Uncertainty Assessment in Transport Policy Modeling on the Conversion of Vehicles from Petroleum to Compressed Natural Gas

by

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

October, 2012

Tanzila Khan

Dedicated

To

My Mother

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ABSTRACT

In order to control the vehicular emission-induced air-pollution and consequent health hazards in Dhaka, recently one major policy initiative was taken by Bangladesh government to switch to a better alternative fuel - Compressed Natural Gas (CNG), from the conventional diesel and/or gasoline fuels. CNG is an attractive alternate automobile fuel primarily due to its less particulate emissions performance. However, CNG conversion can have implications on climate changes through emissions of well-identified green-house gases (carbon-di-oxide, methane) and aerosols (black carbon, organic carbon and sulfur-di-oxide). Therefore, the evaluation of the true impacts of such a wide-scale transport policy requires a comprehensive model. Uncertainty assessment is an integral part of such comprehensive policy-impact assessing models to support the decision-making processes. It is a study of communicating the model results with the complex combination of uncertainty and sensitivity analyses. This research proposes an overall precise framework for evaluation of the stated transport policy impacts by including uncertainty assessment as an important analyzing tool.

The policy is being analyzed for two major impacts – urban-air quality and climate impacts. Following impact-pathway approach, a model is developed in programming language C++ to determine health benefits in monetary terms from reduced $PM_{2.5}$ emissions resulting from the policy. Grid-based vehicular emission of $PM_{2.5}$ for Dhaka city is estimated over Dhaka City Corporation (DCC) and greater Dhaka (GD) region. The corresponding concentrations are estimated using grid based source-receptor matrix (SRM) recently developed for Dhaka. Climate impacts are quantified by climate model through estimating the changes in emissions of the relevant species which affect the overall climate balance by contributing to global warming and/or cooling processes. To communicate the policy model results with uncertainty studies, an approach of seven-step methodology has been formulated. Uncertainties in model factors are represented with sampling-based probabilistic approaches. Uncertainty analysis is conducted by Monte-Carlo simulation method that involves random sampling from the distribution of inputs and successive model runs until a statistically significant distribution of outputs is obtained. 5000 random numbers are generated corresponding to the continuous probability distributions assigned to each uncertain input factor.

Without the consideration of uncertainty, urban-air quality model gives total health benefits of USD 937 million over DCC and USD 1134 million over GD grids (13.45 and 16.28 million BDT respectively, 2010 prices) accrued from the policy. The climate model estimates total increase in emissions of about 941,000 tons/year and a climate cost of about USD 42 million (about 6,03,000 BDT) due to policy. With the inclusion of uncertainty analysis, the mean health benefits is obtained as about USD 1227 million with 95% confidence interval of USD (1213-1241) million (17.41-17.82 million BDT) over DCC. The corresponding values for GD are about USD 1490 million, USD (1473-1506) million respectively or 21.4, (21.15-21.62) million BDT. The mean climate cost accrued from the policy is about USD 26 million (3,73,295 BDT) resulting from a mean change (increase) in global emissions of about 592,000 tons/year.

Sensitivity studies ascertain most-priority transport-specific factor as $PM_{2.5}$ emission factor from gasoline cars for air-quality model. For the climate model input factors, the resource allocation priority order is obtained as emission factors of methane followed by the annual vehicle activity, black carbon and carbon-di-oxide emission factors from specific vehicle-fuel combinations.

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CHAPTER 1

INTRODUCTION

1.1 Background

Road transportation, especially motor vehicles, is a major source of air pollution in all large cities of the world. This is worldwide extensive research issue that has linked motor vehicle induced air pollution to premature mortality (Small and Kazimi 1995, McCubbin and Delucchi 1999 in the USA, Kunzli et al. 2000 in Europe, BTRE 2005 in Australia, Chattopadhyaya 2009 in Delhi). Source apportionment studies, in general, show that motor vehicles are one of the most significant contributors to air pollution.

In developing countries, the scenario is often even worse primarily because of an increase in motor vehicle ownership resulting from a high economic growth and relatively lax emissions control. In Dhaka, several related studies have estimated the source-wise emissions level and have concluded with the fact that motorized transport vehicles are the single largest contributor to particulate air pollution especially to fine particulate matter concentrations (Begum et al. 2006a, 2005a, 2004; Salam et al. 2003). These studies have also identified the specific emitting sources within the vehicle fleet as diesel-powered vehicles and two-stroke engine gasoline vehicles. ADP report (2006) summarizes that petrol-fueled light-duty vehicles (cars/vans) and auto-rickshaws contribute 85% Carbon monoxide (CO), while diesel-fueled buses and trucks contribute 84% of total Nitrogen oxides (NO_x). Two- and three-wheeled auto-rickshaws contribute about half of the total hydrocarbon (HC) emissions, while particulate matter (PM) emissions come mostly from diesel buses and trucks (45%), and auto-rickshaws (40%). Air pollution to such high levels, is estimated to be responsible for approximately 3,580 premature deaths, 10 million restricted activity days and 87 million respiratory symptom days per annum. The alarming situation has raised a prime concern among the policy makers to control the situation. Moreover, motor vehicles are also a major source of carbon emissions, which is a potent greenhouse gas (GHG) that adversely affects the climate system to cause global warming. US personal vehicle fleet alone emits more CO_2 than every individual country in the world, except China (Greene and Schafer 2003).

Recently some policy initiatives have been undertaken in order to improve the air quality of Dhaka, and in some cases, for the whole country. i.e. banning of leaded fuel in the country in 1999, tightening emissions standards for motor vehicles in 2002, banning the two stroke three wheeler auto-rickshaws from Dhaka on January 1, 2003, vehicles older than 20 years of age and high-emitting ones etc. Among all these scattered attempts made by the government to control the worsening air pollution, adopting an alternative fuel for the motorized vehicles was one major policy initiative. Compressed Natural Gas (CNG) is an attractive alternate automobile fuel in order to reduce particulate emissions from vehicles (Hammond & Lalor 2007; Ristovski et.al. 2000; Clark et.al. 1999). CNG as an automobile fuel was first introduced in Dhaka in 1995 (Rupantorito Prakritik Gas Company Limited, RPGCL 2009), although it did not gain a momentum initially. Use of CNG for petroleum vehicles had dual advantages for Bangladesh. Firstly, CNG is an indigenous resource; thereby it has the potential to save foreign currency that would otherwise be used to import petroleum for the transport sector. Secondly, the particulate emissions from CNG are much lower than corresponding petrol or diesel vehicle, helping improve the air quality (Kremer 1999). Accordingly the government made conscious attempts to increase the use of CNG in transportation. The CNG industry got some momentum during early 2000 when CNG run taxis were introduced in Dhaka city. Replacing the old two-stroke petrol run auto-rickshaws with 9,000 new CNG run auto-rickshaws also helped the industry gain a critical mass, especially to expand the CNG refueling network. At the same time the government instructed mandatory retrofitting of all government vehicles with CNG conversion kits. The government also encouraged the conversion of non-government vehicles by making several policy initiatives, e.g. by exempting import duty on CNG conversion kits and CNG storage cylinders, by increasing the prices of petroleum fuel (which were subsidized before), etc. All these initiatives led other vehicles (private cars, SUV’s, minibuses, buses) to gradually switch to CNG from petroleum. Although the air pollution improvement was the prime reason for the switch, the associated benefits accruing to society because of the policy were not measured. Particularly, the CNG conversion can have implications in GHG emissions. Converting petroleum vehicles to CNG results in reduced black carbon emissions, which has positive impact on climate change. On the other hand, the conversion can have an adverse impact on the climate system through increased emissions of carbon di-oxide and methane or by reducing SO_2 (precursor to sulphates) emissions. Therefore the true impacts (whether benefits or costs and to what extent) cannot be determined exactly unless these issues are analyzed.

A CASR (Committee for Advanced Studies & Research) project (funded by Directorate of Advisory, Extension and Research Services (DAERS), Bangladesh university of Engineering

& Technology) in 2010 conducted an ex-post analysis of the benefits (or costs) that can be attributed to CNG conversion of motor vehicles with the underlying limitations. The project was an attempt to introduce the concept of evaluating the effects of such important policy measures, at a simplified form, due to lack of required input models for Bangladesh and also without any significant uncertainty assessment.

1.2 Present State of the Problem

Although various policy measures have been taken to reduce emissions from the motor vehicles, it is, however, important to understand the environmental, climate and economic benefits or costs of these policy measures to curtailing emissions. Without such an analysis, it is impossible for policy makers to make informed decisions, and often the choice of policy tools becomes an ad-hoc decision. Before the attempt made by the project under CASR, there was no model available in Bangladesh to carry out such an integrated analysis of health, climate and associated economic benefits from a policy intervention. There is a dire need for such an integrated policy analysis tool to help the policy makers in informed decision making in transportation.

Developing a generic policy analysis tool for air pollution or GHG mitigation strategies is a challenging task, especially in a developing country like Bangladesh, where the lack of reliable data is a perennial problem. A comprehensive model to evaluate all possible mitigation strategies also requires complex interdisciplinary input from atmospheric modelers, engineers, climate scientists, economists and epidemiologists yet capacity in these fields for such a work is also scarce. Even if there are some recent works on air quality models (Rahman 2010; Arjumand 2010) which are necessary for the analysis, most of the basic inputs to their models may have large uncertainty. Such uncertainty of the input factors imparts uncertainty on the final results as well, and sometimes the accuracy of the final results can be significantly compromised. In general, data from such sectors, particularly in Bangladesh, suffers from large uncertainties and the policy results are sensitive to different scenarios. It is therefore very important to understand these uncertainties in the input as well as their impact on the final valuation of the benefits arising from any policy intervention in the transport sector (or any other sector).

The stated CASR project analysis (Wadud & Khan 2011) lack inputs from adequate air quality model replaced with simplifying assumptions in different steps of computation and consequently provide results with large uncertainty which was not quantified. These are also listed in the limitations of the project report. The report specifically highlights that further quantitative uncertainty assessment is necessary for such a policy tool to be useful and for results to be reliable.

This research is an attempt to propose an overall precise framework for evaluation of important transport policy in order to facilitate the decision-making processes. The research will also aim to overcome the limitations of the previous studies and quantify the precision of the results by developing a quantitative policy assessment model with special focus on conducting the uncertainty assessment. Uncertainty studies include investigating the effect of uncertainties of the important factors or inputs of the model on the final outputs of the CNG conversion policy impacts both in urban-air and climate perspective. Uncertainty assessment includes tests of sensitivity of outputs to the inputs. From the sensitivity analysis, the study also aims to identify the sectors of data which contribute to the variability of the results the most. Therefore, it is possible to determine the effective allocation of resources for the future research, i.e. on which factors more efforts should be given to increase the accuracy and also different scenario analysis for policy options. The detail concept will be discussed in the following chapter. This research addresses the uncertainty assessment as an important analyzing tool in the valuation of any decision making to obtain the accurate results which is still not a very common or popularly practicing analyzing tool in Bangladesh.

1.3 Objectives of the Study

The major goal of this study is to address the importance and contribution of uncertainty assessment in a transport policy implementation and to propose a detail methodology of conducting the uncertainty studies as well. In this thesis, vehicular conversion to CNG is considered as a case study for the purpose. This uncertainty assessment is conducted not only to obtain precise range of results but also to determine the scale of priorities of definite sectors of data, regarding transportation and economic analyses of such important transport policy options.

The specific objectives are:

1. To determine and quantify (benefits/costs) the impacts as the change in emissions of the specified pollutants (both urban-air and climate pollutants) by estimating the emission inventories from the road transport sector in Dhaka before and after the CNG conversion policy intervention

2. To identify the impact of uncertainty in transportation data on vehicular emissions and to analyze the types and effects of the associated uncertainties on the overall results
3. To define an overall methodology framework of conducting uncertainty assessment
4. To conduct the uncertainty assessment by performing Monte-Carlo uncertainty analysis with a view to estimate the final results within a certain confidence interval using statistical methods of computation
5. To conduct sensitivity analysis to determine the priority-based ranking of the factors affecting the result in order to limit the scope of detail studies on the less important factors for further accuracy
6. To prepare a Tornado chart representing the variability of the final results due to factors' variability from their nominal values used for the calculation

1.4 Scope of the Study

The research work is overall designed in a two-step method. First of all, models are developed for the respective economic analysis of the impacts of CNG conversion policy. In the second stage, uncertainty assessment is conducted for the policy evaluation models and the intended results within a particular boundary.

While CNG conversion policy can have many implications, the study is primarily concerned with the urban-air quality which is directly related to the health condition of people. The focus is to determine the (reduced) mortality effects accrued from the improved air-quality due to policy intervention. In this case, the measure of the improved air-quality is in terms of fine particulates emitted from the diesel and/or gasoline vehicles causing cardiovascular and respiratory diseases. The target population is in the study area covering Dhaka City Corporation (DCC) and also the greater Dhaka. For the details in this regard, the discussion is headed toward chapters 3 and 4.

Furthermore, another goal of the study is to estimate the climate impacts in a wider perspective as global climate changes rather than the air quality effects. For this, only the GHG and/or aerosols relevant to road transport and the stated policy will be taken into account. The details can be found into the chapters 3 and 5.

On the other hand, the boundary of the proposed uncertainty assessment framework pertains to the model assumptions, intended results and the overall conduction strategy of the uncertainty studies. Therefore, in order to understand the scope of the study in this regard, it is required to be well-acquainted with the related terminologies and the specific methodology. This can be accomplished by linking the literature reviews in the second chapter to the scope of the proposed methodology discussed in the sixth chapter.

1.5 Thesis Outline

The first chapter is the Introduction to the thesis. The second chapter discusses the detail literature regarding the concepts of uncertainty assessment required for any policy evaluation process. Literature about the impacts of urban-air and climate changes associated with CNG conversion of vehicles is discussed in chapter 3. The detail methodology of the impact modeling and valuation approaches for both health and climate impacts are described in chapter 4 and chapter 5 respectively. Chapter 6 assembles all the data required for the respective computation processes, conducts uncertainty assessment and analyzes the obtained results. Finally, the seventh chapter is the concluding chapter which summarizes all the major findings of the study, lists the limitations of the study and suggests some recommendations in related sectors.

CHAPTER 2

A REVIEW OF UNCERTAINTY & SENSITIVITY ANALYSES IN TRANSPORT POLICY

2.1 Introduction

This chapter introduces and discusses the literature on uncertainty assessment. In general, outputs of any quantitative model require a particular confidence level of the certainty of the accuracy of the results. This, in turn calls for the uncertainty analysis which identifies the uncertainties in model results arising from the uncertainty in model input factors and the sensitivity analysis which determines as to how uncertainty in the output of a model can be apportioned to different sources of uncertainty in model input factors. Uncertainty and sensitivity analyses are referred to as Uncertainty Assessment together (Allaire 2009). An important transport policy modeling, like that of CNG conversion of vehicles, needs such uncertainty assessment in detail to obtain both accuracy of results and scenario analysis to facilitate decision making.

In this chapter, after the introduction to uncertainty assessment in section 2.1, section 2.2 defines the basic terms of uncertainty studies. Section 2.3 discusses the importance of such studies and section 2.4 describes the overall methodology framework of conducting uncertainty assessment. Section 2.5 describes the conventional methods of conducting uncertainty and sensitivity analyses available in literature along with the different means of representing data uncertainty. Section 2.6 gives the summary of the chapter.

2.2 Important Terminologies of Uncertainty Studies

There are some technical jargons in uncertainty assessment studies that are commonly mistaken in English usage and hence are frequently confused with each other. These term definitions are important to understand before going for such analyses. Some of the most important definitions are given below which will be used throughout the study.

Uncertainty:

Uncertainty refers to lack of knowledge about specific factors, parameters or models. Uncertainty is generally classified as *aleatory*, which arises through natural randomness, or *epistemic*, which arises through imperfect knowledge. The fundamental difference between these two categories is the fact that aleatory uncertainty is irreducible, whereas epistemic uncertainty may be reducible if more knowledge of the uncertainty is obtained (Allaire 2009).

Variability

Variability refers to observed differences attributable to true heterogeneity or diversity in a data sample or true population or exposure parameter. It is the extent to which data points in a data set or a sample diverge from the average or mean value. Variability also refers to the extent to which these data points differ from each other. Most commonly used measures of variability are: range, mean, variance, standard deviation and standard error.

Sensitivity

Sensitivity generally refers to the variation in output of a mathematical model with respect to changes in the values of the model's input. It can refer to how conclusions may change if models, data or assessment assumptions are changed.

As mentioned before, uncertainty and sensitivity analyses together are referred to as *Uncertainty Assessment* (Allaire 2009).

Factor:

Model factor is an external input to a model that is not contained in the definition of the model itself (Allaire 2009). Due to variation in the values of the model factors, the results will often vary significantly.

2.3 Necessity of Conducting Uncertainty Assessment Studies

There is a substantial body of literature that addresses challenges associated with using formal policy analysis models as aids in decision-making and communication issues at the science-policy interface. Recommendations from literature have strongly emphasized effective communication of uncertainties in results and findings. The public and policy-makers form opinions about the likelihood of events, and it is important that these opinions are based on the state of current knowledge. Uncertainty assessment help describe the nature of the problem even if the information presented is imperfect, which is often the case for model derived results (Mahashabde 2009). For example, for transport demand modeling, one of the most essential model factors is the traffic growth rate which is most likely to contain uncertainty; it cannot be estimated precisely, at best it can be projected or extrapolated from the existing or survey data to a future date. The uncertainty of this model factor is obvious to propagate into the model computation process and hence affect the overall result. Uncertainty assessment is required in order to avoid such inaccuracies in the model result and to find out the significance of the factor into the overall uncertainty relative to other factors as well.

Uncertainty analysis represents the effects of known sources of uncertainties (i.e. epistemic uncertainty) lying within the input factors, on the calculated results so that the results can be expressed within a range of reasonable values with particular confidence level. On the other hand, sensitivity analysis seeks to determine the high priority factors for which the uncertainties in the results are more, i.e. which input factors are responsible for most of the variability. It can also measure the ranges of values within which the results can vary when the most important factors vary among the possible values. Therefore, sensitivity studies can focus toward further research on the high priority factors to reduce uncertainty of the results and effectively save effort and time by limiting the scope.

2.4 Methodology Framework of Uncertainty Assessment

A detail comprehensive uncertainty assessment study should be conducted under the 7 steps of methodology given below (Allaire 2009):

Step 1**:** To establish the objectives of the uncertainty assessment - the objectives include uncovering technical errors, establishing research priorities through finding out the ranking of priorities, attaining particular level of certainty of the results etc.

Step 2: Documentation of the assumptions and limitations of the model - there will be some assumptions and limitations of the model itself used for the computation which may in turn comprise uncertainties. Stating those, uncertainty studies will be conducted within that boundary but will not include those assumptions within the study.

Step 3: Documentation of factors and outputs of the model - This step includes listing of the definitions of all the factors and the corresponding outputs which may again pass uncertainty to the final outcome.

Step 4: Classifying and characterizing factor uncertainty - Some factors will carry random irreducible uncertainty while will also contain some amount of epistemic or reducible uncertainty. The uncertainty study focuses on epistemic type of uncertainty of the different factors. Also the ranking of the important factors, according to the contribution to the variability of the results, will be enlisted.

In characterizing uncertainty, there are many different methods of representing uncertainty, such as probability theory, possibility theory, Dempster-Shafer evidence theory, imprecise probabilities, interval analysis, and several others.

Steps 5 & 6**:** Conducting uncertainty & sensitivity analyses - There are many techniques available for performing both uncertainty and sensitivity analyses, such as Monte Carlo methods, differential analysis, and variance-based approaches. The broader areas of the conventional methods will be discussed in the section 2.6.

Step **7:** Presentation of results: Results from uncertainty studies are typically given in terms of model output means, variances etc. Visual representation, i.e. construction of output histograms, tornado charts can be used to provide quantitative comparisons of various policy scenarios and quantitative evaluation of the performance of the model relative to fidelity requirements, which will be discussed in detail in the sensitivity analysis section 2.6.5.

It is important to mention here that the different steps of the methodology may vary among the studies depending on the objectives of the study, model types, scope of a model, characteristics and way of expressing data uncertainty etc. Therefore, in general, the overall framework of methodology for uncertainty assessment studies covers the stated seven steps as a whole and not necessarily will be the same for all the policy analysis.

2.5 Conventional Methods for Uncertainty Assessment

Methods for sensitivity analysis and uncertainty propagation can be broadly classified into four categories: (Isukapalli 1999)

(a) Analytical methods

(b) Computer algebra based methods and

(c) Sampling based methods

(d) Sensitivity Analysis

Each of the methods is described briefly in the following sub-sections:

2.5.1 Analytical Methods

Analytical methods involve either the differentiation of model equations and subsequent solution of a set of auxiliary sensitivity equations, or the reformulation of original model using stochastic algebraic/differential equations.

Some of the widely used analytical methods for sensitivity/uncertainty are:

(a) Differential analysis methods

(b) Green's function method

(c) Spectral based stochastic finite element method and

(d) Coupled and decoupled direct methods

2.5.2 Computer Algebra Based Methods

Another sensitivity analysis method is based on direct manipulation of the computer code of the model, and is termed automatic differentiation. Computer algebra based methods involve the direct manipulation of the computer code, typically available in the form of a high level language code (such as C or FORTRAN), and estimation of the sensitivity and uncertainty of model outputs with respect to model inputs. These methods do not require information about the model structure or the model equations, and use mechanical, pattern-matching algorithms, to generate a derivative code based on the model code. One of the main computer algebra based methods is the automatic differentiation, which is sometimes also termed automated differentiation.

2.5.3 Sampling Based Methods

The sampling based methods involve running the original model for a set of input/parameter combinations (sample points) and estimating the sensitivity/uncertainty using the model outputs at those points. Sampling based methods do not require access to model equations or even the model code. These methods involve running a set of model at a set of sample points, and establishing a relationship between inputs and outputs using the model results at the sample points.

When employing the sampling-based probabilistic method for representing uncertainty, assigning a probability distribution to a given factor is in fact implying that more is known about the uncertainty associated with that factor than is known about the data from information at hand. The propagation of this uncertainty, through model-to-model outputs, can then lead to estimates of output probability distributions, which gives the appearance of fully quantified uncertainty (Allaire 2009). Following is a brief literature review on statistical probability distribution used to characterize the data uncertainty.

2.5.3.1 Statistical Probability Distributions

A probability distribution is an equation that links each outcome of a statistical experiment with its probability of occurrence and a cumulative probability refers to the probability that the value of a random variable falls within a specified range.

There are primarily two types of probabilistic distributions - Continuous and Discrete:

Continuous distribution

If a variable can take on any value between two specified values, it is called a continuous variable. If a random variable is a continuous variable, its probability distribution is called a continuous probability distribution. The probability that a continuous random variable will assume a particular value is zero. An equation or formula is used to describe a continuous probability distribution.

Discrete distribution

If the value of a variable is fixed, then it is called a discrete variable. If a random variable is a discrete variable, its probability distribution is called a discrete probability distribution. With a discrete probability distribution, each possible value of the discrete random variable can be associated with a non-zero probability.

Each of the above two fundamental probability distributions can take many forms: Normal, Log-normal, Uniform, Triangular, Exponential Distribution, Weibull, Gamma, Laplace, Pareto, Beta etc. Most often, in nature, objects chosen randomly will fall under normal distribution, i.e. human heights. That is the reason why normal distributions are most commonly used in the maximum probability related problems of statistics. However, in case of characterizing uncertainty of a model factor, the choice of the appropriate probability distribution is often a critical issue. Although there are several statistical tests available to determine the probability function(s) that fits the data best, the choices are most often restricted by the limited data of a variable found in the real world and also the behavior of output distributions varying significantly among the choices of assigned input distributions.

For this reason, despite the popularity and wide use of normal distribution or others in regular theoretical statistics, in real world problems where data availability is generally scarce, uncertainties of random input variables are most often characterized by two types of distributions: uniform and triangular distributions. These are the simplest and most commonly used distributions and hence in this study, the discussion is limited to these two types and the most popular normal distribution.

Normal Distribution

A normal distribution, which is also referred to as a Gaussian distribution, is typically defined by a mean, μ, and a variance, σ^2. A random variable, X, with such a distribution is said to be distributed normally with mean, μ, and variance, σ^2. Figure 2.1 shows an example of a normal distribution with $\mu = 0$ and $\sigma^2 = 1$.

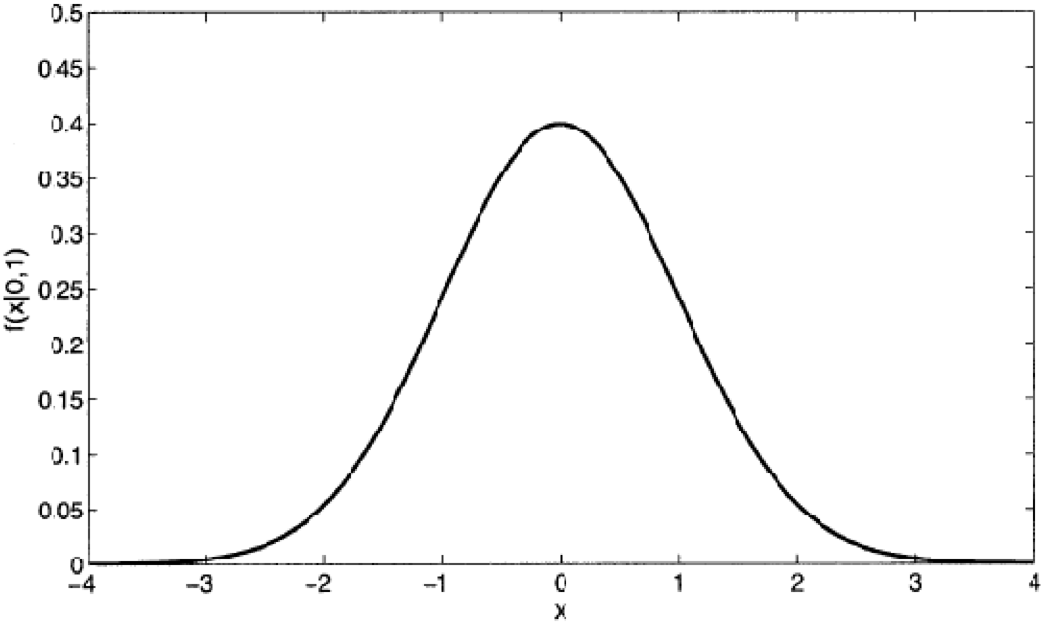

Figure 2.1: Example of a Normal Probability Distribution

Besides serving as a way of expressing uncertainty of a model input factor, this distribution is also useful in determining the statistical results of interest from an output distribution. This is because the combination of various distributions, assigned to characterize model input factors' uncertainties, finally end up often with a resulting distribution almost similar to a normal distribution.

Uniform Distribution

The simplest probability distribution occurs when all of the values of a random variable occur with equal probability. This probability distribution is called the uniform distribution or continuous uniform distribution. If *a* and *b* are the minimum and maximum values respectively for a variable, then it may assume any value between these two values *a* and *b* and the resulting distribution is continuous uniform distribution. Figure 2.2 shows an example of a uniform distribution on the interval [0, 1].

Discrete uniform distribution is a probability distribution whereby a finite number of values are equally likely to be observed; every one of *n* values has equal probability *1/n*. Figure 2.3 shows an example of a discrete uniform distribution for the case where x can take the values in the set $\{k_1, ..., k_5\}$.

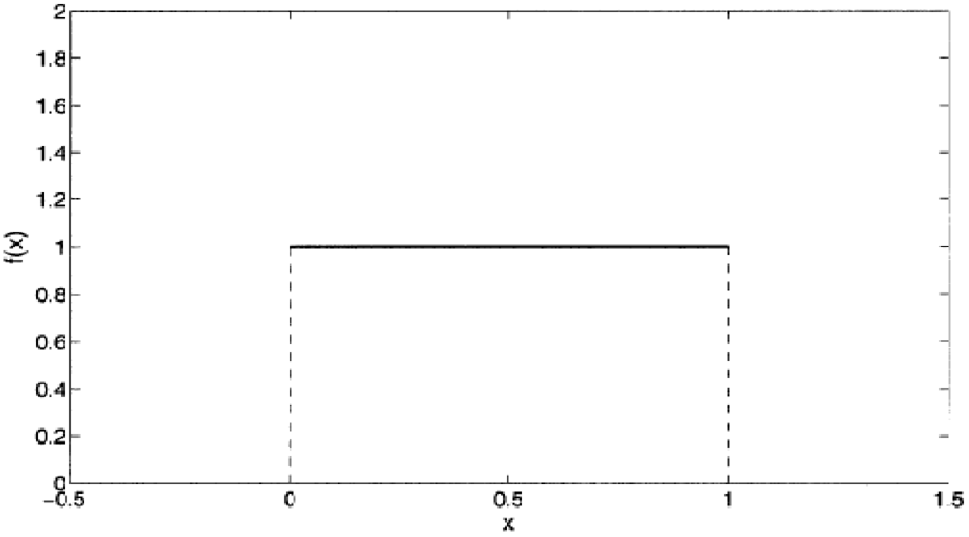

Figure 2.2: Example of a Continuous Uniform Distribution

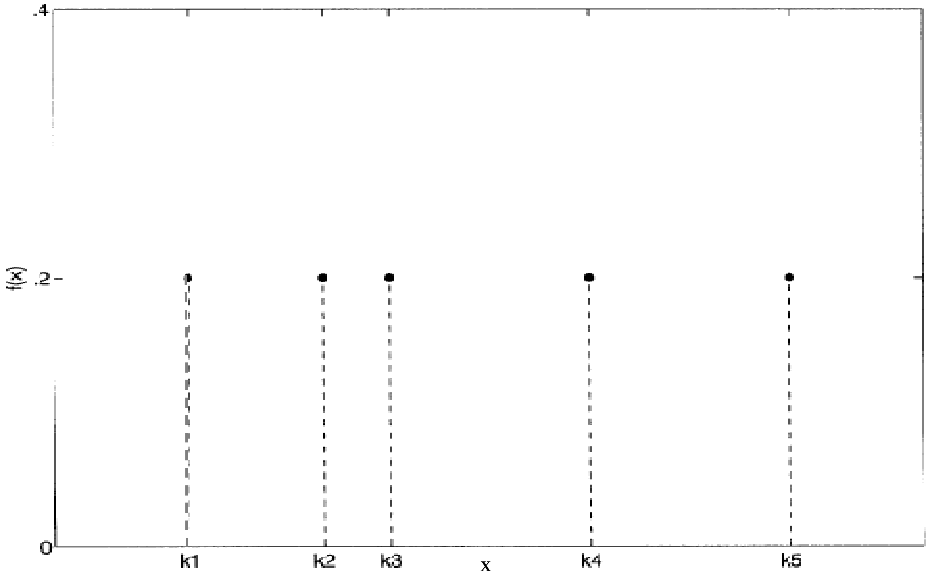

Figure 2.3: Example of a Discrete Uniform Distribution

Triangular Distribution

The Triangular Distribution is typically used as a subjective description of a population for which there is only limited sample data. It is based on knowledge of the minimum and maximum and an inspired guess or the most likely value. Despite being a simplistic description of a population, it is a very useful distribution for modeling processes where the relationship between variables is known, but data is scarce (possibly because of the high cost of collection). It is also used as an alternative to the Beta distribution.

