuels - new mains
32	Extraction, proc. and distribution of liquid fuels
33	Fat, edible and non-edible oil extraction
34	Fertilizer use - other N fertilizers
35	Fertilizer use - urea
36	N - fertilizer production
37	Food and drink industry
38	Industrial application of adhesives (use of high performance solvent based adhesives)
39	Industrial application of adhesives (use of traditional solvent based adhesives)
40	Industry: chemical industry (combustion in boilers)
41	Industry, transformation sector, combustion in boilers
42	Industry: other sectors; combustion of fossil fuels other than brown coal/lignite and hard coal

ID	Sector
43	Industry: paper and pulp production (combustion in boilers)
44	Industry: Other combustion (used in emission tables)
45	Industry: Other combustion, pulverized
46	Other industrial use of solvents
47	Other industrial sources
48	Industrial paint applications - General industry (continuous processes)
49	Industrial paint applications - General industry
50	Industrial paint applications - General industry (plastic parts)
51	Inorganic chemical industry, fertilizers and other
52	Other industrial NH3 emissions
53	Mining: Bauxite, copper, iron ore, zinc ore, manganese ore, other
54	Nonenergy use of fuels
55	Organic chemical industry, storage
56	Other NH3 emissions
57	Organic chemical industry - downstream units
58	Other Hg emissions not included separately in GAINS and statistical differences
59	Other PM emissions not included separately in GAINS and statistical differences
60	Other SO2 emissions not included separately in GAINS and statistical differences
61	Products incorporating solvents
62	Polystyrene processing
63	Power & district heat plants with internal combustion engines
64	Power & district heat plants, existing; coal/lignite fired, large units (> 50 MW th)
65	Power & district heat plants existing, non-coal; for GAS - boilers
66	Power & district heat plants, existing; coal/lignite fired, small units (< 50 MW th)
67	Power & district heat plants: Integrated Gasification Combined Cycle
68	Power & district heat plants new, non-coal; for GAS - turbines
69	Power & district heat plants (total); used for reporting total fossil fuels inputs, inputs of non-fossil fuels as well as total electricity and heat generation
70	Ind. Process: Aluminum production - secondary
71	Ind. Process: Cast iron (grey iron foundries)
72	Ind. Process: Cast iron (grey iron foundries) (fugitive)
73	Ind. Process: Carbon black production
74	Ind. Process: Cement production
75	Ind. Process: Electric arc furnace
76	Ind. Process: Fertilizer production
77	Ind. Process: Glass production (flat, blown, container glass)
78	Ind. Process: Lime production
79	Ind. Process: Nitric acid
80	Ind. Process: Other non-ferrous metals prod. - primary and secondary
81	Ind. Process: Production of glass fiber, gypsum, PVC, other
82	Ind. Process: Paper pulp mills
83	Ind. Process: Crude oil & other products - input to Petroleum refineries
84	Ind. Process: Small industrial and business facilities - fugitive
85	Ind. Process: Sulfuric acid
86	Printing, offset, new installations
87	Flexography and rotogravure in packaging, new installat
88	Rotogravure in publication, new installations
89	Polyvinylchloride produceduction by suspension process
90	Residential: Meat frying, food preparation, BBQ

ID	Sector
91	Residential: Cigarette smoking
92	Share of population cremated annualy
93	Residential: Fireworks
94	Manufacturing of shoes
95	Steam cracking (ethylene and propylene production)
96	Storage and handling: Agricultural products (crops)
97	Storage and handling: Coal
98	Storage and handling: N,P,K fertilizers
99	Storage and handling: Other industrial products (cement, bauxite, coke)
100	Synthetic rubber production
101	Other transport: agriculture and forestry
102	Other transport: air traffic - civil aviation
103	Other transport: mobile sources in construction and industry
104	Evaporative emissions from gasoline vehicles
105	Other transport: inland waterways
106	Other transport: other off-road; sources with 4-stroke engines (military, households, etc., for GAS also pipeline compressors)
107	Other transport: off-road; sources with 2-stroke engines
108	Other transport: rail
109	Other transport: maritime, large vessels, >1000 GRT
110	Other transport: maritime, medium vessels <1000GRT
111	Heavy duty vehicles - buses
112	Heavy duty vehicles - trucks
113	Motorcycles, mopeds and cars with 2-stroke engines
114	Light duty vehicles: cars and small buses with 4-stroke engines
115	Evaporative emissions from 4-stroke cars
116	Light duty vehicles: light commercial trucks with 4-stroke engines
117	Evaporative emissions from 4-stroke trucks
118	Motorcycles with 4-stroke engines
119	Tyre production
120	Vehicle refinishing
121	Vehicle refinishing (new installations)
122	Treatment of vehicles
123	Waste: Agricultural waste burning
124	Waste: Open burning of residential waste
125	Waste treatment and disposal
126	Wood preservation (not creosote)
127	Wood preservation (creosote)
128	Wood coating
129	Waste treatment and disposal
130	Biogenic emissions

