Service Contract for Carrying out Cost-Benefit Analysis of Air Quality Related Issues, in particular in the Clean Air for Europe (CAFE) Programme

Methodology for the Cost-Benefit Analysis for CAFE:

Volume 3: Uncertainty in the CAFE CBA: Methods and First Analysis






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Executive Summary

It is sometimes said that the usefulness of cost-benefit analysis of environmental protection issues is very much constrained by the various uncertainties that are present in the analysis. It is certainly true that in an assessment as broad ranging and complex as that carried out for the CAFE programme there are a number of significant uncertainties present in the analysis. However, this report[1] demonstrates:

- An awareness of the uncertainties that are present on both sides of the cost-benefit equation;
- The techniques that are available for addressing these uncertainties -
  - Statistical analysis;
  - Sensitivity analysis, particularly where there are discrete choices made in the methodology;
  - Consideration of otherwise unquantified biases.
- The use of these methods in combination to give an overview on uncertainty in the analysis;
- Linkage between uncertainty assessment and policy advice, to enable uncertainty to be accounted for by decision makers in a way that will permit assessment of the robustness of conclusions drawn.

The report does not include analysis of specific scenarios – this will be done as work on the various scenarios considered in CAFE is completed. However, it is possible to draw the following general conclusions from the analysis presented in this report:

Statistical analysis
Quantifiable statistical uncertainties in the benefits analysis will be dominated by the health impact assessment and associated monetisation. The report shows how information on this part of the analysis can be used to generate probabilised ranges.

Although similar statistical assessment of uncertainty in the cost estimates is not yet possible, it is possible to investigate the *effect* of uncertainty in costs using a stepwise sensitivity analysis during comparison with benefits. This would involve assessment of the probability of benefits exceeding a series of cost estimates varying by set percentages around the core estimates from RAINS.

Sensitivity analysis
Important conclusions from this part of the report are:

1. Variation in results through the use of different methods for mortality valuation is not as important for PM assessment as originally suspected, with significant overlap in the ranges for VOLY (value of life year) and VSL (value of statistical life) based methods. However, it is sufficiently important to report separate results for the two approaches.
2. It is not yet possible to assess sensitivity to differences in the risk posed by different types of particle. This should be investigated as soon as it is possible to make proposals on such variation.
3. The core analysis takes a cut-point of 35 ppb for ozone health impact assessment. The effect on the analysis of not using a cut-point should be quantified where

[1] This is the third in a series on the methods used for CBA in the CAFE programme. This and the other reports are available on the internet at http://www.cafe-cba.org .

there is specific concern over the effects of ozone. Where ozone is not a key driver it is unlikely that this sensitivity will be important.

4. The choice of meteorological year is important for modelling pollutant dispersion and chemistry. It can make a 50% difference to estimated exposure within countries, though errors are reduced when taking a pan-European perspective. This variability can be accounted for by using 4 different and contrasting meteorological years (1997, 1999, 2000 and 2003). Where this is not done, the effect on health impact assessment can be estimated for each country by reference to figures presented in this report.
5. The stratified sensitivity analysis used previously in assessment of the NEC and Ozone Directives and the Gothenburg Protocol should be retained principally for ozone assessments. For scenarios dominated by PM, its role is diminished by increased confidence in quantification of the dominant impact (mortality from chronic exposures), and the very limited effect of the functions identified in Volume 2 for sensitivity analysis. These add just a few percent to the total PM damage.

Assessment of biases

It is concluded here that the most important biases in the CAFE analysis concern:

- **EMEP modelling**
  - Omission of secondary organic aerosols
- **RAINS modelling**
  - Emission starting point bias
  - Omission of some abatement techniques
  - Lack of account of future technical developments
  - Lack of differentiation of particle species by effect
- **Benefits modelling**
  - Omission of impacts on ecosystems, cultural heritage, etc.
  - Lack of differentiation of particle species by effect

The analysis undertaken here provides an indication of the direction and potential importance of these biases.

Clearly, these uncertainties should not be considered in isolation. Stakeholders should instead seek to develop an overview of them in order to understand the reliability of any conclusions drawn on the balance of costs and benefits for particular cases. A protocol is defined at the end of the report to permit information on the different uncertainties that are present to be brought together in a unified assessment.

In conclusion, based on the findings of this report, it is the view of the authors that uncertainty is not a barrier to effective and efficient decision making for European air quality policy because:

- We know a lot about the uncertainties that are present;
- It is now possible to carry out a mix of quantitative and semi-quantitative analysis to demonstrate how important these uncertainties are likely to be;
- Within the CBA we can combine our understanding of uncertainty of both costs and benefits, to take a view on the probability of specific policies attaining a net benefit.

Contents

Chapter 1 Introduction

1.1 About this report

This report is the third in a series produced under contract to European Commission DG Environment that describes the methodology to be used for cost-benefit analysis of the CAFE (Clean Air For Europe) Programme. The first two reports in the series, available at http://www.cafe-cba.org, deal with:

- An overview of the methodology for benefits assessment and for consideration of the relationship between costs and benefits.
- Health impact assessment – this was given a separate volume of its own because of the importance of health impacts in determination of the overall level of *quantifiable* benefit attributable to air quality improvement.

This volume deals with uncertainties in the quantification of benefits, and also in the comparison of costs and benefits. In consideration of both sides of the cost-benefit equation it has been necessary to consider not just those parts of the analysis that concern the quantification of benefits, but also the dispersion modelling work carried out using the EMEP model (http://www.emep.int/) and the costs analysis carried out at IIASA using the RAINS model (http://www.iiasa.ac.at/rains/index.html). A full appraisal of uncertainty in EMEP and RAINS is, however, outside the scope of this report, and readers should refer to reports specifically written about those models for further details.[2]

It is not intended that a full analysis of uncertainty along the lines of this report is presented for each and every scenario investigated in the CBA. Instead, the general lessons developed in this report will be applied to the analysis as it proceeds. These lessons will concern factors such as:

1. The biases and statistical uncertainties likely to be most important.
2. The circumstances under which other specific uncertainties become prominent within the analysis.
3. The methods available to describe uncertainty in a meaningful manner.
4. Methods for accounting for uncertainty in the formulation of air quality policy.

Another issue considered in this report is the way that errors propagate through the different models (EMEP, RAINS, CAFE-CBA) used in the analysis.

[2] Further information on the CAFE programme and the CAFE-CBA is available at the following websites:

- http://europa.eu.int/comm/environment/air/cafe/index.htm : Providing general information on the CAFE Programme, latest reports, etc.
- http://cafe-cba.org/ : Specifically for information on the CAFE-CBA.

1.2 Types of uncertainty

1.2.1 Uncertainties that can be described quantitatively

Discussion of uncertainty often focuses purely on those aspects of analysis that can be quantified using statistical techniques. These techniques address uncertainty associated with the extraction of information from observations on a limited sample drawn from a population of people, crops, industrial plant, etc. They describe the behaviour of the sample (e.g., how it responds to change in a variable such as increased air pollution) and show how reliable the conclusions drawn from use of the sample are as a representation of the behaviour of the total population. Key characteristics of a sample are average (also referred to as 'mean') or median values and the spread of values around them. Spread is typically characterised as the standard deviation and the range within which 90, 95 or 99% of observations are likely to occur.

Whilst statistical analysis provides a benchmark for uncertainty assessment it is important to recognise that a variety of uncertainties cannot be described using standard statistical techniques:

- Omission of impacts from the benefits analysis.
- Existence of alternative views on methodology amongst experts (e.g. in relation to mortality valuation).
- Transfer of data on exposure-response, valuation, etc. from one situation to another.

Although a statistical treatment of these uncertainties is not possible, it is still necessary to account for them in the analysis in some way if they seem likely to have a significant effect on the balance of costs and benefits. This can be done using the other techniques described in this report, bias analysis and sensitivity analysis.

1.2.2 Biases

Biases reflect limitations in the design of the tools available for quantification of (in this case) the costs and benefits of pollution control. They are issues for which quantification and associated assessment of uncertainty in a sufficiently detailed manner for inclusion in the analysis is not possible. They need to be brought into the assessment in some way because many of them have the potential to influence results significantly (e.g. the omission of secondary organic aerosols from the dispersion modelling, of abatement options from RAINS, and of ecosystem damage from the benefits assessment). Further to this, biases are considered likely to affect results in a systematic manner – either in. In many cases the direction of the bias on the balance of costs and benefits is obvious. In a few cases, however, it is not.

The treatment of biases proceeds through the following stages:

- Identification of biases
- Assessment of the direction of bias
- Assessment of the potential effect of biases on the cost-benefit balance
- Interpretation of the overall effect of the biases identified.

1.2.3 Sensitivities

There are several methods available that come under the general title of sensitivity analysis:

- Observation of the effect on outputs of a systematic stepwise change in one or more variable(s). This could, for example, involve assessment of the effect of a series of incremental changes of 5% or 10% around the core estimate for a specific variable.
- Use of alternate estimates for a specific parameter based on different methodologies. Examples include:
  - Monetisation of mortality impacts using VOLY (value of a life year) and VSL (value of statistical life) based methods.
  - Use of European average or country specific valuations.
  - Use of different approaches to discounting.
- Division of impacts into confidence bands, to differentiate between those effects that can be assessed with greatest confidence and those that can be quantified with less confidence.

The past cost-benefit analysis of the National Emission Ceilings and Ozone Directives and the Gothenburg Protocol (AEA Technology, 1999a, b, c) used two forms of sensitivity analysis. First, it grouped quantifiable benefits into five confidence bands, demonstrating the confidence of stakeholders and analysts in the quantification of each impact. Those effects for which quantification was considered most robust were put into confidence band 1, whilst those for which quantification was considered least robust were placed in confidence band 5. A stepwise comparison was then made with costs. If the benefits from the impacts in confidence band 1 outweighed abatement costs for any country, that country would have great confidence that overall, benefits would outweigh costs. If all five confidence bands were required, confidence that benefits would outweigh costs would be lower (acknowledging that some important impacts were left out of the quantification altogether, as now). A weakness of the approach is that there is subjectivity in defining which effects can be quantified with greatest confidence. It was noted that few stakeholders felt able to respond to the questionnaire distributed at the time. Of those that did, many expressed the view that they could only comment on the impacts (e.g. health effects) with which they were most familiar. Although the approach was clearly not perfect, a number of stakeholders involved with the CAFE work have requested that a similar method be considered this time also.

The second method used in the earlier CBAs was the separate investigation of the effect of individual sensitivities, with particular attention given to mortality valuation using the value of statistical life (VSL) and value of life year (VOLY) approaches, and the use of European average and country specific data for valuation.

1.2.4 Model validation and quality control

There is a risk of error in any analysis during model construction, the handling of data and processing and handling of results. The complexity and multi-disciplinary nature of the CAFE analysis raises the potential for such error. The developers of the EMEP and RAINS models have their own protocols for dealing with the issue of model validation and quality control. For the benefits analysis component of the CBA, the

approach for dealing with uncertainty due to model validation and quality control has been as follows:

- The principal modelling tool has been developed at AEA Technology. A simpler tool has been developed in parallel by EMRC, permitting results to be compared for each endpoint.
- A series of marginal damage estimates per tonne pollutant emission have been generated by the project team. These can be used to check results of a full scenario analysis.
- The health functions provided in the methodology report require some computation before integration with the model (e.g. in converting odds ratios to change in incidence per unit pollution). All functions were checked independently of the main authors at IOM by EMRC during the writing of Volume 2 of the CAFE-CBA Methodology report.
- Results have been compared against background rates, crop yield, etc., to assess whether or not they are plausible. .
- Whilst direct validation is not possible, consideration has been given during the development of the benefit assessment methodology to information that shows impacts to be real. A good example would be the various 'intervention studies' that show significant changes in mortality and morbidity rates following interventions such as the analysis of the Dublin coal ban that lead to a large stepwise reduction in emissions, which showed a clear improvement of health.

Chapter 2 Statistical uncertainties

2.1 *Approach for the benefits assessment*

The approach used here for statistical analysis is based on the use of the @RISK model. @RISK permits investigation of statistical uncertainties through the definition of probability distributions for key parameters in terms of mean values and the spread of values around them, and subsequent sampling across these distributions.

The first stage in the analysis is definition of the scope of the model to be used for quantifying uncertainty. Here, we focus on health impacts, as they provide the largest monetised air pollution damage for the CAFE analysis. The analysis presented in this report is not concerned with particular scenarios, but with identifying which uncertainties are important for the benefits analysis. We consider uncertainty in quantification first of ozone damage to health and second of PM effects, again on health.

The next part of the analysis is to identify the different stages of the analysis, and the areas where quantifiable uncertainties are likely to be most significant. Probability distributions are then defined for each parameter of interest, drawing particularly on data given in Volume 2 of the CAFE-CBA Methodology Report.

@RISK is then used to sample across the defined probability distributions using a Monte Carlo sampling procedure. At each iteration of the model a new output estimate is generated. @RISK concludes by describing the distribution of the values of the output. In addition to defining probability distributions for key outputs, the model results also describe sensitivity to each of the key inputs.

Of course, the further the analysis proceeds through the chain from release to exposure to impact assessment to valuation, the greater the uncertainty in the final estimate (simply because more parameters, each bringing their own level of uncertainty to the analysis, are introduced). On this basis, we can have the highest confidence in concentration data, followed by (in order) total population exposure, exposure of specific groups within the population, impact results, and finally monetised estimates of damage. So far as the benefits analysis is concerned this makes it appropriate to describe separately the uncertainty in the estimated impacts that are driving the CAFE process (mortality from exposure to PM and ozone) in addition to the uncertainty present following monetisation and summation across impacts.

Having demonstrated how statistical confidence intervals can be defined for this analysis and applied, the chapter concludes with a discussion of ways in which the results can be applied within CAFE.

2.1.1 Identifying uncertainties in the analytical chain

The first stage in the analysis is the identification of the key inputs and outputs for assessment. In this report we concentrate on health impacts for this part of the

analysis, as these dominate CBAs of this type. To identify which parameters will give rise to the greatest level of uncertainty, consider first the chain of analysis for benefits quantification:

Pollution concentration
× *population at risk*
× *incidence rate (for deaths, respiratory hospital admissions, etc.)*
× *response function*
× *valuation*

The first parameter, pollution concentration attributable to a certain level of emission, is taken here as given. There are clearly uncertainties in this parameter, but the extent of error will vary significantly from place to place around Europe, between meteorological years, and so on. To be positive, however, models are compared with monitored data, so there is a lot of data on the deviations between models and the real world. At the present time we are not aware of information that would permit integration of uncertainty in modelled concentration data from EMEP with the other uncertainties discussed here.

The second parameter, population at risk, is known with a reasonably high level of accuracy from standard national demographic statistics. There is some uncertainty from the need to forecast population in the future, though as the analysis only goes out to 2020 this is unlikely to be of great importance. This, too, is not considered further in the uncertainty assessment.

Uncertainty in the remaining three factors, incidence rate (particularly for morbidity), response functions, and valuations, is, however, assessed in the analysis presented here.