Therefore, a triangular distribution is typically defined by three parameters, a minimum, *a,* a maximum, *b,* and a mode, *c.* A random variable, X, with such a distribution is said to be triangularly distributed with parameters *a, b* and *c.* An example of a triangular distribution with parameters, (-1, 1, 0), is shown in Figure 2.4.

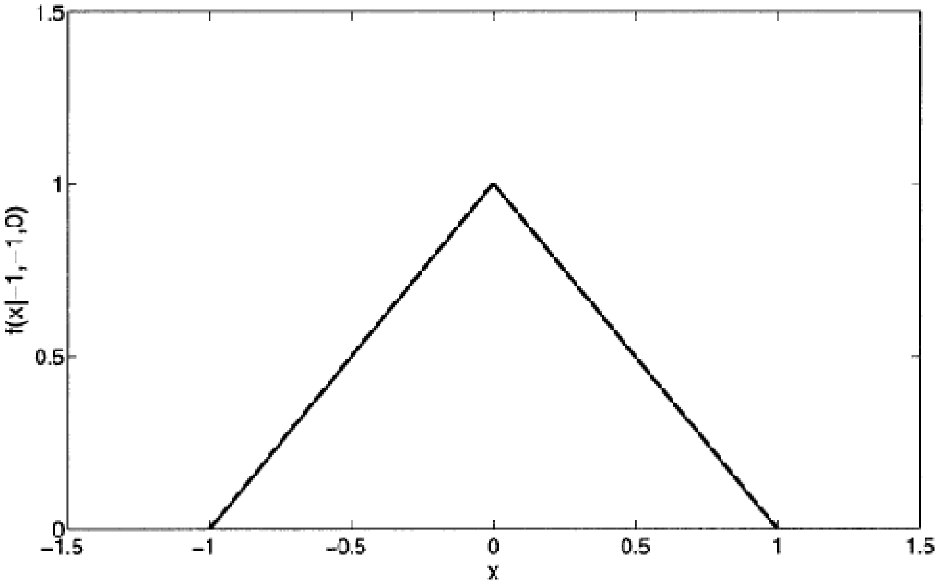

Figure 2.4: Example of a Triangular Distribution

Given the different methods of representing uncertainties, this research focuses only on sampling-based probabilistic approaches to uncertainty assessment due to their general applicability, effectiveness and wide use. After characterizing uncertainty of a model factor through sampling based approach, it calls for the choice of an appropriate method for conducting uncertainty assessment.

2.5.3.2 Methods of Uncertainty Assessment under Sampling-based Approach

Some of the widely used sampling based sensitivity/uncertainty analysis methods are:

(a) Monte Carlo and Latin Hypercube Sampling methods

(b) Fourier Amplitude Sensitivity Test (FAST)

(c) Reliability based methods and

(d) Response surface methods.

Monte Carlo (MC) methods are the most widely used means for uncertainty analysis, with applications ranging from aerospace engineering to zoology. Monte Carlo analysis is a computer based method of analysis developed in the 1940’s that uses statistical sampling techniques in obtaining a probabilistic approximation to the solution of a mathematical equation or model.

These methods involve random sampling from the distribution of inputs and successive model runs until a statistically significant distribution of outputs is obtained. There are several other different sampling strategies that can be used to evaluate expressions. The most common methods are brute force pseudorandom sampling, quasi-Monte Carlo sampling, and Latin hypercube sampling (Allaire 2009). Brute force pseudorandom sampling consists of selecting samples of factors randomly from their probability distributions. The method is referred to as pseudorandom sampling because a computer's pseudorandom number generator is typically used to generate the samples. When using a pseudorandom number generator it is important to be sure that it has been tested and verified using for example, the diehard battery of tests of randomness. Quasi-Monte Carlo sampling selects samples of factors deterministically using what are referred to as low-discrepancy sequences that aim to sample a space as uniformly as possible. In high-dimensions, these methods tend to have problems with some factors being highly correlated with other factors, and thus, care should be taken in the application of quasi-Monte Carlo sampling for high-dimensional models. The Latin Hypercube Sampling is one widely used variant of the standard Monte Carlo method and it is a method of selecting samples of factors in a manner that ensures all factors have been sampled across their entire domains. The advantages of Latin hypercube sampling are greatest when the number of samples is small, and diminishes as the number of samples increases.

Each method can dominate the other methods in terms of the number of samples required to achieve equally accurate estimates under certain circumstances, thus, the best sampling strategy depends on the model and the quantity being estimated. In this study, Monte Carlo analysis will be adopted for the uncertainty analysis since this is the most flexible, widely used and least time-consuming method of conducting uncertainty assessment studies. This method facilitates the process of generating a large sample of random numbers, simulation or iteration process in order to conduct the overall uncertainty and sensitivity analyses in a very flexible and effective way. The basic goal of a Monte Carlo analysis is to characterize, quantitatively, the uncertainty and variability in estimates of exposures or risk. A secondary goal is to identify key sources of variability and uncertainty and to quantify the relative contribution of these sources to the overall variance and range of model results. This secondary goal is satisfied through sensitivity analysis.

2.5.4 Sensitivity Analysis

The objective of conducting sensitivity analysis in the approach to uncertainty assessment is to find out two important features: the key factors that contribute to variability in model outputs the most and on which factors future research should aim at reducing output variability focus (Allaire 2009). There are several methods that can be used for sensitivity analysis. Among the most common methods are iterated fractional factorial design (IFFD), the standardized regression coefficients (SRC), the Spearman rank correlation test, vary-all-but-one analysis (VABO) and global sensitivity analysis. While all the methods have their own features and applicability, relatively easier and better interpretable approach is probably VABO. The method proceeds by running a Monte Carlo simulation and computing output variance. Then, a particular factor is fixed to a point on its domain, and another Monte Carlo simulation is conducted. The difference between the variance of the first Monte Carlo simulation and the second, is considered the contribution of the fixed factor to output variability. This process is repeated for each factor in the model. The key drawback to this method of apportioning output variance is that it is not obvious where each factor should be fixed on its domain, which can lead to a variety of different variance apportionments depending on how the factors are fixed, and can even at times lead to situations where fixing a given factor increases output variability. Thus, VABO methods are also not a rigorous means for finding out the key features stated.

The method of global sensitivity analysis is an extension of the VABO method that takes into account all possible locations each factor can be fixed on their domains. As a result, it is considered a rigorous method for quantitatively apportioning output variance, and is chosen in this study for identifying the key factors that contribute to output variability.

2.5.4.1 Global Sensitivity Analysis (GSA)

As stated earlier, global sensitivity establishes the importance of various factors within the model in terms of the contribution to the total variance of the result and this is done by fixing the value of a particular factor at a time while all other factors vary and hence by comparison of the computed variance to the total variance (when all vary). The more or less difference between these implies the more or less sensitive respectively the result/model is to that factor (which was fixed).

The results of a global sensitivity analysis permit a ranking of model factors that can be used in different development settings such as *factor prioritization* for future research, where the goal is to determine which factors, once fixed will cause the largest reduction in variance, and *factor fixing*, for which the goal is to identify non-influential factors that may be fixed without substantially affecting model outputs (Allaire 2009).

The process of apportioning output variance across model factors in a global sensitivity analysis can be carried out by both a Fourier Amplitude Sensitivity Test (FAST) method, and the Sobol' method. The FAST method is based on Fourier transforms, while the Sobol' method utilizes Monte Carlo simulation.

Detail of the Sobol's method is explained in Allaire (2009). In this study, only the derived basic mathematical equation is presented which is used to calculate global sensitivity and the parameter is called main effect sensitivity index, given below in equation (2.1):

$$\mathrm{S_i} = \frac{\mathrm{D_i}}{\mathrm{D}} \tag{2.1}$$

where,

S_i = main effect sensitivity index for the factor i (when only factor i is fixed for experiment)

D = Total variance of the model result when all the factors vary

D_i = Partial variance due to factor i

The sum of all global sensitivities of this form for a given function is unity. Global sensitivity includes another form of sensitivity which is termed as total effect sensitivity index as shown in equation (2.2).

$$\tau_i = 1 - S_i^c \tag{2.2}$$

where, $$S_i^c = \frac{D_i^c}{D} \tag{2.3}$$

D_ic = partial variance when only factor i varies (all others held constant) and hence S_ic is the sensitivity index computed when only i is re-sampled.

The main effect sensitivity indices, S_i, may be used for factor prioritization by ranking factors according to their main effect indices, which give the percentage of how much output variability can be expected to be eliminated by fixing a particular input somewhere on its domain. The total effect sensitivity indices, τ_i may be used for factor fixing, since a low total effect index reveals a given input has a small main effect and also does not take part in substantial interactions among other factors. In this thesis work, initially the factor prioritization is more important and hence the main effect sensitivity analysis will be applied here.

Although global sensitivity analysis is a rigorous method for output variance apportionment, its key drawback is that it results in the factor prioritization setting (that is, to direct future research), with the assumption that a given factor can, through further research, be fixed to some point on its domain. For epistemic factors, this is an optimistic assumption, which can lead to inappropriate allocation of resources. Further, for factors containing both aleatory and epistemic uncertainty, the assumption cannot be met. To account for the inherent limitations in using global sensitivity analysis results for directing future research, Allaire (2009) suggests an original method, referred to as *Distributional Sensitivity Analysis*. Rather than look at *factor prioritization* by considering which factors, once fixed, cause the greatest reduction in output variance, the method focuses on determining which factors would on average cause the greatest reduction in output variance, given that the portion of a particular factor's variance that can be reduced is a random variable.

There is another form of sensitivity analysis, in addition to global sensitivity, referred to as local sensitivity analysis and the overall approach is termed as a double-loop approach together. The outer loop is the local sensitivity while the inner loop is the global sensitivity.

One can roughly interpret the outer loop as being almost independent from the internal (inner loop) uncertainty influences and more likely to be affected by the chosen discrete values of the model factors at a time.

2.5.4.2 Local Sensitivity Analysis (LSA)

The influential factors i.e. important contributors to total output variance, may vary among a set of fixed, discrete values. Therefore, once the most important factors are obtained from global sensitivity analysis under probabilistic approach, factors may be varied, one at a time, keeping other factors constant at the nominal values, within a range of possible values to obtain how much the output varies from that computed at the nominal values, i.e. the base values of all the factors. The more the result varies from the nominal result by the variation of the values of the factor, the more sensitive the result is to that factor and hence before fixing, proper research is necessary on the factor. This analysis is also very essential for the cases when the factors are such that these cannot be represented by probability distribution.

Certain types of inputs and model factors that fall under the epistemic classification cannot be defined as random variables such as projections of future anthropogenic activity, growth scenarios, discount rate, impulse response function, etc (Mahashabde 2009). Also included in the LSA are those factors identified by the inner-loop GSA to be significant contributors to output variance. For such factors, results are simulated using different realizations of epistemic modeling uncertainties to capture uncertainty in the factors. The main difference between the global sensitivity and the local sensitivity approach is that the inner loop sampling or the global sensitivity analysis apportions output uncertainty among different inputs and model factors that can be expressed as random variables with probability distributions while the LSA assesses variability in outputs resulting from different realizations of certain epistemic modeling uncertainties that are expressed as modeling choices and are not captured through probabilistic distributions. Together the LSA and GSA identify the most influential inputs and model factors.

In LSA, values of the factors, one at a time, may vary between the possible two extreme points, i.e. minimum and maximum, or in some cases may be shifted to all possible realizations while holding all other factors at their nominal values. The nominal result, computed at the nominal or base values of all the factors, is taken as the reference or base line value. Then the variation of result from this base value is observed by varying the value of a factor among the possible set of values, while all others are held at their nominal values. This analysis is commonly represented with the help of a graphical tool, Tornado chart (Allare 2009; Mahashabde 2009). One of the important objectives of this study, mentioned in the Introduction chapter, is to construct this tornado chart to aid in future research on fixing the values of the significant factors within its domain.

An example of a tornado chart is shown in Figure 2.5. The selected output is plotted on the X axis, where the nominal result is indicated by a vertical line. Vertical axis plots different factors which are varied one by one to bring out the changes in the output with respect to the vertical bar, the nominal result. This variation in result for each factor is shown by the horizontal bars. Each of the horizontal bars indicates the variability in the output when the corresponding model factor is perturbed from its nominal value while fixing all other model factors at their nominal values.

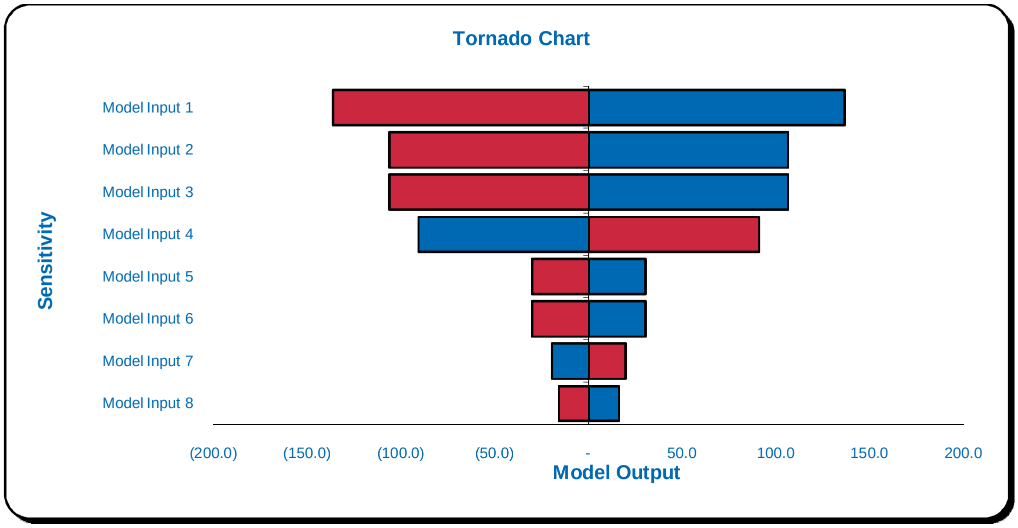

Figure 2.5: Example of a Typical Tornado Chart

2.6 Summary

This chapter introduces the detail concepts, methodology and objectives of uncertainty and sensitivity analysis in a policy analysis. The thesis work is intended to implement this approach and propose a simple methodology for the application of uncertainty assessment for the stated policy and for future policy analysis as well in any sector. The boundaries of work for this application are also mentioned in this chapter and will be discussed later in chapter 6. The next chapter will continue the discussion on the literature review of urban-air and climate perspectives and the impacts on these due to CNG conversion policy implementation.

CHAPTER 3

REVIEW OF ENVIRONMENTAL AND CLIMATE CHANGES DUE TO VEHICULAR CONVERSION FROM PETROLEUM TO CNG

3.1 Introduction

The main objective of the policy of converting petroleum vehicles to compressed natural gas is to improve the environmental condition in order to reduce the losses of lives from urban-air pollution induced from road transport. These losses are quite often related to adverse health impacts leading to premature deaths from air-pollution related diseases. In addition to the urban-air quality impacts, the CNG conversion policy also has another climate impact, on climate change. In this chapter, the overall literature regarding the urban-air pollution from road transport, climate changes and conversion of vehicles to CNG related to vehicular emissions are discussed. Section 3.1 is the introduction to the chapter. Section 3.2 reviews the urban-air pollution induced from motor vehicles, relevant pollutants and associated impacts and finally an overview of air quality in Dhaka city arising from particulate emissions. Section 3.3 discusses the introduction of CNG conversion policy as an alternate solution. Section 3.4 discusses the detail literature review over climate changes and greenhouse effects and the contribution from road transport. Section 3.5 gives a summary of the whole chapter.

3.2 Urban-air Pollution from Motor Vehicles

Air pollution can be of different scales: local, regional and global or climate changes (Rahman 2010). Local-air (or urban-air) pollution is a result of emissions of pollutants from different sources such as the industry, motor vehicles, biomass burning etc. Although such air pollution is related to different types of impacts depending on the type of pollutants and sources causing the pollution, the major adverse effect is on human health (USEPA 2007).

There are different types of pollutants with known health effects and are classified based on different criteria. Based on origin, there are primary and secondary pollutants such as Sulpher Oxides (SO_x), Nitrogen Oxides (NO_x), Hydrocarbons (HC) and Ozone (O_3), peroxyacetyle nitrate (PAN) respectively. These pollutants can again be classified as organic (Hydrocarbons) and inorganic (SO_x, NO_x) pollutants. According to the state of matter, there are two types of pollutants – gaseous (carbon monoxide, methane, SO_x, NO_x etc) and particulates/aerosols (dust, smoke, fume, mist, spray, virus etc). There are also six well-recognized criteria pollutants: carbon monoxide, lead, Nitrogen di-oxide, ozone, Sulpher dioxide and particulate matter. From the health point of view, the most important urban-air pollutant causing the major risk and associated with motor vehicles is the particulate matter (PM). Hence, the discussion in this study is limited to particulate emissions from vehicles.

Particulates are complex mixtures of organic and inorganic substance, except pure water, that exist as liquid or solid in the atmosphere under normal conditions and are of microscopic or submicroscopic size, but larger than molecular dimension. Particulate matter is the general term used for a mixture of solid particles and liquid droplets in the air. It includes aerosols, smoke, fumes, dust, ash and pollen. In contrast, aerosol is also a PM which refers to particles and the gas together. The composition of particulate matter varies with source, place, season and weather conditions. The anthropogenic sources are more harmful or toxic than the natural ones (Rahman 2010).

Particulate matter is emitted from a wide range of man-made or anthropogenic sources; the most significant primary sources being the road transport (25%). There is a strong relationship between vehicles and particulate matter health hazards found from different studies (WHO 2004; Bahauddin and Uddin 2010; Begum et al. 2011). There are also secondary sources of particulates formation such as from SO_2. However, the primary PMs are initially more important which enter the environment first with the known adverse health effects. Again, the associated health effects vary with the respective sizes of the PMs' (generally, the smaller the more dangerous). Hence the sizes are more important factors and not all the sizes of particulates are dangerous to health. The following sub-sections discuss on the sizes of PM, associated health effects and contribution of road transport to such effects.

3.2.1 Particulates and Particle Size: Aerodynamic Diameter

Particle sizes are often described by an equivalent 'aerodynamic diameter' determined by comparing them with perfect spheres having the same settling velocity. Particulate matter is characterized according to size - mainly because of the different health effects associated with particles of different diameters (Rahman 2010).

Particles of most interest have aerodynamic diameter in the range of 0.1 to 10 micrometer (µm). Particles smaller than these undergo Brownian motion and through coagulation, generally grow to sizes greater than 0.1 µm. Particles larger than 10 µm settle quite quickly. Two types (sizes) of particulate matters are most frequently used while considering health impacts: PM_{10} and $PM_{2.5}$.

PM_{10}: Particulates with aerodynamic diameter less than or equal to 10 µm. These are inhalable.

$PM_{2.5}$: Particulates with aerodynamic diameter less than or equal to 2.5 µm. These are respirable.

In general, coarse particulates can be regarded as those with a diameter greater than 2.5 µm, and fine particles less than 2.5 µm. Coarse particles usually contain rock and dust from wind erosion. Fine particles include soot, inorganic salts, and organic compounds.

$PM_{2.5}$ is mostly made up of two important components. These are – Black Carbon (BC) or elemental carbon or soot and organic carbon (OC). Black carbon and organic carbon are formed through incomplete combustion of carbonaceous fuel. They are used to describe aspects of ambient particulate matter (Begum et al. 2011). Organic carbon is the carbon fraction of the aerosol that is not black (Bond et al. 2004). Both of these are considered as aerosols having negative health effects. These also contribute to global warming and cooling processes as described in section 3.4.

The smaller and lighter a particle is, the longer it will stay in the air. Larger particles (greater than 10 micrometers in diameter) tend to settle to the ground by gravity in a matter of hours whereas the smallest particles (less than 1 micrometer) can stay in the atmosphere for weeks and are mostly removed by precipitation. Fine particles of less than 10 micrometres (µm) in diameter can penetrate deep into the lung and cause more damage, as opposed to larger particles that may be filtered out through the airways' natural mechanisms. This is why the finer the particles, the more important they are in terms of their adverse effects. The health effects of the particulates are discussed below.

3.2.2 Health Effects of PM and Contribution from Road Transport

The size of particles is directly linked to their potential for causing health problems. It has been already discussed in the previous sub-section that the greatest effect on health is from particles 2.5 microns or less in diameter, because they can get deep into the lungs, known as respirable particles and some may even get into the bloodstream. Effects of particulates are also important since they are often present in the atmosphere at a considerable amount. Vehicular air pollution is a major cause for such respiratory diseases in urban Bangladesh (IRIN 2009). Exposure to fine particulate matter has been associated with hospital admissions and several serious health effects, including premature death. People with asthma, cardiovascular or lung disease, as well as children and elderly people, are considered to be the most sensitive to the effects of fine particulate matter.

Adverse health effects have been associated with exposure to $PM_{2.5}$ over both short periods such as a day and longer periods for about a year or more. Long term exposure to air pollution can lead to premature death by increasing the rate at which lung tissue ages, by contributing to chronic obstructive lung disease, and by exacerbating cardiovascular disease. Sudden rise of pollution level (acute exposure), on the other hand, can cause the people who have history of cardiopulmonary diseases or simply weak or susceptible to die prematurely. This is known as the short-term or acute effect.

Epidemiological studies have provided real world evidence of associations between concentrations of PM and several health outcomes including mortality, hospital admissions for cardiovascular and respiratory diseases, urgent care visits, asthma attacks, acute bronchitis, respiratory symptoms and restrictions in activity (WHO 2004). Although there can be such various adverse health impacts of particulates pollution, studies have shown that premature mortality impacts dominates all other health impacts in monetary terms (USEPA 2007).

Since PM emission is of prime concern among the air pollutants, it is important to identify the contribution of motor vehicles or other sources to such emissions. This is essential for the decision-makers to allocate the resources efficiently. Source apportionment results show that vehicular exhaust is the largest contributors to PM in Dhaka (Begum et al. 2011). Rahman (2010) summarized the results from a number of studies on the source apportionment of particulate matter of concerned sizes. The results state that major sources of PM_{10} are road dust and motor vehicles while motor vehicles account for most of the $PM_{2.5}$. A study conducted for Dhaka city reports that in Dhaka, 23% of PM_{10} come from motor vehicles and 48% of $PM_{2.5}$ is contributed by the road transport (Begum et al. 2004). Motor vehicles are once again found to be the major contributors for both $PM_{2.5}$ (around 40%) and PM_{10} at two hot-spot locations in Dhaka (Begum et al. 2005). Therefore, a closer look over the scenario of urban air quality in Dhaka due to large PM emissions from its motor vehicles is important.

3.2.3 PM Emissions and Health Hazards from Motor Vehicles in Dhaka City

In Bangladesh, the estimated economic costs associated with environmental degradation are about 4.3% of GDP with urban air pollution accounting for almost one-fourth of that

(Rahman 2010). In Dhaka alone, this translates to health costs of almost USD 500 million per year. The World Bank has estimated that the economic costs of sickness and deaths associated with air pollution in Dhaka city are approximately USD 200-800 million per year. Within this, the contribution of motor vehicles' PM emissions is already discussed in section 3.2.2.

In terms of PM concentrations, typical urban annual mean values are 10-40 μgm^{-3}. Background levels in rural areas range from 0-10 μgm^{-3}. During pollution episode, particulate levels can rise to several hundred μgm^{-3}. Department of Environment, Bangladesh, reports that since 2002-07, the maximum concentration of $PM_{2.5}$ and PM_{10} of Dhaka city was 405 $\mu g/m^3$ and 543 $\mu g/m^3$ respectively. The city's average particulate matter levels are about 2 times higher than the Bangladeshi standard of 200 $\mu g/m^3$ in residential areas and are more than 10 times higher than the WHO guidelines of 120 $\mu g/m^3$ (24 hours) in commercial areas (Bahauddin & Uddin 2010).

A high concentration of black carbon, important constituent of $PM_{2.5}$ discussed earlier, in Dhaka City air has been reported. Vehicular emissions are one of the main contributors to these emissions as well. The characterization of these fine particles is very important for the regulators and researchers due to their potential impact on human health, their ability to travel thousands of kilometers across countries, and also their influence on global climate.

Bahauddin & Uddin (2010) reported that Dhaka's motor vehicles emit more than 3,700 tons of particulate matter less than 10 microns in diameter (PM_{10}) per year. The monthly average concentration of $PM_{2.5}$ and PM_{10} of Dhaka city was 73.34$\mu g/m^3$ and 132.11$\mu g/m^3$ in 2009 respectively. The high rising concentration affects badly also on health of roadside population responsible for causing the diseases like severe asthma, sudden cardiac failure, collapse respiratory tracts, continuous cold and fever, different eye diseases etc. (Bahauddin & Uddin 2010).

Under the prevailing conditions discussed so far, the policy-makers' view is to gain a control over these emissions from road transport sector in order to improve the urban-air quality and consequently reduce the health hazards in Dhaka. In order to achieve this goal, it becomes important to disaggregate the emissions sources among the fuel types (i.e. diesel, gasoline etc) within the existing transport system which finally leads to the stated policy of switching to a better fuel option for motor vehicles. The literature study behind such policy option is discussed in the following section.

3.3 Literature Review favoring Choice of CNG as an Alternate Automobile Fuel

There are many research works which have taken attempts of switching to Compressed Natural Gas (CNG) fuel with a view to reduce overall emissions level from vehicles in many countries. It is well-established and widely known from such works that CNG fuelled transportation provides better emissions performance compared to conventional diesel and gasoline fuelled vehicles. This emission reduction is associated with both health and climate impacts.

Studies, available in the literature, justify reduced emissions of the pollutants, through conversion to CNG, which are responsible for negative health effects and climatic impacts. In spite of the well-established positive results regarding CNG conversion, there are also some contradictory findings which focus on the particle size range and count concentrations emitted from CNG retrofit vehicles (Ristovski et al. 2003). One such study addresses that particles from CNG emissions are smaller than from diesel or even petrol emissions (majority of them are in the range between 0.02 and 0.06 µm); but at the same time it concludes with the fact that the particle emissions, from two large CNG spark ignition engines, in the size range between 0.5 and 30 µm were very low at a level below 2 particles/cm^3 (Ristovski et al. 2000). Moreover, $PM_{2.5}$ is the size of most of the masses emitted by diesel and gasoline vehicles (Cadle et. al. 1999) with known adverse health impacts. As a result, CNG produced the greatest advantage in the areas where diesel vehicles have the most problems: NO_X and PM. The NO_X emissions from CNG fueled vehicles were consistently reduced by a substantial amount compared to their diesel counterparts. Particulate emissions from CNG vehicles were also consistently and substantially lower (by 80-99%) than their diesel counterparts (Dhaliwal et. al. 2000). Conventional diesel buses have average particle count concentrations (i.e. particle numbers per unit volume) 3 to 4 times greater than CNG bus (Hammond et. al. 2007). This suggests that CNG replacement for similar-vintage diesel engines would produce substantial emissions reductions. Total hydrocarbon emissions from CNG fueled vehicles are usually higher than those from conventional diesel vehicles. Since the majority of this increase is non-reactive methane, this is not a concern for climate impacts (Dhaliwal et. al. 2000).

Large gains in further emissions reduction in the transport sector can be obtained by fuel change to CNG from petrol and diesel. Sulfur dioxide emission is completely eliminated as natural gas in Bangladesh does not contain any sulfur. CNG powered vehicles emit 85% less

NO_x, 70% less reactive HCs and 74% less CO than similar gasoline powered vehicles (Ravindra et. al. 2006). A comparison of the annual average concentration of SO_2, before and after the implementation of CNG conversion policy for diesel vehicles in Delhi, shows approximately a 50% reduction in ambient air (Ravindra et. al. 2006). Clark et al. 1999 found from two laboratories that NO_x and PM emissions were substantially lower for the natural gas buses than for the diesel buses.

Some studies (Lev-On et. al. 2002; Ayala et. al. 2002) suggest that ultra-low sulfur diesel (ECD/ECD-1) fuels with after-treatment, i.e. diesel particle filters (DPF), may prove to be a better alternative relative to CNG by lowering emissions more than that by CNG without oxidation catalyst. However, the possibility of a switch to ultra low sulfur diesel (ULSF) in Bangladesh in near future is remote, as Bangladesh still could not implement low sulfur diesel. ULSF also works with the recent diesel engines, and the existing old vehicle engines will not work well with ULSF. Also its limited application is due to the problems of fast aging of catalysts and temperature control during regeneration of traps (Turrio-Baldassarri et. al. 2005).

Often variations of results are found among different studies with OEM (Original Equipment Manufactured) and retrofitted CNG tests, CNG retests (just immediate after conversion and then again sometime elapsed after the conversion) etc. Before going directly for comparisons among such test results, it is important to know the test conditions. There are a number of factors that affect emissions from vehicles and hence it becomes difficult to compare such emission results. Some of the important factors are: test cycle, fleet years/technology, vehicle age and mileage, vehicle maintenance and low ambient temperature (Dhaliwal et. al. 2000) of which the most important one for CNG conversion may be the CNG conversion technology. Large differences among emissions of PM from CNG vehicles based on four different conversion technologies were observed. The study concluded that simply using a given fuel is not likely to produce lower emissions. This statement is also in agreement with Ristovski et. al. (2003) that the condition of vehicles is an important determinant of the emission levels, often more important than fuel or engine types. Similarly, another study found that PM emissions were far higher for aggressive driving style and small differences in driver's aggression and acceleration manner leads to significant changes in emissions of NO_x for CNG vehicles (Clark et. al. 1999).

From a recent study conducted at two hot spot locations in Dhaka, the long-term PM trend is found to exhibit a decrease of fine particulate matter concentrations over time which is due to government policy interventions like that of CNG conversion along with other actions (Begum et al. 2011). All these discussions lead to the conclusion that CNG conversion policy may prove to be an effective one for Dhaka city from health point of view.

3.4 Climate Change and Greenhouse Effects

Climate change is a significant and lasting change in the weather patterns, i.e. average temperature, amount of rainfall etc, over periods of time. It may be a change in average weather conditions, or a change in the frequencies of occurrences of extreme weather events with respect to the average conditions. Any system affecting the climatic balance through increased or decreased temperature or by altering net solar energy, in turn affect the whole global weather adversely which are referred to as Greenhouse effects.

The greenhouse effect is a process by which radiative energy leaving a planetary surface is absorbed by some atmospheric gases, called greenhouse gases. They transfer this energy to other components of the atmosphere, and it is re-radiated in all directions, including back down towards the surface. This transfers energy to the surface and lower atmosphere, so the temperature there is higher than it would be if direct heating by solar radiation were the only warming mechanism.