10 Annex IV: Activities considered for the Porto Region

ID	Activity
1	Non exhaust PM emissions - road abrasion
2	Adhesives
3	Non exhaust PM emissions - brake wear
4	Crude oil
5	Derived coal (coke, briquettes)
6	Dairy cows - liquid (slurry) systems
7	Dairy cows - solid systems
8	Emissions of NMVOC
9	Ethylene and Propylene
10	Expandable polystyrene beads consumption
11	Fur animals
12	Fuelwood direct
13	Gas
14	Gasoline and other light fractions of oil (includes kerosene)
15	Hydrogen
16	Hard coal, grade 1
17	Heavy fuel oil
18	Horses
19	Printing inks
20	Laying hens
21	Liquefied petroleum gas
22	Medium distillates (diesel, light fuel oil)
23	No fuel use
24	Other poultry
25	Other cattle - solid systems
26	Biomass fuels
27	Other biomass and waste fuels
28	Paint and glue produced
29	Pigs - liquid (slurry) systems
30	Paint use
31	Population
32	Pigs - solid systems
33	PVC produced by suspension process
34	Renewable energy other than biomass
35	Synthetic rubber
36	Coated surface
37	Seeds
38	Sheep and goats
39	Shoes
40	Solvent use
41	Textiles (clothing)
42	Wood treated
43	Tyres
44	Non exhaust PM emissions - tyre wear
45	Vehicles

11 Annex V: Removal efficiencies for abatement measures in the Porto Region

Table 30: Combustion in energy and transformation industries (SNAP 1)

Sector	Activity	Technology	Removal efficiency (%)				
			NOx	PM_{10}	$PM_{2.5}$	SOx	NH3
10	13	Combustion modification on oil and gas industrial boilers and furnaces	50	0	0	0	33.3
10	17	Good housekeeping: industrial oil boilers	0	30	30	0	0
10	17	Combustion modification on oil and gas industrial boilers and furnaces	50	0	0	0	37.5
10	17	Low sulphur fuel oil (0.6 %S)	0	0	0	84.2	0
10	22	Good housekeeping: industrial oil boilers	0	30	30	0	0
10	22	Low sulphur diesel oil - stage 1 (0.2 % S)	0	0	0	33.3	0
10	22	Low sulphur diesel oil - stage 2 (0.045 % S)	0	0	0	85	0
65	13	Combustion modification on existing oil and gas power plants	65	0	0	0	33.3
65	17	Good housekeeping: industrial oil boilers	0	30	30	0	0
65	17	High efficiency deduster - power plants	0	99.6	99.5	0	0
65	17	Combustion modification on existing oil and gas power plants	65	0	0	0	37.5
65	17	Power plant - wet flue gases desulphurisation, already retrofitted	0	0	0	90	0
65	17	Power plant - wet flue gases desulphurisation	0	0	0	95	0
65	22	Good housekeeping: industrial oil boilers	0	30	30	0	0
65	22	Low sulphur diesel oil - stage 1 (0.2 % S)	0	0	0	33.3	0
65	22	Low sulphur diesel oil - stage 2 (0.045 % S)	0	0	0	84.9	0
65	22	Combustion modification on existing oil and gas power plants	0	0	0	0	33.3
65	26	Electrostatic precipitator: 1 field - power plants	0	93.2	93	0	0
65	26	Electrostatic precipitator: 2 fields -power plants	0	96.4	96	0	0
65	26	Combustion modification on existing hard coal power plants	50	0	0	0	40

Table 31: Non-industrial combustion (SNAP 2)