2.1.2 Defining probability distributions

A variety of probability distributions can be considered appropriate to the input data used for the CAFE analysis. Those adopted for assessment of uncertainties in the health analysis are as follows, with further information shown in Figure 1 which demonstrates the differing shapes of the distributions used.

- **Uncertainty in incidence data, death rates:** A triangular distribution is used for the spread around data on death rates and morbidity incidence, defined in terms of a best estimate and fixed maximum and minimum estimates. There is a lack of data on which to define statistical distributions for incidence data of many of the health effects of interest to CAFE. However, there is sufficient information available in volume 2 of the CAFE-CBA Methodology report to make reasonable estimates of the range over which incidence data may vary. The range is substantially more restricted for death rates than for other effects, given that mortality is not prone to uncertainty in diagnosis and is universally reported. Some uncertainty in death rates is accounted for, however, in view of the need to estimate death rates for the future.

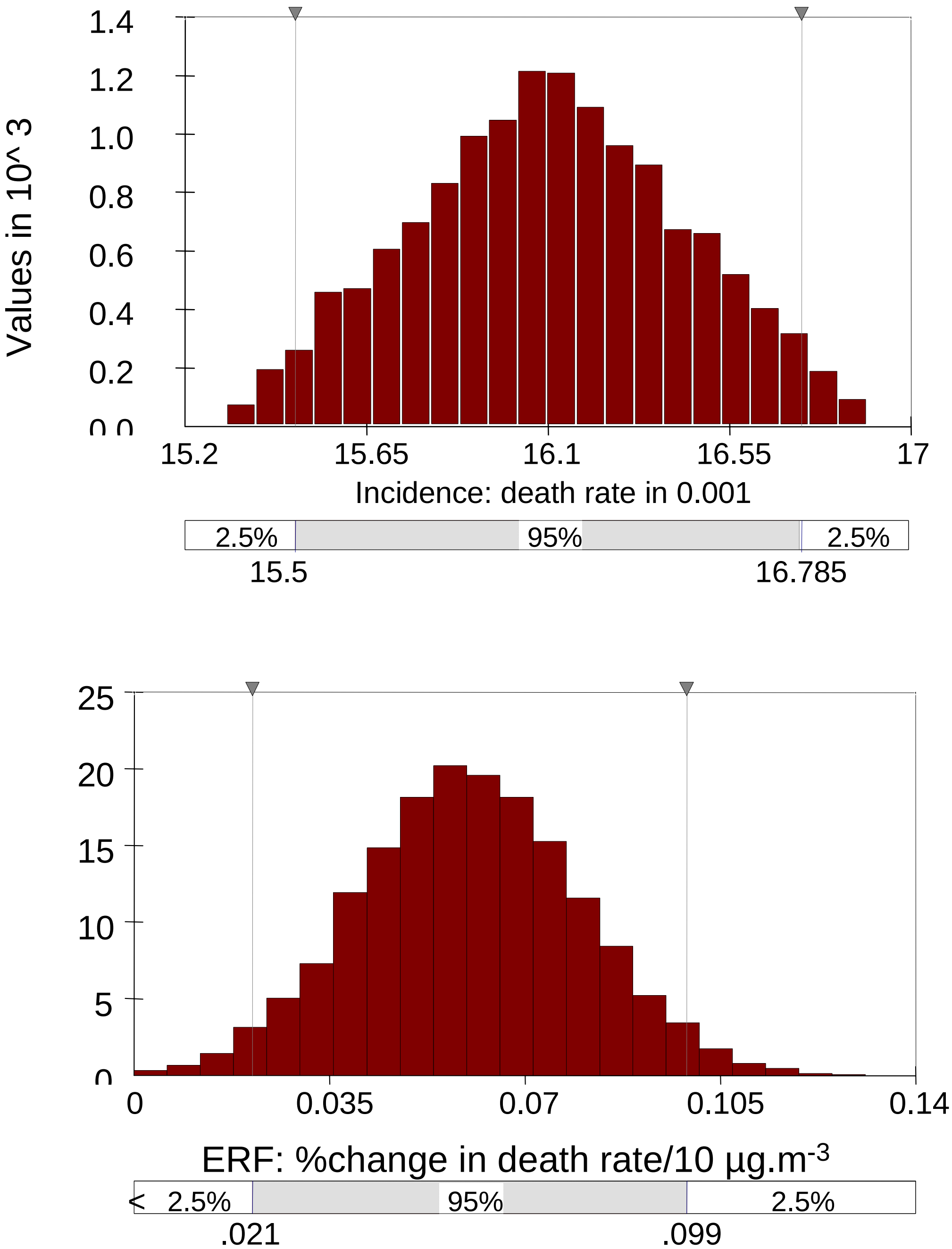


Figure 1 – Different types of probability distribution for the example of PM effects on mortality, generated from Monte Carlo sampling over 10,000 iterations using the data shown in Table 2. Top: Triangular distribution for death rates. Bottom: Normal distribution for exposure response function.

- **Uncertainty in exposure-response functions (ERFs):** Here, a normal (Gaussian) distribution has been used, defined in terms of the best estimate and standard deviation. Based on standard statistical relationships, the

standard deviation is estimated as half the 95% confidence interval identified for each effect in Volume 2 of the CAFE-CBA Methodology Report.

- **Uncertainty in valuation estimates – mortality:** The NewExt and other original valuation studies describe extensive variation in individual estimates of willingness to pay (WTP) for the VOLY and VSL. However, for CAFE we are less interested in the variation in individual estimates than we are of the potential variation in the representative values selected to show average WTP across the population – the mean and median estimates. Variability in mortality valuations is therefore represented through the standard errors (i.e. the standard deviation of the mean/median) from the NewExt study (Table 1). A normal distribution is again taken.

Table 1 – Standard errors of the mean and median estimates of VOLY and VSL from the NewExt Study.

	Median	SE	%(SE/median)	Mean	SE	%(SE/mean)
VOLY	€ 52,000	€ 3,724	7%	€ 120,000	€ 14,646	12%
VSL	€ 980,000	€ 73,593	8%	€ 2,000,000	€ 234,721	12%

For infant mortality there is additional uncertainty associated with the need to account for the additional risk aversion of parents with respect to protection of their children than themselves. There is little information on which to base this increased uncertainty. Here, we adopt a standard error of 33% for valuation of infant mortality in recognition of the increase in uncertainty. Although this decision is somewhat arbitrary it has almost no consequence on the overall results of the uncertainty assessment, given the very limited importance of infant mortality on total estimates of economic damage (see Figure 10 and Figure 11, below, on page 26).

- **Uncertainty in valuation estimates – morbidity:** Volume 2 of the CAFE-CBA Methodology report provides the following range for quantification of new incidence of chronic bronchitis (per case, values in year 2000 prices):
  - High range estimate: €250,000
  - Best estimate: €190,000
  - Low range estimate: €120,000

This indicates a variation of around 33% around the best estimate.

Most of the valuation estimates used in the CAFE benefits assessment for other cases of morbidity are based on the work of Ready et al (2004). The study was undertaken in five European countries (the Netherlands, Norway, Portugal, Spain and the UK) and covered six effects (admission to hospital or a casualty department, cough, illness requiring days spent in bed, eye irritation and stomach upset). The headline figure on uncertainty from the Ready et al paper is an error of 38% attributable to random sampling variation and also transference of estimates between countries. Sampling variation on its own had an average uncertainty of 16%. Note that these figures do not represent

standard errors or deviations, but instead, the average of differences between pair-wise comparisons.

For CAFE the uncertainty of transfer of the results of a multi-country European study between European countries is of limited interest, given that we are investigating policy at the EU level. On this basis, the use of pooled data from a study covering five countries clearly provides very useful guidance for CAFE. It may therefore seem appropriate to use the standard errors of estimates of the effects considered by Ready et al pooled across countries. These ranged from 4% to 8% of the best estimates.

A problem here is that there is additional uncertainty outside the scope of the work of Ready et al, in the consistency of the impact quantified using the exposure response functions and the effect for which valuation has been performed. This will concern the precise symptoms addressed, the severity of those symptoms, and, for some effects, the duration of ill health. Some increase in the spread around the best estimates, as reported by Ready et al, would therefore seem appropriate, though it is debatable how far this should go. We assume a range of ±33%, the same as identified above for valuation of chronic bronchitis. We use this for all morbidity effects as a standard error for the purposes of the Monte Carlo analysis that follows rather than absolute limits of the distribution.

Table 2 and Table 3 provide data on the ranges and best estimates entered into the @RISK model. From comparison of best estimates and standard errors, it may at first sight appear that uncertainty in valuation of mortality is underestimated compared to uncertainty in valuation of morbidity. However, a large part of the uncertainty in mortality valuation is accounted for by the reporting of separate results based on the median and mean estimates of the VOLY and VSL. Against this background, the use of broader spreads than those recommended here around the separate mortality estimates would double count uncertainties.

Table 2 – Best estimates and ranges used for incidence data, exposure response functions and valuation data in the analysis of statistical uncertainties in the health impact assessment for ozone effects, based on information presented in the CAFE-CBA Methodology Report, Volume 2.

Annual incidence rate: distribution – triangular	**+/-**	**Best estimate**
Mortality rate (deaths per head of population)	5%	0.011
Respiratory hospital admissions, >64 years (cases/100,000 population)	20%	2,496
Minor restricted activity days (per person)	40%	7.8
Adult use of respiratory medication (days per person)	40%	0.045
Respiratory symptoms, adults (dummy variable)	40%	1
Response function: distribution - normal	**Std deviation**	**Best estimate**
Acute mortality (% change in mortality rate per 10µg.m^{-3})	0.075%	0.30%
Respiratory hospital admissions (%change in incidence/10 µg.m^{-3} O_3)	0.35%	0.50%
Minor restricted activity days, population 18-64 (%change in incidence/ 10 µg.m^{-3} O_3)	0.45%	1.48%
Respiratory medication use (days /10 µg.m^{-3} O_3 /1000 adults aged 20+)	456	730
Minor restricted activity days, (%change in incidence for population aged >64 /10 µg.m^{-3} O_3)	0.45%	1.48%
Respiratory symptoms (symptom days/1000 adults/10 µg.m^{-3} O_3)	175	343
Valuation (all units - €/case): distribution – normal	**Standard error**	**Best estimate**
Acute mortality (VOLY, mean) (€/case)	14,600	120,000
Acute mortality (VOLY, median) (€/case)	3,700	52,000
Respiratory hospital admissions (€/event)	670	2,000
Minor restricted activity days, (€/day)	13	38
Respiratory symptoms in adults (€/day)	13	38
Respiratory medication use by adults (€/day)	0.33	1

Table 3 – Best estimates and ranges used for incidence data in the analysis of statistical uncertainties in the health impact assessment for PM effects. Data are based on information presented in the CAFE-CBA Methodology Report, Volume 2.

Annual incidence rate: distribution - triangular	**+/-**	**Best estimate**
Mortality rate, >30 years	5%	1.61%
Infant mortality rate, ages 1 to 12 months	10%	0.19%
Chronic bronchitis, % of population aged >27 years affected	40%	0.38%
Respiratory hospital admissions (cases/100,000 population)	20%	617
Cardiac hospital admissions (cases/100,000 population)	20%	723
Restricted activity days (RADs, days / person)	40%	19
Use of respiratory medication by adults (% symptomatic adults)	40%	4.50%
Use of respiratory medication by children (% of children who are symptomatic)	40%	20%
Lower respiratory symptoms, adults (% of adults who are symptomatic)	40%	0.30
Lower respiratory symptoms, children (dummy variable)	40%	1
Consultations asthma (consultations / 1000 children)	40%	47.1
Consultations asthma (consultations / 1000 adults of working age)	40%	16.5
Consultations asthma (consultations / 1000 elderly)	40%	15.1
Consultations URS consultations / 1000 children)	40%	574
Consultations URS (consultations / 1000 adults of working age)	40%	180
Consultations URS (consultations / 1000 elderly)	40%	141
RADs, young + elderly (days/person)	40%	19

Table 3 (continued).

Response function: distribution – normal	Std deviation	Best estimate
Mortality (change in mortality risk / 10 µg.m^{-3} PM_{10})	2%	6.00%
Mortality (years of life lost (YOLL)/µg.m^{-3})	11	65.1
Infant mortality (change in mortality risk / 10 µg.m^{-3} PM_{10})	1.00%	4.00%
Chronic bronchitis, >27 years (%change in incidence/10 µg.m^{-3} PM_{10})	3.70%	7.00%
Respiratory hospital admissions (%change in incidence/10 µg.m^{-3} PM_{10})	0.26%	1.14%
Cardiac hospital admissions (%change in incidence/10 µg.m^{-3} PM_{10})	0.15%	0.60%
Restricted activity days (%change in incidence/10 µg.m^{-3} PM_{10})	0.03%	0.48%
Use of respiratory medication by adults (additional days of bronchodilator usage per 1000 symptomatic adults per 10 µg.m^{-3})	900	908
Use of respiratory medication by children (additional days of bronchodilator usage per 1000 children per 10 µg.m^{-3})	430	180
Lower respiratory symptoms (symptom days / symptomatic adult /10 µg.m^{-3} PM_{10})	0.57	1.30
Lower respiratory symptoms (symptom days/child aged 5-14/10 µg.m^{-3} PM_{10})	0.45	1.85
Consultations asthma (% increase in consultations amongst children/ 10 µg.m^{-3} PM_{10})	1.25%	2.50%
Consultations asthma (% increase in consultations amongst working age adults / 10 µg.m^{-3} PM_{10})	0.95%	3.10%
Consultations asthma (% increase in consultations amongst the elderly / 10 µg.m^{-3} PM_{10})	2.30%	6.30%
Consultations URS (% increase in consultations amongst children / 10 µg.m^{-3} PM_{10})	0.35%	0.70%
Consultations URS (% increase in consultations amongst the working age population / 10 µg.m^{-3} PM_{10})	0.45%	1.80%
Consultations URS (% increase in consultations amongst the elderly/ 10 µg.m^{-3} PM_{10})	0.80%	3.30%
RADs, young+elderly (%change in incidence/10 µg.m^{-3} PM_{10})	0.03%	0.48%
Valuation (all units – €/case): distribution – normal	**Standard error**	**Best estimate**
Chronic mortality (VOLY, mean, €/life year)	14,600	120,000
Chronic mortality (VOLY, median, €/life year)	3,700	52,000
Chronic mortality (VSL, mean, €/death)	235,000	2,000,000
Chronic mortality (VSL, median, €/death)	74,000	980,000
Infant mortality (€/death)	1,000,000	3,000,000
Chronic bronchitis, >27 years (€/case)	63,000	190,000
Respiratory hospital admissions (€/event)	670	2,000
Cardiac hospital admissions (€/event)	670	2,000
Restricted activity days, working age (€/day)	27	82
Lower respiratory symptoms, adults and children (€/day)	13	38
Consultations asthma, URS (€/event)	18	53
RADs, young, elderly (€/day)	23	69
Use of respiratory medication (€/day)	0.33	1

2.1.3 Analysis using defined probability distributions

With the probability distributions defined, the model has been run using Monte Carlo sampling for a total of 10,000 iterations. For the separate analysis of ozone and PM effects, the principal result of interest is the probabilised distribution of the product of incidence rate, response function and valuation data summed over the set of endpoints

quantified for each pollutant referred to as the **aggregated damage factor or function** for ozone or PM. Two versions of the aggregated damage function are considered, the first including only the 'core functions' for health impact assessment identified in Volume 2 of the Methodology Report, and the second including also the 'sensitivity' functions.