In general, the incoming solar radiation has a shorter wavelength than the outgoing energy radiated by the earth and the atmospheric constituents can let the radiant energy pass through, scatter the energy by reflection or they can stop it by absorption. Most long-wavelength energy radiated by the earth is absorbed by a combination of radiatively active gases, most important of which are water vapor, carbon di-oxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Oxygen (O_2) and Ozone (O_3).These gases, which are known as radiatively active gases that absorb wavelengths longer than 4 µm, are called Greenhouse Gases. This absorption heats the atmosphere, which in turn radiates energy back to the earth as well as out to space. As a whole, the process leads to increase in global temperature or global warming, called radiative forcing in short and the effect is referred to as Greenhouse Effect. Not only the greenhouse gases, but also there are some other important species, i.e. particulates or aerosols, which also exert such forcing as explained below.

3.4.1 Radiative Forcing

In climate science, radiative forcing is loosely defined as the change in net irradiance at the atmospheric boundary between the troposphere and the stratosphere (the tropopause). Net irradiance is the difference between the incoming radiation energy and the outgoing radiation energy in a given climate system. In general, if there is a difference between the incoming and outgoing solar radiations, due to the absorption and/or further re-radiation of energy by the global pollutants (greenhouse gases) as stated earlier, a net forcing is applied to the climate which can be either positive or negative (in relative terms) and the effects can be direct or indirect.

A positive forcing (more incoming energy than it is supposed to be) tends to warm the system, while a negative forcing (more outgoing energy) tends to cool it. The result of positive forcing is global warming and that of negative forcing is global cooling. Both the forcing may occur through direct (i.e. absorption or reflection) and indirect effect (i.e. by affecting the shape of the cloud and hence the albedo or reflectivity,).

An increase in global temperature (global warming) will cause sea levels to rise and will change the amount and pattern of precipitation, probably including expansion of subtropical deserts. Other likely effects include changes in the frequency and intensity of extreme weather events, species extinctions, and changes in agricultural yields. Warming and related changes will vary from region to region around the globe, though the nature of these regional variations is uncertain. Global warming is mainly due to greenhouse gases, i.e. CO_2, CH_4 and also particulates, i.e. BC etc, by directly absorbing radiations or indirectly by reducing albedo of the frozen surface which accelerates melting rates, when deposited on snow and ice.

Global cooling, a gradual reduction in the amount of global direct irradiance at the Earth's surface, has partially counteracted global warming. The main cause of this cooling is aerosols produced by volcanoes and pollutants (organic carbon, SO_2 etc.) These aerosols exert a cooling effect by increasing the reflection of incoming sunlight.

From the above discussion, it is clear that it is the global warming or cooling processes that measure the effects on the climate change or the contribution to the global climatic system from the greenhouse gases and/or particulates or aerosols discussed so far. So this measurement needs a scale or metric to express this contribution in terms of either warming or cooling and which are referred to as global warming and cooling potentials respectively.

3.4.2 Global Warming and Global Cooling Potentials

Global warming or cooling potential (GWP or GCP) is a measure of how much a given mass of greenhouse gas or aerosol is estimated to contribute to global warming or cooling respectively. It is a relative scale which compares the gas or particulate in question to that of the same mass of carbon dioxide (whose GWP is by convention equal to 1). A GWP or GCP is calculated over a specific time interval. A high GWP correlates with a large infrared absorption and a long atmospheric lifetime.

The finer particles stay up to several weeks in the atmosphere. Black carbon stays in the atmosphere for only several days to weeks, whereas CO_2 has an atmospheric lifetime of more than 100 years. But still, global warming contribution of BC is much more because of the higher GWP of BC which makes it the most important global pollutant. The values of GWP and GCP are taken from Reynolds & Kandlikar (2008). The values are respectively CO_2 (1), CH_4 (23), SO_2 (-35), BC (455) and OC (-100). The negative (-) signs before the values indicate negative forcing or global cooling while the positive values indicate positive forcing or warming. Further detail information can be found in the chapter 5.

Recent research has demonstrated that there are regional and global climate impacts of atmospheric BC and it has been proposed that control of BC emissions could be an economical means of reducing anthropogenic climate impacts (Reynolds and Kandlikar 2008). Again, organic carbon, which is a higher percentage of $PM_{2.5}$ emitted from CNG fuelled vehicle, contributes to global cooling which is desirable. But there might be corresponding increases in CO_2 and CH_4 emissions from CNG converted vehicles since natural gases in Bangladesh contain a high percentage of these gases. So the precise impacts must be determined through proper modeling.

3.5 Summary

This chapter discusses detail about the impacts of CNG conversion of petroleum vehicles in the aspects of both urban-air and global climate changes. The chapter also provides justification of probable benefits of CNG conversion policy through summarizing the results from different researches and studies in the relevant field available in the literature. Now the next two chapters are designed to investigate the true impacts in measurable quantities, the methods of which will be discussed in the respective chapters in detail.

CHAPTER 4

MODELING AIR QUALITY IMPACTS OF VEHICULAR CONVERSION TO CNG

4.1 Introduction

This study focuses on two different types of impacts associated with the vehicular conversion to CNG. Urban-air pollution primarily affects health and wellbeing of the people within the city, whereas greenhouse gas emissions' impact is global, through the changes in the climate system. This results in two different approaches to monetizing the impacts of intervention through CNG conversion. This chapter is designed to describe the detail methodology of the model developed in this study to estimate the health benefits accruing from this policy. Also the data required and used from different sectors for the various steps of the model, are discussed in this chapter while the global climate impacts will be discussed in the following chapter.

The impact pathway approach to determine the air quality impacts due to the policy is described briefly in section 4.2. Based on this approach, a model is developed and the methodology is further discussed in section 4.3. Section 4.4 will describe the emission inventory part of the model. Section 4.5 describes the method to obtain the corresponding change in concentrations obtained from the change in emissions. Section 4.6 models how to relate the measured improvement in concentration to the health impacts via concentration-response (C-R) functions. The methodology and different estimates of the parameter from literature are also summarized in this section. The next section 4.7 will discuss on the method to compute the particular health effects, i.e. avoided premature deaths or lives saved, from the policy. Standard valuation procedures, i.e. value-of-statistical-life, of certain health benefits due to policy are discussed on section 4.8. This section also summarizes different published estimates on the parameter for different countries and derives the values for Bangladesh. Section 4.9 gives the summary of the chapter.

4.2 Impact Pathway Approach – Estimating Urban-air Effects

In determining the benefits of a policy intervention to improve the urban-air quality, it is important to relate the reduction in emissions to well defined improvements in damage end points and associated benefits. There is a sequence of events in a model to value environmental externalities, which can be best explained by the impact-pathway approach (European Commission 2003, ExternE 2005).

As shown in the Figure 4.1, the first step in an impact-pathway approach is to quantify the emissions (or changes in emissions for a policy intervention), in this case, which can be determined from a vehicle emission inventory model. It is discussed in the previous chapter that the greatest advantage of the CNG conversion transport policy in urban-air quality is the reduced particulates emissions and more specifically the finer fractions, $PM_{2.5}$. Again, from the literature review in chapter 3, it is clear that $PM_{2.5}$ is the major concerning urban-air pollutant having known health hazards. Hence, this study will estimate the emissions of $PM_{2.5}$, using the vehicular emission inventory model.

In the second step of Impact pathway approach, for the current policy case which alters the emission characteristics of the vehicle fleet, the $PM_{2.5}$ emissions are fed into an air quality model in order to determine the changes in ambient air quality (i.e. change in $PM_{2.5}$ concentration) to which people are exposed. In the third step, the modeled improvement in ambient air quality is coupled with population distribution and epidemiological concentration-response (CR) functions of the health impacts to determine the avoided health incidences of different types. Here the most important adverse health effect measure is the premature mortality, as was discussed in the last chapter. Finally, each of the health cases (i.e. premature mortality to be considered) are then valued using the costs associated with those specific health end points or willingness to pay to avoid those health cases (Figure 4.1) to determine the avoided costs, or benefits, of the policy intervention. The European Commission (2003) and United States Environmental Protection Agency (USEPA 2007) follow this approach for their regulatory impact analyses.

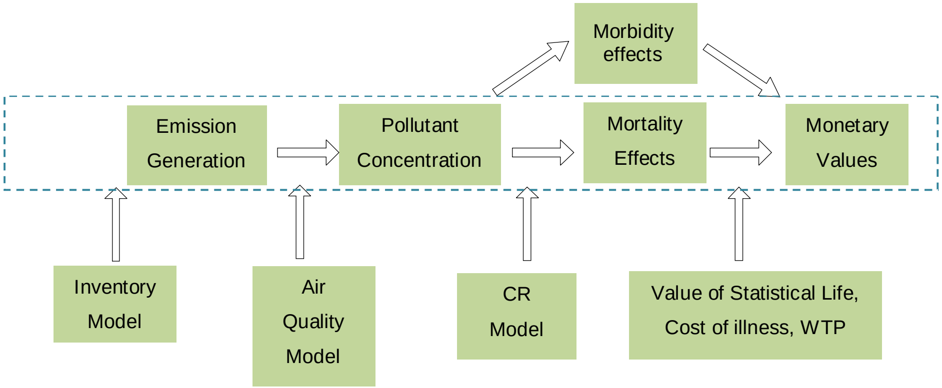

Figure 4.1: Impact Pathway approach for Air Quality Related Premature Deaths

(Source: Wadud and Khan 2011)

The methodology designed to develop the model, intended for the urban-air quality evaluation from policy, follows the impact pathway approach. The major challenges lie in the step-models or sub-models of the approach described briefly earlier in this section. The model itself is composed of various models. These sub-models include vehicular emission inventory model which in turn depends on vehicle inventory, air quality model to estimate the changes in $PM_{2.5}$ concentration induced from the changes in emissions due to policy, concentration-response functions, intended health effects to be measured etc and finally the valuation or monetizing parameter which converts the achieved benefits in monetary terms.

Therefore, a model has been developed, using a user-friendly and widely used programming language, C++, which includes all the model factors, data or inputs and all the information required for different sub-models of such an integrated policy model evaluation. The final goal of the model is to determine health benefits in monetary terms through the impact pathway approach by taking inputs from different required sectors in a systematic manner as to easily observe the results from different steps and for further easy updating. The following section shows the outline of the methodology of the developed model in C++ through a flowchart in Figure 4.2 and explains its different components.

4.3 Outline of Methodology of the Model

Figure 4.2 shows the overall methodology along with the required inputs and uncertainty analysis at different steps of the model intended to estimate the urban-air quality impacts of the policy according to impact-pathway approach. It can be seen from Figure 4.2 that the flowchart methodology is divided into two parts – one indicated with solid arrows and the other one with dashed arrow. The solid part dominates over the entire computation process as per impact-pathway approach based on nominal (i.e. most likely values without considering uncertainty) values of the input factors while the dashed part introduces uncertainty inputs from the uncertain data sources. This uncertainty is combined with the main (nominal) results from solid part to conduct the uncertainty analysis of the policy as was discussed in chapter 2. The solid part denotes the model results from nominal values of the factors not taking into account the uncertainties from possible data sources. The details on this topic will be discussed in chapter 6.

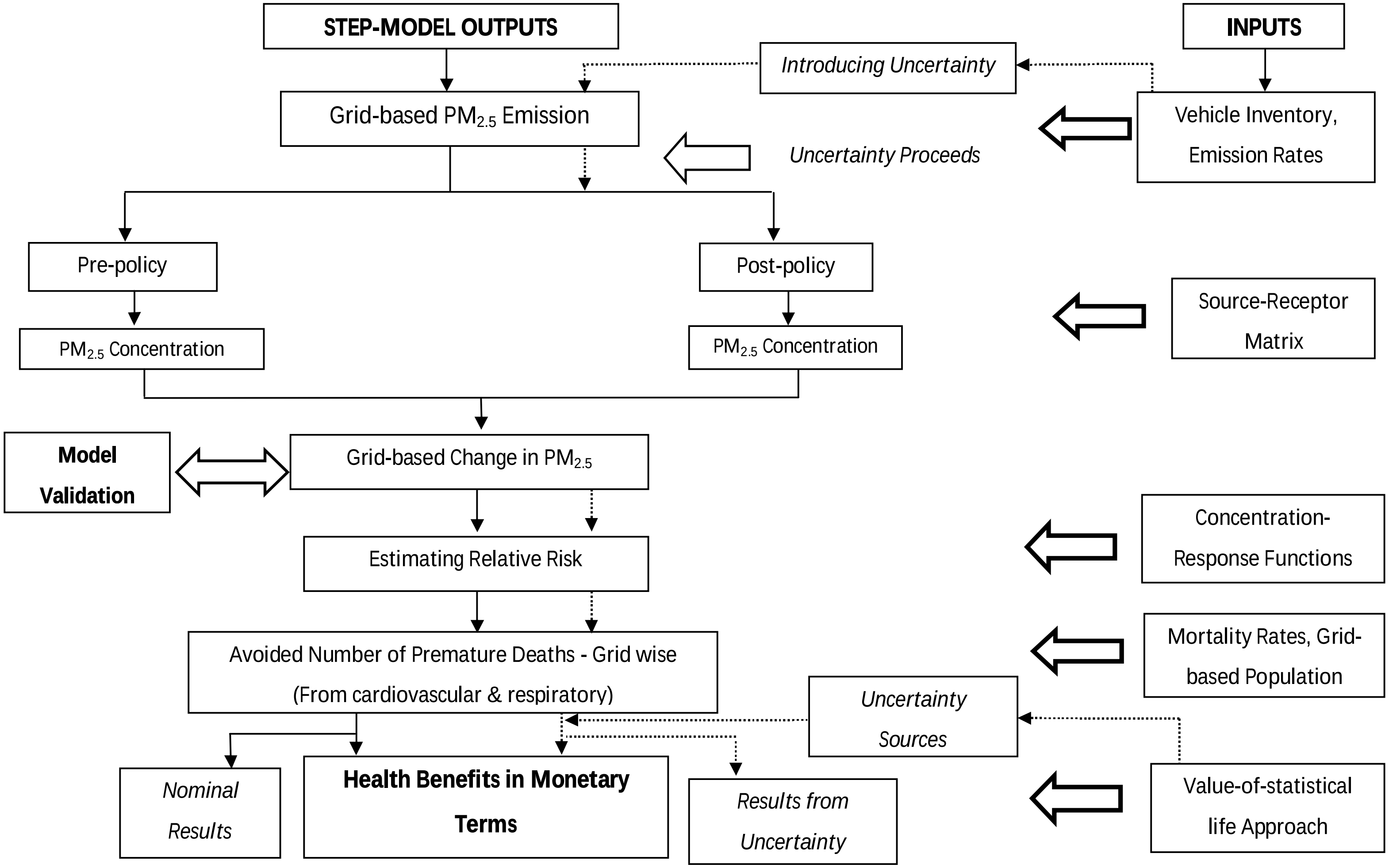

Figure 4.2: Flowchart of the Methodology of Developed Model

The impact pathway methodology consists of five major steps for the model. First, for emission inventory model, grid-based vehicular emission of $PM_{2.5}$ for Dhaka city is calculated using the grid distribution techniques of Arjumand (2010) and Rahman (2010). Grid-based distribution technique is advantageous as easy updating of the future inventory is possible and also specific impacts due to policy can be investigated directly through grid-based outputs. Grid-based emissions generation also facilitates the decision-making since it can easily locate the high-emitting areas within the entire study area.

This step requires inputs from vehicle inventory and emission rates of $PM_{2.5}$ from vehicles to generate emissions from emissions model. The major sources of uncertainty, discussed above, arise at this step within these inputs. The consideration for this uncertainty is shown in Figure 4.2 indicated by the dotted arrow from the first input at right toward the left at the very beginning step of the model. Also this uncertainty analysis proceeds down the steps of the model towards the output.

With the available emissions model, the grid-wise emissions are estimated for both base case (i.e. without policy taking place) and current case (i.e. CNG conversion taking place) referred to as pre-policy and post policy respectively in Figure 4.2. It should be mentioned here that the cases are for the same year, i.e. year 2010, with the same number of vehicles comparing between the two situations when the conversion is not done and when the conversion has taken place.

In the second step of the model, the corresponding $PM_{2.5}$ concentrations (on a volumetric basis) are estimated using grid based source receptor matrix (SRM) over Dhaka developed by Rahman (2010). Then the grid wise change in concentration is calculated. At this step, a model validation is conducted to check the accuracy of the developed model. The model concentration results by Rahman (2010) are used for the validation. The changes in concentration are combined with concentration-response (C-R) functions in the third step to calculate the grid wise change in risk of the focused health effects, i.e. premature mortality rates due to cardiovascular and respiratory diseases.

At the fourth step of the model, grid wise number of avoided premature deaths for Dhaka city is estimated which takes grid wise population distribution in both Dhaka City Corporation (DCC) and Greater Dhaka (GD) from Rahman (2010). Finally, the benefits achieved from avoided premature deaths are calculated using the value-of-statistical life (VSL) approach. Again, VSL adds to the uncertainty of the model which will be discussed in section 4.8.

The final output, as shown in the flowchart, can be either from the model's nominal data (i.e. without considering uncertainty) or from the uncertainty analysis. For the uncertainty analysis, the induced uncertainties in the first step propagates through the grid-wise concentrations, change in risks, premature deaths avoided and finally combines with the uncertainty from VSL to estimate the health benefits. The program has a provision to be executed for both the approaches, i.e. with nominal data and uncertainty analysis.

Therefore, the inputs to the model include:

- Grid wise vehicle inventory and emission factors to calculate the desired pollutant emissions
- Transfer matrix which converts emissions to concentrations
- CR functions
- Grid-wise population
- VSLs'

The major outputs include:

- Grid wise health effects, i.e. premature deaths that can be avoided due to policy implementation and
- Associated costs saved or benefits gained by saving the lives or by avoiding the deaths

Also segregated outputs (i.e. emissions, concentrations, risks etc) at different steps of the model can be obtained and can be brought into Microsoft Excel from the model for use in further calculations or to check the computation accuracy. The C++ code used to build up the stated model is given in Appendix C. The model is itself a beginning to such integrated policy assessment which can be further modified or modified data can be easily incorporated to obtain the modified results directly.

The following sections of this chapter (from section 4.4 to section 4.8) are arranged in a way to give the detail description of the calculations for each of the 5 steps of the model, as is done in the C++ program, with all the associated terminologies, concepts and sources of the input factors or data used. The calculations are all done for grid-wise divided Dhaka city and the consideration of uncertainties, once introduced from some model factor, follow links with all other related steps to derive the result precision.

4.4 Emissions Inventory: Modeling Vehicular Emissions of Dhaka

The first step of the model is the vehicular emissions inventory for pre and post policy cases. This is usually estimated using emissions model requiring data from transport sector. A comprehensive and reliable emissions inventory from all emissions sources in Dhaka city is not available from a unified government source. Therefore it is essential to model the emissions inventory from vehicles following the well known formulae:

$$\text{Emissions}_i = \sum_j \sum_k N_{jk} \times A_{jk} \times EF_{ijk} \tag{4.1}$$

where, N refers to number of vehicles;

A activity of those vehicles per day (vehicle kilometers/miles traveled referred to as VKT or VMT);

EF respective emission factors;

subscripts i, j and k refer to pollutant type, vehicle type and fuel type respectively.

Therefore, the basic input data are from the transport sector including the vehicle numbers, the vehicle activity and the emission factors of the concerned pollutants according to vehicle and fuel type. Hence at first, a detail vehicle inventory is required.

4.4.1 Vehicle Inventory

Data on the number of vehicles registered in Dhaka roads are available from Bangladesh Road Transport Authority (BRTA 2010). However, fuel wise distribution is not available. Also very little information about the converted vehicles are available. Although RPGCL provides some breakdown of the vehicle types that were converted, once again, the pre-conversion fuel types were not given. The VKT information is even scarcer. Therefore, this study adopts the data on vehicle inventory from Wadud and Khan (2011) which conducted a spot survey on roads including road intersections covering different areas and bus stops, truck and tempo stands for three days to collect information on fuel-wise split and other important data including VKT. The data is shown in Table 4.1. Within the existing CNG vehicles plying on the streets of Dhaka, a significant proportion was originally imported as CNG vehicles (unlike others which are primarily retrofitted). Although these dedicated CNG vehicles in different categories (except taxis and auto-rickshaws) are the post-policy case, these are fuel-wise split into non-CNG vehicles for pre-policy case and hence the total numbers of vehicles are essentially the same for both the scenario. The reasoning behind this is the fact that if the policy were not attempted, then these vehicles would be some other fuel and therefore their contributions must be taken into account. The taxis and three-wheeler auto-rickshaws run on CNG and are all original equipment manufactured (OEM). It is important to mention here that the emissions benefits attributable to CNG conversion of auto-rickshaws and taxis are not considered, which happened earlier within a very brief period and hence the impacts are the same for the same number of CNG vehicles (i.e. taxis and auto-rickshaws) in both pre and post policy cases. The category ‘others’ contain small human haulers (small pickup/truck converted to public transit of around 10~15 people), commercial covered vans etc., and show large conversion as well. One vehicle class which did not show significant uptake of CNG as a vehicle fuel is the trucks.

Table 4.1: Vehicle Inventory (2010)

Vehicle Types	**Original Fuel**	**Number of Vehicles**			**Vehicle Activity (Km/day)**	
		No Policy	After CNG Conversion			
			CNG	Other Fuel	CNG	Other Fuel
Motor cars	Petrol	147283	126663	20620	60	50
SUV/station wagons	Petrol	14275		4395		60
			10198		65	
SUV/station wagons	Diesel	3307		2989		75
Microbus	Petrol	34051		2872		50
Microbus	Diesel	6975	35282	2872	100	55
Taxis	CNG	12000	12000	_	200	_
Buses	Diesel	8210	6240	1970	120	120
Minibuses	Diesel	8317	7568	749	120	120
Trucks	Diesel	30015	2701	27314	130	130
Auto-rickshaws	CNG	14820	14820	_	150	_
Motor cycle	Petrol	219443	_	219443	_	55
Others	Petrol	26073		1196		50
Others	Diesel	3833	26616	2094	100	50

After the vehicle inventory, another important factor for generating emissions according to equation 4.1 is the emission factors of the specified pollutant (in this case $PM_{2.5}$ considered) emitted from particular vehicle-fuel combination under average or representative condition. Emission factor/rate is a representative value of the quantity of the pollutant produced in a given activity under different driving conditions. Ideally, emission factor of a pollutant from a particular fuelled-vehicle with certain usage or odometer readings is determined by driving a number of vehicles on a Chassis Dynamometer under different representative test conditions and driving cycles. Due to absence of these types of test facilities in Bangladesh, emission rates of the concerned pollutants in this study are collected from the vast information available in the international literature. The following section discusses on the sources and other details of required vehicular emission rates.

4.4.2 Emission Factors

Due to unavailability of emission testing facilities in Dhaka or Bangladesh, it is essential to turn to the international literature for the data. The emission factors required for the study are primarily taken from Urbanemissions (2010) which has a focus on South Asian countries, with some modification. It is already stated that for estimating health impacts from urban-air quality improvements due to policy, particulates and more specifically, the finer portion, i.e. $PM_{2.5}$ is the most important. Also the air quality model by Rahman (2010), used in this study to relate the change in emissions to respective change in concentrations in the ambient air, targets $PM_{2.5}$ as the major health affecting particulate. Hence, $PM_{2.5}$ emissions inventory from the vehicular source in Dhaka will be determined for both base and current cases.

For particulates, emission factors of PM_{10}, black carbon and organic carbon emitted from road transport are more common in literature than those of $PM_{2.5}$. Although Urbanemissions (2010) does have emission factors on $PM_{2.5}$ but to be in a more reliable range of data inputs, it is necessary to go for further estimates on this factor. Some sophisticated software, i.e. MOBILE6 or MOBILE 6.1 developed by AASHTO, PMcalc, MOVES by USEPA etc are available for the direct computation of emission factors from different emission sources but these models require extensive information on the vehicle fleet characteristics which are again uncertain. Therefore, a different approach is followed to derive the $PM_{2.5}$ emission factors. Despite the less available values on $PM_{2.5}$, the emission factors can be computed based on the particle size distributions, i.e. fractions of $PM_{2.5}$ in the coarser one, i.e. PM_{10}.

Derivation of emission factors of particulates from transport sources is often based on this particle size distribution even in the models mentioned above.

PM_{10} emission factors from a number of sources have been taken assembled by Wadud & Khan (2011), corresponding emission factors of $PM_{2.5}$ can also be estimated once the fraction is known. This size distribution is also a variable which varies according to sources, i.e. diesel/gasoline vehicle exhaust, CNG vehicles etc (AASHTO 2004; Charron & Harrison). A few numbers of reliable estimates are available in the literature on this (Cadle et al. 1999; AASHTO 2004; Bond et al. 2004; USEPA 2006; Charron & Harrison) confirming that the major part of PM_{10} is composed of $PM_{2.5}$. The values from different references are assembled in Table 4.2. From a detail review of these sources, a conservative value of $PM_{2.5}$ to PM_{10} ratio (i.e. 90%) is assigned for all the types of fuels.

Table 4.2: Particle-size Distributions collected and estimated from Literature Review

Sources	**Fuel type**	**$PM_{2.5}/PM_{10}$ ratio**
Charron & Harrison	Catalyst petrol and diesel exhaust	0.9
Derived from Bond et al. (2004)	Diesel	0.95-0.99
	Petrol	0.94-0.98
Cadle et.al (1999)	_	0.9
Derived from AASHTO (2004)	Gasoline exhaust	0.93-0.97
	Diesel exhaust	0.92-0.98
	Natural Gas	Similar to gasoline exhaust
USEPA (2006)	_	0.96

For particulate matter emissions from road transport, increased emissions are often found than the usual (regular emitters) ones from some vehicles within the entire vehicle fleet. In this regard, a term “super-emitter” or “smoker” is commonly and frequently used implying excessive particulate emissions from a certain number of vehicles, particularly diesel and also sometimes gasoline-fuelled vehicles. In Bangladesh, one of the most important reasons behind pollution severity is the greater proportion of high polluting vehicles (Karim et. al. 1997). So it is necessary to include the contribution of these high-emitting vehicles in the determination of total emissions along with the normal emissions from the regular emitters. The insertion process requires information on both the fractions of super-emitting vehicles and also the increased emission rates in order to represent the combined emissions (normal + super emitters) from the traffic composition. Hence the emissions estimating formula in equation 4.1 also needs to be modified.

Inserting the fraction and emissions of super-emitters, equation 4.1 becomes,

$$\text{Emissions}_i = \sum_j \sum_k N_{jk} \times A_{jk} \times \sum_l \left(EF_{ijkl} \times X_{ijkl} \right) \qquad (4.2)$$

where, X is the fraction of vehicle type j, fuelled with k and fuel-technology combination l emitting pollutant i (i.e. higher emission factors, EF). Here, fuel-technology implies those with normal and high emissions. For each fuel-technology combination, $\sum X=1$.

It is a challenging and difficult task to determine the exact proportions of the super-emitting vehicles within the traffic in Dhaka. Also the identification process varies among the countries and according to prevailing standards of emissions. Usually, super-emitters are identified by conducting tests on the vehicles with smoke meters or opacity meters and measuring opacity of the visible black smoke under different standard test conditions (Brodrick et. al.). Opacity is expressed in percentage or Hartridge Smoke Unit (HSU) and has various standard values differing from vehicle to vehicle, among different test conditions or procedures and among different countries. Failure of opacity test or having higher opacity value than the standard value is generally considered to be the indicator of high PM emitters and hence can identify the fractions of high-emitting vehicles within the vehicle fleet.

In this study, the data on the fraction and emission factors of super-emitters in the vehicle fleet of Dhaka city are collected from Wadud and Khan (2011) where the proportions of super emitting vehicles for different vehicle classes were taken from Rouf et al. (2008) and Reynolds and Kandlikar (2008) and super-emitters' emission factors were calculated as per Bond et.al. (2004). These data are summarized in Table 4.3.

Table 4.3: Fractions (%) and Emission Factors (gm/km) of Super-emitters

Fuel	**Vehicles**	**Fraction of Super-emitter (%)**	**EF_{BC} (gm/km)**	**EF_{OC} (gm/km)**
Gasoline	Car	40	0.047	0.05
Diesel	Jeep & Mi-bus	73.8	0.72	0.23
Diesel	Bus	46	1.93	0.61
Diesel	Mini bus	70.4	1.45	0.46
Diesel	Truck	77.2	1.74	0.55

(Source: Wadud and Khan 2011)

Since super-emitters or excessive emissions are commonly used to indicate the excessive particulate matter emissions, as stated earlier, hence this formula, i.e. equation 4.2, will be used only for the calculation of PM_{10} or $PM_{2.5}$ or its major components black and organic carbon. Emissions of all other pollutants are computed from equation 4.1 in this study to compare those before and after CNG conversion.

With the contribution of super-emitters, the combined emission factors from different vehicle-fuel combinations are obtained following a number of sources giving data on regular emitters. Wadud and Khan (2011) collected three sources of emission factors for particulates, i.e. PM_{10}. The sources are: Bond et.al. (2004), Urbanemissions (2010) and Narain & Krupnick (2007). Among these sources, only Urbanemissions (2010) gives emission factors for $PM_{2.5}$ directly. From the sources, PM_{10} emission factors are corrected for super-emitters and then the $PM_{2.5}$ to PM_{10} ratio is applied, as shown in equation 4.3 to obtain the emission factor for $PM_{2.5}$.

$$EF_{PM_{2.5}} = EF_{PM_{10}} \times \frac{PM_{2.5}}{PM_{10}} \tag{4.3}$$

where, $EF_{PM2.5}$ and EF_{PM10} are the (combined) emission factors for $PM_{2.5}$ and PM_{10} respectively.

The emission factors of $PM_{2.5}$ obtained from different sources are enlisted in Table 4.4. Table 4.4 shows calculated emission factors of $PM_{2.5}$ from three different sources: from PM_{10} emission factors of Bond et.al (2004), from PM_{10} of Urbanemissions (2010) and from PM_{10} of Narain & Krupnick (2007). Another source is directly $PM_{2.5}$ emission factors from Urbanemissions (2010), which are also corrected for super-emitters. It is seen from Table 4.4 that the emission factors for both regular and combined emitters are given. CNG vehicles are not super-emitters, rather emit reduced particulates and hence only single emission factors are given. Also Bond et.al. (2004) does not have any emission factors for CNG vehicles, so for judgment, other sources will be used.

For some of the types of the vehicles, as shown in Table 4.4, the $PM_{2.5}$ emission factors are the same for both regular and combined emitters. There is no available information on these vehicles as being super-emitters. Table 4.4 can be used for comparison among the $PM_{2.5}$ emission factors obtained from different sources. In general, comparison among the sources ends up with the observation that Narain & Krupnick (2007) gives lower estimates while others vary within a narrower range.