Sector	Activity	Technology	Removal efficiency (%)		
			VOC	PM10	PM2.5
21	12	Fireplace improved	75	44	44
21	12	Fireplace new	85	70	70
27	12	Biomass stove improved	85	63	63
27	12	Biomass stove new	95	80	80

Table 32: Combustion in manufacturing industry (SNAP 3)

Sector	Activity	Technology	Removal efficiency (%)				
			NOx	PM_{10}	PM2.5	SOx	NH3
42	13	Combustion modification on oil and gas industrial boilers and furnaces	50	0	0	0	33.3
42	17	Good housekeeping: industrial oil boilers	0	30	30	0	0
42	17	High efficiency deduster - industrial combustion	0	99.2	99	0	0
42	17	Combustion modification on oil and gas industrial boilers and furnaces	50	0	0	0	37.5
42	17	Industry - wet flue gases desulphurisation	0	0	0	85	0
42	22	Good housekeeping: industrial oil boilers	0	30	30	0	0
42	22	Low sulphur diesel oil - stage 1 (0.2 % S)	0	0	0	33.3	0
42	22	Low sulphur diesel oil - stage 2 (0.045 % S)	0	0	0	85	0
42	26	Electrostatic precipitator: 1 field - industrial combustion	0	93.2	93	0	0
42	26	Electrostatic precipitator: 2 fields - industrial combustion	0	96.4	96	0	0
42	26	Combustion modification on solid fuels fired industrial boilers and furnaces	50	0	0	40	0
44	5	Electrostatic precipitator: 2 fields - industrial combustion	0	97.2	95.9	0	0
44	13	Combustion modification on oil and gas industrial boilers and furnaces	50	0	0	33.3	0
44	22	Good housekeeping: industrial oil boilers	0	30	30	0	0
44	22	Low sulphur diesel oil - stage 1 (0.2 % S)	0	0	0	33.3	0
44	22	Low sulphur diesel oil - stage 2 (0.045 % S)	0	0	0	84.9	0
44	26	Electrostatic precipitator: 2 fields - industrial combustion	0	96.4	96	0	0

Table 32 continued

Sector	Activity	Technology	Removal efficiency (%)				
			NOx	PM_{10}	PM2.5	SOx	NH3
78	23	Electrostatic precipitator: 2 fields - industrial processes	0	98.6	96	0	0
78	23	High efficiency deduster - industrial processes	0	99.8	99	0	0
78	23	Process emissions - stage 1 NOx control	40	0	0	0	0
71	23	Cyclone - - industrial process	0	38.5	30	0	0
71	23	Electrostatic precipitator: 1 field - industrial processes	0	93.4	93	0	0
71	23	Electrostatic precipitator: 2 fields - industrial processes	0	96.6	96	0	0

Table 33: Production processes (SNAP 4)

Sector	Activity	Technology	Removal efficiency (%)			
			NOx	PM_{10}	$PM_{2.5}$	VOC
83	4	Leak detection and repair program, stage II	0	0	0	50.8
79	23	Process emissions - stage 1 NOx control	40	0	0	0
79	23	Process emissions - stage 2 NOx control	60	0	0	0
82	23	Electrostatic precipitator: 1 field - industrial processes	0	93.2	93	0
82	23	Electrostatic precipitator: 2 fields - industrial processes	0	96.3	96	0
82	23	High efficiency deduster - industrial processes	0	99.1	99	0
80	23	High efficiency deduster - industrial processes	0	99.1	99	0

Table 34: Solvent and other product use (SNAP 6)

Sector	Activity	Technology	VOC Removal efficiency (%)
8	45	Adsorption, incineration	75
17	30	Simulation of changes in paint formulation and application patterns in order to comply with the EU Product Directive	59.1
19	40	Closed (sealed) degreaser: use of A3 solvents	95.3
19	40	Closed (sealed) degreaser: use of chlorinated solvents	93.3
19	40	Cold cleaner	85
19	40	Water based cleaning process	100
24	31	Reformulation of products (stage 1 - see BIPRO, 2002 study; researched options)	10
29	41	New generation closed circuit machine	54.5
29	41	Water cleaning	100
86	19	Incineration	65.8

Table 35: Road Transport (SNAP 7)