It is very important that readers understand why we focus on these aggregated damage functions. Information on the aggregated damage functions is a key result of the CAFE-CBA methodology, as damage can be estimated for each scenario by multiplying these functions by population exposure at national and European levels.

A second type of result shows the sensitivity of the outcome to each parameter, highlighting those parameters that contribute most to the overall uncertainty.

2.2 Results

2.2.1 Ozone and health

Figure 2, Figure 3 and Figure 4 show the output for the following parameters:

1. Function for quantifying deaths through exposure to ozone, per person.µg.m^{-3}, combining death rate with the ERF;
2. Aggregated damage function, €/person.µg.m^{-3}, for the core health effects of ozone, combining incidence rate, ERF and valuation for each impact identified for the 'core' analysis and then totalling the results;
3. Aggregated damage function, €/person.µg.m^{-3}, for the core and sensitivity effects of ozone. As [2], but including also the functions identified for sensitivity analysis.

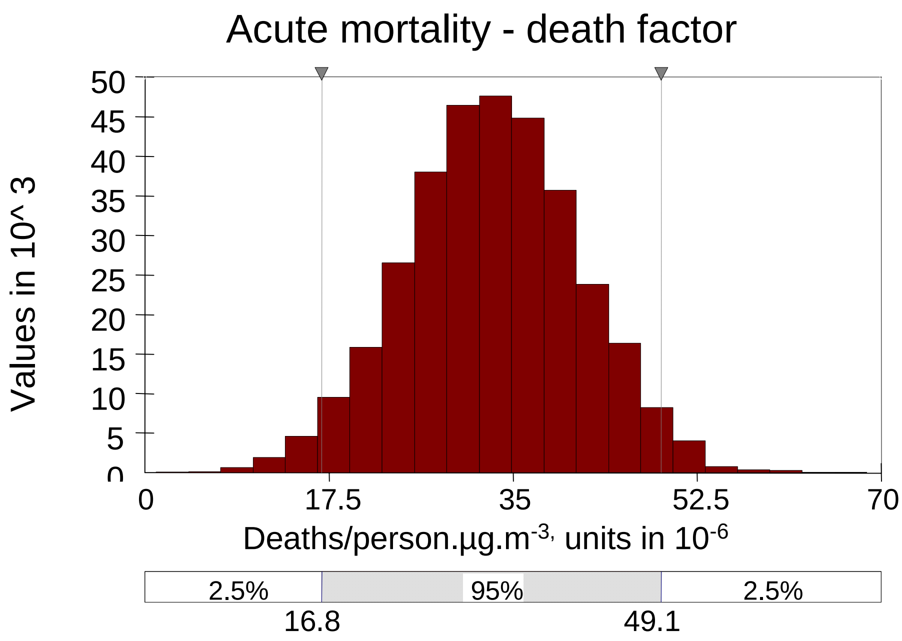


Figure 2 – Probability distribution for ozone-mortality assessment.

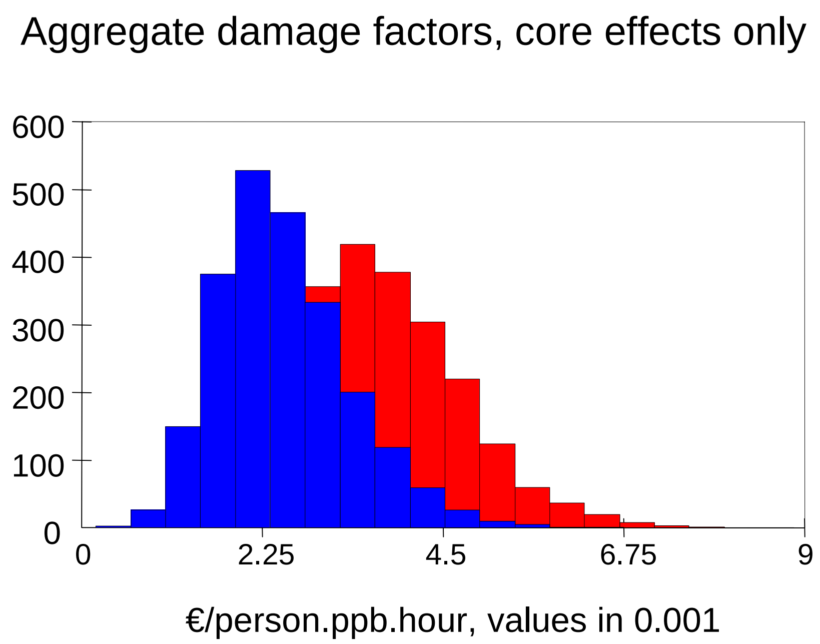


Figure 3 – Probability distribution for aggregate damage functions (combining mortality and various morbidity effects) for ozone assessments for health core functions only. Blue bars show estimates including the median value of the VOLY, red bars show estimates including the mean value. Bars on the left side of the figure are made transparent so that the full shape of both curves is visible. Note the difference in scales compared to Figure 4.

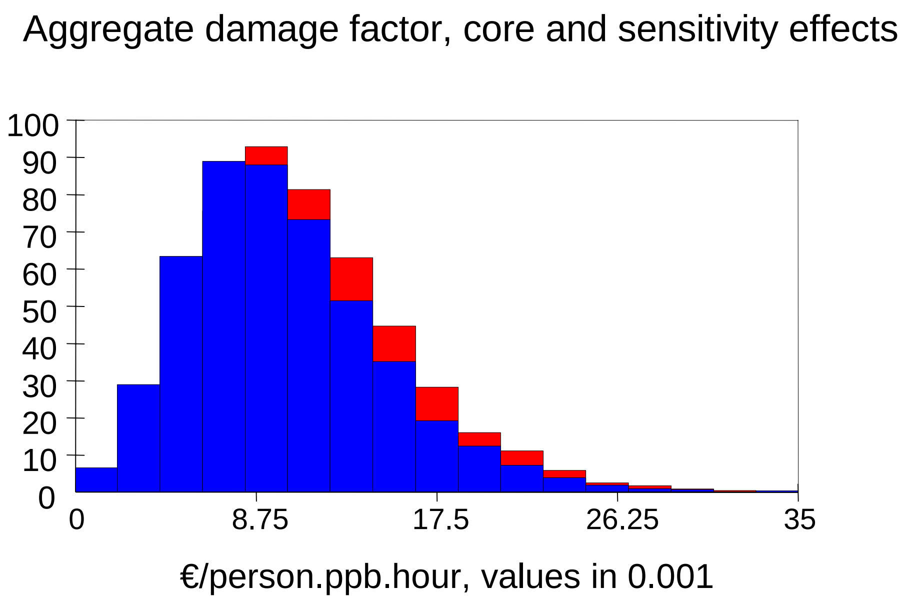


Figure 4 – Probability distribution for aggregate damage functions (combining mortality and various morbidity effects) for ozone assessments for health core and sensitivity functions. Blue bars show estimates including the median value of the VOLY, red bars show estimates including the mean value. Bars on the left side of the figure are made transparent so that the full shape of both curves is visible. Note the difference in scales compared to Figure 3.

Figure 2 shows that the result for deaths is more or less normal in distribution, whilst Figure 3 and Figure 4 demonstrate that the graphs for the aggregated functions are skewed, reflecting the multiplicative nature of the analysis. The latter two figures also show that the sensitivity functions add considerably to the damage factors for ozone (noting the change in scale on the x-axis). Table 4 and Table 5 show the spread around the mean values for the different combinations of mortality valuation method, valuation metric and inclusion or exclusion of the sensitivity functions. Partly in view of the limited number of effects quantified for ozone, the spread around mean estimates from quantification of core effects only is small. It increases substantially once the sensitivity functions are brought into the analysis. A further constraint on the ranges is the separate consideration given to mean and median estimates of valuations.

Table 4 - Summary statistics, mean and 95% confidence interval (2.5% to 97.5%) for assessment of aggregated ozone functions, showing differences arising from adoption of median or mean values as the preferred measure of population WTP, and inclusion of core functions only, or core + sensitivity functions.

Mortality valuation method	Mean or median	Sensitivity functions included?	2.5%-ile	Mean	97.5%-ile
VOLY	Median	×	0.0012	0.0025	0.0044
VOLY	Median	✓	0.0025	0.0101	0.0212
VOLY	Mean	×	0.0020	0.0037	0.0059
VOLY	Mean	✓	0.0036	0.0113	0.0226

Table 5 – 95% confidence interval for aggregated ozone functions, accounting for factors listed for Table 7.

Mortality valuation method	Mean or median	Sensitivity functions included?	Mean / 2.5%-ile	97.5%-ile / mean
VOLY	median	×	2.08	1.76
VOLY	median	✓	4.04	2.10
VOLY	mean	×	1.85	1.59
VOLY	mean	✓	3.14	2.00

Figure 5 shows that the most important uncertainties in the analysis for the core health functions for ozone, where the median VOLY is used for mortality valuation, concern minor restricted activity days (MRADs) for those of working age, largely because they contribute most to monetised damage. The role of mortality is more prominent when the mean VOLY is used. However, Figure 6 shows that when the sensitivity functions are brought in, the uncertainties in both MRADs and mortality become secondary to respiratory symptoms in adults and its valuation, because this becomes the most important impact. These results emphasise the need for further work to characterise what may appear to be relatively minor effects: though certainly less

severe than mortality or hospital admissions to the individual, these effects appear to affect so many people so regularly that they should clearly not be ignored.

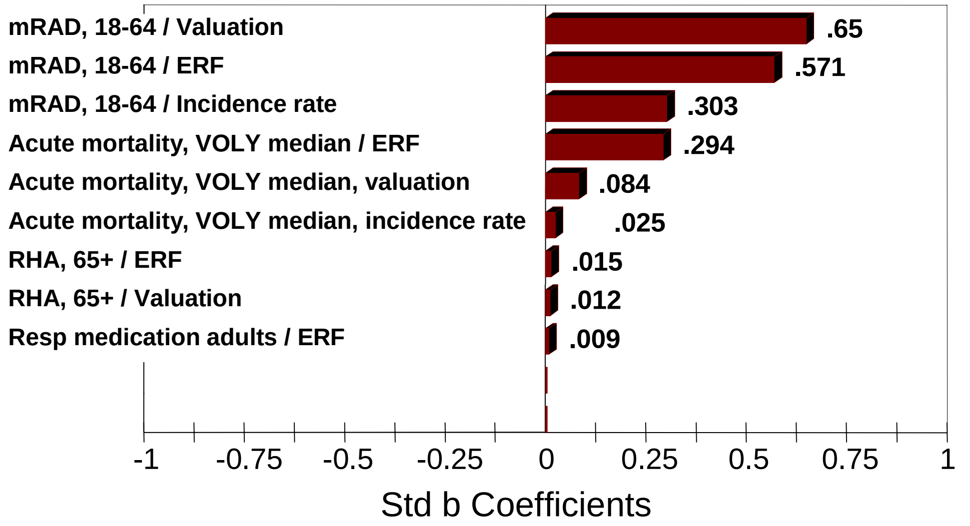


Figure 5 – Regression sensitivity for ozone, core health effects only, median VOLY used for mortality valuation.

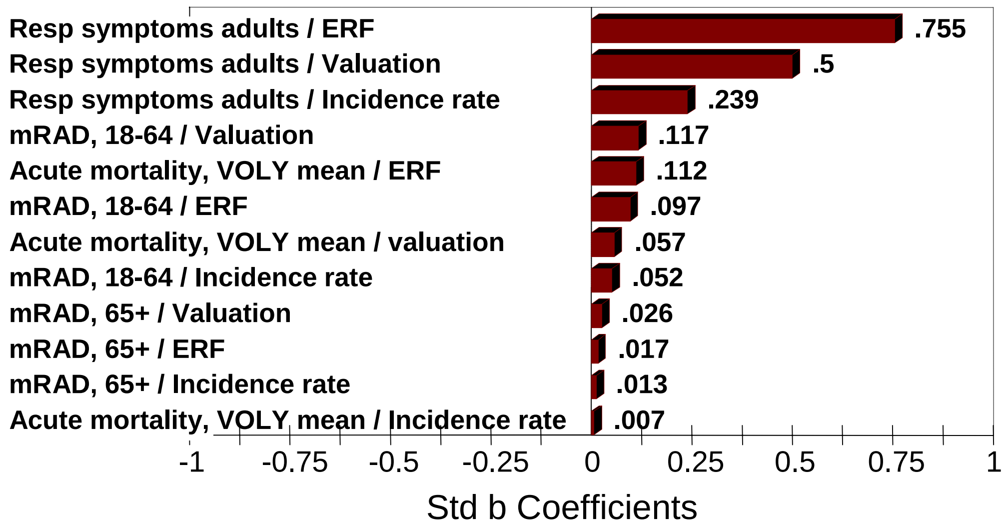


Figure 6 – Regression sensitivity for ozone, core and sensitivity health effects, mean VOLY used for mortality valuation.

2.2.2 PM and health

Table 6 and Figure 7 show the outputs of the analysis for the following key parameters:

1. Death function for exposure to PM, per person.µg.m^{-3}, combining death rate with the ERF;
2. Years of life lost (YOLL) function for exposure to PM, per person.µg.m^{-3}.

Table 6 – Summary statistics, mean and 95% confidence interval (2.5% to 97.5%) for assessment of PM mortality impacts, expressed either as deaths or Years of Life Lost (YOLL). Analysis accounts for uncertainty in incidence rate and exposure-response function, but not valuation.

	Deaths per person.µg.m^{-3}	YOLLs per person.µg.m^{-3}
2.5%	2.2E-05	2.1E-04
Mean	6.0E-05	6.5E-04
97.5%	1.0E-04	1.1E-03
Mean/2.5%	2.7	3.1
97.5%/mean	1.7	1.7

In both cases the 95% confidence interval is around a factor 3 below the mean to a factor 2 above it. This range is a little higher than the normalised spread around the ozone mortality result from Figure 2.

As for ozone, the probability distributions for mortality impacts prior to valuation follow a near-normal distribution (Figure 7).

The next stage in the assessment goes beyond impact functions to look at the **aggregate damage functions** that each cover a number of impacts and proceed as far as valuation:

a) Aggregated PM core function, €/person.µg.m^{-3}, mortality quantified as deaths, combining incidence rate, ERF and valuation for each impact identified in Volume 2 of this Methodology report as ‘core’ and then totalling the results. There are two variants of this function, one calculated using the median VSL and the other using the mean;
b) Aggregated PM core function, €/person.µg.m^{-3}, as [a], but with mortality quantified as YOLL, again with median and mean variants;
c) As [a] and [b], but including also the sensitivity functions.