Table 4.4: Calculated Emission Factors (gm/Km) of PM$_{2.5}$ for Normal / Combined Emitters from Different Sources

Vehicles	**From Bond et.al. (2004) PM$_{10}$**		**From Urbanemissions (2010) PM$_{10}$**			**From Urbanemissions (2010) – PM$_{2.5}$**			**From Narain & Krupnick (2007) PM$_{10}$**		
	Diesel	Gasoline	Diesel	Gasoline	CNG	Diesel	Gasoline	CNG	Diesel	Gasoline	CNG
Motor cars	_	0.037/0.081	_	0.09/0.11	0.045	_	0.03/0.077	0.02	_	0.009/0.065	0.0045
Jeep/SUV/station wagons	0.33/0.93	0.047/0.047	1.12/1.14	0.09/0.09	0.045	0.5/0.98	0.3/0.3	0.01	0.041/0.86	0.009/0.009	0.0045
Microbus	0.33/0.93	0.047/0.047	1.12/1.14	0.09/0.09	0.045	0.5/0.98	0.3/0.3	0.01	0.041/0.86	0.009/0.009	0.0045
Taxis	_	_	_	_	0.045	_	_	0.02	_	_	0.0045
Buses	0.89/1.89	_	1.35/2.14	_	0.018	0.8/1.84	_	0.01	0.33/1.59	_	0.0054
Minibuses	0.67/1.81	_	1.35/2.02	_	0.045	0.8/1.85	_	0.01	0.33/1.71	_	0.0054
Trucks	0.80/2.31	_	1.8/2.54	_	0.018	1.0/2.36	_	0.01	0.07/2.14	_	0.0054
Auto-rickshaws/Tempo	_	_	_	_	0.09	_	_	0.05	_	_	0.0045
Motor cycle	_	0.009/0.009	_	0.09/0.09	_	_	0.05/0.05	_	_	0.024/0.024	_
Others	0.33/0.93	0.047/0.047	1.12/1.14	0.09/0.09	0.045	0.5/0.98	0.3/0.3	0.01	0.041/0.86	0.009/0.009	0.0045

4.4.3 Grid-wise Distribution of Vehicular $PM_{2.5}$ Emissions

Grid-wise emissions are generated for Dhaka city following the division of all the major and minor roads of entire city (DCC and Greater Dhaka) into 252 grids of (12x21) as per Arjumand (2010). The grids are modified by Rahman (2010) in order to tackle some of the discrepancies in spatial grid locations of Arjumand (2010) and grid locations for the air quality model. These new modified grids are of (10x20). In absence of any further grid-wise distribution of emissions for Dhaka city at present, these grid-wise emissions are calculated using program C++.

The basis of the grid-wise emission distribution following Arjumand (2010), is the estimated annual average daily traffic (AADT) on each road included within the study domain grids multiplied with the respective road lengths (in kilometers). The AADT data used in the referred study is from Strategic Transport Plan (STP 2004). The mentioned parameter actually defines vehicular activity, i.e. VKT (vehicle-km/day) per grid for different types of vehicles plying on the roads within the grids. The grid-wise distributed vehicular activity, done by Arjumand (2010), is shown in a snapshot of the excel worksheet in Appendix A. These VKTs will be the basis to determine the new VKT inventory for the current thesis.

On the other hand, VKT for a given vehicle-fuel represents daily average activity of the vehicles of that category, i.e. kilometers driven per day. For example, cars in Dhaka on average run 50 kilometers per day. Therefore in order to make the grid-wise calculations of emissions, these simple VKTs are first converted to a format compatible with those of Arjumand (2010). This specific format of VKT will be referred to as composite VKT throughout the entire study hereafter.

Composite VKTs are obtained by multiplying the individual average daily VKT with the total numbers of a given vehicle-fuel type. These separate composite VKTs for each vehicle-fuel category (considered for the entire study domain) will be distributed among the 252 grids based on the simple ratio-wise relationships with respect to the VKTs of Arjumand (2010).

In order to calculate $PM_{2.5}$ emissions, emission factors require to be imposed on respective vehicle-fuel type, as shown in equations (4.1) and/or (4.2). Arjumand (2010) used a fuel split but the source information is not very clear or reliable neither very recent. Hence, this study will use a different approach to find out the fuel-wise fractions of composite VKTs explained in Appendix A. All the calculations are done for both base and current cases as required for the current study. The step-by-step explanation of the entire computation procedure is given in the Appendix A.

Table 4.5 shows a comparison among the total composite VKTs for different vehicles estimated in the current study, obtained from Arjumand (2010) and another study by World Bank (2004) collected from Arjumand (2010). For the current study, the policy scenario is taken into account for comparison with others. Also VKT data only for the vehicle types, consistent with other sources, are given in Table 4.5 for comparison.

Table 4.5: Comparison of Total Composite VKTs (10^6 Km/day) among Sources

Vehicles	**Current Study, VKT Data 2010**	**Arjumand (2010) VKT Data 2004**	**World Bank (2004) VKT Data 2004**
Car	8.63	2.64	5.65
Taxi	2.40	1.01	1.11
Bus	0.99	1.41	1.60
Truck	3.90	0.78	1.16
Auto-rickshaw	2.22	2.31	1.49
Motor-cycle	12	0.78	3.49

In Table 4.5, it can be observed that much higher values for most of the vehicles are found for the current study, the highest for motor-cycles among the three sources. It can be explained from the fact mentioned by Arjumand (2010) that it considered only traffic along all major roadways of specific grid of the used study area. It did not consider the total number of vehicles of each category of Dhaka city whereas the current thesis has done the reverse. Also an important fact is that the current thesis data is more recent, i.e. 2010 and the other references are for the year 2004 which implies that the number of vehicles is certainly increased during the several years and hence the VKT. VKT of auto-rickshaws are somewhat lower than Arjumand (2010) since in that study gasoline fuelled auto-rickshaws are also considered while those are not allowed within Dhaka city now and only CNG auto-rickshaws are considered. VKT of buses derived in the current study is the smallest relative to other estimates. The reason may lie in the fact that only the buses travelling on internal routes within Dhaka are taken and not the interstate buses.

A sample calculation to derive the composite VKT and grid-wise composite VKT with fuel splits for car is shown via excel worksheet snapshots in Appendix A. Up to this, the calculations are done by Microsoft Excel. At this point of calculation, C++ programming is introduced to the model. The computed data are taken as inputs to the step-by-step model built in C++ program to determine the final outputs.

4.4.4 Emissions Calculation in Model: Introducing Uncertainty

As mentioned in section 4.4.2, the $PM_{2.5}$ emission factors have significant uncertainty as the data is collected from secondary sources in other countries. This calls for the uncertainty consideration at the very beginning of the model for the accuracy of the final intended result. Therefore, after the grid-wise distribution of vehicular activity discussed in section 4.4.3, computation in C++ begins with the consideration of uncertainty.

In C++ program, random numbers for emission factors (or any other uncertain model factors wherever applicable), as high as 5000, are generated for each vehicle-fuel category which will simulate the random scenarios in uncertain cases. The major inputs to the program at this step are the values of emission factors from all vehicle-fuel types for generating random numbers and the composite VKTs obtained. The generated random values of emission factors are shown in Appendix A via snapshot from the excel worksheet where the result from C++ is taken. Generated random numbers of emission factors of $PM_{2.5}$, according to vehicle and fuel type, are multiplied with the (fixed) corresponding composite VKTs. Adding the contributions from all the vehicles for a particular grid, $PM_{2.5}$ emissions for that grid is obtained and expressed in tons/year. The similar calculations are done for all the 252 grids for both the pre and post-policy cases.

Hence, a matrix of order of (5000x252) is actually formed where 5000 (random) emissions are generated per grid of total 252 grids. It is important to remember the fact that these 5000 emissions per grid are due to the uncertainty consideration of $PM_{2.5}$ emission factors for which 5000 random values are generated within specified values following particular distribution.

As stated in section 4.4.3, these emissions are shifted to the grids developed by Rahman (2010) since the study will follow the air quality model of the stated study. This modification of grids is done in the developed model in C++ program as per Rahman (2010). Thus the generated emissions in 252 grids are shifted to the 200 (10x20) grids of Rahman (2010). Now, the respective modified emission matrices are of (5000x200) order each. Appendix A shows the modified emissions matrix for base case taken as output to excel worksheet from the C++ program. After completing the first step of the model, i.e. grid-wise emissions generations (with uncertainty) for both cases, the next section 4.5 will discuss the second step which converts the emissions to respective concentrations and then determines the changes in concentrations of $PM_{2.5}$ due to policy implementation.

4.5 Air Quality Model

The purpose of an air quality model in impact pathway approach is to relate the emissions to specific concentrations. This study adopts the Source-Receptor (S-R) model as the required air quality model developed by Rahman (2010). A brief discussion on the model will be discussed in this study as summarized from the stated study. The details will not be addressed here and further information may be obtained from Rahman (2010).

4.5.1 Source-Receptor (S-R) Model

The Source-Receptor (S-R) model is the indication of the relationship between the source of emission and the receptor (person, building etc.). S-R model presents the incremental change in concentrations due to an incremental change in emissions. It can be defined as change in concentrations in a receptor grid per unit change in emissions in the source grid (Guttikunda 2010). S-R matrix, also known as transfer coefficient/matrix, plays an important role in the calculation of ambient air concentration provided emission loads are given and vice-versa.

A typical air quality (AQ) model for a single source can be defined as the product of total emissions and transfer coefficients:

$$C = mQ \qquad (4.4)$$

where,

C = ambient concentration of pollutant;

m = transfer coefficient and depends on model domain, source type, pollutant types and meteorological parameters;

Q = total emissions

The transfer coefficient/matrix indicates the incremental change in concentration in a cell for a unit change in emissions in each of the other cells. Once transfer matrix is obtained, S-R model requires only the emission within the domain. In matrix form, equation 4.5 can be re-written as,

$$C = MQ \qquad (4.5)$$

where,

C = Concentration vector

M = Source-Receptor Matrix (SRM)

Q = Emission vector

Rahman (2010) developed source-receptor matrix or transfer matrix which is of (200x200) order. This is taken as input to the model of this study to determine the required pollutant concentrations.

4.5.2 Input of Transfer (S-R) Matrix to Model

Rahman (2010) developed transfer matrices for a number of pollutants, i.e. PM_{10}, $PM_{2.5}$, SO_x, NO_x etc. Since the priority of the study is to determine the health impacts associated with change in $PM_{2.5}$ (of primary origin) emissions due to policy implementation, the model takes the input of transfer matrix for $PM_{2.5}$. According to equations (4.4) or (4.5), the calculated emissions are multiplied with the transfer matrix and the desired concentrations are obtained for both base and policy cases.

Since the emission matrix is of (5000x200) order, as was discussed in section 4.4.4, and the transfer matrix is of (200x200) order, the resulting concentration matrices (base and current case) have again an order of (5000x200). The concentrations are obtained in micro-gram per cubic meter ($\mu g/m^3$). In this step of model, uncertainty consideration (for emission factors) in the grid-wise emissions continues over the converted respective grid-wise concentrations. Finally, the difference or change in concentration matrix is obtained by deducting the current concentration matrix from that of base concentration of $PM_{2.5}$. This matrix is a positive-value matrix since the current $PM_{2.5}$ concentrations are supposed to decrease due to conversion policy.

4.6 Modeling Health Risks associated with $PM_{2.5}$ Exposure

The next step of impact pathway approach is to define the relationship between exposure and a damage valuation end point e.g., respiratory, cardiovascular problems due to $PM_{2.5}$ concentration. This is often conducted by using Dose-Response functions, also known as Concentration-Response (CR) or Exposure-Response functions.

A concentration-response function (C-R function) is a mathematical equation that describes the relationship between exposures and a health outcome (California Air Resources Board (ARB), 2010). The C-R function expresses the changes in relative risk of mortality associated with an incremental change in $PM_{2.5}$ concentration. For air pollution, a CR function for O_3-asthma would indicate the per cent increase in asthma attacks in the exposed population due to a unit increase in the ambient O_3 concentration (Wadud 2009).

C-R functions for premature mortality for a short term but acute exposure to $PM_{2.5}$ have long been available but recent studies show that CR functions due to a continued exposure to $PM_{2.5}$ are almost an order of magnitude higher than those for short term exposure (Dockery et al. 1993, Pope et al. 2002, Krewski et al. 2000, Laden et al. 2006, Pope and Dockery 2006). California Air Resources Board (ARB 2010) reports that in the associated risk assessment, mortality related to long-term exposure of $PM_{2.5}$ is likely to include mortality related to short-term exposures and hence the report focused on USEPA's quantification of premature mortality associated with long-term exposure. Moreover, since the stated policy intervention is also related to long-term health effects of $PM_{2.5}$ reduction, the research focuses on the premature mortality related to long-term exposure of $PM_{2.5}$.

There is another issue regarding the choice of premature mortality type – all cause or cause specific. In general, CR functions for increases in all cause mortality are used in modeling policy interventions (USEPA 2005, USEPA 2007, Kunzli et al. 2000). However, the causes of deaths vary significantly between the USA (and developed countries in general) and developing countries, like Bangladesh (Cropper and Simon 1996). For example, deaths from infectious diseases are much higher in the developing countries than in the developed countries. Use of all cause CR functions with all cause mortality rate in Bangladesh may grossly overestimate the avoided number of premature deaths due to the policy intervention, similar to what demonstrated by Cropper and Simon (1996) for India. Therefore cause-specific CR functions are employed with cause-specific mortality rates, i.e. from cardiovascular and respiratory diseases, for Bangladesh.

4.6.1 Determination of CR Functions

The CR functions are generally determined through different types of econometric and epidemiological models. A common method to determine CR functions is to use Relative Risk (RR) defined as the ratio of the probability of death in a given circumstance (say, exposed to pollution) to the probability of death in a given base circumstance (say, no pollution). If p_0 is the probability of death of an individual in the no pollution case and p_1 is the probability of death when exposed to a given amount of pollution, then

$$RR = \frac{p_1}{p_o} \tag{4.6}$$

An RR of 1.15 thus indicates an increase in the mortality risk of 15% over the base case. It is important to note that the cohort econometric studies use Cox Proportional Hazard model where,

$$RR = e^{(k\Delta c)} \tag{4.7}$$

where, k is the parameter estimated from the data, and Δc is the difference in concentrations of the pollutant between the base case and polluted case. RR therefore is not linear in changes in concentration. Accordingly, the increases in risk of mortality due to a 10 $\mu g/m^3$ change in the concentration of the pollutant is not exactly 10 times the increase in the risk due to a 1 $\mu g/m^3$ change in concentration, although the differences are often negligible at smaller RR values (Wadud 2009).

Relative risks are given in a form of increase in risk usually with respect to an incremental threshold or base concentration value, i.e. 10$\mu g/m^3$ of $PM_{2.5}$ or sometimes directly in the form of k values. From these k values, the relative risks can be determined according to equation (4.7) corresponding to given threshold or background concentration of pollutant. Finally, reduced risk is obtained by relating the known k values to the changes in ambient concentration due to the policy implementation.

4.6.2 Discussion on the Values of Relative Risks

A number of values and/or wide range of values of relative risks (or k-values), associated with different health outcomes and exposure metrics, are investigated and summarized in the literature. In most of the cases, the values are reported as that of k, often referred to as β in the literature.

Ostro (2004) recommended values of k (co-efficient β) along with the upper and lower bounds which are associated with long-term exposure to $PM_{2.5}$. For cardiovascular mortality, the best estimate reported by the study is 0.00893 (RR=9.3% increase in risk per 10$\mu g/m^3$ of $PM_{2.5}$) with the lower and upper values of 0.00322 (3.27%) and 0.01464 (15.7%) respectively. For mortality related to lung cancer or respiratory diseases, the corresponding values are 0.01267 (13.5%), 0.00432 (4.4%) and 0.02102 (23.39%) respectively. More recent and extensive detail study in this regard is that conducted by Krewski et.al. (2009). It conducted an extended follow-up and spatial analysis of the American Cancer Society (ACS) cohort in order to further examine associations between long-term exposure to particulate air pollution and mortality both in nation-wide scale and intra-urban scale in large U.S. cities including Los Angeles and New York.

Relative risk or CR function for $PM_{2.5}$ is not developed for Dhaka or Bangladesh as per the current knowledge. Therefore, relative risk may be a factor whose variation can affect the variability of the output. The detail discussion on conducting uncertainty assessment with this factor will be discussed in the chapter 6. The key elements of the $PM_{2.5}$ risk assessment are an exposure assessment based on air quality data, the $PM_{2.5}$ concentration response function from epidemiological studies, baseline health incidence information, and population in the study area (CARB, 2010). The next section discusses on the remaining procedure and required data.

4.7 Estimating Deaths Avoided in Model

The next step is to give inputs on CR functions, associated mortality rates (both for cardiovascular and respiratory diseases) and grid-based population to the model. Then along with the change in concentration (Δc) of $PM_{2.5}$ per grid, avoided premature deaths attributable to CNG conversion is estimated from the following formula:

$$\text{Deaths avoided} = \Delta c \times CR \times \text{mortality rate} \times \text{population} \qquad (4.8)$$

Grid-based population (above age 30) is taken for Dhaka City Corporation (DCC) and also Greater Dhaka from Rahman (2010). On the other hand, there are issues about the reliability of the mortality risk statistics in Bangladesh. CIA (2009) estimates 9.23 deaths per thousand in 2009, the World Health Organization (WHO 2009) estimates a mortality rate of 8.15 per thousand in 2004, while Bangladesh Bureau of Statistics (BBS 2009b) suggests a death rate of 5.8 in 2004. Cause specific mortality statistics also differs: BBS (2009b) estimates cardiovascular and respiratory diseases to be responsible for 26.2% and 33.2% deaths nationally and in urban areas respectively, while WHO (2009) reports 29% for cardiovascular (23.6%) and respiratory diseases (5.3%) nationally, rising to 38.6% when including respiratory infectious diseases. This study follows WHO (2009) estimates including respiratory infectious diseases for the mortality risk. The C-R response functions for $PM_{2.5}$ mortality mentioned above are for population aged above 30, which represents 35.9% of total population in Bangladesh (BBS 2009b). Therefore, in absence of any other updated data, the mortality risks from cardiovascular and respiratory diseases among adults above 30 are taken as 5.36 and 3.40 per thousand respectively.

The change in concentration matrix, discussed in section 4.5.4, when combined with appropriate k values from C-R functions according to equation 4.7, computes similar relative risk matrices for cardiovascular and respiratory diseases separately. Then the corresponding mortality rates and grid-wise population are combined with the relative risk matrices according to equation 4.8 to estimate the total grid-wise avoided deaths for cardiovascular and respiratory diseases in each of the 200 grids. All the steps of calculations continue with the uncertainty consideration of emission factors (5000 random numbers) for each grid so that the results in terms of total premature deaths avoided are also obtained in a matrix of order of (5000x200) from the program. At this point of calculation in the program, the outputs (gridded deaths avoided) are taken to read in MS-Excel and further valuations, as is discussed in the following section, can be either done in C++ or in Excel. Appendix A shows the results for grid-wise deaths avoided due to policy through a snapshot taken from the excel file.

4.8 Valuation of Health Benefits

Once the number of avoided deaths is found, they are assigned a monetary value in order to arrive at an economic valuation of the benefits from the policy. The most common approach is to use a Value of Statistical Life (VSL), defined as the amount people are willing to pay (accept) to reduce (increase) the mortality risks (probability of death) they face. Health benefits are calculated as:

$$\text{Health Benefits} = \text{Deaths avoided} \times \text{VSL} \qquad (4.9)$$

This result can be either obtained grid-wise or the deaths avoided over the 200 grids can be summed (each time for total 5000 values under a grid) to combine with appropriate VSL to determine the total health benefits in monetary terms. It is clear from equation 4.9 that the amount of health benefits may largely vary depending on the VSL estimates and hence VSL is another important model factor to be taken into uncertainty analysis. The next sections 4.8.1 and 4.8.2 discuss on the approach and the estimates of VSL from the literature.

4.8.1 Approach to Value of Statistical Life (VSL)

The preferred approach that researchers have taken to estimate values for avoiding premature mortality is based on individual Willingness to Pay (WTP) for risk reduction. The WTP approach is preferred because it more closely conforms to economic theory. The common WTP measures of the value of life-saving programs include the value of statistical life (VSL) (Aktar & Shimada 2005).

The Value of a Statistical Life is the value of a risk reduction divided by the size of the risk reduction which can be expressed in mathematical form shown below (Simon et.al. 1999):

$$\mathrm{VSL} = \frac{\text{Value of } \Delta r}{\Delta r} \qquad (4.10)$$

where, Δr is the size of the risk reduction.

Therefore, the value of statistical life is an expression of preferences for reducing risks of death in monetary terms (Krupnick 2006). More technically, VSL is the marginal rate of substitution between an individual's wealth and mortality risk (Hammit 2008).

A variety of valuation techniques have been used to estimate this value: labor-market (hedonic) studies, the contingent valuation method (CVM), and various types of market-based analysis. Labor market studies generally attempt to infer the compensation required in exchange for the increased risks associated with particular occupations while standardizing for all other attributes of the job and the worker. The contingent valuation method asks individuals hypothetical questions related to their willingness to pay for reductions in their risk of encountering particular hazards. The market based approach attempts to infer willingness to pay for reductions in risk from the purchase of goods whose only purpose is to reduce the risks confronting an individual (Aktar & Shimada 2005).

There are two types of WTP approaches to estimate VSL or more specifically to measure the preferences of people to reduce a certain amount of risk (Krupnick 2006):

1. Observed choices – **revealed preferences**

Hedonic price methods: wage-risk trade-off, use compensating wage (CW) differentials to value risk of death, use data on purchase of safer vehicles or safety equipment, e.g., bicycle helmets (Cropper 2011).

2. Asking people questions -- **stated preferences**

Contingent valuation (CV method), Conjoint analysis: Asking people directly what they would pay for a change in risk of death (Cropper 2011).

Although revealed preference is the most common method in estimating VSL, the associated problems, mentioned by Krupnick (2006), include: the method considers accidental not cardiopulmonary (air quality/pollution related) deaths; relatively healthy and young population, not older unhealthy population; there are also lots of unobserved reasons for wage differentials.

There are a number of VSL estimates available in the literature for different countries, in some cases, with large differences. The following section discusses on these estimates summarized from literature review.

4.8.2 Estimates of VSL from Literature

VSL is a widely researched area with over hundreds of studies published, although estimates for developing countries are not as frequent. The published estimates vary widely: USEPA (2007) uses a central value of USD 5.5 million (1999 USD), with an order of magnitude difference between high and low estimates (USD 1- 10 million), DEFRA (2007) uses an implicit value of GBP 1.1 million (2002 GBP) while ExternE (2005) in Europe uses € 1 million (2000 €).

Mahmud (2005) reports that using data from the Indian labor market, Shanmugam (2000) provides VSL in the range of USD 0.76 million-1.026 million and Simon et al. (1999) provide VSL for India from an independent wage-risk study in the range of USD 0.15-0.35 million. Other estimates for India include: Rs. 1 million (Bhattacharya et al. 2007), Rs. 14.5 million (Madheswaran 2007), Rs. 15 to 35 million (Simon et al. 1999) to Rs. 56 million (Shanmugam 2001).[1]

The lower values of VSL are generally found from Contingent Valuation studies while the higher values are found from revealed Preference studies. Krupnick et al. (2006), on the other hand, find that the willingness to pay to reduce health risks are around USD 1 million for China, similar to those in developed country when estimated using the same techniques and corrected for purchasing power parity (PPP). Rafiq and Shah conducted a study for Pakistan and estimated the Value of Statistical Life (VSL) to be between USD 122,047 (10.4 million PKR) and USD 435,294 (37 million PKR) per statistical life. The only published estimate of VSL for Bangladesh is by Miller (2000), who suggests a value of USD 40,000 (1997 USD) with a range of USD 30,000-0.7 million.

Due to such large variations among the studies over different countries, it becomes difficult to obtain specific value or ranges of values of VSL. However, USEPA (United States Environmental Protection Agency) keeps a well-tracking record of such valuation parameters used for different purposes and also updates these values as per the latest studies. As a result,

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[1] All Rs. were converted to 2000 Rs. using Indian CPI (IMF 2008). The numbers correspond to PPP adjusted USD 0.12, 1.7, 1.8, 4 and 6.5 million respectively (2000 USD).

information from this source is more reliable and a brief overview is given here on the estimates of VSL used and recommended by USEPA.

USEPA Estimates of VSL at Different Times

Akter and shimada (2005) reports Viscusi (1992) that summarized literatures on VSL, including almost forty studies providing VSL estimates relevant for policy application. USEPA (1997) and USEPA (1999) identified 26 studies from that review that reflect the application of the most sound and defensible methodological elements. Using a Weibull distribution to describe the distribution of the mean risk valuation of mortality, USEPA (1997) and USEPA (1999) measured the mean estimate of the distribution, which is USD 4.8 million with a standard deviation of USD 3.2 million (1990 USD).

Dockins et.al. (2004) summarizes a number of estimates of VSL used by EPA. The study also mentioned that EPA 1999 used USD 6.2 (2002) and in air regulations EPA has used an estimate of USD 5.5 million (2003 USD). Krupnick (2006) stated that EPA’s VSL is USD 6 million (2000 USD). Other than USEPA studies, there is another extensive meta-analysis by Desvosges et al. (1998) reported by Akter & Shimada (2005). The study estimated VSL as USD 3.3 million in 1990 US dollar equivalent, with a 90% confidence interval between USD 0.4 million and USD 6.3 million.

Most recently, according to mortality risk valuation guidelines by EPA, the recommendation is that the central estimate of USD 7.4 million (USD 2006), updated to the year of the analysis, be used in all benefits analyses that seek to quantify mortality risk reduction benefits regardless of the age, income, or other population characteristics of the affected population until revised guidance becomes available. Recent VSL used by EPA is USD 7.4 million (2006). Previous values used by EPA include USD 5.5 million (1999) and USD 6.6 million (2006).

From the above discussion, both from specific studies and EPA used values, it is clear that largely varying estimates of VSL are available in literature depending upon various countries, population characteristics including age, income etc. Therefore any single source cannot be reliably followed; rather there should be a procedure for calculating VSL directly for Dhaka or Bangladesh.

4.8.3 Method to Estimate VSL for Bangladesh

In case of Bangladesh or Dhaka, a major uncertainty that complicates an application of the base value of WTP to Dhaka city arises from the big differences in income levels. One of the fundamental issues in valuing the reductions in risk is that willingness to pay rises with income (Aktar and Shimada 2005).

Since the existing VSL and other WTP estimates are taken from the United States or converted to US dollars, there is a clear need to adjust them for income effects before applying the results to Dhaka city. The general formula for adjusting the differences in income level is given specifically for Bangladesh.

$$\mathrm{VSL}_{\mathrm{BD}} = \mathrm{VSL}_{\mathrm{USA}} \times \left[\left(\frac{\mathrm{Y}_{\mathrm{BD}}}{\mathrm{Y}_{\mathrm{USA}}}\right)^{\varepsilon}\right] \tag{4.11}$$

where, $\mathrm{VSL}_{\mathrm{BD}}$ and $\mathrm{VSL}_{\mathrm{USA}}$ are the respective VSLs for the two countries Bangladesh and United States;
Y is the per capita (PPP adjusted) GDP (Gross Domestic Product) and the subscripts denote those for the stated countries;
ε is the income elasticity of the VSL.

Determination of VSL following the above equation is also reported as the most common approach by Cropper (2011) for India. Usual assumption is that $\varepsilon = 1$ so that the computation is also easier (Akter and Shimada 2005). There are various estimates of epsilon available in the literature. Viscusi and Aldy (2003) suggested the range of ε from 0.5 to 0.6. But the recent studies including Hammitt and Robinson (2010), Costa and Kahn (2004), Hammit, Liu and Liu (2000) suggest using an income elasticity of 1.5. Cropper and Sahin (2009) also suggest $\varepsilon = 1.5$ based on a life-cycle consumption model (Cropper 2011).

Therefore, this study uses the estimates from different countries and converts those to VSL of Bangladesh using equation 4.11 where each estimate is obtained using two values of ε. The two values of ε are 0.55 (mid-value of 0.5 and 0.6 as suggested by Viscusi and Aldy 2003)) and 1.5. The GDP values of different countries are collected from International Monetary Fund (IMF 2011). The estimates are summarized in Table 4.6. The VSLs of different countries used in the computation are collected from Wadud and Khan (2011) and are expressed in 2005 USD.

Table 4.6: Transferring VSL Estimates to Bangladesh

Countries	VSL (USD 2005)	Adjusted VSL in 2010 USD	GDP/capita adjusted (2010 USD)	Calculated VSL (2010 USD) using $\varepsilon = 0.55$	Calculated VSL (2010 USD) using $\varepsilon = 1.50$
Bangladesh	53,000	54,344	1584.5	_	_
USA	63,30,000	7,200,000	46860	11,17,726	44,769
India	19,90,000	22,21,871	3408	14,58,013	7,04,277
China	6,74,000	7,52,533	7544	3,18,995	72,436
UK	18,90,000	21,10,219	35059	3,84,266	20,276
Pakistan*	278670 (08 USD)	2,82,233	2720.5	2,09,650	1,25,452

*mid-value of the given range for Pakistan (Rafiq & Shah) is taken (2008 USD)

All the VSLs of different countries are adjusted to that of 2010 USD. Then using per capita GDP (PPP adjusted) of the respective countries, as given by World Economic Outlook Database, IMF (2011), VSLs for Bangladesh are calculated using equation 4.11 for the stated two values of ε. The estimates show large variations for using different ε values. A conservative estimate for VSL of USA is used for the calculation: USD 7.2 million, 2010 converted from EPA's previous value = USD 5.5 million, 1999; rather than the latest guideline as stated in the previous section. It appears that a PPP adjusted estimate of USD 1 million, or BDT 13 million, is a reasonable measure of VSL in Bangladesh (Wadud and Khan 2011). At the current exchange rate this represents USD 199,818 (2010 USD).

Since the VSLs largely vary depending upon both estimates of different countries and income elasticity, health benefits would also vary according to equation 4.9. Therefore, uncertainty is added from VSL to health benefits along with the contribution from the preceding uncertain factors related to deaths avoided. VSL, as another important uncertain model factor, will be discussed in the chapter 6. An excel snapshot of the generated random values for VSL is shown in Appendix B.

4.9 Summary

This chapter discusses the detail methodology regarding the urban-air or environmental impacts of the policy. The modeling is based on the impact pathway approach and is done in a C++ program. The literature and used data regarding the different model factors are also discussed in different sections of the chapter while modeling the steps. Some of the variables are identified as important uncertain model factors affecting the accuracy of the overall model results. The inclusion process of those observed uncertainties into the model are also discussed which will be analyzed in the chapter 6.

It was stated at the beginning of this chapter that CNG conversion policy for vehicles has two associated impacts: air quality related health impacts, already discussed in this chapter and the other one is related to global climate changes. Methods for estimating the climate change benefits or costs from a policy intervention follow a different path other than using impact pathway approach as is used for obtaining health benefits. This methodology of determining the overall climate costs/benefits associated with the policy is discussed in the next chapter.