Sector	Activity	Technology	Removal efficiency (%)				
			NOx	VOC	PM10	PM2.5	SOx
112	22	EURO I on heavy duty diesel road vehicles	28.2	50.6	31.0	31.0	0.0
112	22	EURO II on heavy duty diesel road vehicles	21.0	66.6	61.2	61.2	0.0
112	22	EURO III on heavy duty road vehicles	40.8	70.6	68.4	68.4	0.0
112	22	EURO IV on heavy duty diesel road vehicles	63.9	98.8	93.9	93.9	0.0
112	22	EURO V on heavy duty diesel road vehicles	77.0	98.8	93.8	93.8	0.0
112	22	EURO VI on heavy duty diesel road vehicles	97.1	98.8	99.7	99.7	0.0
112	22	Low sulphur diesel oil - stage 3 (0.001 % S)	0.0	0.0	0.0	0.0	99.6
114	22	Low sulphur diesel oil - stage 3 (0.001 % S)	0.0	0.0	0.0	0.0	99.6
114	22	EURO 1 on light duty diesel road vehicles	0.7	63.0	55.3	55.3	0.0
114	22	EURO 2 on light duty diesel road vehicles	6.3	75.4	72.7	72.7	0.0
114	22	EURO 3 on light duty diesel road vehicles	8.8	84.4	77.1	77.1	0.0
114	22	EURO 4 on light duty diesel road vehicles	21.4	86.3	79.7	79.7	0.0
114	22	EURO 5 on light duty diesel road vehicles	33.0	84.5	98.9	98.9	0.0
114	22	EURO 6 on light duty diesel road vehicles	62.5	83.3	98.8	98.8	0.0
116	22	Low sulphur diesel oil - stage 3 (0.001 % S)	0.0	0.0	0.0	0.0	99.6
116	22	EURO 1 on light duty diesel road vehicles	33.3	36.0	59.9	59.9	0.0
116	22	EURO 2 on light duty diesel road vehicles	33.3	43.0	59.9	59.9	0.0
116	22	EURO 3 on light duty diesel road vehicles	44.6	15.3	70.6	70.6	0.0
116	22	EURO 4 on light duty diesel road vehicles	62.1	67.3	83.5	83.5	0.0
116	22	EURO 5 on light duty diesel road vehicles	56.7	67.1	99.1	99.1	0.0
116	22	EURO 6 on light duty diesel road vehicles	87.0	65.8	99.0	99.0	0.0
118	14	Low sulphur gasoline (0.001 %S)	0.0	0.0	0.0	0.0	98.0
118	14	Stage 1 control on motorcycles (4-stroke engines)	0.0	50.0	65.7	65.7	0.0
118	14	Stage 2 control on motorcycles (4-stroke engines)	0.0	63.8	23.8	23.8	0.0
118	14	Stage 3 control on motorcycles (4-stroke engines)	13.0	79.4	97.3	97.3	0.0

Table 36: Other mobile sources and machinery (SNAP 8)

Sector	Activity	Technology	Removal efficiency (%)			
			NOx	VOC	PM10	PM2.5
101	22	Stage 1 control on construction and agriculture mobile sources	34	35	43.4	43.4
101	22	Stage 2 control on construction and agriculture mobile sources	47.2	42	74.45	74.45
101	22	Stage 3A control on construction and agriculture mobile sources	55.12	60	74.45	74.45
101	22	Stage 3B control on construction and agriculture mobile sources	73.07	60	94	94
101	22	Stage 4 control on construction and agriculture mobile sources	96.23	62	94	94
105	22	Stage 1 control on railway and inland waterways mobile sources	34	35	33.3	33.3
105	22	Stage 2 control on railway and inland waterways mobile sources	40	47	50	50
105	22	Stage 3A control on railway and inland waterways mobile sources	55	60	85	85
106	14	EURO 1 on light duty spark ignition road vehicles (4-stroke engines)	71	71	45	45
106	14	EURO 2 on light duty spark ignition road vehicles (4-stroke engines)	87	87	45	45
108	22	Stage 1 control on railway and inland waterways mobile sources	34	35	33.3	33.3
108	22	Stage 2 control on railway and inland waterways mobile sources	40	47	50	50
108	22	Stage 3A control on railway and inland waterways mobile sources	55	60	85	85
108	22	Stage 3B control on railway and inland waterways mobile sources	70	60	97	97