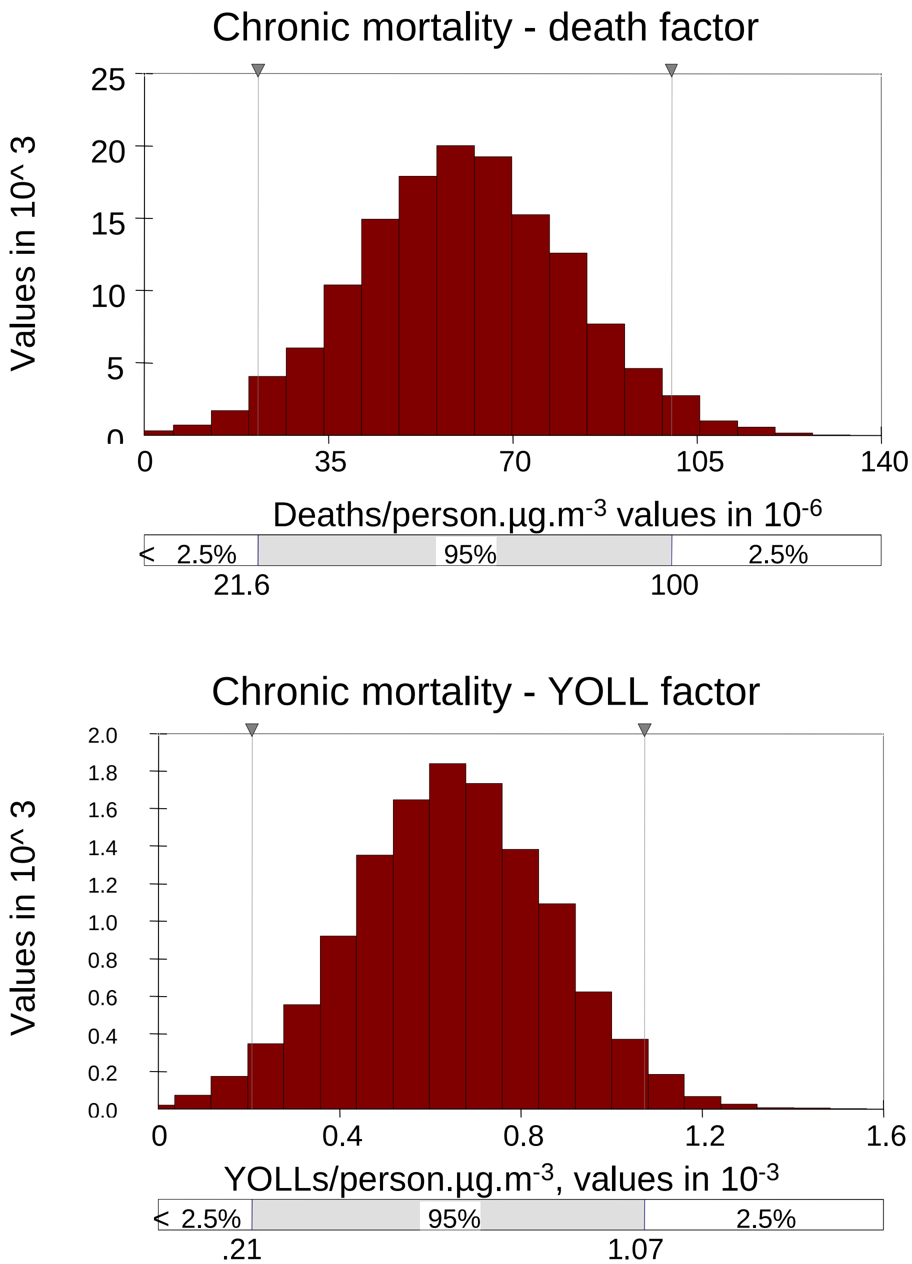


Figure 7 – Probability distributions from quantification of factors for estimating deaths (upper figure) and YOLLs (lower figure).

Table 7 - Summary statistics, mean and 95% confidence interval (2.5% to 97.5%) for assessment of aggregated PM functions, showing differences arising from approach to mortality assessment, adoption of median or mean values as the preferred measure of population WTP, and inclusion of core functions only, or core + sensitivity functions.

Mortality valuation method	Mean or median	Sensitivity functions included?	2.5%-ile	Mean	97.5%-ile
VOLY	median	✗	23	48	73
VOLY	median	✓	25	50	75
VOLY	mean	✗	38	92	150
VOLY	mean	✓	41	94	152
VSL	median	✗	34	74	116
VSL	median	✓	36	76	118
VSL	mean	✗	54	135	224
VSL	mean	✓	56	138	226

Table 8 – 95% confidence interval for aggregated PM functions, accounting for factors listed for Table 7.

Mortality valuation method	Mean or median	Sensitivity functions included?	Mean / 2.5%-ile	97.5%-ile / mean
VOLY	median	✗	2.09	1.52
VOLY	median	✓	2.00	1.50
VOLY	mean	✗	2.42	1.63
VOLY	mean	✓	2.29	1.62
VSL	median	✗	2.18	1.57
VSL	median	✓	2.11	1.55
VSL	mean	✗	2.50	1.66
VSL	mean	✓	2.46	1.64

Results show roughly a factor 2.5 below the mean value and a factor 1.7 above it. There is little increase in the mean values when the sensitivity functions are added in.

Figure 8 (where mortality valuation is based on use of the VOLY) and Figure 9 (where mortality valuation is based on use of the VSL) plot the probability distributions for the aggregated PM functions, with each graph showing the extreme combinations (i.e. median VOLY, core only, combined with mean VOLY, core+sensitivity, omitting the other two variants in the interests of clarity as they fall between the two shown).

Figure 10 (median VOLY, core effects only) and Figure 11 (mean VSL, core + sensitivity effects) show that for the aggregated PM functions, uncertainty is dominated by quantification of mortality, chronic bronchitis and restricted activity days (RADs). Results for the other two aggregated PM functions are not shown as they are more or less similar.

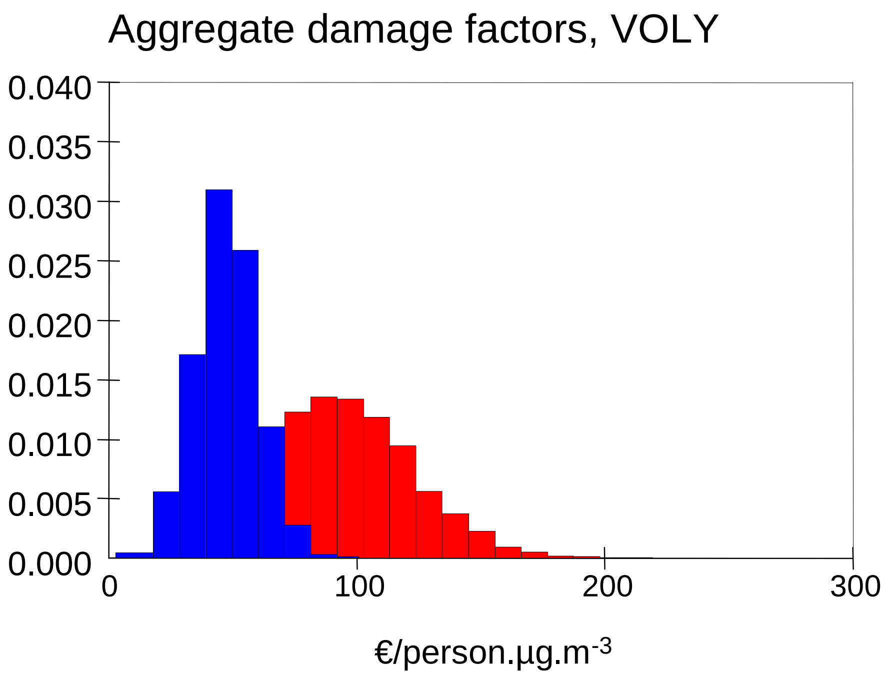


Figure 8 – Probability distributions for aggregated VOLY-based PM damage factors. Blue bars: Assessment based on median VOLY, core functions only. Red bars: Assessment based on mean VOLY, core and sensitivity functions. Overlapping bars are shown transparent, to permit inspection of the full shape of both curves.

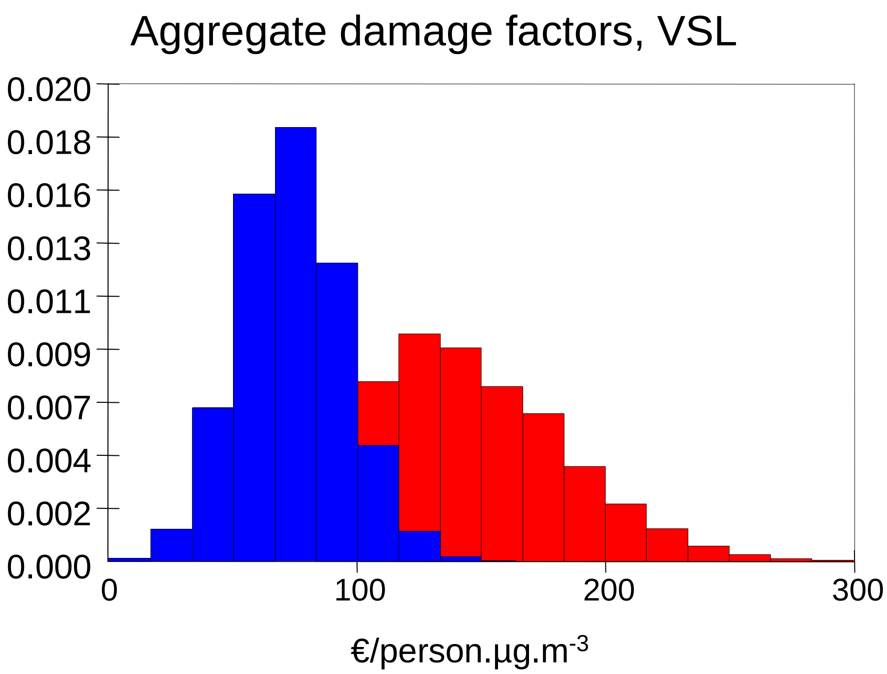


Figure 9 – Probability distributions for aggregated VSL-based PM damage factors. Blue bars: Assessment based on median VSL, core functions only. Red bars: Assessment based on mean VSL, core and sensitivity functions. Overlapping bars are shown transparent, to permit inspection of the full shape of both curves.

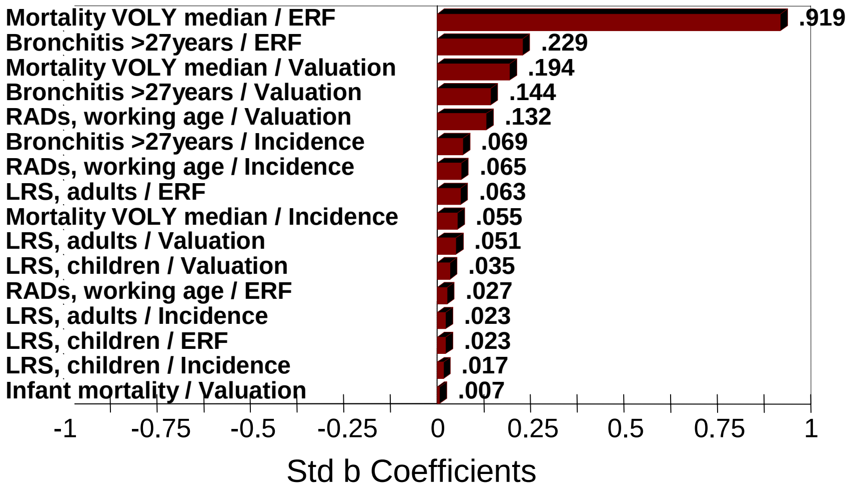


Figure 10 – Regression sensitivity for PM, median VOLY valuation, core health effects only.

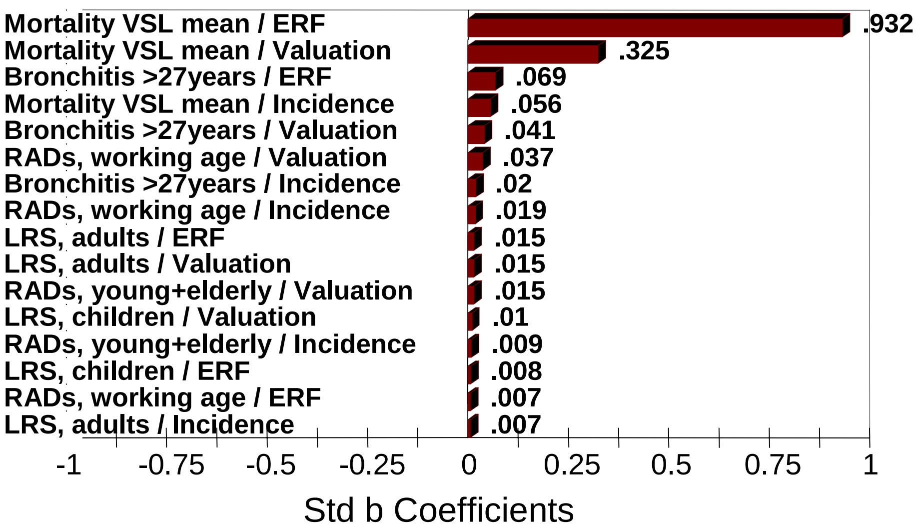


Figure 11 – Regression sensitivity for PM, mean VSL valuation, core and sensitivity health effects.

2.3 Alternative estimates

Detailed analysis of the uncertainty in benefits estimation is, regrettably, rare, particularly in Europe. A prominent European exception to this, however, is the work of Rabl (1999, 2000) in the ExternE Project. Rabl investigated the propagation of uncertainty from emission of pollutants from individual large combustion plant, such as power plants or waste incinerators. Analysis was based around the lognormal distribution. For each stage of the analysis he derived a geometric standard deviation ($\sigma_{g1..n}$). These were combined as follows to generate the overall geometric standard deviation, σ_g:

$$[ln(\sigma_g)]^2 = [ln(\sigma_{g1})]^2 + [ln(\sigma_{g2})]^2 + \ldots + [ln(\sigma_{gn})]^2$$

Examples given by Rabl are particularly relevant here as they focused on the health impacts of fine particle exposure.

Table 9 – Sample calculations from Rabl (1999) showing estimation of the geometric standard deviation for health effects of PM_{10}.