CHAPTER 5

ECONOMIC ANALYSIS OF CLIMATE CHANGES FROM POLICY INTERVENTION

5.1 Introduction

In general, road transportation emissions impart climate changes through emissions of the greenhouse gases or other aerosols from vehicle exhaust, as was discussed in chapter 3. Therefore, it is clear that the stated CNG conversion policy will certainty have impacts on global climate. This climate change should also be addressed while analyzing such wide-scale policy impacts economically. Along with the health impacts resulting from the policy, as discussed in the previous chapter, these climate changes should also be quantified in monetary terms in order to make informed decision choices. This chapter will discuss the methodology and all the necessary data to estimate the climate impacts. Unlike the impact pathway models used for estimating health impacts, modeling the changes in climate due to changes in emissions and modeling the corresponding damages, i.e. crop losses, coastal inundation, increased flooding, cyclones, diseases etc. is a challenging task, requiring large, specialized resources and extensive damage models. Therefore, a different approach is used for climate cost/benefit estimation. All climate related terminologies and concepts required for understanding this chapter are defined and described in the third chapter. In this chapter, section 5.2 will provide the outline methodology of the climate impacts analysis due to policy, section 5.3 will describe in detail the steps of the global climate impact model including the required formula, data and relevant information. Section 5.4 gives a summary of the chapter.

5.2 Outline of Methodology for Climate Impacts Analysis

In general, climate changes arising from the policy of CNG conversion of vehicles include the contribution to global warming and/or cooling processes, affecting the overall climate balance from GHGs and particulates/aerosols related with proposed changes in vehicular emissions. Impact of different GHGs on radiative forcing balance, described in the third chapter, and thus climate is also different. However, it is possible to normalize the changes in emissions (determined from the emissions inventory model) of different GHGs due to the policy using global warming/cooling potentials (UNFCCC 2010, Reynolds and Kandlikar 2008) into a common equivalent unit (equivalent CO_2 emissions) and then use the market price of carbon, or social costs of a ton of carbon emission to determine the monetized benefits of avoided damages. The simple methodology is shown in Figure 5.1 which evaluates the climate changes induced from the policy.

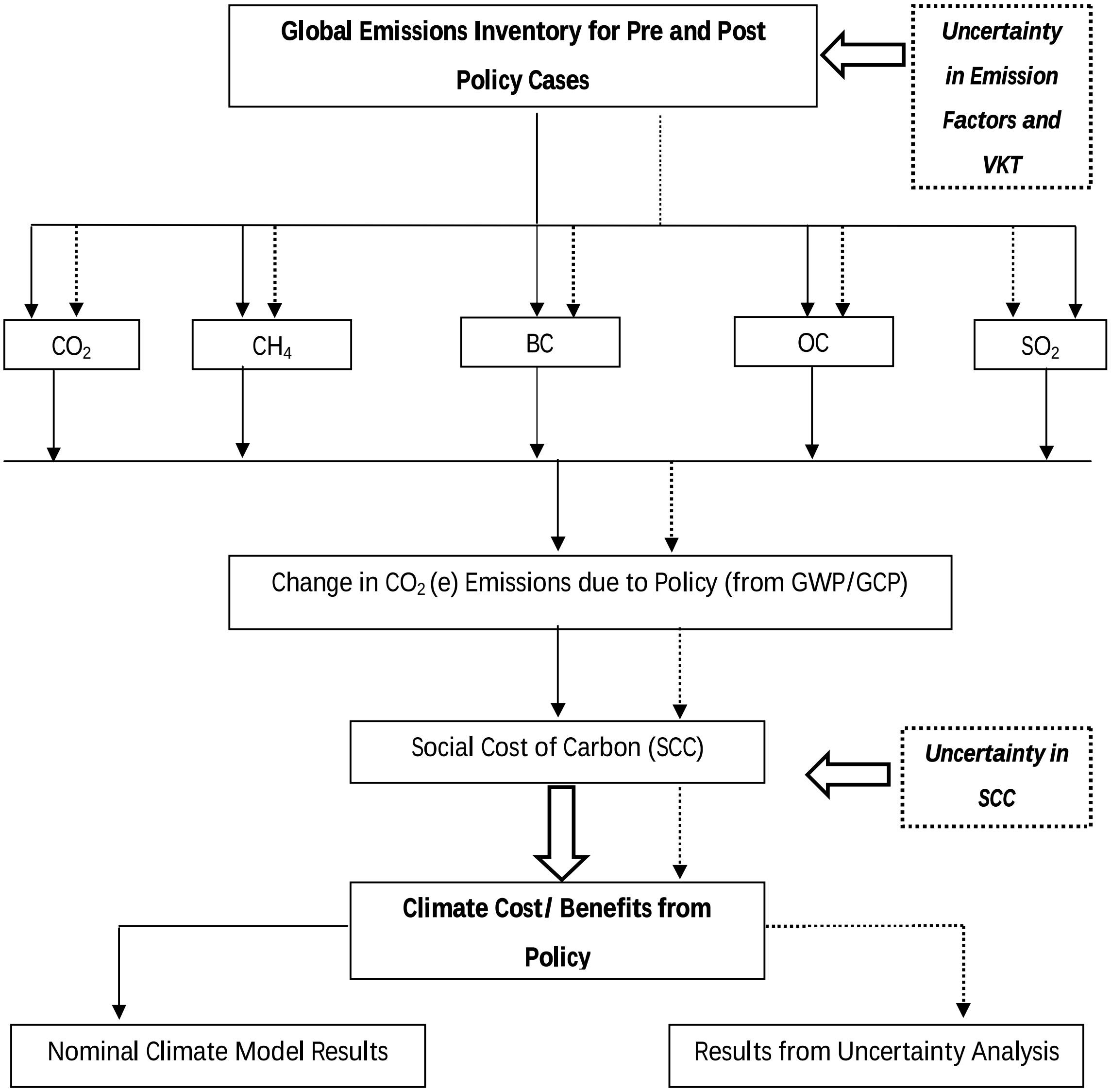

Figure 5.1: Methodology of Estimation of Climate Changes from Policy

It can be seen from Figure 5.1 that the entire computation initiates with the emissions inventory of the climatologically important species which are again related to road transport emissions, particularly in this case, CNG conversion policy. This sector of data contains important uncertainties, i.e. emission factors of each of the pollutant, vehicular activity (VKT) etc. Hence, once again, the entire methodology of impact estimation model can be conducted by two approaches, i.e. with nominal data and uncertainty analysis, as was done in air quality impacts in chapter 4 (Figure 4.2). The model with nominal results is one which takes the most-probable or best guess data in the computations and finally gives the (nominal) output based on these nominal values. On the other hand, uncertainty once introduced in a step, propagates through all the following steps of calculations, combines with other sources of uncertainty (if any) and ultimately reaches the final output.

Once the vehicular emissions inventory for all the globally important pollutants, for both base and current cases, are obtained (whether with nominal or uncertainty consideration), the CO_2(e) emissions are calculated using the equivalent metric, GWP or GCP whichever applicable. Imposing the social cost of carbon (SCC) on the changes in global emissions induced from the policy, the associated climate benefits or cost can be determined. It is shown in Figure 5.1 that SCC is an important uncertain valuation parameter which will be discussed in section 5.3.2. When conducting the uncertainty analysis, the previous uncertainty is combined at this point with the uncertainty from SCC and finally the results are obtained in terms of climate cost or benefits.

5.3 Modeling Global Climate Impacts from Policy Implementation

From the outline of methodology for estimating overall climate impacts, it is clear that the first step is to determine the global emissions inventory which includes the related GHGs and aerosols emissions. These emissions have different impacts through different global warming or cooling potentials. Also, some of the emissions may have beneficial impacts, so reducing these emissions can result in a negative impact. The following section 5.3.1 discusses on the required global emissions inventory.

5.3.1 Emissions Inventory

The emissions inventory model for climate change impacts is similar to the one in air quality model discussed in the previous chapter. The pollutants are different and the grid-wise method of obtaining emissions in a particular study area is not required in this case since the change is considered upon the global climate as a whole. As was discussed in the third chapter, among motor vehicle emissions, CO_2 and CH_4 are established GHGs', contributing directly to global warming (UNFCCC 2010). These gases can be even more important in case of CNG vehicles. However, recent studies (Reynolds and Kandlikar 2008) show aerosols such as sulphates (SO_2), black carbon (BC) and organic carbon (OC) can also have important influence on the earth's radiation balance and thus on global climate. Black and organic carbons are the primary components of $PM_{2.5}$ of which black carbon has a potentially large impact on global warming (Bond et al. 2004). On the other hand SO_2 (precursor to sulphates) and organic carbon have cooling effects on the climate through facilitating the formation of aerosols (Reynolds and Kandlikar 2008). Although NO_x emissions can also have an impact on global warming through secondary effects (formation of nitrates, shortening lives of CH_4 - both of which have a cooling effect, or formation of Ozone- which has a warming effect), it is assumed in the study, following Reynolds and Kandlikar (2008) that NO_x changes from fuel switching have a negligible climate impact. The study therefore focuses on the inventory of five global emissions (CO_2, CH_4, SO_2, black carbon, organic carbon) for the policy impact analysis on the climate.

Recalling the vehicular emissions calculation processes and formula (equations 4.1 and 4.2), the same factors are required for global emissions estimation with only the exceptions of global warming/cooling potential and the unit of VKT. The global warming/cooling potential expresses the contribution of specific species to the overall climate warming/cooling and more specifically the equivalent emissions in terms of CO_2 while the VKT is expressed in km/year. Hence the emissions calculation equation 4.1 is modified to the following form as given by Reynolds & Kandlikar (2008):

$$CO_{2(e)} = \sum(A_v \times N_v \times EF_{v,i} \times P_i) \qquad (5.1)$$

where, $CO_2(e)$ is the GHG/aerosols' emissions in terms of equivalent CO_2;
A_v and N_v are the vehicle activity (in Km/year per vehicle) and numbers of vehicle respectively;
$EF_{v,i}$ is the vehicular emission factor for emission species i and P_i is the global warming or cooling potential of that species with respect to the reference species, CO_2.

Equation 5.1 calculates equivalent CO_2 emissions from stated global pollutants and is expressed in 1000 tons/year. Among the global pollutants specified for the analysis, only the black and organic carbon emissions require the insertion of super-emitters, as was discussed in chapter 4. Hence only black and organic carbon emissions from vehicles are determined using super-emitters' contribution from equation 4.2. Other pollutants' emissions will be estimated directly using equation 5.1. Global warming/cooling potential to compute the corresponding CO_2 (e) will be discussed in detail in the section 5.3.1.2.

For the emissions calculation, the basic vehicle inventory is taken from that given in Table 4.1. However, in this case, vehicle activity is taken into uncertainty consideration and the values obtained as random numbers from the program for VKT for different vehicle-fuel types both before and after the conversion are shown in Appendix B via excel snapshots. The other important factor for estimating vehicular emissions is the emission factor. It was mentioned in the fourth chapter while modeling $PM_{2.5}$ emissions that since no systematic testing of vehicles is available in Dhaka to determine the emission factors, it is important to turn to the international literature for collecting the emission factors for different vehicle classes and fuel type. However, it is also possible, in some cases, to derive the emission factors with some simple calculations. The detail sources, derivation in possible cases and modification procedures of emission factors for each stated pollutant are discussed in the following sub-section 5.3.1.1.

5.3.1.1 Emission Factors

A number of estimates of emission factors of each of the global pollutants are available from literature and own estimates wherever possible. To account for such inherent uncertainties of emission factors, random numbers are generated to simulate the real scenario. According to equation 5.1, emissions will be generated for both no policy and current conversion cases for each of the vehicle-fuel combination classes. With initial uncertainty considerations for emission factors and VKT, each class will contain a number of random emissions and altogether these individual emissions will contribute to the whole emissions of a particular global pollutant.

Emission Factors: CO_2

CO_2 emission factors for different vehicle-fuel classes are collected from Reynolds and Kandlikar (2008). These can also be directly calculated using the following formula:

For diesel and gasoline vehicles,

$$EF_{CO_2} = FE \times CC \times 1000 \qquad (5.2)$$

And for CNG vehicles (converted from diesel/gasoline),

$$EF_{CO_2} = FE \times CC \times \left[\left(1 + \frac{l}{100}\right) \times \left(1 - \frac{CE}{100}\right)\right] \quad (5.3)$$

where, EF_{CO_2} is the estimated emission factors of CO_2 (gram/kilometers) for different fuelled vehicles;

FE is the fuel efficiency/economy in litre/Km;

CC is the carbon content in Kg/litre;

l is the loss of fuel efficiency (%);

CE is the carbon efficiency (%)

Fuel economy values are collected from those used by Wadud & Khan (2011). Carbon content for diesel and gasoline vehicles is 2.66 and 2.32 respectively. Loss in fuel efficiency or fuel penalty for CNG vehicles are taken from Reynolds & Kandlikar (2008) and the values are 25% when converted from diesel and 5% when converted from gasoline fuel. Carbon efficiency for CNG vehicles are 12.7% and 12.6% for diesel and gasoline respectively (Reynolds & Kandlikar 2008). The emission factors of CO_2 from both sources, Reynolds & Kandlikar (2008) and the estimated ones, are listed in Table 5.1.

Emission Factors: CH_4

CH_4 emission factors are available from Reynolds & Kandlikar (2008) containing CH_4 leakage emission rates for the CNG vehicles and from Lipman & Delucchi (2002) without consideration for CH_4 leakage emissions. In addition to the unburnt Methane emissions through the exhaust, Methane can escape during fueling as well as through leaks of the retrofitted vehicles. Since Methane is a more potent GHG than CO_2, leaked Methane can have a large impact on warming. CNG emission factors from these sources are shown in Table 5.2 corrected for the leakage rates.

Emission Factors: SO_2

SO_2 is an important global pollutant since its contribution to the climate is negative forcing or global cooling. It is also a precursor to the secondary formation of PM. But this secondary effect is not taken into consideration in the current study. Urbanemissions (2010) and Reynolds & Kandlikar (2008) are the two important sources of the emission factors of SO_2 in the literature. These are given in Table 5.3.

Table 5.1: Emission Factors of CO_2 (gm/Km) from Various Sources

Vehicle – Fuel	**Reynolds & Kandlikar**	**Estimated (Diesel/Gasoline)**	**Estimated – CNG / Converted CNG from**
Motor cars – Gasoline	157	258	237
Motor cars – CNG	144		_
Jeep/SUV/station wagons – Diesel	157	332.5	363
Jeep/SUV/station wagons – Gasoline	157	331.4	304
Jeep/SUV/station wagons – CNG	144		_
Microbus – Diesel	157	332.5	363
Microbus – Gasoline	157	331.4	304
Microbus – CNG	144		_
Taxi – CNG	144	_	237
Bus – Diesel	1063	887	967
Bus – CNG	1160		_
Minibus – Diesel	1063	665	726
Minibus – CNG	1160		_
Truck – Diesel	1063	799	872
Truck – CNG	1160		_
Auto-rickshaw – CNG	62	_	85
Motor cycle – Gasoline	67	69.6	_
Others – Diesel	157	332.5	363
Others – Gasoline	157	331.4	304
Others – CNG	144		_

Table 5.2: Emission Factors of CH_4 (gm/Km) from Various Sources

Vehicle – Fuel	**Reynolds & Kandlikar (2008)**	**Lipman & Delucchi (2002)**
Motor cars – Gasoline	0.14	0.137
Motor cars – CNG	2.53	6.47
Jeep/SUV/station wagons – Diesel	0.14	0.012
Jeep/SUV/station wagons – Gasoline	0.14	0.137
Jeep/SUV/station wagons – CNG	2.53	6.47
Microbus – Diesel	0.14	0.012
Microbus – Gasoline	0.14	0.137
Microbus – CNG	2.53	6.47
Taxi – CNG	2.53	6.47
Bus – Diesel	0.06	0.062
Bus – CNG	8.49	11.93
Minibus – Diesel	0.06	0.062
Minibus – CNG	8.49	11.93
Truck – Diesel	0.06	0.062
Truck – CNG	8.49	11.93
Auto-rickshaw – CNG	1.41	6.33
Motor cycle – Gasoline	0.08	0.137
Others – Diesel	0.14	0.012
Others – Gasoline	0.14	0.137
Others – CNG	2.53	6.33

Table 5.3: Emission Factors of SO_2 (gm/Km) from Various Sources

Vehicle – Fuel	**Reynolds & Kandlikar (2008)**	**Urbanemissions (2010)**
Motor cars – Gasoline	0.015	0.07
Motor cars – CNG	0	0
Jeep/SUV/station wagons – Diesel	0.015	0.3
Jeep/SUV/station wagons – Gasoline	0.015	0.07
Jeep/SUV/station wagons – CNG	0	0
Microbus – Diesel	0.015	0.3
Microbus – Gasoline	0.015	0.07
Microbus – CNG	0	0
Taxi – CNG	0	0
Bus – Diesel	0.233	1
Bus – CNG	0	0
Minibus – Diesel	0.233	1
Minibus – CNG	0	0
Truck – Diesel	0.233	1
Truck – CNG	0	0
Auto-rickshaw – CNG	0	0
Motor cycle – Gasoline	0.006	0.02
Others – Diesel	0.015	0.3
Others – Gasoline	0.015	0.07
Others – CNG	0	0

Tables 5.1 through 5.3 have tabulated the emission factors of CO_2, CH_4 and SO_2 respectively from various sources for different types of vehicle-fuel combinations. Similarities among some of the vehicle-fuel classes are assumed to use the same emission factors due to unavailability of all the classes in the sources. Observing the data in the Tables 5.1 and 5.2, it is clear from the higher emission rates of CO_2 and CH_4 from CNG vehicles that the overall global emissions will certainly increase due to CNG switching policy from these two GHGs. On the other hand, Table 5.3 shows that the counter-acting (global-cooling) aerosol, SO_2 has a zero emission rate from the CNG vehicles which has a positive health impact but will impart negative climate impact (indirect positive forcing) by reducing SO_2 emissions.

Emission Factors: Black Carbon & Organic Carbon

Black carbon and organic carbon are emitted as parts of particulate matter. Following Wadud and Khan (2011), for emissions inventory, they are calculated as:

$$\text{BC(OC)} = \text{PM}_{10} \times \frac{\text{PM}_{1.0}}{\text{PM}_{10}} \times \frac{\text{BC(OC)}}{\text{PM}_{1.0}} \quad (5.4)$$

This formula is given by Bond et.al. (2004). The fractions $PM_{1.0}/PM_{10}$, $BC/PM_{1.0}$ and $OC/PM_{1.0}$ may depend on vehicle and environmental characteristics such as vehicle type, combustion technology, fuel type, operating conditions. In the absence of Bangladesh or Dhaka specific information on these, Wadud and Khan (2011) used data from Bond et al. (2004) to get the values of these factors for different vehicle and fuel types, i.e. petrol and diesel.

These formulas calculate emission factors for regular emitters. The insertion of the super-emitters is necessary to represent the actual scenario as is discussed in chapter 4. With the proper insertion of the super-emitters' contribution to the total emissions from diesel and gasoline motor vehicles, the PM_{10}, BC and OC emissions are calculated using equation 4.2.

This study uses emission factors of black and organic carbon from a number of sources collected by Wadud and Khan (2011). These sources are: Reynolds & Kandlikar (2008), Bond et.al. (2004), Urbanemissions (2010) and Narain & Krupnick (2007). Among these, only Reynolds & Kandlikar include the emission factors of BC and OC directly along with the super-emitter's contribution and hence do not require any correction for the purpose. For the rest three sources, first the emission factors are determined for normal emitting vehicles from respective (normal) PM_{10} emission factors (as is obtained from different sources) and the PM fractions (given by Bond et.al. 2004) and then also corrected for the super-emitters as per equation 4.2 using required data from Table 4.3. Here the only variation is in the use of different normal emitting PM_{10} emission factors from different sources and these are combined with the same super emitting emission factors.

For CNG fuelled vehicles, in absence of any further specific formula like equation 5.4, the same equation, i.e. equation 5.4, is used to compute the emission factors of BC and OC from CNG vehicles. It is assumed that the particle-size distributions are the same for gasoline and CNG vehicles (AASHTO 2004). Therefore, it is only required to obtain the PM_{10} emission factors from CNG vehicles from the stated references and then equation 5.4 is used to estimate the corresponding emission factors for BC and OC where these are not given directly. Tables 5.4 through 5.7 represent the emission factors of PM_{10}, BC and OC as collected by Wadud and Khan (2011) from the stated sources.

Table 5.4: Calculated Emission Factors (gm/Km) of PM_{10}, BC and OC for Normal Emitters / Normal combined with Super-emitters from Bond et.al. (2004)

Vehicles	**Emission Factors of PM_{10} (gm/Km)**		**Emission Factors of BC (gm/Km)**		**Emission Factors of OC (gm/Km)**	
	Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline
Motor cars	_	0.041/0.09	_	0.012/0.026	_	0.013/0.028
Jeep/SUV/station wagons	0.372/1.04	0.053/0.053	0.211/0.59	0.015/0.015	0.067/0.19	0.016/0.016
Microbus	0.372/1.04	0.053/0.053	0.211/0.59	0.015/0.015	0.067/0.19	0.016/0.016
Taxis	_	_	_	_	_	_
Buses	0.992/2.1	_	0.563/1.19	_	0.179/0.38	_
Minibuses	0.744/2.01	_	0.422/1.14	_	0.134/0.364	_
Trucks	0.893/2.57	_	0.507/1.46	_	0.161/0.46	_
Auto-rickshaws/Tempo	_	_	_	_	_	_
Motor cycle	_	0.011/0.011	_	0.003/0.003	_	0.003/0.003
Others	0.372/1.04	0.053/0.053	0.211/0.59	0.015/0.015	0.067/0.19	0.016/0.016

Table 5.5: Emission Factors of PM_{10} (Urbanemissions 2010) and Calculated Emission Factors of BC and OC for Normal / Combined Emitters (gm/Km)

Vehicles	**Emission Factors of PM_{10} (gm/Km)**			**Emission Factors of BC (gm/Km)**			**Emission Factors of OC (gm/Km)**		
	Diesel	Gasoline	CNG	Diesel	Gasoline	CNG	Diesel	Gasoline	CNG
Motor cars	_	0.1/0.126	0.05	_	0.029/0.036	0.014	_	0.031/0.0385	0.015
Jeep/SUV/station wagons	1.25/1.27	0.1	0.05	0.71/0.72	0.029	0.014	0.226/0.229	0.031	0.015
Microbus	1.25/1.27	0.1	0.05	0.71/0.72	0.029	0.014	0.226/0.229	0.031	0.015
Taxis	_	_	0.05	_	_	0.014	_	_	0.015
Buses	1.5/2.37	0.1	0.02	0.85/1.35	_	0.0058	0.270/0.429	_	0.006
Minibuses	1.5/2.24	0.1	0.05	0.85/1.27	_	0.014	0.270/0.404	_	0.015
Trucks	2/2.82	0.1	0.02	1.14/1.60	_	0.0058	0.361/0.509	_	0.006
Auto-rickshaws/Tempo	_	_	0.1	_	_	0.029	_	_	0.0306
Motor cycle	_	0.1	_	_	0.029	_	_	0.031	_
Others	1.25/1.27	0.1	0.05	0.71/0.72	0.029	0.014	0.226/0.229	0.031	0.015

Table 5.6: Emission Factors of PM_{10} (Narain & Krupnick 2007) and Calculated Emission Factors of BC and OC for Normal / Combined Emitters (gm/Km)

Vehicles	**Emission Factors of PM_{10} (gm/Km)**			**Emission Factors of BC (gm/Km)**			**Emission Factors of OC (gm/Km)**		
	Diesel	Gasoline	CNG	Diesel	Gasoline	CNG	Diesel	Gasoline	CNG
Motor cars	_	0.010/0.072	0.005	_	0.003/0.021	0.0014	_	0.003/0.022	0.0015
Jeep/SUV/station wagons	0.046/0.95	0.01	0.005	0.026/0.54	0.003	0.0014	0.008/0.172	0.003	0.0015
Microbus	0.046/0.95	0.01	0.005	0.026/0.54	0.003	0.0014	0.008/0.172	0.003	0.0015
Taxis	_	_	0.005	_	_	0.0014	_	_	0.0015
Buses	0.37/1.76	_	0.006	0.21/1.00	_	0.0017	0.067/0.319	_	0.0018
Minibuses	0.37/1.90	_	0.006	0.21/1.08	_	0.0017	0.067/0.344	_	0.0018
Trucks	0.08/2.38	_	0.006	0.045/1.35	_	0.0017	0.014/0.430	_	0.0018
Auto-rickshaws/Tempo	_	_	0.005	_	_	0.0014	_	_	0.0015
Motor cycle	_	0.027	_	_	0.008	_	_	0.008	_
Others	0.046/0.95	0.01	0.005	0.026/0.54	0.003	0.0014	0.008/0.172	0.003	0.0015

Table 5.7: Emission Factors of BC and OC (gm/Km) from Reynolds and Kandlikar (2008) (incorporated super-emitters)

Vehicles	**BC**			**OC**		
	Diesel	Gasoline	CNG	Diesel	Gasoline	CNG
Motor cars	_	0.16	0.001	_	0.17	0.003
Jeep/SUV/station wagons	0.16	0.16	0.001	0.17	0.17	0.003
Microbus	0.16	0.16	0.001	0.17	0.17	0.003
Taxis	_	_	0.001	_	_	0.003
Buses	1.52	_	0.002	0.48	_	0.005
Minibuses	1.52	_	0.002	0.48	_	0.005
Trucks	1.52	_	0.002	0.48	_	0.005
Auto-rickshaws/Tempo	_	_	0.008	_	_	0.024
Motor cycle	_	0.01	_	_	0.19	_
Others	0.16	0.16	0.001	0.17	0.17	0.003

Tables 5.4 through 5.7 have enlisted emission factors of PM_{10}, black and organic carbon from various sources. PM_{10} emission factors are not directly used in the emissions estimation for any impact, i.e. urban-air or global climate, analysis related to the policy. It is necessary in this study to derive the emission factors of BC and OC.

5.3.1.2 Global Warming/Cooling Potentials

In order to take into account the contribution of the global pollutants to the climate, i.e. positive or negative forcing, it is important to know the global warming/cooling potentials. It was already discussed in the third chapter that global warming/cooling potential is a measure of the total contribution of a GHG or aerosol in the processes of global warming/cooling or exertion of positive or negative forcing respectively. It is a relative scale where the reference is the carbon dioxide gas (whose GWP is by convention equal to 1) and others are compared with respect to the same mass of CO_2.

The 100 year global warming/cooling potentials of each of the pollutants are used to normalize them to an equivalent scale. The normalization allows to use a common metric, CO_2 equivalent emissions, which can be added or subtracted (depending on net warming or cooling effect) to generate net warming-weighted emissions of the different pollutants. This is determined for each of the stated pollutant according to equation 5.1. Although the GWP/GCP values are still uncertain and ranges of values for uncertainty are being provided in the literature, this study will not consider this factor into the proposed uncertainty assessment; rather the assessment will focus onto the transport, i.e. vehicles' VKT, EF etc and policy valuation, i.e. VSL for health impacts and SCC for climate impacts, related factors' uncertainty.

It was stated in the outline of methodology in section 5.2 that after the determination of the changes in total global emissions in terms of equivalent CO_2 metric, the climate cost/benefits will be obtained through using social cost of carbon. If the changes in emissions are reduced, the total cost will be decreased in the policy case or vice-versa. Hence to quantify the amount of this cost/benefit, carbon price or social cost of carbon is important which is discussed in the following section 5.3.2.

5.3.2 Valuation of Global Emissions – Social Cost of Carbon

The social cost of carbon, or SCC, is an estimate of the damage caused – today and in the future – by the release of an additional ton of carbon dioxide into the atmosphere. The "social cost of carbon" (SCC) is the present value of the future damages from one additional unit of carbon emissions (carbon di-oxide or carbon, discussed later) in a particular year (National Center for Environmental Economics (NCEE), USEPA 2010). SCC is a commonly estimated measure of the economic benefits (or costs) of greenhouse gas (GHG) emission reduction (or increases). It represents the present value of the marginal social damages of increased GHG emissions in a particular year—including the impacts of global warming on agricultural productivity and human health, loss of property and infrastructure to sea level rise and extreme weather events, diminished biodiversity and ecosystem services, etc.—and therefore it also represents the marginal social benefits of emissions reductions. Properly defined, the SCC is the correct "shadow price" to place on GHG emissions in a benefit-cost or social welfare analysis of climate change policies (Newbold et.al. 2010).

To calculate the SCC, the atmospheric residence time of carbon dioxide must be estimated, along with an estimate of the impacts of climate change. The impact of the extra ton of carbon dioxide in the atmosphere must then be converted to the equivalent impacts when the ton of carbon dioxide was emitted. In economics, comparing impacts over time requires a discount rate. This rate determines the weight placed on impacts occurring at different times. The SCC increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change (Interagency Working Group, USA, 2010).

From economic theory, if SCC estimates were complete and markets perfect, a carbon tax should be set equal to the SCC. Emission permits would also have a value equal to the SCC. In reality, however, markets are not perfect, and SCC estimates are not complete (Yohe et al. 2007).

An amount of CO_2 pollution is measured by the weight (mass) of the pollution. Sometimes this is measured directly as the weight of the carbon dioxide molecules. This is called a ton of carbon dioxide and is abbreviated "tCO_2". Alternatively, the pollution's weight can be measured by adding up only the weight of the carbon atoms in the pollution, ignoring the oxygen atoms as is mentioned earlier in this section. This is called a ton of carbon and is abbreviated "tC". Estimates of the dollar cost of carbon dioxide pollution is given per ton, either carbon, USD X/tC, or carbon dioxide, USD X/tCO_2. One tC is roughly equivalent to 4 tCO_2 (accurately 44/12=3.66) and this relationship is used in this study whenever SCC estimates are found in literature as per ton of carbon to convert that into carbon cost per ton of CO_2. Though limited, there are various published estimates of social cost of carbon or carbon price available in literature. The study focuses on such few works from which the values will be assembled for the climate cost analysis and uncertainty assessment in the following chapter.

Published Estimates of SCC in Literature

Estimates of the SCC are highly uncertain. Yohe *et al.* (2007) summarized the literature on SCC estimates. Peer-reviewed estimates of the SCC for 2005 had an average value of USD 43/tC with a standard deviation of USD 83/tC. The wide range of estimates is explained mostly by underlying uncertainties in the science of climate change, different choices of discount rate, different valuations of economic and non-economic impacts and how potential catastrophic impacts are estimated. Other estimates of the SCC spanned at least three orders of magnitude, from less than USD 1/tC to over USD 1,500/tC. The true SCC is expected to increase over time. The rate of increase will very likely be 2 to 4% per year.

American Association of Wine Economists (AAWE) working paper (2007), by Colman & Paster, enlists different values of carbon price depending on different scenarios. The study mentioned that the current true cost of carbon is USD 45 per ton of CO_2 according to UN estimate while the SCC is USD 142.68 per ton.

Department of Environment, Food & Rural Affairs (DEFRA), London (2002) reported a number of works on SCC. In 1996 the IPCC's Working Group III published a range of USD 5-125 per ton of carbon (in 1990 prices, or USD 6-160/tC in 2000 prices). This is considered to be the range of best guesses from existing studies for carbon emitted in the period 1991-2000. For the period 2001-2010, the relevant range increases to USD 7-154 per ton of carbon (in 1990 prices, or USD 9-197/tC in 2000 prices). The most sophisticated of the published studies reviewed by the study produces an estimate of marginal damage figure of approximately £70/tC (2000 prices) (USD 106.4 per ton carbon in 2000 USD) for carbon emissions in 2000. This increases by approximately £1/tC (USD 1.52 in 2000 prices) per year in real terms for each subsequent year to account for the increasing damage costs over time. This figure is subject to significant levels of uncertainty and hence the study suggests an upper value of £140/tC (i.e. 2x£70/tC) and a lower value of £35/tC (i.e. 0.5x£70/tC) (all 2000 prices) to perform uncertainty/sensitivity analyses.

NCEE, USEPA (2010), summarized one study that reported a 90-percent confidence interval for the SCC of USD 1.1 to USD 15. Another study reported by USEPA (2010) concludes the median value USD 12, the mean USD 43, and the 95th percentile to be USD 150. The National Research Council concluded that the range of estimates of marginal climate damages (social cost of carbon) can vary by two orders of magnitude, from a negligible value of about USD 1 per ton to USD 100 per ton of CO_2 (e). The stated study estimated SCC values in 2005 as USD 6.6, USD 10, and USD 11 per metric ton of CO_2 per year, with average growth rates over the first 50 years of 2.4%, 2.3%, and 2.3% per year, respectively.

Interagency Working Group on Social Cost of Carbon, United States Government (2010), selected four SCC values in five year increments from 2010 to 2050 for use in regulatory analyses. Among these, three values are based on the average SCC from three integrated assessment models, at discount rates of 2.5, 3, and 5 percent and the values for the year 2010 are respectively USD 35.1, USD 21.4 and USD 4.7 per ton CO_2. The fourth value, which represents the 95th percentile SCC estimate across all three models at a 3 percent discount rate is USD 64.9 per ton CO_2 (all 2007 USD) for year 2010.

The stated study differentiated between domestic and global SCC. Domestic SCC is meant to reflect the value of damages in the United States resulting from a unit change in carbon dioxide emissions, while a global SCC value is meant to reflect the value of damages worldwide. A domestic SCC value of USD 2 per ton of CO_2 and a global SCC value of USD

33 per ton of CO_2 for 2007 emission reductions (in 2007 dollars), are used by Department of Transport (DOT), increasing both values at 2.4 percent per year.

DOT assumed a domestic SCC value of USD 7 per ton CO_2 (in 2006 dollars) for 2011 emission reductions (with a range of USD 0-14 for sensitivity analysis), also increasing at 2.4 percent per year. A regulation finalized by Department of Environment (DOE) in October, 2008 used a domestic SCC range of USD 0 to USD 20 per ton CO_2 for 2007 emission reductions (in 2007 dollars). EPA's global mean values were USD 68 and USD 40 per ton CO_2 for discount rates of approximately 2 percent and 3 percent, respectively (in 2006 dollars for 2007 emissions).

The outcome of the preliminary assessment by the interagency group was a set of five interim values: global SCC estimates for 2007 (in 2006 dollars) of USD 55, USD 33, USD 19, USD 10, and USD 5 per ton of CO_2. The USD 33 and USD 5 values represented model-weighted means of the published estimates produced from the most recently available versions of three integrated assessment model at approximately 3 and 5 percent discount rates. The USD 55 and USD 10 values were derived by adjusting the published estimates for uncertainty in the discount rate at 3 and 5 percent discount rates, respectively. The USD 19 value was chosen as a central value between the USD 5 and USD 33 per ton estimates. All of these values were assumed to increase at 3 percent annually to represent growth in incremental damages over time as the magnitude of climate change increases.

From the discussion on the various estimates of SCC or carbon price, it is clear that this is an important factor that must be included within uncertainty analysis. Due to uncertainty of this parameter, uncertainty in the final result, i.e. global climate cost saved or lost due to policy, increases. In this study, the SCC values as suggested by DEFRA (2002) are used for nominal calculation or uncertainty analysis. These values are used since the defined range covers almost all the values reported from other sources in the literature discussed above. The generated random values for SCC are listed in Appendix B.

5.4 Summary

This chapter describes the detail methodology of global emissions inventory for the specified global pollutants associated with the CNG conversion policy. Emission factors of the pollutants, as important model factors, are discussed which are in some cases directly collected from various sources and are also modified or estimated (i.e. emission factors of

CO_2). The contribution of these emission factors and annual VKT to overall uncertainty in results are considered and will be discussed in detail in the next chapter. The pollutants' global warming or cooling potentials convert the respective contribution to climate impact in equivalent CO_2 emissions. This helps to determine the changes in global emissions in terms of total CO_2 emissions due to policy. Finally the valuation parameter, social cost of carbon is discussed and a number of estimates are reported from the literature. This factor is also taken into uncertainty assessment and the detail results will be discussed in the next chapter.

CHAPTER 6

APPLICATION OF UNCERTAINTY ASSESSMENT FOR THE CNG CONVERSION POLICY

6.1 Introduction

The primary objective of this research is to address and investigate the contribution of uncertainty assessment to the impacts of an important transport policy. While analyzing a policy impact, the view of such uncertainty assessment is not only to obtain precise range of results (reducing uncertainty of the model results) but also to determine the order of priorities (through sensitivity analysis) of related sectors of data to facilitate the decision maker's choice. Uncertainty assessment is a key to any policy or decision-making processes. The study takes the CNG conversion of vehicles as an important and wide-scale transport policy for case study which requires adequate impacts analysis through uncertainty assessment.

In this chapter, the overall methodology of conducting uncertainty assessment specific to the stated policy will be proposed in section 6.2 according to the original framework (described in the second chapter). This chapter will estimate the impacts determined from the respective models for air quality and climate impacts due to policy which are already discussed in the previous two chapters. Each impact analysis model will contain two approaches – one with nominal values and the other based on the consideration of uncertainty of the model factors, as was mentioned in the last two chapters. All the model factors and their uncertain data ranges, nominal values etc will be collected and finally, the obtained model results will be analyzed in this chapter under section 6.3. The analysis and the results will help the decision maker to make informed choices and also narrow down the limitations associated with the model assumptions and factors. This will also help to define specific future scope of further related studies in order to allocate resources efficiently on reducing the uncertainties of the most influential input factors through further research.

6.2 Uncertainty Assessment for the Policy Results

As mentioned in the second chapter in section 2.2 that uncertainty assessment includes both uncertainty and sensitivity analyses which is applied for the CNG conversion policy in this study. The policy is being analyzed for two major impacts – firstly the health impacts, primarily accruing from reduced $PM_{2.5}$ emissions from CNG vehicles and secondly the climate impacts arising from changes in GHG and particulate emissions. In both of the impact estimation methodology, described in the fourth (health effects) and fifth chapters (climate impacts), two types of results from the model are derived, i.e. with nominal data and with uncertainty analysis.

In case, where the data contains significant uncertainties, sometimes with a probable or relatively large range of choices, it becomes difficult to assign a single confident value to a factor and hence it is necessary to treat that factor as a random variable. Considering this randomness of the model factors, required uncertainty analysis is conducted according to the standard procedure to define the factor uncertainty and finally to reduce the overall uncertainty of the model results. On the other hand, in spite of the factor uncertainties, it is possible (and also necessary) to choose a most-likely or nominal value for a model factor among the existing number of choices for that factor. The model which runs, with the same methodology as that for the uncertainty analysis, but based on these nominal values, will be referred to as an approach to nominal model results in this study.

Approaches of uncertainty will be applied to both urban-air quality effects and global climate changes as per the general 7-step methodology framework, discussed in the second chapter in section 2.4. This 7-step method is only the standard procedure or framework for any uncertainty assessment studies which requires to be formulated for a specific policy model. Hence, at first, these 7 steps will be discussed in accordance with both the stated policy impacts which will also define the scope (as mentioned in section 1.5 in chapter 1) of the uncertainty assessment studies of the research. Then the respective results will be analyzed separately for uncertainty and sensitivity analyses.

Step 1: Establishing objectives of uncertainty assessment

The objectives of the uncertainty assessment for the proposed policy analysis fall in two major categories:

Objectives intended to support decision maker’s choice

i. To reduce uncertainties in results by narrowing down the range of epistemic uncertainties related to different factors of the models

ii. To provide with relatively more specific range of results with known certainty and confidence levels

iii. To provide with different scenario analysis through sensitivity analysis and hence a set of comparable options within the proposed boundary of the policy analysis to refer to most favorable choice

iv. To represent and interpret the technical information and analytical results in a easily understandable approach through graphs, histograms etc

Objectives related to future research

i. To identify the major uncertain branches of factors used in the model as per the latest available knowledge

ii. To find out the area or sector-wise uncertain factors, i.e. transport related or valuation related factors, to address the specific source of uncertainty in outputs due to particular field of data

iii. To determine the relative importance, i.e. ranking, of the uncertain factors in terms of contribution to overall variability of final outputs and hence different choices

iv. To aid future research in related field by confining the studies within the most important factors only and hence to allocate the resources (time, money, efforts etc) efficiently

Step 2: Documentations of assumptions and limitations of the models

Every model has its own limitations and boundaries within which it estimates the intended results. These limitations again lead to some sources of uncertainty and affect the overall results which must be documented. The final results will be confined within this boundary with the known sources of uncertainty. Hence, this documentation will help the future attempts through detail guided procedure along with the limitations to overcome those by focusing onto the related assumptions.

As was seen in chapter 4, in the proposed model for estimation of health benefits, the basic data required for generating vehicular emissions are from the transport sector with large uncertainties which are passed to the consecutive steps of the model and finally accuracy of results is affected. Beyond those transport specific factors which are included in the uncertainty analysis, the basis of the model computation process or more specifically the individual steps of the models (sub-models, i.e. emissions model, concentration model, SRM etc) and some of the computed model factors have some limitations which are listed below.

i. *Limitations regarding built-in uncertainties arising from Model boundaries/Assumptions*

Emissions Model

Vehicular emissions is generated grid-wise following Arjumand (2010) and also modified as per Rahman (2010) to feed into the transfer matrix, i.e. Source receptor model, developed for Dhaka city. Obviously the limitations of the referred models, i.e. study area, techniques of division into grids, measurements of major/minor road lengths, lack of updated data on vehicle numbers, VKT computation procedure etc, apply for the current model as well and hence bring epistemic source of uncertainty within the model computations. With the latest available knowledge, these references are the only means to generate such systematic grid-wise calculations under their respective limitations or validity. With progress in any related future attempts to overcome these model limitations, the current model will require only the inclusion of the modifications or latest updates to reach the ultimate accuracy.

Air-quality model – regarding Source-receptor matrix (SRM)

Data on transfer matrix, i.e. emissions converting to corresponding concentrations, was developed for Dhaka city by Rahman (2010) using local meteorological conditions. Limitations of this model will increase uncertainties within the current calculations affecting the overall result. Again, since this uncertainty depends on the validation and updating of the referred model, it can be reduced or eliminated only if the referred model's uncertainties are overcome which is out of the scope of the current research.

Assumptions regarding computation of fixed model factors

Vehicle Number, Fuel-wise split & Gridded data

There are a few model factors which are not taken into uncertainty analysis assuming that the latest available or computed data can be used in overall estimation without significant uncertainty, yet their computation process involves some limitations. In the current study, as is discussed in the section 4.4.3 in chapter 4, the vehicle number corresponding to various categories for the entire Dhaka city is split with the ratio of total current vehicles to total vehicles in Arjumand (2010) to distribute the vehicles into the grids derived by Arjumand (2010). The ratio-wise distribution may not be valid in all the cases as vehicle in a particular grid could increase more as compared to an adjacent grid.

Also, the data on vehicle numbers, collected from BRTA is cumulative of all registered vehicles up to 2010, but does not contain scrappage information. The fuel-wise split of different vehicles is determined from field survey on vehicle inventory conducted by Wadud and Khan (2011). But again the limited numbers of areas covered within the survey and finally the ratio-wise distribution of total vehicle numbers as per the obtained vehicle-fuel split provide necessary information with underlying uncertainties.

Mortality risks and related mortality rates

Cardiovascular and respiratory diseases are considered as the major health affecting diseases causing premature deaths, from vehicular $PM_{2.5}$ emissions and impacts (benefits) are estimated for these two diseases causing the total health benefits due to policy. Associated mortality risk values (CR functions) are not found for Bangladesh or Dhaka for which uncertainty is included within the estimates. Such exposure or dose-response functions cannot be defined by continuous probability distribution and hence C-R function is not considered into the sample-based probabilistic uncertainty analysis (Mahashabde 2010). Discrete values of CR from the literature (shown in Table 6.2) are used for the sensitivity analysis in section 6.3.2.2.

Due to lack of reliable sources of data on mortality rates for Dhaka, the only available data from WHO (2009) is used. No uncertainty due to this factor is taken into the analysis assuming negligible contribution to overall uncertainty of results from this factor.

Limitations regarding global climate impacts estimation

The most important underlying uncertainty within the adopted approach arises from climate science related uncertainty, i.e. global warming/cooling potentials of different global pollutants considered. Since this study is more focused to the overall impacts from road transport emissions, this purely environmental or climate related factor is not taken into uncertainty analysis; rather specific values are directly used from Reynolds & Kandlikar (2008). But it should be mentioned here that these types of parameters usually vary within a considerably wide range of values; specifically the ranges and hence the uncertainties for black carbon, organic carbon and SO_2 are much wider than other GHGs.

Assumptions related to estimated emission factors

Although in all the cases, whether estimating health or climate impacts, emission factors are taken into uncertainty analysis and the model is run from the very beginning with the consideration of uncertainty, there are some assumptions related to calculation of some of the pollutants' emission factors. While deriving $PM_{2.5}$, black and organic carbon emission factors, some particle size distributions are used which are taken from the available information in literature. Super-emitters' fractions for Dhaka city, required for particulate emissions from vehicles, are available from one study for very limited types of vehicles. These sources of uncertainties are actually meant to be included while considering them within the overall uncertainty analysis of emission factors (within specified boundary values within which the random numbers are generated). Nevertheless, more specific sources of data or detail uncertainty analysis in a more disaggregated level in this regard, i.e. for each type of super-emitters' emission factors or particle size-fractions etc, may reach the extreme accuracy level.

Similarly, CO_2 emission factors are both estimated and taken from literature to generate a more representative estimate. Estimated CO_2 emission factors require data on fuel economy, fuel penalty (loss in fuel efficiency for CNG vehicles) etc which may again contain uncertainties. It is assumed that the boundary values defining the associated uncertainty distributions have included these variations and uncertainty analysis is not required in a disaggregated level.

Step 3: Documentation of factors and outputs of the model

Since there are two models to evaluate the policy results on urban-air and climate impacts, the final outputs will be from two different observations – health impacts from urban-air improvement and total climate costs/benefits in monetary terms due to policy. The input factors are almost similar since the same source, i.e. transport or vehicular emissions, is analyzed in two respects following two different methodologies. The impacts due to policy, analyzing approaches, steps or sub-models of the approaches, step-by-step input factors along with their units and corresponding outputs are summarized in Table 6.1 without information on used data or uncertainty. Here in Table 6.1, only the steps are summarized as were shown in the outline of methodology in the Figure 4.2 (chapter 4) and Figure 5.1 (chapter 5). The final outputs of the considered impacts are health benefits (USD million) and climate costs/benefits (USD million) respectively (all 2010 prices).

Table 6.1: Summary of all Models, Factors and Outputs of the Impacts Analysis

Impact Analysis	**Approach**	**Models/ Functions/Steps**	**Inputs/Factors**	**Units**	**Step-by-step Outputs of Policy (units)**
Urban-air	Impact-pathway	Emissions	Vehicle No.	#	$PM_{2.5}$ Emissions (tons/year per grid)
			Grid-wise composite VKT matrix	Km/day per grid	
			$PM_{2.5}$ Emission Factors	gm/Km	
		Air-quality	Source-Receptor (transfer) Matrix for $PM_{2.5}$	$\mu g/m^3$ per grid	$PM_{2.5}$ concentrations ($\mu g/m^3$)
		Concentration-Response	Mortality risks – Relative risk (*C & R)	% increase per unit change in concentration	Relative Risks
		Mortality Effects	Constants k_c, k_r		(*C & R)
			*C & R Mortality rates	# per 1000	Total Deaths avoided
		Valuations	Grid-wise Population	# per grid	
			Value-of-statistical life (VSL)	USD (2010)	Health benefits (USD million)
Global Climate	Climate Model	Global Emissions	Vehicle Numbers	#	Global Emissions (1000 tons/year)
			Annual VKT (individual)	Km/year	
			Emission Factors of global pollutants	gm/Km	
			Global warming/cooling potential	Eqv. CO_2 scale	
		Valuation	Social cost of carbon (SCC)	USD (2010) per ton CO_2	Climate Costs (USD million)

*Cardiovascular & respiratory

Step 4: Classifying & Characterizing Uncertainty

All the factors which are considered into the uncertainty analysis so far are known to have epistemic uncertainty, since very little is known about aleatory uncertainty or that arises from natural randomness. As stated in chapter 2, sample based probabilistic distribution is adopted for the uncertainty analysis in the current study. Table 6.2 lists the assigned probability distributions for all the input factors of the model considered under epistemic uncertainty, with their sources of data.

In Table 6.2, T(a,b,m) defines values of a factor under triangular distribution where a is the minimum, b is the maximum and m is the modal or most probable value. Uniform distribution of a factor is defined by U(a,b) where a is the minimum and b is the maximum value defining the distribution. Factors shown in Table 6.2 are all under continuous distributions except mortality risk constants defining relative risks for cardiovascular and respiratory i.e. k_c and k_r, under discrete distributions and the assembled discrete values are denoted by D(discrete points) in Table 6.2.

Table 6.2: Uncertainty Information on the Factors considered into Uncertainty Assessment

Data Type	**Transport Specific Factors: Defining Values for Uncertainties in**						
Impacts due to Policy	**Health Impacts**	**Climate Impacts Analysis**					
Details of the Factors under Uncertainty	Emission Factors (gm/Km)						Annual VKT (10^4 Km/year)
V – F	$PM_{2.5}$	CO_2	CH_4	SO_2	BC	OC	
Car-Gasoline	T(0.065, 0.37, 0.081)	T(150, 300, 258)	T(0.12, 0.15, 0.137)	T(0.015, 0.1, 0.07)	T(0.021 ,0.16, 0.036)	T(0.028, 0.17, 0.038)	U(1.46, 1.825)
Car-CNG	T(0.0045, 0.045,0.02)	T(144, 300, 236)	T(2.5, 7.5, 6.47)	T(0, 0, 0)	T(0.001,0.011,0.0011)	T(0.003, 0.033, 0.0033)	U(1.825, 2.19)
**Jeep/Microbus/Others-Diesel	T(0.86, 1.14, 0.978)	T(150, 400, 332)	T(0.011, 0.14, 0.124)	T(0.015, 0.4, 0.3)	T(0.16, 0.72, 0.59)	T(0.17, 0.23, 0.19)	**U(2.19, 2.7375)
Microbus-Diesel							U(2.0075, 2.19)
Others-Diesel							U(1.825, 2.19)
**Jeep/Microbus/Others-Gasoline	T(0.047, 0.5, 0.09)	T(150, 400, 331)	T(0.12, 0.15, 0.137)	T(0.015, 0.1, 0.07)	T(0.015, 0.16 ,0.029)	T(0.016,0.17,0.03)	U(1.46, 2.19)
Microbus/Others-G							U(1.46,1.825)
** Jeep/Microbus/Others - Diesel to CNG	T(0.0045, 0.045 ,0.01)	T(200, 400, 363)	T(2.5, 7.5, 6.47)	T(0, 0, 0)	T(0.001,0.011,0.0011)	T(0.003,0.034,0.0033)	U(2.19, 2.3725)
Microbus/Others- Diesel to CNG							U(2.19, 3.65)
** Jeep/Microbus/Others - Gasoline to CNG		T(150, 350, 304)					
Microbus/Others- Gasoline to CNG							
Bus-Diesel	T(1.58, 2.14, 1.89)	T(700, 1063, 887)	T(0.055, 0.065, 0.06)	T(0.1, 1, 0.233)	T(1.19, 1.52, 1.35)	T(0.38, 0.48, 0.43)	U(3.65, 5.475)
Bus-CNG	T(0.005, 0.018, 0.01)	T(800, 1160, 967)	T(8.5, 13, 11.93)	T(0, 0, 0)	T(0.0015,0.005,0.002)	T(0.0018, 0.006, 0.005)	U(3.65, 5.475)
Minibus-Diesel	T(1.71, 2.01, 1.85)	T(550, 800, 665)	T(0.055, 0.065, 0.06)	T(0.1, 1 ,0.233)	T(1.14, 1.52, 1.27)	T(0.36, 0.48, 0.40)	U(3.65, 5.475)
Minibus-CNG	T(0.005, 0.045, 0.01)	T(600, 850, 726)	T(8.5, 13, 11.93)	T(0, 0, 0)	T(0.015,0.013,0.002)	T(0.0018, 0.015, 0.005)	U(3.65, 5.475)
Truck-Diesel	T(2.14, 2.54, 2.36)	T(700, 950, 800)	T(0.055, 0.065, 0.06)	T(0.1, 1, 0.233)	T(1.35, 1.6, 1.46)	T(0.43, 0.51, 0.46)	U(2.19, 4.745)
Truck-CNG	T(0.005, 0.018, 0.01)	T(750,1000, 872)	T(8.5, 13, 11.93)	T(0, 0, 0)	T(0.0015, 0.005, 0.002)	T(0.0018, 0.006, 0.005)	U(2.19, 4.745)
Sources of Data	Summarized in Table 4.4 (chapter 4)	Summarized in Table 5.1 (chapter 5)	Summarized in Table 5.2 (chapter 5)	Summarized in Table 5.3 (chapter 5)	Summarized in Tables 5.4, 5.5, 5.6, 5.7 (chapter 5)		Survey (2010)+Khaliquzzaman (2006)

Valuation Specific Factors	**Health Impacts**			**Climate Impacts**
Defining Values	Risk Constants		VSL (2010 USD)	SCC (2010 USD)
	For Cardiovascular, k_c	For Respiratory, k_r	T(20275, 384266, 199818)	T(21.65, 72.18, 38.5)
	D(0.0032,0.0058,0.0087,0.01293,0.01464)	D(0.00432,0.0077,0.00953,0.01414,0.02102)		
Sources of Data	Ostro 2004; Kewski 2009 (see chapter 4)		Summarized in Table 4.6 (chapter 4)	DEFRA 2002

**same emission factors are taken for Jeep, Micro-bus and Others, but different for VKT inputs; emission factors vary in case of CO_2 only based on pre-conversion fuel (i.e. from diesel/gasoline to CNG);

T(a,b,m) defines minimum, maximum and most-probable values respectively under triangular distribution, U(a,b) defines minimum and maximum values respectively under uniform distribution,

D(discrete points) refer a set of chosen discrete values under discrete distribution for sensitivity analysis only

In Table 6.2, the factors are listed as being included within either of the two classified forms of data, i.e. transport specific or impact valuation specific. Factors under same group are shown together in the Table 6.2 while these may be used in separate models for health and climate impacts as shown in Table 6.1. Emission factors, being tabulated as transport specific uncertain factors, are shown for each type of vehicle-fuel (V-F) combination as were discussed in chapters 4 and 5. Each category of data has more than one source, as stated in chapters 4 and 5, used for assembling the boundary values from which random numbers of the stated probability distribution are generated. These sources of data are also shown in Table 6.2 corresponding to each type of data. Data for some vehicles, i.e. taxis, auto-rickshaws, motor-cycles, are not included in this Table or further in the calculation for the reason stated in section 4.4.1 in chapter 4.

Step 5: Conducting Uncertainty Analysis

Monte-carlo uncertainty analysis is done for the assessment in this study with the use of Microsoft Excel. The uncertainty analysis is conducted for both urban-air quality and climate impacts of the CNG conversion policy and as described in chapters 5 and 6. For both the impacts calculation, 5000 random numbers are generated corresponding to the continuous probability distributions assigned to the input factors. Therefore, any calculation is repeated 5000 times with 5000 different values of the uncertain inputs and produces a distribution of outputs with respect to the uncertainty in that input. As a result, the amount of precision increases as the steps are being completed one-by-one with the consideration of uncertainty within its inputs. The number of random values for an input factor generated or the random values themselves may be different each time when they are generated, but the distributions, if drawn, would yield the same distribution each time within the same boundary (defining) values. Since the number, i.e. 5000, is quite a large number being considered, almost precise input distributions can be ensured.

In chapter 4 in section 4.4.4, it is discussed that under uncertainty consideration, the $PM_{2.5}$ emissions inventory gives a matrix of (5000x200) order where each of the 200 grids contains 5000 random emissions values from different types of vehicles in tons/year. The continuation of this uncertainty consideration proceeds over the remaining steps and thereby continues to form concentration matrix (change in $PM_{2.5}$ concentration), relative risks, deaths avoided and finally health benefits, all having an order of (5000x200) order. On the other hand, chapter 5 discussed the methodology of climate impacts analysis. 5000 random numbers are generated for each of the 5 global pollutants' emission factors and annual VKT of each type of vehicle-fuel combination thereby forming 5000 outputs of (change in) global emissions. The changes in the global emissions due to policy are combined with the continuous distribution of social cost of carbon to determine the final distribution of output in the form of climate cost saved or accrued from the policy. The method to represent the obtained results from uncertainty analysis is discussed in step 7 and the results are discussed in the results and analysis section 6.3.

Step 6: Conduct Sensitivity Analysis

Both global and local sensitivity analyses are conducted in Microsoft Excel. As stated in chapter 2 in section 2.5.5.1, global sensitivity analysis is used to find out the input factors which can be fixed at a discrete value without affecting the output variability significantly. The most important factors usually have higher values of global (main-effect) sensitivity indices when the factors are kept fixed at some values, one at a time, while others vary and showing large differences in the computed variances from that when all vary. In this research, main effect sensitivity indices are calculated from global sensitivity approach via Monte-carlo analysis for all the factors with continuous distribution tabulated in Table 6.2.

After determination of the most important factors from global sensitivity approach, local sensitivity analysis is conducted for these and also other factors (expressed by discrete distributions etc). This approach usually gives a range of possible outputs computed using different discrete values of the factors and hence allows obtaining the ranking of the factors in terms of importance more clearly.

From the above discussion on the approaches of sensitivity analysis, it is clear that both approaches require a model result based on nominal values for each type of impact evaluation of the policy. Table 6.3 summarizes the nominal values of the uncertain factors used to compute the model results with these nominal/most likely values for both the impacts analysis. In Table 6.3, the same factors, as those in Table 6.2, are tabulated with the nominal values which will be used for the sensitivity analysis in both the models and also for other purposes like comparison and/or model calibration.

Table 6.3: Nominal Values of the Model Factors for Sensitivity Analysis

Impact Analysis	**Urban-air Model Factors (units)**				**Climate Model Factors (units)**						
Transport Details **Vehicle-Fuel**	**$EF_{PM2.5}$ (gm/km)**	**k_c**	**k_r**	**VSL (2010 USD)**	**EF_{CO2} (gm/km)**	**EF_{CH4} (gm/km)**	**EF_{SO2} (gm/km)**	**EF_{BC} (gm/km)**	**EF_{OC} (gm/km)**	**VKT (Km/year)**	**SCC (2010 USD)**
Car-Gasoline	0.0814	0.00889	0.01266	199818	258	0.137	0.07	0.036	0.038	18250	45
Car-CNG	0.02				236	6.47	0	0.0014	0.003	21900	
**Jeep/Microbus/Others-Diesel	0.978				332	0.124	0.3	0.589	0.187	27375	
Microbus-Diesel										20075	
Others-Diesel										18250	
** Jeep/Microbus/Others -Gasoline	0.09				331	0.137	0.07	0.0289	0.0306	21900	
Microbus/Others-Gasoline										18250	
** Jeep/Microbus/Others -CNG	0.01				363/304	6.47	0	0.0014	0.003	23725	
Microbus/Others-CNG										36500	
Bus-Diesel	1.89				887	0.06	0.233	1.35	0.428	43800	
Bus-CNG	0.01				967	11.93	0	0.002	0.005	43800	
Minibus-Diesel	1.85				665	0.06	0.233	1.27	0.4044	43800	
Minibus-CNG	0.01				726	11.93	0	0.002	0.005	43800	
Truck-Diesel	2.35				800	0.06	0.233	1.46	0.46	47450	
Truck-CNG	0.01				872	11.93	0	0.002	0.005	47450	

**Vehicle-Fuel class belongs to same values for the emission factors & different values for VKT inputs

Step 7: Presentation of Results

Results from uncertainty analysis are usually represented quantitatively via statistical outcomes from a considerably large population of data, e.g. mean, standard deviation of the mean, 95% confidence interval etc and also pictorially through histograms showing the frequency distribution plots. As discussed in chapter 2 in section 2.5.5, sensitivity analysis results of interest include those from global and local sensitivity analyses. Both of the analyses help to determine ranking or order of the factors in terms of contribution to the output variability. Ranking of the factors obtained from global sensitivity analysis are expressed via global sensitivity index (main effect sensitivity index) with larger values usually implying more important factors. Besides this, local sensitivity analysis results are often represented through tornado charts where the deviations of the outputs from nominal results, computed using set of discrete values of the factors are visually obtained. This visual aid is very useful and helps to determine the most important factors for which a reduction in uncertainty will be most resource efficient.

Along with the information summarized in different steps, steps 5, 6 and 7 direct toward the results and analyses of the policy impacts from which the objectives of the thesis, as mentioned in chapter 1, are fulfilled. The following section discusses and analyzes the obtained results for different impacts from uncertainty assessment.

6.3 Results and Analysis

The detail methodology adopted in this study for the uncertainty assessment of the policy impacts and its communication with the different steps of the individual models, are already described in detail in the previous section. The uncertain factors of the respective models, along with their boundary values defining the associated uncertainties through probabilistic distribution and nominal fixed values (most probable values) for sensitivity analysis, are tabulated (Tables 6.1, 6.2 & 6.3). Since there are two types of impact results obtained from different models/approaches, the results also constitute of two parts. Each part comprises two steps, i.e. model results from nominal values and from uncertainty and sensitivity analyses.

Policy Impacts Evaluation

From the discussion in chapter 4 and also from this chapter, the air quality related impacts are known to have effects on health which are investigated on mortality effects of two types of diseases, i.e. cardiovascular and respiratory. The associated results are number of premature deaths due to the stated diseases that can be avoided from reduced $PM_{2.5}$ emissions from CNG converted vehicles. The entire computation is conducted grid-wise for Dhaka city and hence specific grid-wise health benefits accrued from the avoided deaths can be obtained with or without the consideration of uncertainty. As discussed in chapter 5, the resulting climate impacts are change in global emissions in terms of equivalent CO_2 emissions which can be monetized to obtain the total climate cost/benefits due to policy.