	Chronic mortality	Acute mortality	Hospitalisation
Emission, TSP	1.2	1.2	1.2
Dispersion	2	2	2
Response function	1.3	1.3	1.3
TSP to PM conversion	2	2	2
Cost per day			1.2
Duration			1.2
YOLL (years of life lost)	1.5	4	
VSL	2	2	
VOLY	1.3		
Latency (including discount rate)	1.4		
Total	**4.0**	**6.4**	**2.9**

The final row shows the overall value of σ_g for each effect. These can be applied as multiplicative confidence intervals around the geometric mean (μ_g = median), in other words μ_g/σ_g, $\mu_g.\sigma_g$ for the 68% confidence interval and μ_g/σ_g^2, $\mu_g.\sigma_g^2$ for the 95% confidence interval. The later paper gives a generally lower result, with σ_g around 3 rather than 4. The reported (normalised) confidence intervals given here (see Table 7 and Table 8) are smaller, for a number of reasons:

1. A significant amount of the uncertainty in mortality valuation is dealt with here separately through differentiation of results by median and mean VOLY/VSL estimates.
2. Our analysis has not considered the uncertainties associated with dispersion modelling. However, there are good reasons to suspect that this is less important in the CAFE context than for the analysis of Rabl et al, which dealt with emissions from specific industrial facilities. The uncertainty in modelling the dispersion from a single plant is likely to be significantly greater than the uncertainty in modelling human exposures at the European scale where model validation against monitoring networks provides a better level of verification than from Rabl's generic assessment.
3. The conversion from TSP to $PM_{2.5}$ is not necessary in CAFE, though conversion from $PM_{2.5}$ to PM_{10} is for some morbidity endpoints.

4. Valuation of mortality relevant to the CAFE context is now backed up with specific research studies, such as NewExt that have reduced uncertainty.
5. Sensitivity to the choice of discount rate could be assessed externally using sensitivity analysis if necessary. This is a more appropriate way of dealing with uncertainties that are a function of discrete choices.

2.4 Applying statistical analysis to CAFE scenarios

It is necessary for a moment to consider the objective of this CBA, namely to identify approaches that represent least cost to society. ‘Cost’ here includes environmental and health costs as well as pollution abatement costs. In a recent paper Rabl et al (2005) focus on the effect of uncertainty in determining the least cost position. They conclude that for continuous choices such as the development of emission ceilings for sectors or regions, the cost penalty turns out to be “*remarkably insensitive to error*”. They observed that an error of a factor 3 (similar to their latest estimates of uncertainty) up or down in damage estimates for NOx and SO_2 would potentially increase the social cost <u>by at most 20%</u> and in many cases much less. The costs analysis used for the paper was based on RAINS cost curves, and so is particularly relevant to CAFE.

Analysis of the type presented here can be applied in the CAFE work, first to describe the statistical uncertainty around best estimates of benefits. This would combine the analysis of PM and ozone effects, something that is easily done, but not illustrated here given that this paper is more about methodological development.

More interestingly, the analysis of uncertainty in benefits can be used to quantify the probability that benefits will exceed costs for any scenario. This could be performed against estimated costs ideally with probability functions around cost estimates. At the present time the development of probability distributions around cost-curves is not performed by the CAFE modelling. It has the following additional complexities compared to assessment of benefits:

1. The results of cost-curves are very sensitive to the assumed starting point;
2. Uncertainties in costs and effectiveness of emission control measures have the potential to change the order of measures in cost-curves;
3. The potential for future changes in costs and effectiveness of specific measures that have yet to be introduced on a significant scale is difficult to model. Some assessment could be made based on the difference between historic estimates of abatement costs prior to legislation, and actual costs after legislation.

Some work to address these issues has been performed in a UK assessment of the costs of abating non-agricultural ammonia emissions (Handley et al, 2001). However, integration of uncertainty with the RAINS model is not straightforward. In the absence of definitive information on the probability distribution around cost estimates it may be appropriate to carry out a stepwise sensitivity analysis on cost estimates to see how large errors need to be to have a significant effect on the benefit:cost relationship.

Chapter 3 Sensitivity Analysis

A combination of conventional sensitivity analysis and stratified sensitivity analysis was used successfully in the previous CBAs of the Gothenburg Protocol and the National Emission Ceilings and Ozone Directives. This chapter investigates key sensitivities for the CAFE analysis and assesses their importance, before recommending which sensitivities should be accounted for explicitly and which methods should be used.

From consideration of the data used to quantify impacts, the following key areas for sensitivity analysis are apparent:

- Valuation of mortality in terms of lives impacted or life years lost, using the median or mean value of statistical life (VSL) or value of a life year (VOLY).
- Accounting for variation in the health risk associated with different types of particle.
- Use of a cut-point for the ozone-health analysis.
- Inter-annual variability in meteorology (in cases where this has not been accounted for explicitly in the modelling).
- Inclusion of some health endpoints which are supported by limited research.

Two issues have not been considered here that some may have considered worth addressing:

- The use of a threshold for assessment of PM effects. This issue has been addressed in detail by WHO in their input to the CAFE process. In addition to the views expressed there, it is to be remembered that the EMEP and RAINS dispersion modelling excludes non-anthropogenic particles and secondary organic aerosols. On this basis the analysis already operates with an effective threshold of several $\mu g.m^{-3}$.
- The use of alternative factors for $PM_{2.5}$ to PM_{10} conversion for some of the morbidity functions. We do not consider that these would have a major effect on the analysis, particularly because the dominant PM effect (mortality) is characterised directly against $PM_{2.5}$.

The following issues are also omitted from this Chapter as they are dealt with in other parts of this report:

- Variation in the risk factor used for quantification of chronic impacts on mortality (Working Group on Effects, 2003). Inclusion of such factors would duplicate some of the work done in the statistical assessment carried out in Chapter 2.
- Use of concentration and flux based approaches to quantification of ozone impacts on crop production (Chapter 4).
- Sensitivity to omission of impacts from quantification (Chapter 4 and 4.6).

It would of course be possible to add in further sensitivity analysis, such as on the parameters listed above. However, it is necessary to ask whether such analysis would further aid understanding.

Having considered the importance of each sensitivity, the extent to which it is possible or necessary to factor them specifically into the analysis is considered.

3.1 Effects of alternative assumptions on the valuation of mortality from exposure to fine particles and ozone

The quantification and valuation of mortality generates the largest estimates of damage associated with the CAFE analysis, as shown in Table 10 and Figure 12, in common with other recent CBAs of air quality policy.

Table 10 – Annual health damage costs (baseline), and annual benefits of current policies, in Million Euro for the EU25, 'core' functions only.

Pollutant	2000 CLE Baseline (BL) – 1997 met data	2020 CLE Climate Policy (CP) – 1997 met	Benefit from 2000 to 2020
O_3 mortality	1,100 to 2,500	1,100 to 2,400	39 to 87
O_3 morbidity	6,300	4200	2,100
PM mortality	160,000 to 580,000	100,000 to 420,000	58,000 to 160,000
PM morbidity	78,000	49,000	29,000
Total Health	240,000 to 670,000	150,000 to 480,000	89,000 to 190,000

Note for acute mortality (O_3), two alternative values are presented, based on a range reflecting the median and mean values from the NewExt study. For chronic mortality (PM), four alternative values are presented, based on quantification using years of life lost (using the median and mean YOLL value from NewExt) and numbers of deaths (using the median and mean VSL value from NewExt) .

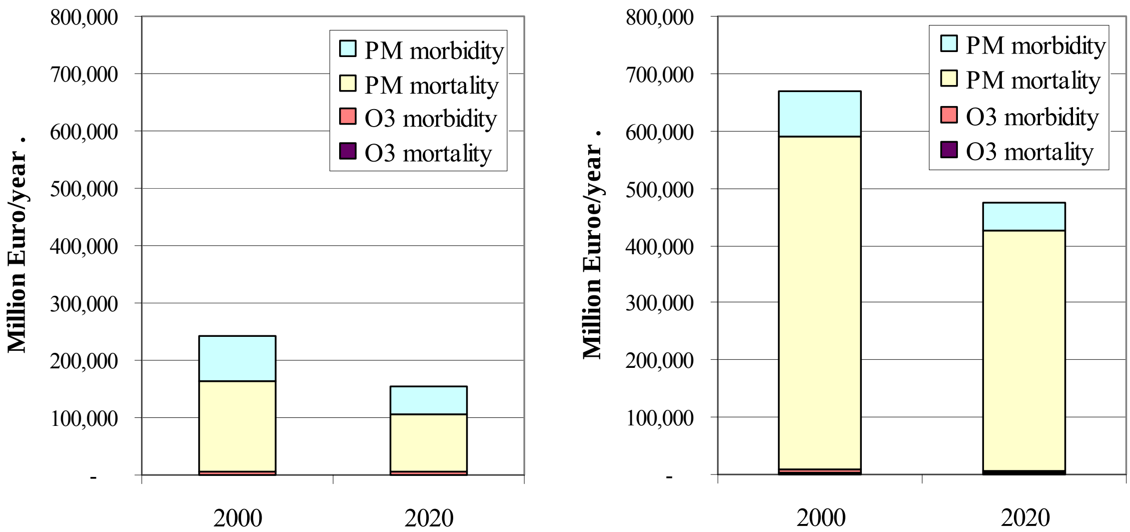


Figure 12 – Baseline Health Impacts (Million Euro) across EU 25 (left VOLY: Right VSL)

Experts are split between those who would adopt the VSL out of preference and those who prefer the VOLY. This is compounded by the debate as to whether to use the

median or mean estimates from the valuation literature (specifically, the NewExt study), adding a further factor 2 into the variability.

In part, this debate arises because there is a general assumption that the use of the VOLY and VSL provide fundamentally different estimates of costs, different by an order of magnitude or more. Analysis carried out here demonstrates that this is not the case. The large (factor 40) difference in valuations (VOLY median = €52,000; VSL mean = €2,000,000) is much reduced when combined with (respectively) estimates of life years lost and deaths brought forward. This is summarised in Table 11, which takes as its baseline the use of the median estimate of VOLY (for no other reason than this gives the lowest estimate of damage). Estimated mortality damage based on use of the mean VSL are only a factor 3.6 higher, rather than the factor 40 difference in the unit valuations given above. This shrinks to a factor 2.8 once other health impacts are integrated with the analysis. Interestingly, the table shows that there is overlap between the median to mean ranges for VOLY and VSL.

Table 11 – The effect of variation in approach to mortality valuation on the size of $PM_{2.5}$ health damage, results expressed relative to VOLY median.

	Mortality only	Mortality and core morbidity
VOLY median	1.0	1.0
VSL median	1.8	1.5
VOLY mean	2.3	1.9
VSL mean	3.6	2.8

The extent of overlap between the VOLY and VSL based approaches is also evident from inspection of the cumulative probability distribution of damage factors for mortality, calculated using the statistical distributions defined above. Results are shown in Figure 13. These factors combine information on population at risk, exposure-response and valuation. Although the VSL based line is clearly shifted to the right, it shares much of the same territory as the VOLY based line.

It is concluded (not surprisingly) that this effect is important for particles and needs to be taken into account in sensitivity analysis of the CAFE programme.

We note that there are other estimates of the VSL and VOLY in the literature that are outside the range considered here. A recent UK study for DEFRA provided a very low estimate in the region of €10,000, whilst US CBA work has often used a VSL of around $6 million. The lower figure, from the UK study is not recommended for use by the original authors. The upper figure is excluded here because it includes consideration of wage-risk studies which we consider not to be sufficiently robust. Notably, the recommended value from the UK study is quite similar to the result from NewExt, though the two analyses were carried out independently and there were differences in the methods used. The similarity in results suggests a greater robustness in WTP estimates than some commentators would give credit for.

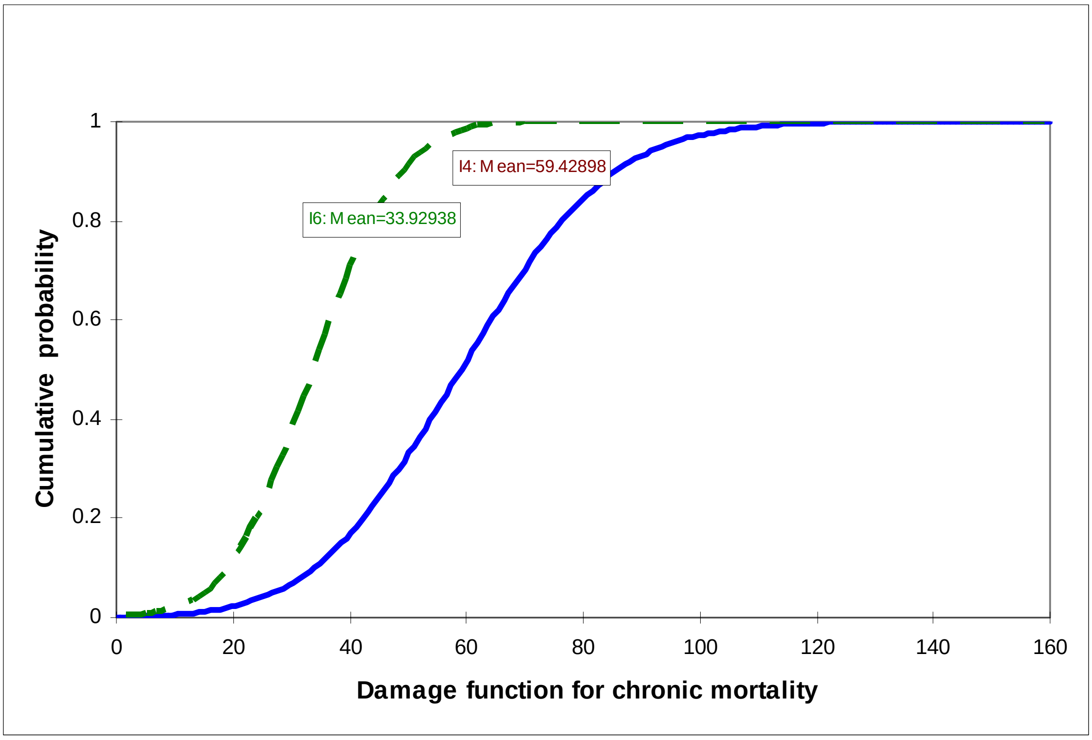


Figure 13 – Probability distributions of damage factors for quantification of chronic mortality impacts of $PM_{2.5}$ using the YOLL/median VOLY approach (dashed green line) and the deaths/median VSL approach (blue line).

3.2 Particle speciation and risk

In the core analysis it is assumed that all particles are equally aggressive per unit mass, irrespective of their physical or chemical characteristics. This builds on the fact that the only risk factor for long-term effects due to fine particles uses the mass metric $PM_{2.5}$ with no differentiation by particle composition. There is additional information on the increased hazard from toxicological studies of various fractions such as the content of metals, organic matter and endotoxins. However, there is a lack of a quantitative base from which to establish different risk rates for different particles. As a result, experts, including those working on the WHO Review, have declined to take a position on the differences in risk between particles per unit mass. It is, however, an area where sensitivity analysis would seem prudent, for example to see which measures that may be recommended for adoption under the CAFE Programme and follow up work are most robust to changed assumptions on the risks posed by different particles.

3.3 Use of a cut-point for the ozone health impact analysis

The importance of using a cut-point for ozone analysis in CAFE is considered using the results of the Benefits Table (BeTa) modelling carried out as part of the CAFE contract. This is based on modelling carried out at EMEP where for each country the effect of a 15% change in emission of each pollutant was considered from baseline emissions in 2010.

At first sight, the use of a cut point at 35 ppb may be expected to have a very major impact on results. However, the consequence of this assumption is limited by the fact that we are not seeking to quantify total impacts of ozone for any scenario, but the impacts associated with policy-relevant changes in concentration.