The following sub-sections will summarize and analyze the results from nominal factors and from uncertainty assessment each separately for the air-quality and climate impacts. A model validation part will also be discussed using the nominal results regarding grid-wise calculations of health impacts to check the accuracy of the obtained results and the comparison is made with the model results from Rahman (2010).

6.3.1 Nominal Air-quality Model Results and Model Validation

According to the methodology described in chapter 4, the entire air quality model calculations are done grid-wise and the results constitute different step models' results.

Instead of heading directly toward the major output, i.e. premature deaths avoided or health benefits due to improved air quality from policy, the step results can be identified as a whole or in particular grids from the model. Following this, it will also be possible to locate the high vehicle-emitting zones, the reduction in emissions due to policy over the grids and the corresponding changes in concentrations in particular grids. Figure 6.1 shows the arrangement of grids. The notation of the 200 grids (10x20) are done in a way that it starts from a to j following the columns and 1 to 20 through the rows.

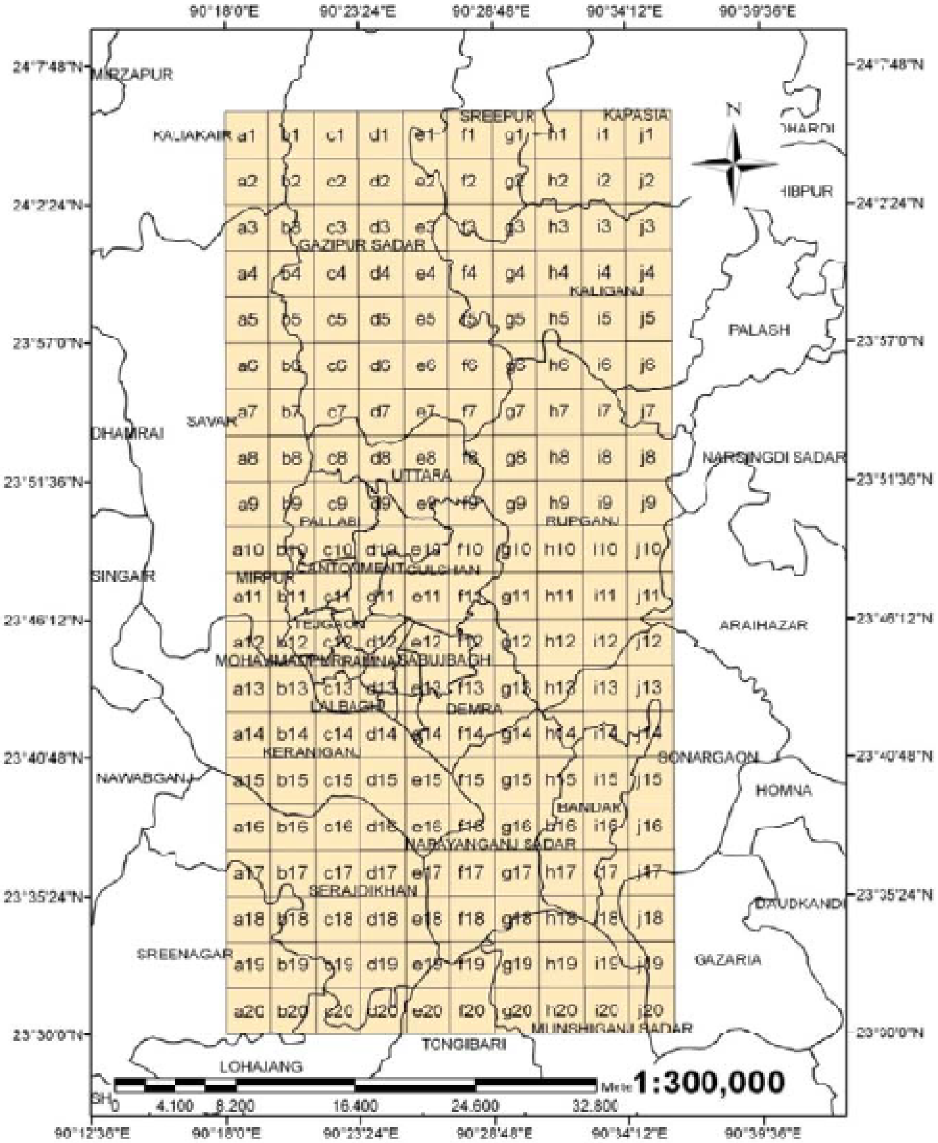

Figure 6.1: Division of Dhaka City into Grids (Source: Rahman 2010)

It was stated in chapter 4 that the health impacts from policy are evaluated both for the population of DCC and the greater Dhaka (GD). The required data on grid wise population distribution are collected from Rahman (2010). Table 6.4 presents the nominal air-quality model results for which the nominal data inputs are taken from Table 6.3. The VKTs are the same as those listed under climate model factors, with the exception of units in km/day (divided by 365 each time). A model validation is also set by comparing between the 'similar' item results from Rahman (2010).

In Table 6.4, the nominal results from the model on health impacts are given focusing a major or highlighted portion of the 200 grids. Therefore, all the 200 grids are not taken into consideration; rather a particular range of grids is selected on the basis of 2 features: population and high-emission zone. The higher the population in some grid for a given change in vehicular emission or pollutant concentration, the larger the policy impacts will be, on the contrary, there will be no effects corresponding to a grid of negligible or zero population even with high change in emissions.

Such defined range of grids for DCC is a (6x6) square, as can be seen from Figure 6.1, taken from a_8 to f_8 through a_{13} to f_{13}. The included major areas are: Uttara, Pallabi, Cantonment, Gulshan, Mirpur, Tejgaon, Mohammadpur, Ramna, Shobujbag and Lalbagh. On the other hand, a (14x7) grid range is selected for study within the entire greater Dhaka (GD) from a_3 to g_3 through a_{16} to g_{16} (Figure 6.1).

Table 6.4: Summary of Nominal Air-quality Model Results from Transport Policy Evaluation

Grid-based Result Items	**Nominal Results over the chosen Grids**	
	From Current Study	From Rahman (2010)
Change in $PM_{2.5}$ Emissions(tons/year) – DCC (6x6) grids	-634	-634
Change in $PM_{2.5}$ Emissions(tons/year) – GD (14x7) grids	-1145	-1145
Change in $PM_{2.5}$ Concentrations ($\mu g/m^3$) – DCC(6x6) grids	-8.7	-7.9
Change in $PM_{2.5}$ Concentrations($\mu g/m^3$) – GD(14x7) grids	-7.6	-7.3
Premature Deaths Avoided (Health Benefits, USD million) – Total over DCC only	4690 (937)	_
Premature Deaths Avoided (Health Benefits, USD million) – DCC major (6x6) grids	3735 (746)	_
Premature Deaths Avoided (Health Benefits, USD million) – Total over entire GD	5673 (1133.6)	_
Premature Deaths Avoided (Health Benefits, USD million) – GD major (14x7) grids	5252 (1049)	_

Excluding the DCC portion within the selected 98 grids of GD, the upper exterior portion (a_3 to g_7 as a whole) includes Gajipur, Savar etc while the lower exterior part (a_{14} to g_{16} as a whole) includes Keraniganj, Demra, Narayanganj. It can be seen from Table 6.4 that the total reductions in vehicular $PM_{2.5}$ emissions over the chosen 36 DCC grids is about 634 tons/year and over the 98 grids of GD is 1145 tons/year due to policy. The results are totally agreeable with the results obtained individually from the model developed by Rahman (2010) for the same emissions generated in previous 252 grids and then transformed to the 200 grids. Therefore, the validation of the developed model in C++ is assured.

Also the associated reductions in concentrations are 8.7 $\mu g/m^3$ when averaged over the DCC grids and 7.6 $\mu g/m^3$ averaged over the selected areas of GD as can be seen from Table 6.4. The corresponding values are derived individually from Rahman (2010) model by giving the emissions inputs. The values show deviations of about 8% for the 36 grids of DCC and about 4% for the 98 grids of greater Dhaka from the current model. The total number of premature deaths avoided due to policy implementation over all the grids under DCC is about 4690 giving a health benefit of USD 937 million (13.45 million BDT, all 2010 prices) and that within the GD is about 5673 with a benefit of USD 1133 million (16.27 million BDT). It is clear from Table 6.3 that the major grid portions (36 grids) of DCC account for about 80% of the total benefits. Similarly, for the GD, the selected grid portion contributes more than 92% to the total health benefits indicating the high emitting zones within the respective study areas. These results are not directly comparable with those of Rahman (2010) since the risk functions or other mortality rates are different between the studies.

6.3.2 Urban-air Quality Results: Uncertainty and Sensitivity Analysis

The results of the uncertainty analysis are summarized in Table 6.5 that tabulates the results on total number of premature deaths that can be avoided and consequent health benefits achieved from the policy both for the grid-wise DCC and greater Dhaka (GD). Having conducted the uncertainty analysis, the results are obtained in statistical terms and effectively points toward the more reliable results along with a defined range with particular confidence level. Nominal results do not have such ranges given under some confidence level (which are also given in the Table 6.5 for comparison).

Table 6.5: Summary of Urban-air Quality Results from Uncertainty Analysis

Statistical Results from Uncertainty Analysis	**Total No. of Premature Deaths Avoided**		**Health Benefits (USD million, 2010)**	
	DCC	Greater Dhaka	DCC	Greater Dhaka
Mean	6068	7365	1227	1490
Standard Deviation	975.6	1193.9	496.7	603.8
Standard Error	13.79	16.89	7.02	8.54
Lower Limit of 95% Confidence Interval	6041	7332	1213	1473
Upper Limit of 95% Confidence Interval	6095	7398	1241	1506
Nominal Results	4690	5673	937	1133.6

Average numbers of premature avoided deaths, over all the grids, are about 6068 in DCC and 7365 in GD with the respective standard errors of about 14 and 17 respectively. Results show that around 82% of the benefit from the overall greater Dhaka is accrued within the DCC region. Therefore, the largest population group or the highest vehicle-emitting zone lies within the DCC which is also evident from the nominal results, i.e. number of avoided deaths being 4690 from DCC and 5673 from GD due to policy and hence 82% of the benefit comes from the DCC grids. However, inclusion of uncertainty shows that the results vary by about 30% with respect to the nominal results. Uncertainty analysis allows having a closer range of results with particular confidence limit, i.e. 95% confidence level as is taken here. The upper limit is about 6041 and the lower limit is 6095 for DCC and the corresponding limits for GD are found to be 7332 and 7398. Given the various sources of uncertainty in the input factors, it appears the uncertainty in the output is not particularly egregious.

Health benefits, using the nominal value of VSL, can be obtained as USD 1212.5 and 1472 million (17.4 and 21.13 million BDT) respectively for DCC and entire GD respectively. The results are very close to the averages or the boundary limits of 95% confidence level as obtained from the uncertainty results when VSL is considered to be an uncertain factor. In general, average health benefit from DCC is found to be USD 1227 million or 17.62 million BDT (1213-1241 interval) with a standard error of USD 7.02 million or 0.1 million BDT. The corresponding values for GD are USD 1490 and 8.54 million (1473-1506 interval) or 21.4 and 0.12 million BDT respectively. As before, the results from uncertainty show about 30% variation from the nominal result, i.e. approximately 1.3 times higher than the nominal results. The reasoning behind this increase in case of results from uncertainty is usual since the uncertainty distributions of the selected uncertain factors defined by some data ranges vary within the given limits and hence their combinations will always tend to be greater than the nominal results which are based on single-point values. The results from urban-air quality are also presented qualitatively through frequency distribution plots as shown in Figures 6.2 (a) and 6.2 (b) for DCC and in Figures 6.3(a) and 6.3 (b) for GD.

In each case, (whether for DCC or greater Dhaka) the shape of the Histogram (i.e. Figures 6.2 (a) or 6.3 (a)) showing the frequency distribution plot for total number of avoided deaths obtained from the policy gives a left-skewed distribution resulting from triangularly distributed emission factors. On the other hand, the histograms showing distributions for health benefits in respective zones exhibit a central tendency (toward the mean) which is evidently due to the combination of the uncertain VSL (triangular) distribution with that of the deaths avoided (uncertain $PM_{2.5}$ emission factors).

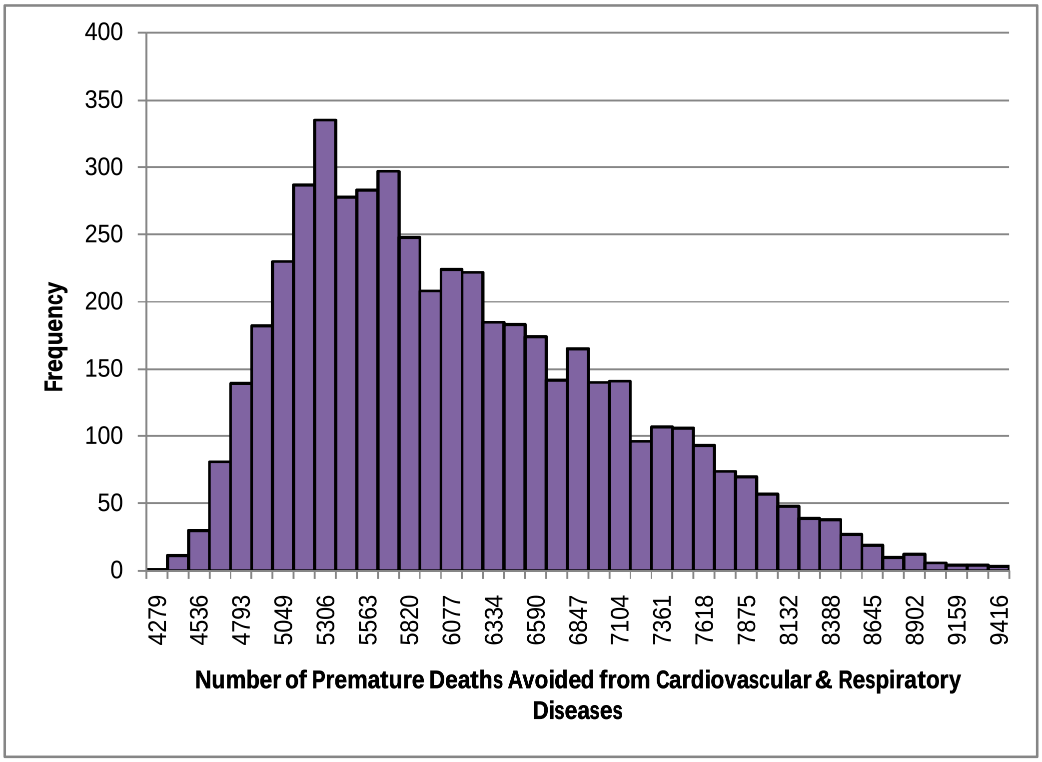

Figure 6.2 (a): Histogram of Numbers of Premature Deaths Avoided from improved Air-quality in DCC

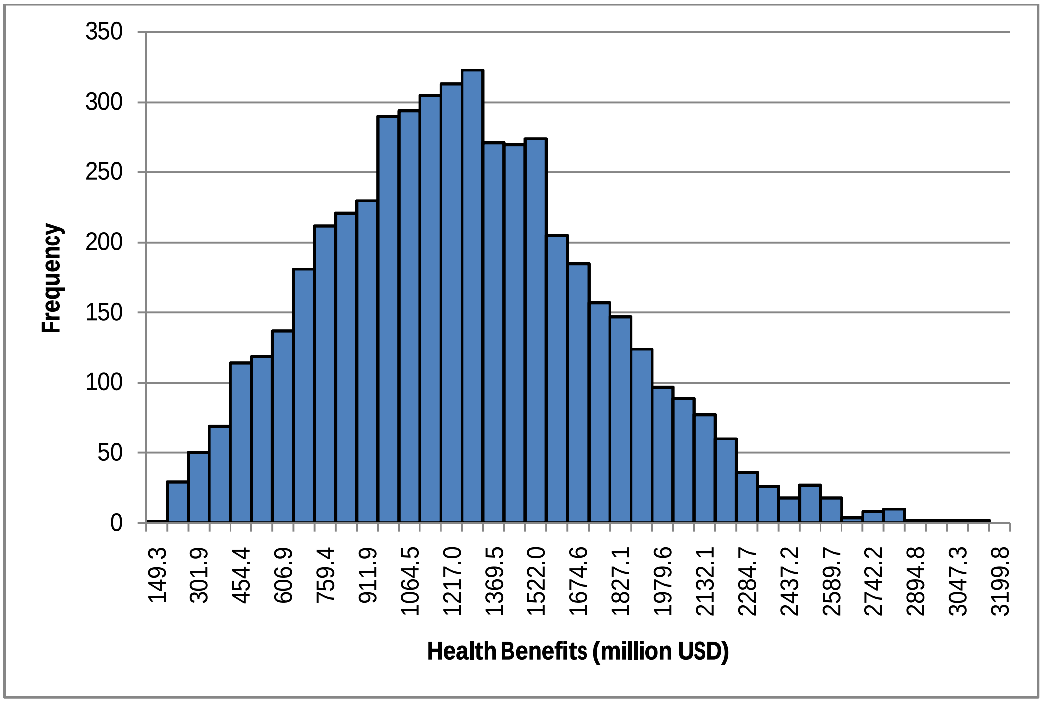

Figure 6.2 (b): Histogram of Health Benefits obtained from Policy Implementation in DCC

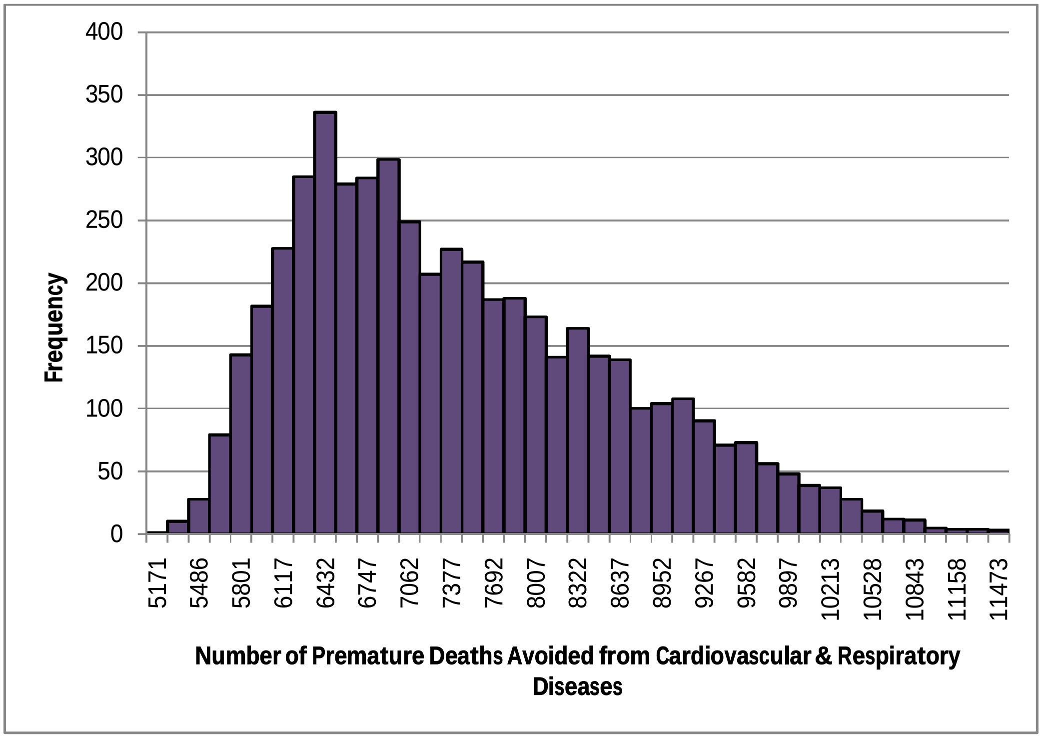

Figure 6.3 (a): Histogram of Numbers of Premature Deaths Avoided from improved Air-quality in GD

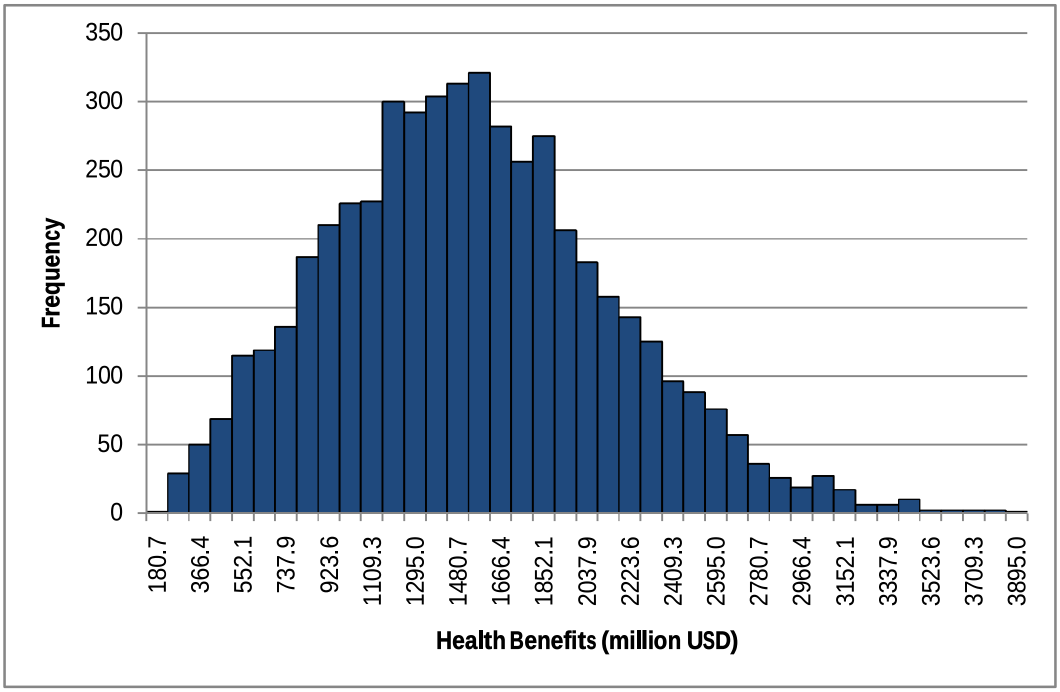

Figure 6.3 (b): Histogram of Health Benefits obtained from Policy Implementation in GD

Besides the mean values of the respective results, other important information may also be obtained from the Histograms shown above. From these frequency distribution plots, statistical results of interset include those of the modal values with the highest frequencies, the central tendency of data, the range of values within desired frequency boundaries etc. From Figure 6.2 (a), it is clear that the highest frequancy value for deaths avoided in DCC is 5306 which readily gives a benefit of approximately USD 1060 million (without any uncertainty for VSL). Figure 6.3 (a) gives a similar result for greater Dhaka and the values are USD 6432 and 1285 million respectively. The modal values, in each case, for deaths avoided are about 12.6% lower than their respective mean values which have a frequency of about 66%.

Considering uncertainty of the policy valuation parameter, Figures 6.2 (b) and 6.3 (b) give the health benefits obtained from the grids of DCC and GD respectively. Providing a similar trend, Figure 6.2 (b) shows a modal benefit value of USD 1293 million for DCC while that for GD from Figure 6.3 (b) is about USD 1574 million. These high-frequency values show relatively less variation of about 5% from their respective means with about 97% frequency and therefore very close approach toward the mean. The modal values are far higher (around

22%) than those calculated from the modal values of deaths avoided with nominal value of VSL.

From the Figure 6.2 (a), a boundary may be defined for the results under approximately 80% frequency band within a minimum of 4921 and a maximum of 6590 number of deaths avoided in DCC due to policy. Similar boundary may be defined for the corresponding results in GD from Figure 6.3 (a), i.e. 5959 to 8007 within approximately 80% frequency band. Since it is clear from the above discussion on the uncertainty analysis of air-quality impacts of policy that similar trends are obtained for both DCC and GD and also DCC constitutes the majority portion of the exposed population and hence the impacts (or benefits), the sensitivity analysis will be conducted on the results for DCC only.

6.3.2.1 Results from Global Sensitivity Analysis regarding Health Benefits

At first, the global sensitivity analysis or GSA (more specifically the main-effect sensitivity index) will be conducted as per the methodology described in chapter 2 and in the previous section 6.2 of this chapter. The nominal values of the factors which are used while fixing a particular factor for conducting GSA are tabulated in the Table 6.3. For air quality impacts from policy affecting the health, there are mainly two uncertain factors, emission factor of $PM_{2.5}$ ($EF_{PM2.5}$) for all vehicle-fuel combination and value-of-statistical life (VSL), taken into account for the global sensitivity study. Uncertainties regarding vehicle activity (VKT) and risk factors (k_c and k_r) are not included in continuous probabilistic distribution and will be discussed in connection with local sensitivity analysis or LSA. The main effect sensitivity indices (S_i) for the stated factors, calculated from equation (2.1), are summarized in Table 6.6.

From Table 6.6, it is observed that the actual variance of health benefits computed when all the factors, i.e. $EF_{PM2.5}$ and VSL, vary according to Monte Carlo method is about 246741. The influences of emission factors on the variance of the model output, i.e. health benefits in USD million, are obtained in a disaggregated level, according to each vehicle-fuel types and also as a whole. This is the model input factor considered from transport specific factors while the value-of-statistical life (VSL) is another important model factor as the policy valuation factor.

Table 6.6: Summary of GSA Results for Urban-Air Quality Related Impacts

Model Output	**Total Variance (when EF and VSL all vary)**	**Fixed Factors**	**Partial Variance (for fixed factor)**	**S_i**
Health Benefits	246741	$EF_{PM2.5}$ (V-F)		
		Car-Gasoline	136761	0.45
		Car-CNG	249212	0.01
		Microbus-Diesel	246493	0.001
		Microbus-Gasoline	233464	0.054
		Microbus-CNG	249019	0.009
		Bus-Diesel	247395	0.002
		Bus-CNG	246855	0.0004
		Minibus-Diesel	245183	0.006
		Minibus-CNG	247854	0.004
		Truck-Diesel	246933	0.0008
		Truck-CNG	246770	0.0001
		Others-Diesel	246634	0.0004
		Others-Gasoline	235590	0.045
		Others-CNG	248584	0.007
		EF for All V-F	121259	0.51
		VSL	38004	0.85

When emission factors of $PM_{2.5}$ for all vehicle-fuel types are fixed to their nominal values, as listed in Table 6.3, and VSL is allowed to vary, the variance of the health benefits is 121259. The corresponding main effect sensitivity index value is about 0.51 which implies that if emission factors of $PM_{2.5}$ can be fixed to definite values, the overall variance will be reduced to about 50%. This effect is also investigated in a more disaggregated form to find out the vehicle-fuel combination(s) for which the influence over the variability of the model output is the greatest and hence also the ranking of the important emission factors. It can be observed from the results in Table 6.6 that within the 51% contribution to the variability of the entire output from the emission factors, gasoline car accounts for about 88% of the variability with the corresponding sensitivity index of about 0.45. Therefore, the overall variance is reduced to about 45% due to only the constant emission factor of gasoline car. Hence the other vehicle-fuel combinations contribute relatively much less to the overall variability reduction and can be held to some constant values without significant changes of the result.

Among these less-influencing factors, micro-bus and ‘others’ category vehicles fuelled with gasoline can be mentioned contributing to about 5% and 4.5% respectively to the overall variability reduction. From Table 6.6, the least important factors in terms of least S_i values can be listed as the emission factors from CNG bus, diesel and CNG trucks and diesel ‘others’. The GSA results discussed regarding the emission factors can be justified from the fact that the lower values of emission factors for a particular vehicle-fuel type certainly contributes to the least amount of output variability and vice versa. Moreover, the number of vehicles and the vehicle activity (VKT) also exert reasonable influences over such results, i.e.

the greater the fraction of vehicle-fuel spilt and/or the corresponding VKT, the greater should be the effect and vice versa.

However, when the VSL is fixed to its nominal value allowing all the emission factors to vary according to the assigned distributions, the variance is lower, i.e. 38004, which is about only 15% of the overall variance and hence contributes to about 85% variability reduction due to fixity of VSL alone. This result can be explained by the fact that the corresponding distribution for VSL varies within a relatively larger bound as can be seen from Table 6.2. Since this is a policy valuation parameter, the associated uncertainties are larger than others and hence add to larger uncertainty when combined to the model output.

Furthermore, it is to be noted that due to variation or fixity of emission factors or VSL, the affected outputs are different each time: fixity of emission factors affect only the results of deaths avoided which finally combines with the variation of VSL to obtain health benefits whereas fixity of VSL affects the health benefits only; it has no effect on the number of avoided deaths. The resulting distributions obtained from the most important model input factors (when they are fixed) are shown via Histograms shown in Figures 6.4 to 6.6.