Results from the BeTa model suggest an average 46% increase in estimated ozone health impacts from VOC emissions when using SOMO 0 instead of SOMO 35 (36% increase if crops are also included). For NOx the situation is more complex with many countries experiencing higher ozone concentrations for small cuts in emissions because of the non-linearity of relationships between NOx and ozone. In the context of the current CAFE process, however, where the benefits of controlling ozone have been found to be very small compared to the benefits of particle control (see Table 10 and Figure 12) the effect of this sensitivity is small. Once impacts of particles are factored into the equation for NOx the difference in estimated impacts when using SOMO 0 and SOMO 35 assumptions falls to between -4% and 8%, depending on country, with only four countries showing a difference greater than 3%.

It is therefore concluded that analysis that considers ozone and particles together is unlikely to be influenced substantially by alternative assumptions on the use or not of a cut-point of 35 ppb for ozone assessment.

3.4 Effects of inter-annual variability in meteorology

Modelling of costs and benefits should be carried out for a range of meteorological years in order to factor year-on-year variability out of the analysis. It is planned that analysis for the main scenarios considered in CAFE will be performed for 4 years, 1997, 1999, 2000 and 2003.

Figure 14 for $PM_{2.5}$, Figure 15 for ozone (as SOMO 35) and Figure 16 for ozone (as SOMO 0) demonstrate the variability in pollution concentrations for the four years. In each year and for each country, the mean of the 4 years is normalised to a value of 1, and the position of each year relative to the mean is shown.

1997 provides the most variable results, with some countries scoring high and others low for $PM_{2.5}$ and SOMO 35. The Scandinavian and Baltic states all score low for $PM_{2.5}$ in this year. Figures for SOMO 0 are low in most countries for this year.

1999 and 2000 are similar. Both score low for $PM_{2.5}$ but are quite variable for SOMO 35 and SOMO 0.

2003 was an exceptional year across Europe, with record temperatures recorded over the summer. It provides the highest $PM_{2.5}$ and ozone concentrations in most countries for the four years.

Provision of these graphs permits stakeholders to assess whether the results for any particular year may be considered representative for any particular country or not. Most emphasis in the analysis has so far gone on the 1997 data.

Figure 14 – Sensitivity to choice of meteorological year with respect to human exposure to $PM_{2.5}$ in 1997, 1999, 2000 and 2003.

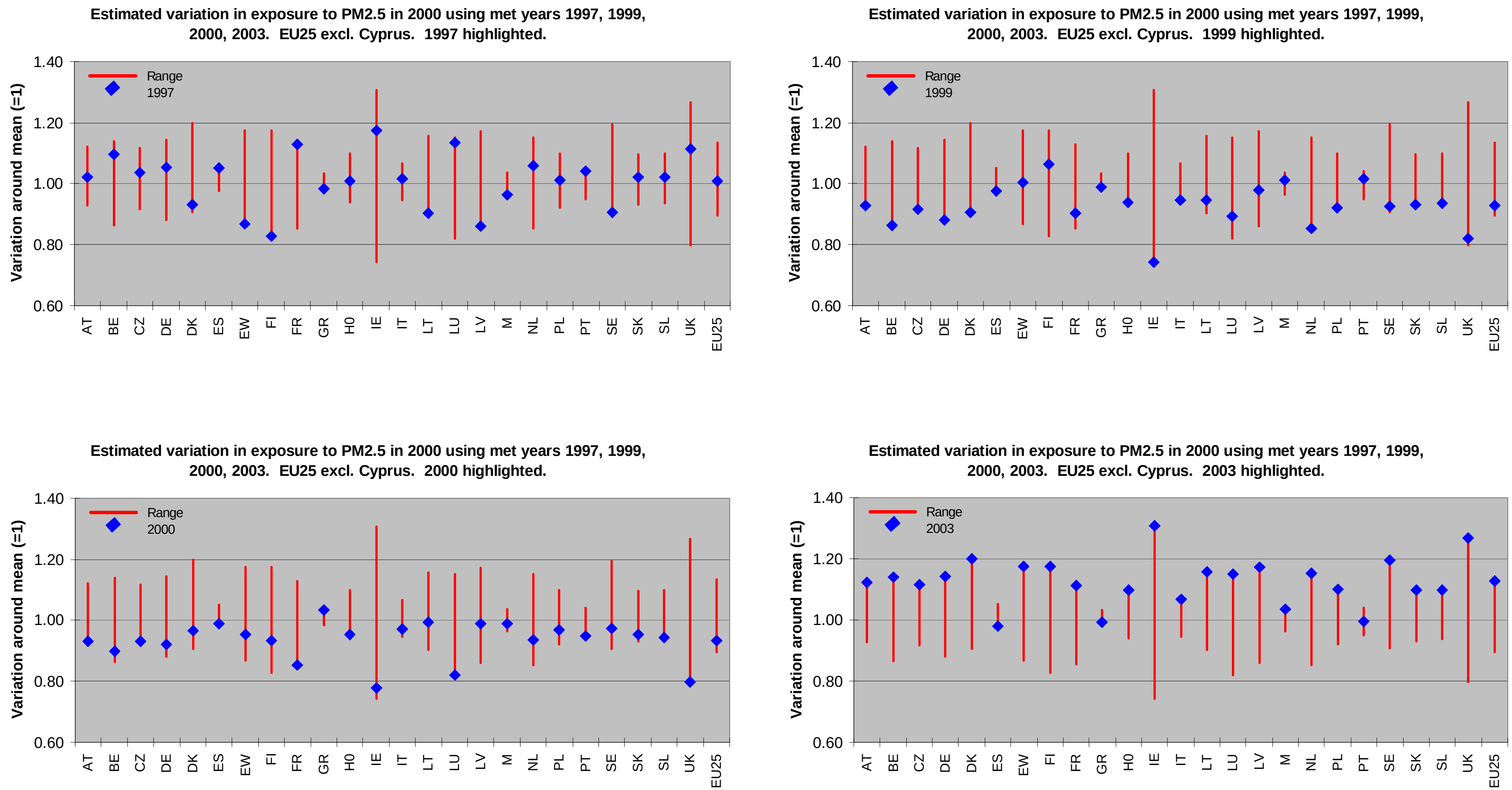


Figure 15 – Sensitivity to choice of meteorological year with respect to human ozone (SOMO 35) exposure in 1997, 1999, 2000 and 2003.

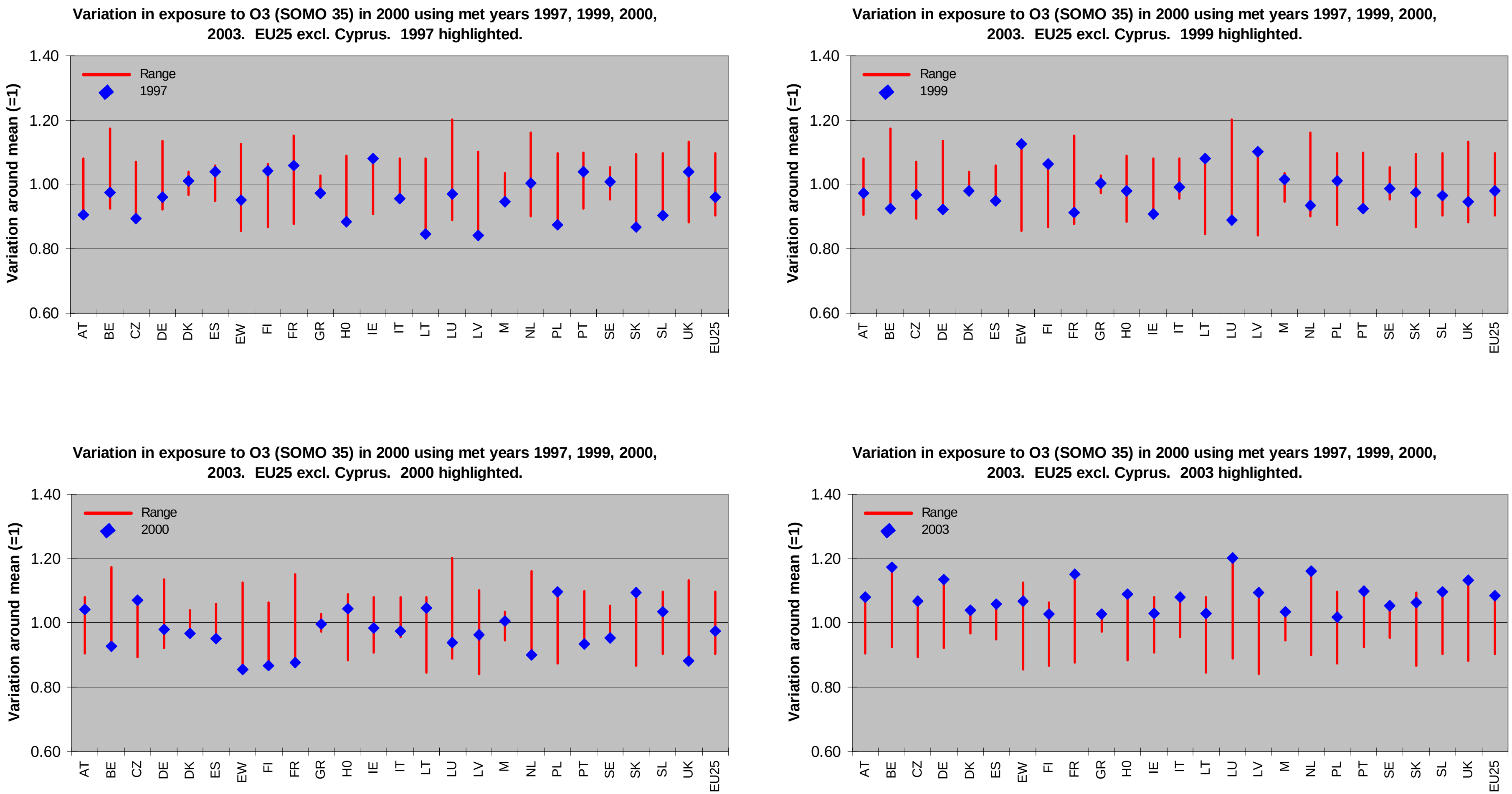
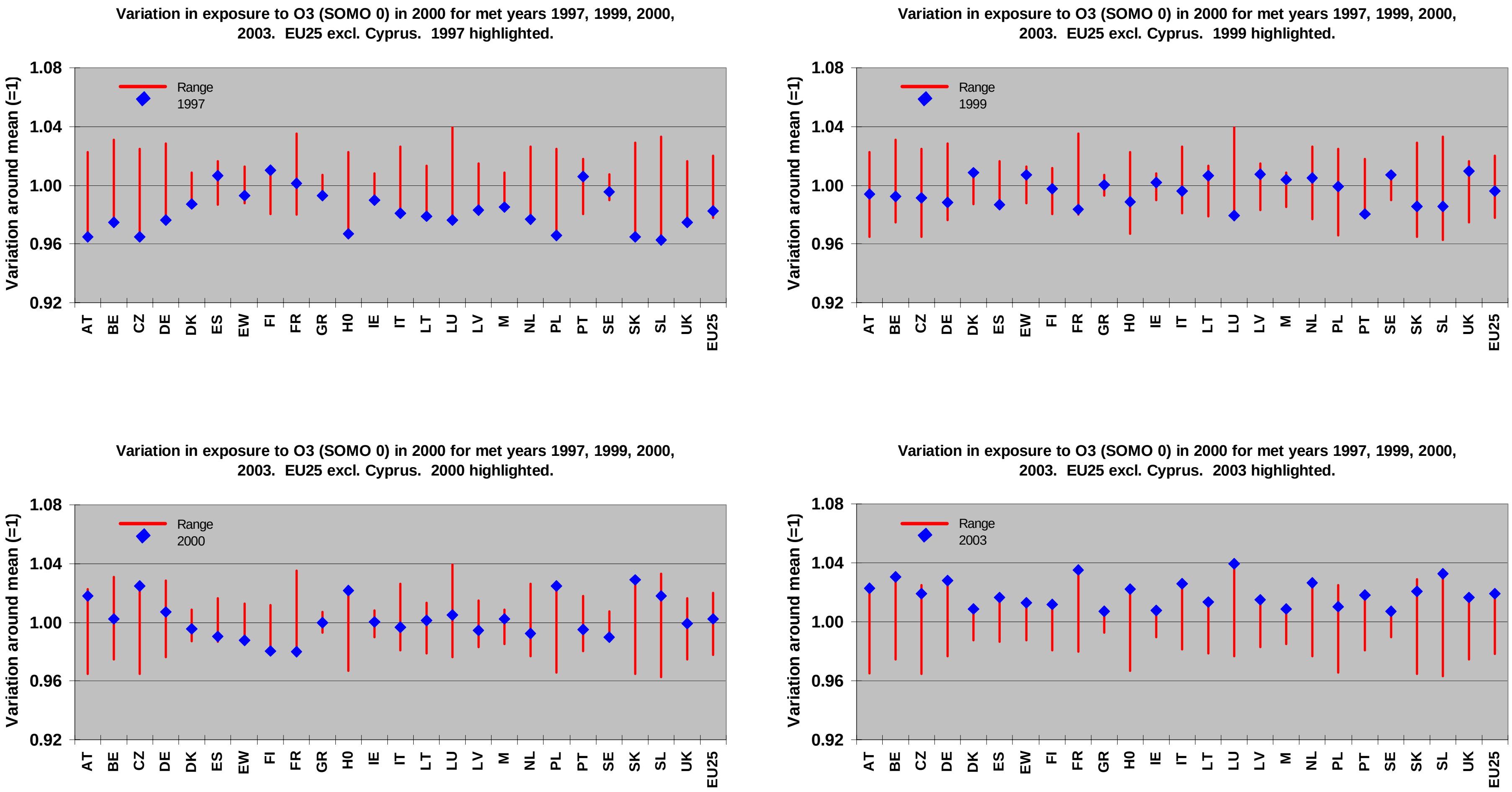


Figure 16 – Sensitivity to choice of meteorological year with respect to human ozone (SOMO 0) exposure in 1997, 1999, 2000 and 2003.



3.5 Inclusion of effects supported by limited research

3.5.1 Earlier work

The earlier CBAs on the NEC and Ozone Directives and the Gothenburg Protocol used 'stratified' sensitivity analysis to distinguish between impacts that could be described with greater and lesser confidence. Impact categories were organised into 5 'confidence bands' - groups of effects arranged in order of confidence with respect to quantification and the link between cause and effect (I = high confidence, V = low confidence). Costs were first compared with the Group I effects, then with Groups I+II and so on until benefits exceeded costs. The logic behind this process was that the fewer groups were necessary for benefits to exceed costs, the greater the confidence that there would be a net excess of benefit. The method has its limitations, but was well received at the time of the original analysis. The original allocation of impacts to confidence bands is shown in Table 12.

Table 12 – Original confidence bands used in earlier CBA studies of the NEC Directive and the Gothenburg Protocol

Group	Effect
I	Materials damage (excluding paint) Crops – N fertilisation effects Acute exposure to air pollutants and mortality (VOLY valuation) Morbidity (excluding Restricted Activity Days (RADs) and chronic bronchitis)
II	Restricted Activity Days Paint damage from acidic deposition Crops – ozone effects Crops –SO_2 effects
III	Acute exposure to air pollutants and mortality (VSL valuation) Chronic effects on bronchitis
IV	Chronic exposure to PM and mortality (VOLY valuation) Ozone damage to forests
V	Chronic exposure to PM and mortality (VSL valuation) Changes in visual range ('visibility')

Care was taken to eliminate various opportunities for double counting of effects. Hence, when the VSL valuation was introduced for acute mortality effects, the VOLY result was subtracted out. Similarly, once mortality from chronic exposure to PM was factored in, mortality from acute exposures to PM was factored out.

3.5.2 Progress since 1998

Since 1998, when the original ratings for the confidence bands were developed, much new information has become available, partly from research and partly from review. This necessitates revision of the original ratings. This is discussed against the original listing in Table 12.

Table 13 – Rankings adopted for the stratified sensitivity analysis in the CBAs for the Gothenburg Protocol and the National Emission Ceilings and Ozone Directives and proposal for changes.

Group	Effect ranking in GBG protocol	Effect – proposed changes
I	Materials damage (excluding paint)	Little change in evidence
	Crops – N fertilisation effects	Unlikely to be significant and omitted from the CAFE analysis
	Acute exposure to air pollutants and mortality (VOLY valuation)	Not now used, given greater confidence in quantified PM mortality effects of chronic exposure, and potential for double counting
	Morbidity (excluding Restricted Activity Days (RADs) and chronic bronchitis)	Increased confidence in various morbidity effects following further research that expands on earlier work
II	Restricted Activity Days	Increased confidence for reasons just given
	Paint damage from acidic deposition	No new information
	Crops – ozone effects	Limited success in the development of 'Level II' approaches
	Crops –SO_2 effects	No new information, unlikely to be significant
III	Acute exposure to air pollutants and mortality (VSL valuation)	CAFE CBA takes a different approach to addressing sensitivity to the different options for mortality valuation.
	Chronic effects on bronchitis	Validity of quantifying chronic effects of PM on health has increased following the HEI (etc.) reanalysis of the papers by Pope et al on effects of chronic exposure on mortality.
IV	Chronic exposure to PM and mortality (VOLY valuation)	Previous quantification was a very early interpretation of the consequences of the findings of Pope et al (1995). Evidence has been strengthened through extensive reanalysis of the base information.
	Ozone damage to forests	Not used in CAFE quantification due to lack of agreed damage function
V	Chronic exposure to PM and mortality (VSL valuation)	Confidence in this effect has increased for reasons given above (chronic mortality, VOLY valuation).
	Changes in visual range ('visibility')	Not used in CAFE quantification through a lack of European data

Taken together with the separation of health functions into 'core' and 'sensitivity' groupings in Volume 2 of the CAFE-CBA methodology, the points raised in Table 13 permit extensive simplification of the structure for a stratified sensitivity analysis. Most notably it is possible to reduce the number of categories shown above given that:

- There is increased confidence in the quantification of chronic mortality effects.
- Visibility and forest damage are not included in the CAFE quantification.
- No additional effects have been added to the quantification that may otherwise have been appropriate for inclusion in Groups IV or V.

The revised structure is shown in Table 14. It is based on the findings presented in Volume 2 of the Methodology Report and views of various expert groups in Europe in relation to quantification. In most cases inclusion of the third category could be dropped given the very limited impact of ozone on the results seen so far in the CAFE

programme. Even the second group is unlikely to have a significant effect on the balance of costs and benefits, as shown by the results presented in Table 7, where mean PM values are little changed by the addition of the 'sensitivity' functions. This form of sensitivity analysis should, however, be retained in cases where ozone, specifically, is under assessment.

Table 14 – Proposal for revised ranking for the stratified sensitivity analysis for CAFE-CBA.

Group	Effect
I	Health – core functions (see CAFE-CBA Methodology Volume 2) for $PM_{2.5}$ and ozone (SOMO 35) Effects of acidity on materials damage (excluding paint) Crops – ozone effects on yield using flux based approaches (when available)
II	Health – sensitivity functions (see CAFE-CBA Methodology Volume 2) for $PM_{2.5}$ and ozone (SOMO 35) Paint damage from acidic deposition Rubber damage from ozone exposure Crops – ozone effects on yield using AOT40 based approaches
III	Health – core + sensitivity functions for ozone quantified against SOMO 0

3.6 Summary of the approach for sensitivity analysis

It is concluded that the following approach should be used for sensitivity analysis:

1. Reporting of separate results based on median and mean estimates of the VOLY and VSL.
2. Sensitivity to differential risks by particle species will be investigated when proposals are made for future policy assessments.
3. The effect of the use of a cut-point for the ozone health assessment will be factored into the stratified sensitivity analysis where there is specific concern over the effects of ozone.
4. The choice of meteorological years for the pollution modelling is clearly important. This should be factored out of the analysis by the use of a number of different meteorological years. Where this is not done, the effect on health impact assessment can be estimated for each country by reference to the series of figures presented in Section 3.4.
5. Stratified sensitivity analysis should be retained, particularly in scenarios where ozone is important. However, the format used should be reduced to that adopted previously, reflecting better knowledge of a number of important impacts (in particular, effects of chronic exposure to particles on mortality) and the removal of some from the quantified assessment (in particular, ozone damage to forests and reduced visibility linked to NO_2 and particles).

Chapter 4 Biases

4.1 Definition

The biases to be dealt with in this section were defined above as those unquantified factors that are likely to push the comparison of costs and benefits in a particular direction.

This chapter focuses on three of the models used in the CAFE analysis, EMEP, RAINS and CAFE-CBA. Consideration has not been given to biases in other models (e.g. TREMOVE or PRIMES) as these do not link directly into the cost-benefit analysis – they are instead considered here as biases of the models that use their outputs directly.

4.2 Method

The method developed here for consideration of these unquantified biases is as follows:

- Identify factors that are not accounted for in the analysis but which are likely (or may be considered likely) to bias the balance of costs and benefits in a particular direction.
- Apply a consistent scoring system that estimates the effects of each source of bias on the balance of costs and benefits.
- Any bias that is likely to lead to an overestimation of costs or underestimation of benefits is given a negative rating, denoting that it is likely to give a pessimistic view of the net benefit of environmental improvement vs. costs. '-' denotes a bias that is likely to have only a small effect (say, less than 5%), '---' denotes biases that are likely to be significant, and '--' denotes biases that may or may not be significant. At this point the bias ratings are simply flags, highlighting which biases need to be considered further. Subsequently, consideration can be given to how significant each bias is.
- Any bias that is likely to lead to an underestimation of costs or overestimation of benefits is given a positive rating, denoting that it is likely to give an optimistic view of the net benefit of environmental improvement vs. costs. '+' denotes a bias that is likely to have only a small effect (say, less than 5%), '+++' denotes biases that are likely to be significant, and '++' denotes biases that may or may not be significant.
- For some parameters it may be clear that there is potential for bias, but the direction of that bias may not be clear. These are given a +/- rating.
- This scoring system is inevitably subjective and wherever used needs to be accompanied with some qualifying text. However, the alternative is to take a purely qualitative position on each bias that would make it extremely difficult to come to any consensus on the overall effect of biases.
- Once biases have been listed and their effects on the balance of costs and benefits estimated, the effect of all biases combined may be considered. This is not done here, as results will be scenario dependent.

The results of this part of the uncertainty analysis, like others, should not be seen in isolation of other factors.

4.3 Biases in the EMEP modelling

4.3.1 Biases in EMEP found in the 2003 review

Table 15 lists the main biases of concern to the CAFE analysis that were identified in 2003 in relation to the EMEP modelling. The main sources of information used to develop this table have been discussions at various CAFE meetings, and the Review of the Unified EMEP Model from the CLRTAP Task Force on Measurements and Modelling (2004). Since that time some of the uncertainties have been addressed but not completely resolved.

With respect to the two main CAFE pollutants, $PM_{2.5}$ and ozone, the 2004 review of EMEP concluded that:

- *The model, in the form presented, underestimated observed PM_{10} and $PM_{2.5}$ due to an incomplete description of relevant processes and emissions. It was, however, able to calculate the regional component of the main anthropogenic PM fractions (sulphate, nitrate, ammonium, some primary components) with enough accuracy to assess the outcome of different control measures.*
- *The model shows an excellent level of performance for daily maximum ozone concentrations.*

Table 15 – Biases in the EMEP modelling. Ratings given in brackets are biases that are unlikely to have a significant effect on the outcome of the CAFE modelling.

Source of bias	Likely effect on benefit:cost ratio	Comment
Underestimation of suspended particle concentrations, particularly through not accounting for secondary organic aerosols Consideration of emission ceilings Consideration of ambient $PM_{2.5}$ concentration standards.	 --- (+++/---)	Overall, secondary organic aerosols contribute around 10% to total aerosol concentrations in the atmosphere over Europe (D. Simpson, personal communication). Part of this will be linked to anthropogenic emissions of VOCs and part to natural emissions. Omission of these aerosols will have several effects on estimates of the costs and benefits of specific national emission ceilings and analysis of different possibilities for ambient $PM_{2.5}$ standards.
Variability in meteorology	(+++/---)	Unlikely to be significant where modelling describes an average based on the use of 4 years meteorology. More information on the effect of this type of uncertainty is given in Section 3.4 enabling readers to assess the effect of variability in meteorology on results that are based on single met years.
Lack of specific account of urban concentrations of: • $PM_{2.5}$ • Ozone		Addressed using the results of the CITYDELTA Project in the RAINS model. This source of bias is therefore not considered further here.

In the context of analysis to support the development of national emission ceilings, the overall effects of the one issue raised as significant in this table (omission of secondary organic aerosols) and not accounted for elsewhere in the report would be:

1. To underestimate PM-health impacts from anthropogenic sources and associated benefits of VOC control.
2. To limit the estimate of *potential* improvement that may be made through control of anthropogenic sources of fine particles.
3. To increase the apparent costs of reducing exposure to $PM_{2.5}$, once beyond the point where VOC controls would enter the cost-curve.
4. Together, therefore, the omission of secondary organic particles would bias analysis against recommending further cuts in VOC emissions.

If the analysis of ambient $PM_{2.5}$ standards were to take the EMEP results as output without urban adjustment, they would underestimate concentrations and make it appear that standards were easier to meet than would actually be the case, leading to a substantial underestimation of the costs of compliance. However, failure to account for additional abatement necessary to reach the standards would also lead to potential benefits being underestimated. The overall effect on the CBA balance could be positive or negative depending on the relative size of the additional abatement cost and associated benefit, and the level at which the standard was set. However, from the perspective of the CAFE Programme this is a hypothetical question, as the EMEP model is not, on its own, adequate for description of ambient concentrations at the level required for analysis of ambient standards that apply at a very fine spatial scale.

4.4 Biases in the RAINS modelling

The peer review of the RAINS model carried out as part of the CAFE Process provides detailed consideration of both statistical uncertainties and biases (Swedish Environmental Research Institute, 2004). This has been used as the basis for the information presented in Table 16. Some of the biases identified in the review are not discussed in the table as they are not considered relevant to the CAFE process. For example, the omission of impacts of particles and ozone on morbidity is addressed through the wider quantification of benefits in the CAFE-CBA[3]. Nonetheless, the modelling is clearly subject to a significant number of possible biases.

As in any case where a large number of uncertainties are identified, there are likely to be some areas where biases cancel each other out to some degree. An obvious example from Table 16 concerns the effects of N deposition to ecosystems, where the peer review concluded that impacts of N on acidification and eutrophication were likely to be (respectively) overstated and understated.

[3] It is, in any case, not necessary to include morbidity impacts in RAINS. Environmental impacts are used by RAINS as indicators to permit optimisation against pre-defined targets. So long as the impacts selected for this process reflect changes in related effects, the use of a single impact to act as indicator is sufficient.

Table 16 – Biases in the RAINS modelling. Ratings given in brackets are biases that are unlikely to have a significant effect on the outcome of the CAFE modelling.

Source of bias	Likely effect on benefit:cost ratio	Comment
Emission starting point bias for NH_3, NOx, $PM_{2.5}$, SO_2 and VOCs	---/+++	Negative bias arises because of uncertainty in emission inventories and the potential for switching to cleaner fuels or production systems by the baseline year for reasons unrelated to air quality regulation. Positive bias arises through uncertainty in emission inventories and possible legislative change in other areas that could cause emissions to increase.
Omission of some existing and future abatement measures from the RAINS model: • Omission of low cost measures • Omission of mid cost measures • Omission of high cost measures	 --- --- --	Biases to overestimation of costs and underestimation of the maximum feasible reduction.
Lack of account of future technical developments for existing measures:	---	Leads to an assumption of lower cost-effectiveness of existing technologies than will be achieved through further development
Lack of differentiation of particles by species for health impact assessment	---/+++	Likely tendency would be to reduce the cost-effectiveness of abatement packages by inadequate focus on the most harmful particles.
Modelling urban exposure: • Urban background $PM_{2.5}$ • Hot spot $PM_{2.5}$ • Urban background ozone • Hot spot ozone	 Accounted for (---) +++ (+++)	Application of the results of the CITYDELTA study enables RAINS to account for elevated background concentrations of $PM_{2.5}$ in urban areas. However, the model does not include adjustment of data for urban background ozone, or assessment of hot-spot $PM_{2.5}$ or hot-spot ozone. The lack of account of hot-spot conditions is considered not so important for health effect quantification as models are calibrated against background concentrations. However, it is a limitation in the applicability of the RAINS model that stakeholders should be aware of.
Restriction of analysis to the EU25 Countries at the centre and western edge of the EU25 Countries at the eastern borders of the EU25	 (-) (---)	The EU has limited possibility to influence the activities of countries that are not members of the Union. On this basis, abatement and damage in non-EU countries are outside the scope of the CAFE process. However, they would clearly be inside the scope of future analysis in the context of the UNECE Convention on Long Range Transboundary Air Pollution.
Inter-annual variability in meteorology		Discussed in Table 15.

Source of bias	Likely effect on benefit:cost ratio	Comment
Underestimation of deposition of S and N to sensitive ecosystems Overestimation of the role of N in critical loads for acidification Underestimation of ecosystem sensitivity to eutrophication	-- ++ --	Given that there is no economic quantification of impacts to ecosystems these impacts do not affect the reported cost-benefit relationship directly, but may influence concern over unquantified ecological impacts where stakeholders use the extended CBA to consider how unquantified effects would alter their attitude to reported cost-benefit relationships.
Omission of health impacts on people aged under 30 years	(--)	Can be accounted for in the benefits assessment as part of the sensitivity analysis.
Use of year 2000 population data and death rates for quantification of ozone effects on mortality	---	Reduces quantified impacts for future years given demographic changes that lead to an aging population in the EU25. Impact limited in CAFE because of the relatively low impact of ozone compared to $PM_{2.5}$.
Use of 'cut-point' for quantification of ozone impacts	--	The use of the cut-point does not reflect a threshold for ozone effects. Impact of the use of the cut-point may, however, be limited, particularly for scenarios that are focused on PM control.

There is a clear dominance in Table 16 of factors that bias costs up and benefits down. Overall this seems likely to lead to a bias to non-action on air pollution generally. Three questions need to be answered:

1. How large is the bias?
2. Does it apply equally to all pollutants?
3. Does it apply equally to all regions?

Quantification of the bias is clearly very difficult – if it were easy it could be incorporated into the modelling. Unfortunately there have been very few attempts to compare ex-ante estimates of control costs with actual costs. Those analyses that have done this have shown a strong tendency for ex-ante estimates to exaggerate costs. However, such studies are purely retrospective and cannot be used as a reliable guide to the quality of future results without further consideration.

Biases will, of course, vary between pollutants, not least because of variability in the quality of emission inventories. SO_2 emissions, for example, are known with a far better level of confidence than PM emissions. Biases will also vary between regions, reflecting differences in the availability of alternative fuels, quality of national data and so on.

4.5 Biases in the benefits analysis

In common with the cost-effectiveness modelling undertaken using the RAINS model, the benefits assessment is prone to a significant number of biases. These are listed in Table 17. Readers who consider that some potential biases have been omitted from this table should consult other sections of the report to see if they are dealt with elsewhere (e.g. alternative positions on mortality valuation). Again, views on the direction and likely significance of biases are the authors' own.

Table 17 – Biases in the benefits analysis

Source of bias	Likely effect on benefit:cost ratio	Comment
Unquantified impacts: • Ecosystem acidification • Ecosystem eutrophication • Impacts of ozone on ecosystems • Damage to cultural heritage • Chronic health effects of exposure to ozone • Chronic effects of PM exposure on cardio-vascular disease	 --- --- --- -- ---? ---?	Further information on the likely importance of omissions from the benefits analysis is given in Section 4.6 of this report.
Lack of differentiation of particles by species for health impact assessment	+++/---	Effect on quantified benefits will depend on the level of control for each type of particle.
Use of health functions from the US and western Europe	++/--	Further research is needed to test whether there are systematic differences between regions.
Quantification of deaths from chronic exposure to PM using techniques not based on life tables.	++	Some potential for double counting of deaths, depending on the time horizon used for the analysis.
Use of uniform incidence data for the whole of Europe for most morbidity effects	++/--	Again, further research is needed to test whether there are systematic differences between regions. The identification of consistent sets of incidence data is recognised as a problem for transferability of health response functions generally.
Use of AOT40 based relationships to quantify impacts of ozone on crops	+	Likely to cause overestimation of impacts amongst un-irrigated crops in drier parts of Europe. Overall effect unclear. Should be resolved in 2005 by a switch to flux-based modelling.

The failure to quantify a significant number of impacts is an obvious problem for the benefits analysis and quite clearly biases to underestimation of the benefit:cost ratio. This issue is addressed further in Section 4.6 on the ‘extended CBA’.

The failure to differentiate particles by species for the health impact assessment seems to be the most important *potential* cause of overestimation of benefits, though it could bias results either way depending on which types of particle are targeted under a specific strategy. Other biases that could lead to overestimation seem less important, reflecting more uncertainty in data extrapolation than anything fundamental.

Another area where bias is likely though it is not clear which direction that bias would go in concerns the morbidity assessment in the benefits analysis. Specifically it relates to two issues, the application of health functions from the US and western Europe across the whole of Europe, and the use of uniform incidence data. Both areas are worthy of further research in the near future. Given variability across Europe any biases that are present may tend to cancel each other out.

A final area concerns probable overestimation of crop damage estimates in drier parts of Europe through the use of AOT40 based functions rather than flux based estimates

(though in northern Europe the AOT 40 based functions may underestimate the damage due to ozone). It is intended that the analysis will move to the use of flux functions later in 2005, drawing on ongoing research programmes. Analysis presented at the February 2004 meeting of ICP Vegetation indicated that this bias may not be as significant as originally thought. It will also be countered to some extent by some impacts of ozone being left out of the analysis (e.g. visible injury to salad vegetables, or the omission of some crops from available maps of agricultural production). These factors, combined with the limited importance of ozone within the CAFE programme, suggest that this bias will not be significant.

4.6 Omissions from the Benefits Analysis, and the Role of Extended CBA

It was considered at the beginning of the CAFE Programme that multi-criteria analysis (MCA) could be useful for assessment of impacts that could not be quantified into the analysis. MCA is based around the elicitation of a series of weightings from stakeholders to show preference across various environmental criteria. It is finding increasing application in policy making circles.

It was concluded, however, that MCA would not be sufficiently robust to make a useful contribution to the CAFE debate. Also, the complexity of the analysis, with its wide variety of endpoints (see Volume 1 for more details) is not well-suited to MCA. The approach developed here (named 'extended CBA') instead seeks to supply decision makers with more contextual information on impacts, so that they can understand them better and, if they wish, factor in their own views on the importance of unquantified impacts.

The extended CBA is based around the provision of a series of datasheets containing a significant amount of descriptive information (qualitative and quantitative), to enable better understanding of the effects and their likely importance. Information is provided in greatest depth for effects that are not quantified through to monetisation. However, it will also be provided for effects that can be monetised, for example, in order to increase understanding of the health impacts. It is intended that decision makers and stakeholders refer to this information when considering how costs and benefits compare, specifically with respect to the effects of biases as identified above.

4.6.1 Development of datasheets for the extended CBA

The extended CBA datasheets contain the following types of information:

- Description of the impact, including components of 'total economic value'
- Discussion of related impacts
- Confidence in attribution of impact to a specific pollutant
- Information on the distribution of impact across Europe (is it a 'European issue' or something to be considered at a more local level?)
- Information on importance in economic or other terms, where available (e.g. from results of willingness to pay case studies, past estimates of expenditure to deal with specific problems, etc.)

An assessment is made in the extended CBA of the likely significance of each unquantified effect, using a three point scale:

★★★	Impacts likely to be significant at the European level
★★	Impacts that may be significant at the European level
★	Impacts unlikely to be important at the European level, but of local significance
No stars	Negligible

The intention in providing information in this way is to prompt stakeholders to consider whether the impacts that have not been quantified are likely to be important enough to change the balance of costs and benefits. It is not intended that anyone should add together the star ratings given to the various impacts – they are simply intended as ‘flags’ to distinguish what is probably important from what is probably not. Stakeholders are of course free to come to their own conclusions on the relative importance of the different impacts considered in this process.

4.6.2 Ratings for effects in the extended CBA

The star ratings shown in Table 18 for the extended CBA as developed on the datasheets identify some health and ecological impacts as the most important of the effects that have been omitted from the CAFE benefits analysis.

4.6.3 Application of the extended CBA

It is not envisaged that these star ratings will change from scenario to scenario (to do so would involve some form of quantification, the lack of data for which is precisely the reason for needing to develop and use an extended CBA). However, indications of change in risk (e.g. extent of critical loads exceedance) will be provided on a scenario by scenario basis where possible.

Decision makers may like to consider these effects in different ways, depending on the result of the quantified cost-benefit comparison:

- In situations where costs exceed benefits:
  - Are unquantified effects likely to be sufficiently important that they would cause benefits to increase to a point where they exceed costs?
- In situations where benefits exceed costs:
  - Are unquantified effects sufficiently important that they would give much greater confidence that benefits are larger than costs?
  - Are unquantified effects large enough to have a significant impact on the ratio of benefits to costs, increasing the importance of dealing with air pollution over other problems?

Table 18 – Position on ratings for the extended CBA in April 2005. Effects considered likely to be negligible are omitted from this table.

Effect	Preliminary rating
Health	
Chronic effects of $PM_{2.5}$ on cardio-vascular disease	★★★
Ozone: chronic effects on mortality and morbidity	★★
SO_2: chronic effects on morbidity	★
Effects of secondary organic aerosols	★★★
Direct effects of VOCs	★
Social impacts of air pollution on health	★★
Altruistic effects	★★
Materials	
Effects on cultural assets	★★
Crops	
Indirect air pollution effects on livestock	★
Visible injury following ozone exposure	★
Effects of air pollution on the quality of crops, irrespective of issues concerning yield and visible injury	★★
Interactions between pollutants, with pests and pathogens, climate...	★★
Forests	
Effects of O_3, acidification and eutrophication	★★★
Freshwaters	
Acidification and loss of invertebrates, fish, etc.	★★★
Other ecosystems	
Effects of O_3, acidification and eutrophication on biodiversity	★★★
Visibility	
Change in amenity	★
Groundwater quality and supply of drinking water	
Effects of acidification	★

4.7 Conclusions on the use of bias analysis

Despite the best efforts of the teams involved, the results of the EMEP, RAINS and CAFE-CBA models are subject to a number of unquantified biases. In general terms, the most important appear to be:

- **EMEP modelling**
  - Omission of secondary organic aerosols
- **RAINS modelling**
  - Emission starting point bias
  - Omission of some abatement techniques
  - Lack of account of future technical developments
  - Lack of differentiation of particle species by effect
- **Benefits modelling**
  - Omission of impacts on ecosystems, cultural heritage, etc.
  - Lack of differentiation of particle species by effect

Several of the biases identified will have a more or less equal effect over the whole of Europe. However, the effect of others will vary from country to country. Despite the inter-linkages present between pollutants and effects, the importance of biases will also vary with the objectives defined for any scenario – a scenario focused on PM control may be little affected by sensitivities in the ozone analysis. It is thus difficult to define general rules on the reliability of the analysis for different stakeholders.

However, this does not mean that it is impossible to do anything about the biases that are present. The listing of biases in the preceding tables makes it possible for any scenario to identify which seem likely to have an important impact on the benefit:cost ratio and which are unlikely to be important. Ratings for each bias should be revised in line with the factors that influence results for any scenario. The overall impression of biases can then be considered alongside other information, for example, the probability that benefits will exceed costs for any scenario, assessed using the methods defined in Chapter 2. Given the qualitative nature of the result it is unlikely to cause a major change in policy, but it may strengthen or weaken the rationale for heading in a particular direction on air quality policy.

Knowledge of biases can also assist in the formulation of policy, designing legislation in a way that (e.g.) is sufficiently flexible that methodological changes in emission inventories over time can be factored out of the analysis.

Chapter 5 Discussion

5.1 Overview

If the costs and benefits of air pollution control were known with absolute confidence there would be no problem in comparing the two. However, costs and benefits are subject to uncertainties and some of them (on both sides of the cost-benefit equation) are significant. The quality of knowledge for identification of these uncertainties is variable, as is the availability of quantitative data with which to describe them. Further to this, some uncertainties are statistical and continuous in nature, some relate to discrete choices (e.g. selection of approaches for the valuation of air pollution – related mortality) whilst some simply relate to a lack of knowledge. It is clear from this that the development of a fully consistent approach to description of uncertainty across the CAFE analysis is not straightforward.

The extent to which uncertainty needs to be considered in any situation is largely dependent on the balance of costs and benefits. Where estimated costs far exceed estimated benefits it is unlikely that any assessment of uncertainty would change the perception of that relationship unless some possible outcomes were politically untenable (an obvious example, though not one relevant to CAFE, concerns major nuclear accidents). Similarly, where benefits far exceed costs, uncertainties should be of limited importance. Much of the CAFE work seems to be focused on what we may refer to as ‘the more interesting region’ where costs and benefits are more closely comparable and where uncertainties could have a significant outcome on the analysis.

Consideration of uncertainty in comparison of costs and benefits cannot, therefore, be an automatic process. Awareness needs to be raised of the component uncertainties of each part of the analysis. This has been addressed in this report. The most important of the component uncertainties should be highlighted and quantified to the extent possible. Again, this is done here. Consideration also needs to be given to how satisfactory the assessment of uncertainty is. We believe that this report lays the ground for a high quality assessment of uncertainty, though this question needs to be asked against analysis of specific scenarios.

This report has identified three main strands for assessment of uncertainty, these being statistical analysis, sensitivity analysis and assessment of biases, the latter being largely associated with gaps in knowledge. Some of these can be addressed relatively easily in quantitative terms. Others cannot, and require a more subjective assessment. Irrespective of whether they can be addressed quantitatively or semi-quantitatively, all of the uncertainties identified here are potentially important and need to be considered.

Other methods of assessing uncertainty do exist and have been suggested to apply in the CAFE program[4]. One possibility is define a series of uncertainty scenarios in which one would attach low, medium and high values to critical parameters and then undertake ‘low’, ‘medium’ and ‘high’ runs. However, this type of analysis would not allow the potential for errors to be randomly positive and negative which would cancel out and prevent the generation of some misleadingly extreme results at both

[4] CONCAWE July 2004

ends of the range. Such analysis would give an unrealistic spread in benefits estimates (i.e. "worst case" and "best case" in all parameters). It would also not permit a probabilised comparison of costs and benefits, giving stakeholders no guidance on the relative likelihood of each outcome. As the purpose of uncertainty analysis is to improve understanding of the robustness of results, it was hence not considered methodologically correct to construct "worst" and "best" case scenarios in this way.

5.2 Combining the different methods identified in this report

Guidance is clearly needed on ways in which the analysis defined here can be brought together to form a coherent approach to uncertainty assessment. For most scenarios the following scheme will be appropriate:

Step 1: Quantify costs and emissions. Identify meteorological year(s) used for the assessment

Step 2: Quantify benefits. As part of the standard assessment, provide results based on median and mean VOLY and VSL estimates. Identify meteorological year(s) used. Where only one year has been used, provide material to demonstrate the bias that this has on results (i.e. the appropriate graphs from Figure 14, Figure 15 and Figure 16 of this report). Investigate other key sensitivities (e.g. cut-point for ozone, particle speciation relative to mortality impacts) as appropriate.

Step 3: Make initial comparison of costs and benefits. Assess under what sets of assumptions results suggest that benefits would exceed costs and vice-versa.

Step 4: Perform statistical analysis around best estimates of benefits, using the methods defined in Chapter 2. Calculate the probability that quantified benefits will exceed costs.

Step 5: Consider which of the biases listed in Chapter 4 are likely to influence the balance of costs and benefits significantly. Then consider the overall effect of these biases – when taken together are they likely to lead to over- or under-estimation of the benefit:cost ratio? Then consider whether the magnitude of bias is likely to be sufficient to alter the benefit:cost relationship significantly.

Step 6: If necessary, carry out a stepwise sensitivity analysis on costs and/or benefits, drawing on the conclusions of the review of biases. Assess the probability that quantified benefits will exceed costs at each point.

5.3 Final conclusion

It is clear from this report that there are a large number of uncertainties that affect the analysis of scenarios being considered in the CAFE Programme. It is the view of the authors that this is not a barrier to effective and efficient decision making, primarily because:

- We know a lot about the uncertainties that are present.
- We have a range of tools for assessment of these uncertainties.
- We can use these tools to see how uncertainty could influence the reported relationship between costs and benefits.

Chapter 6 References

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