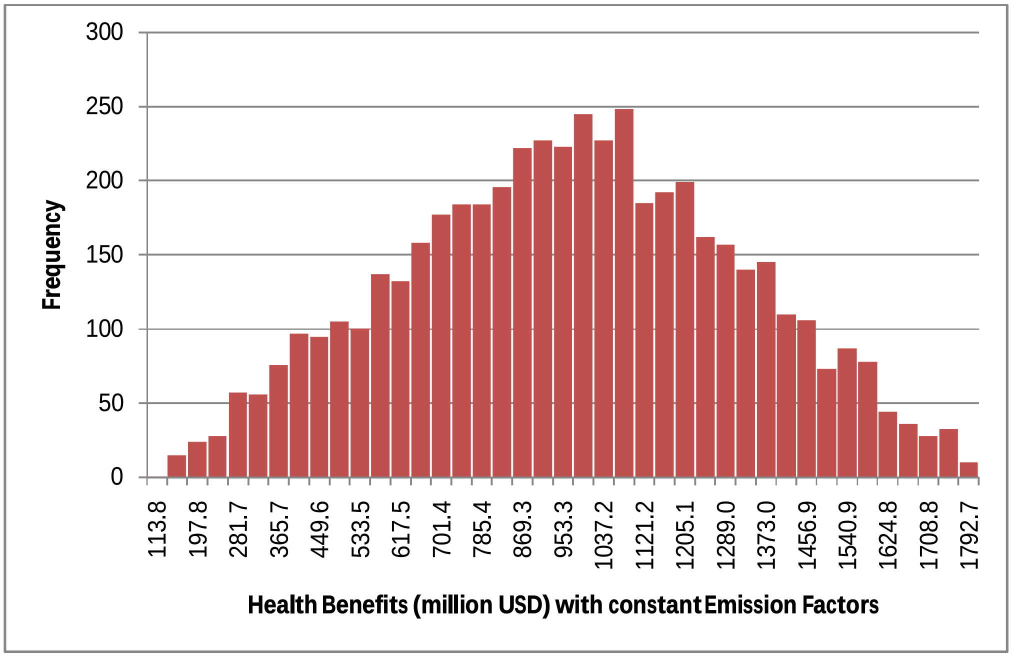

Figure 6.4: Histogram of Health Benefits (USD million) for fixed $PM_{2.5}$ Emission Factors

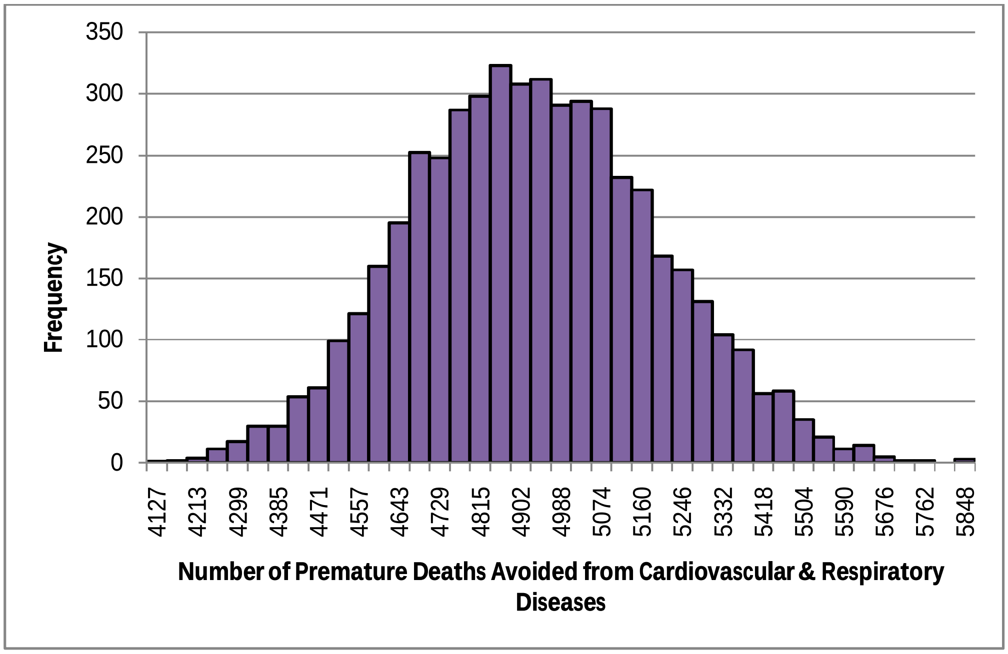

Figure 6.5 (a): Histogram of Premature Deaths Avoided for fixed $PM_{2.5}$ Emission Factors from Gasoline - Car

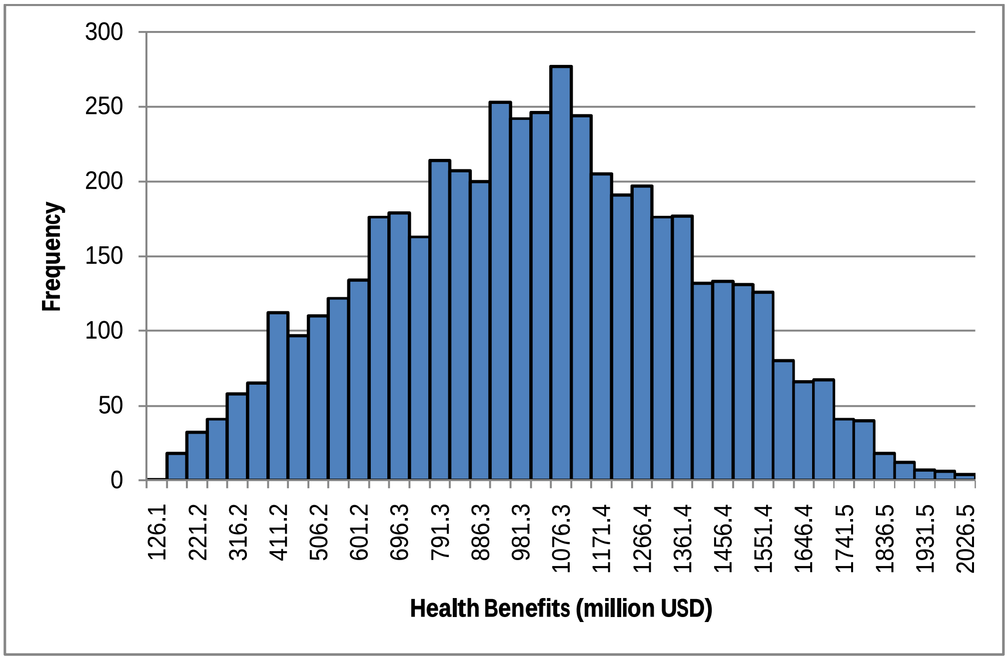

Figure 6.5 (b): Histogram of Health Benefits (USD million) for fixed $PM_{2.5}$ Emission Factors from Gasoline - Car

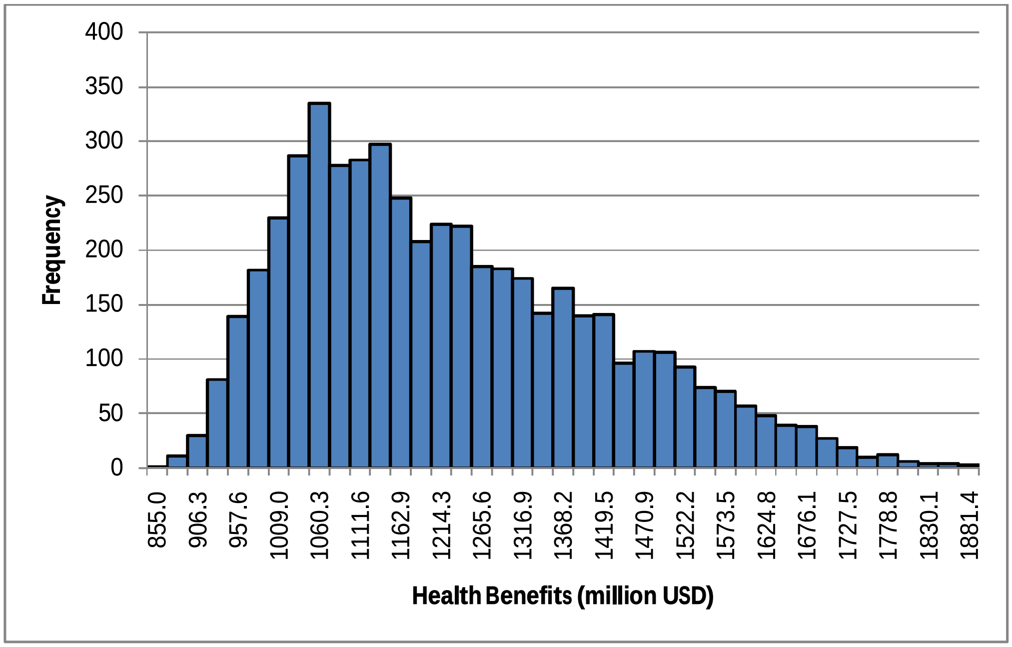

Figure 6.6: Histogram of Health Benefits (USD million) for fixed VSL

Figure 6.4 shows the frequency distribution of health benefits when all the emission factors are held constant to their respective nominal values and only the VSL is allowed to vary. Comparing the distribution to that shown in Figure 6.2 (b) (where both emission factors and VSL vary), it can be said that the overall variance is reduced which is also qualitatively evident. Current distribution is relatively more uniform and the central tendency is also greater with the mean benefits of about USD 950 million which is about 23% lower than that obtained from Figure 6.2 (b). Also the lower and upper bounds in 80% frequency bands vary within a less interval (from USD 701 to 1121 million benefits) than that given by Figure 6.2 (b) (from USD 912 to 1446 million) indicating to a smaller variability of about 21% with constant emission factors. In this case, the distribution is solely due to variation of VSL only.

Figures 6.4 and 6.5 (b) have a reasonable similarity since Figure 6.5 (b) shows the distributions for health benefits when the emission factor from gasoline car is constant which contributes to the majority (about 88%) of variability reduction exerted by the emission factors as a whole. However, in this case distribution of total premature deaths avoided due to policy (Figure 6.5 (a)), can also be obtained since the other emission factors vary. Similarly, Figure 6.5 (a) exhibits greater uniformity and closer central tendency in the distribution than that in Figure 6.2 (a). Variation in health benefits due to fixity of the policy-valuation parameter (VSL) alone is shown through Figure 6.6 which gives a left-skewed distribution with an average of USD 1212 million. The distribution, once again, can be compared to that of Figure 6.2 (b) which shows a relatively closer tendency toward the mean and gives a modal value of about USD 1293 million whereas the corresponding value from Figure 6.6 is about USD 1060 million. This skewed tendency is due to the triangular distributions assigned for all the emission factors only combined with the VSL being constant.

However, from the GSA results discussed above, ranking of the most important urban-air quality model factors can be summarized in terms of contribution to output variability but the values onto which these have to be fixed cannot be determined from the GSA analysis. This decision requires consideration of several points or at least some extreme realizations (minimum and maximum values) which will allow having possible policy options and hence the results, which can even alternate from the results obtained from GSA. Therefore, uncertainty assessment calls for the local sensitivity analysis or LSA, the outer loop of the popular double-loop approach discussed in the following section 6.3.2.2.

6.3.2.2 Results from Local Sensitivity Analysis regarding Health Benefits

Nominal air-quality model results are discussed in section 6.3.1 which forms the basis of LSA. As is discussed before, LSA generally includes those factors with greater S_i values as obtained from GSA and also those model factors which cannot be represented via probability distributions. In this study, $PM_{2.5}$ emission factors from influential vehicle-fuel combinations, vehicle activity or VKT, VSL, risk (C-R) factors are considered for LSA and their effects on the model outputs, i.e. premature deaths avoided and health benefits, are observed through tornado charts. The required nominal values are once again taken from Table 6.3 and the discrete values for different factors are taken from the minimum and maximum values for each factor listed in Table 6.2. Figure 6.7 (a) and 6.7 (b) show the tornado charts representing the scenario analysis related to air quality model results.

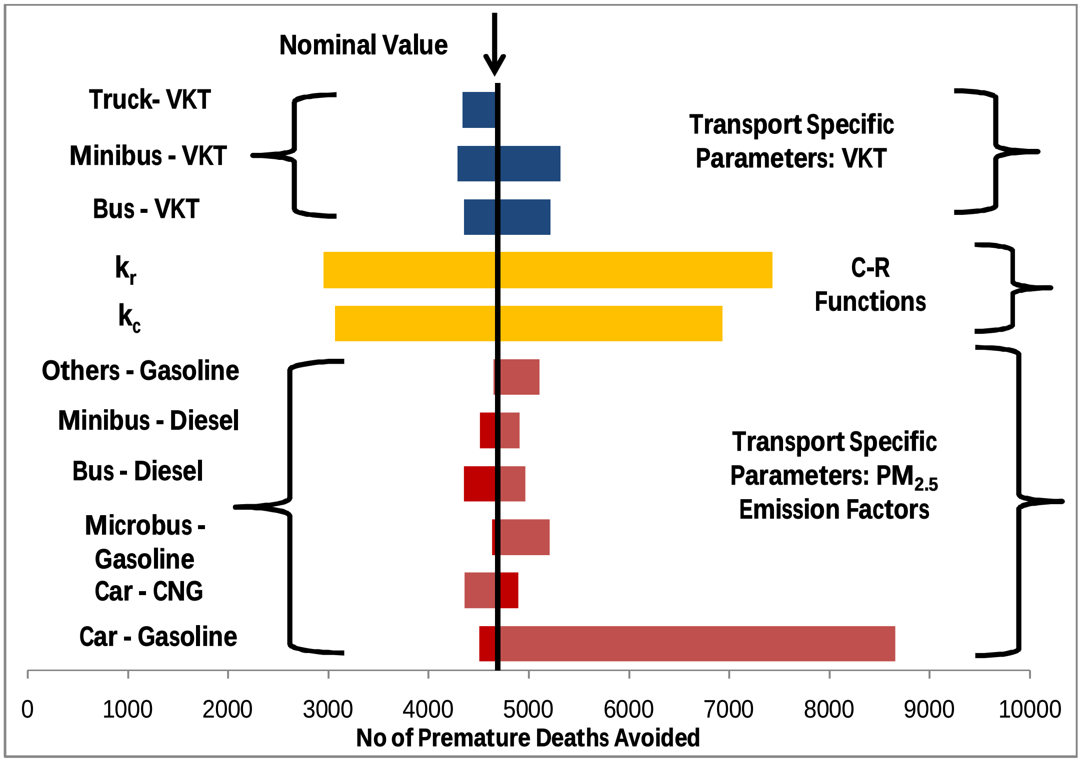

Figure 6.7 (a): Scenario Analysis of Total Number of Deaths Avoided due to Policy

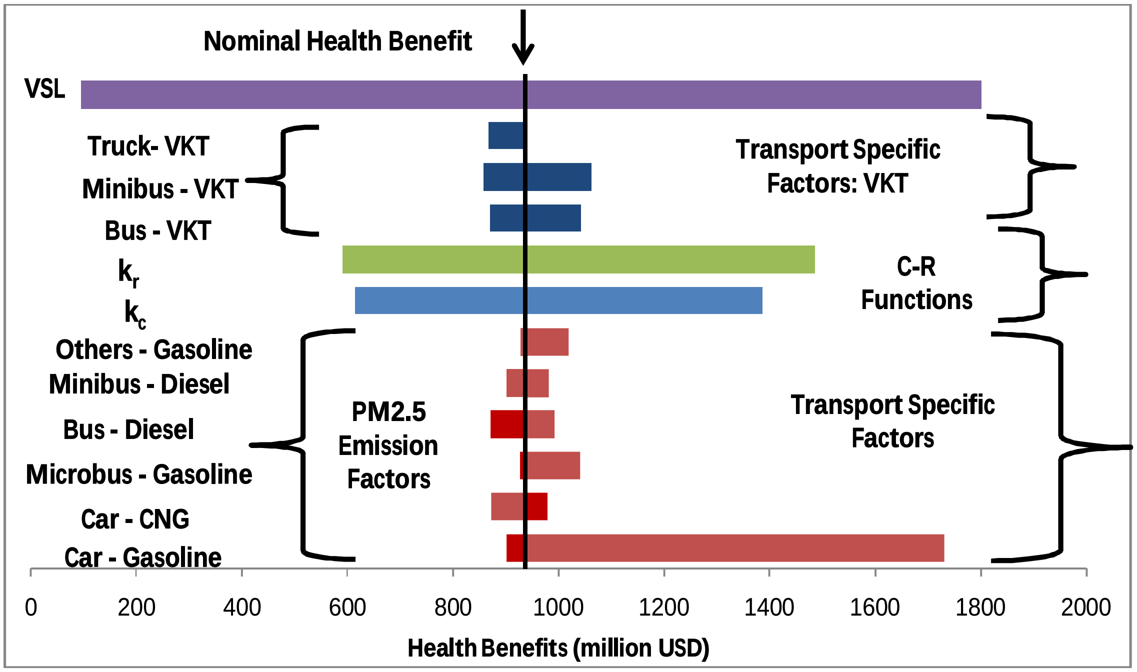

Figure 6.7 (b): Scenario Analysis of Total Health Benefits due to Policy

When emission factors of $PM_{2.5}$, VKT, VSL, risk constants all are kept fixed to the most probable (nominal) values, the total number of deaths avoided from cardiovascular and respiratory diseases is 4690 and that of health benefit is about USD 937 million. The vertical axis, in Figure 6.7 (a) represents the nominal deaths avoided and in Figure 6.7 (b) represents the health benefits obtained from the nominal results, also marked by an arrow. The results are analyzed for possible variations in values of the considered model factors. For some of the selected vehicle-fuel combinations, as labeled in the Figures, horizontal bars present effects on the result when the emission factors from these vehicle-fuels are varied from their respective nominal values, while others are fixed. Similarly, the VKTs are shifted to their possible extreme points in order to obtain the ranges of outputs within which the results may vary from the nominal one and these are shown by the respective labeled horizontal bars. The VKTs and the $PM_{2.5}$ emission factors from different vehicle-fuel types constitute the model factors specific to transport sector. Within these transport specific model factors, gasoline car emission rates have the most important influences on the output as observed by the longer tail rightward from the nominal value. Next important factors are the bus and mini-bus activities due to which the number of avoided premature deaths varies from about 4353 to 5217 and from 4291 to about 5319 respectively with the corresponding health benefits from USD 870 to 1042 million.

Apart from these transport specific factors, the mortality risk factors or concentration-response (C-R) functions are considered as important model factors for scenario analysis. The cardiovascular and respiratory mortality risk constants, k_c and k_r respectively are varied from their nominal value to possible extreme discrete values as shown in Figure 6.7 (a). The same variations are shown in Figure 6.7 (b) for health benefits with labeled horizontal bars. It can be inferred from Figure 6.7 (a) or 4(b) that the model results are more sensitive to the values of k_r, i.e. respiratory risk constant rather than to k_c. But again the domains selected for the analysis is important and hence before confining future studies to some certain factors only, it is important to check all possible and comparable domains (discrete point values) of all the significant factors. There is another very important model factor, which is the policy valuation parameter required for the quantification of the overall policy benefits in monetary terms. Certainly, the range of result due to variation of this parameter, i.e. value-of-statistical life (VSL) for health impacts, is much wider than any other specific factors evident from Figure 6.7 (b). The reason behind the finding is that VSL or such other policy valuation parameters usually vary within larger limits and the same finding was obtained from GSA analysis discussed in section 6.3.2.1. Hence the result is the most sensitive to the VSL, and then to the risk factors and transport specific factors.

However, VSL are often considered separately in such studies since it is a monetizing measure for total number of premature deaths that can be avoided from improved air quality due to policy with wider ranges of uncertainty depending on various factors. In such case, the emission factors of $PM_{2.5}$ from gasoline-car and the mortality risk factors can be said to be the most significant factors affecting the air-quality model results.

6.3.3 Nominal Climate Model Results

As discussed in chapter 5 in section 5.3.1, climate changes induced from CNG conversion policy is expressed in terms of changes in global emissions (equivalent CO_2 emissions in 1000 tons/year) and in the quantified form through climate costs/benefits. Similar to the air quality model, nominal climate model is also based on single nominal or most-likely values for each of the model factor, i.e. emission factors of five global pollutants from different vehicle-fuel types, annual VKT of the vehicles before and after the policy implementation, global warming/cooling potential (GWP/GCP) and social cost of carbon (SCC), discussed in chapter 5. The associated uncertainty of these factors affects the overall model result and will be discussed in the following section. The nominal values of the model factors are taken from Table 6.3 and the nominal climate model results are summarized in Table 6.7.

Table 6.7: Summary of Nominal Climate Model Results from Transport Policy Evaluation

Climate Model Result Items	**Change in Global Emissions over the base case (1000 tons/year)**	**Climate Impact (warming/cooling)**
ΔCO_2 emissions	434.73	Net warming (+)
ΔCH_4 emissions	973.88	Net warming (+)
ΔBC emissions	-527	Net cooling (–)
ΔOC emissions	-15.37	Net warming (+)
ΔSO_2 emissions	-43.99	Net warming (+)
Total equivalent CO_2 (e) emissions	940.89	Net warming (+)
Total Climate Cost/Benefit (USD million)	+42.34 (climate cost)	

In Table 6.7, changes in emissions of the GHGs and aerosols due to the CNG conversion policy and the resulting impacts are shown which all are calculated based on the nominal values of the model factors. It is observed from the Table 6.7 that the emissions of CO_2 and CH_4 increase while that of OC and SO_2 decrease as a result of the policy implementation and overall lead to increased global warming. As discussed in chapter 3 in section 3.4.1, CO_2 and CH_4 are the GHGs that exert positive radiative forcing or global warming and their emission rates are higher from CNG vehicles, thus the change is positive and lead to net warming. Again, OC and SO_2 are global cooling aerosols (negative radiative forcing) and hence their reductions, due to policy, accompany consequent addition to global warming process. On the other hand, since BC exerts positive forcing, the associated reduction in the emissions of BC leads to global cooling and provides the only subtractive quantity from the overall global warming which is about 527,000 tons/year. As a whole, the summation of all the changes in global emissions in common metric of equivalent CO_2 is about 941,000 tons/year which leads to nominal climate cost of about USD 42 million or around 6,03,000 BDT ('+' sign indicates overall increase in global warming and hence climate cost). It can be observed from the Table 6.6 that exclusion of CH_4 emissions from the rest, the change is negative, i.e. (-527+435+15+44) or 33,000 tons/year and hence leads to climate benefit of about USD 1.5 million 21536 BDT. Therefore, the major problem lies in the high emissions of CH_4 which again depends upon the uncertain emission factors. However, emission factors also exhibit uncertainties for other global pollutants and annual VKT can also be major issue from the transport specific model factors.

6.3.4 Climate Model Results: Uncertainty and Sensitivity Analysis

As stated in the previous section, climate impacts evaluation includes the uncertainty analysis of the emission factors of five global pollutants, annual VKT of the vehicles before and after the policy implementation as transport specific uncertainties and SCC as the valuation specific uncertainty. The defining values of these factors characterizing their uncertainties are summarized in Table 6.2. The uncertainty results on climate changes are shown in Table 6.8 via statistical terms and also qualitatively through Histograms in Figures 6.8 and 6.9.

Table 6.8: Summary of Climate Impact Results from Uncertainty Analysis

Statistical Results from Uncertainty Analysis	**Total Change in Global Emissions due to policy (1000 tons/year)**	**Climate Impacts (USD million)**
Mean	592	26
Standard Deviation	474.5	22.5
Standard Error	6.71	0.318
Lower Limit of 95% Confidence Interval	579	25.4
Upper Limit of 95% Confidence Interval	605	26.6
Nominal Results	941	42

It is observed from Table 6.8, the mean value of the change in global emissions due to CNG conversion policy is about 592,000 tons/year. The corresponding cost is about USD 26 million (3,73,295 BDT, 2010) with a standard error of about 0.32. Thus, the climate results from uncertainty analysis are about 37% lower than that from nominal results. Moreover, within 95% confidence boundaries, the values vary within an interval of 579,000 and 605,000 tons/year for increase in global emissions with associated climate costs varying from USD 25.4 to 26.6 million (3,64,680 to 3,81,909 BDT).

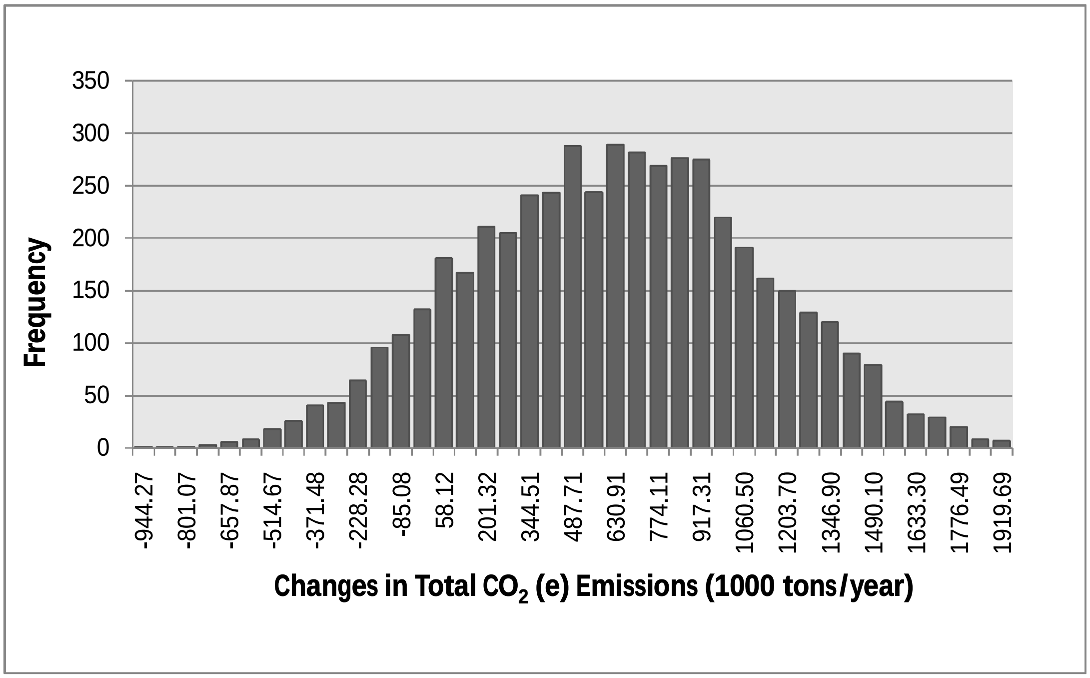

Figure 6.8: Histogram of Changes in Global Emissions in equivalent CO_2 emissions due to Policy

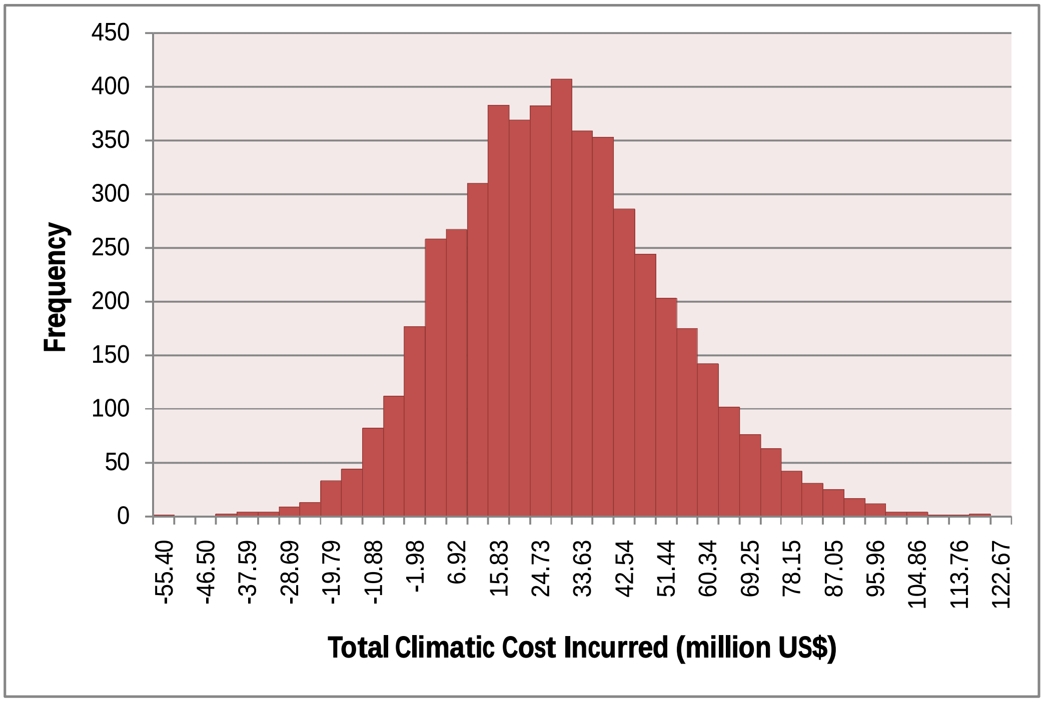

Figure 6.9: Histogram of Climate Costs accrued from the Policy

Figures 6.8 and 6.9 are the excel snapshots simulating results for climate impacts and these show distributions with central tendency. Figure 6.8 presents change in global emissions induced from the policy and Figure 6.9 presents the resulting climate cost associated. A significant contribution to climate costs from the policy implementation may be due to the increased emission factors of CO_2 and CH_4 (global warming gases) and less emission factors of SO_2 and OC (global cooling aerosols, hence counter-acting global warming) from CNG vehicles.

The important information that can be extracted from these two histograms is that reduction of global emissions from CNG converted policy and consequent climate benefits may be possible as indicated by the negative values with low frequencies in the histograms. These values approximately have a frequency of about 40%. Therefore, it’s important to find out the factors due to which the uncertainty is the largest and their contribution may reverse the scenario. As stated in section 6.3.3, such contribution is evident from higher CH_4 emissions. Another important contribution to such uncertainties from road transport sector may be the annual VKT.

During the climate benefits modeling, the VKTs for CNG and non-CNG vehicles were assumed to be the same in order to obtain the true comparison of vehicular emissions before and after the policy. The available survey data on VKT provides information on present VKT only which represents the post conversion case whereas to derive pre-conversion VKTs, either direct detail information or more research is necessary. This information on base VKT is very important because the vehicles are converted to CNG with the intention to run more and hence the comparison should be made between what effect would have occurred if the same mileage or VKT were covered by the gasoline or diesel vehicles and the VKT of the converted ones. Also after conversion, the unconverted vehicles, which are also less in numbers, may run less than the CNG vehicles. As a result, since the CNG vehicles are relatively higher emitters of the GHGs like CO_2 and CH_4, results of conversion policy eventually becomes adverse regarding the climate impacts. On the other hand, if the true information on base VKT were known or more logically if the true comparisons are made between pre and post policy cases (with the same VKT), the climate impacts might be beneficial due to policy. Consequently, these issues bring out the question if the climate impacts from the policy can be in fact beneficial or cost-saving which are also depicted by the negative values in Figures 6.8 and 6.9. Such comparisons of VKT will not affect the urban-air quality model results much except the possible increased health benefits for the same VKT before and after the conversion. This point will be included in the limitations and further scope of the study. Therefore, ranking of these influential climate model-factors, through sensitivity analysis, will help to determine the most important uncertain factor affecting the result and to allocate the research efforts efficiently.

6.3.4.1 Results from Global Sensitivity Analysis regarding Climate Impacts

For the determination of main effect sensitivity indices from GSA for different model factors, nominal values of the factors are taken from Table 6.3. GSA of climate impact results from policy includes all the five global pollutants' emission factors, annual VKTs of all vehicles altogether as the transport specific model factors and the valuation parameter, social cost of carbon or SCC. The main effect sensitivity indices (S_i) for the stated factors, calculated from equation (2.1), are summarized in Table 6.9.

Table 6.9: Summary of GSA Results for Climate Impacts

GSA Result Parameters	**Total Variance of** (when all vary)		**Mean Partial Variance of**		**S_i**	
Fixed Model Factors	Change in Global Emissions	Climate Cost	Change in Global Emissions	Climate Cost	Change in Global Emissions	Climate Cost
EF_{CO2}	225150	506.25	207025	465.5	0.08	0.08
EF_{CH4}			220900	511.5	0.019	0.01
EF_{SO2}			229144	515	0.018	0.017
EF_{BC}			222905	506	0.009	0.0005
EF_{OC}			225332	506	0.0008	0.0005
All EF			204756	488	0.09	0.036
Annual VKT			27441.5	118.6	0.88	0.77
SCC			_	456.5	_	0.098

It is observed from Table 6.9 that the emission factors are taken into GSA both individually for each of the five pollutants and also in combined form. SCC is the impact valuation parameter and as such its influence is tested only on the climate cost accrued from the policy. Since simulation is run for each of the uncertain factors' 5000 randomly generated numbers, the average values are taken for each of the resulting terms, i.e. total or partial variances, S_i etc.

When all the listed model factors vary as per the assigned uncertainty distributions, the total mean variance of change in global emission is about 225,150 and that for climate cost is 506.25. The mean partial variances are listed for all the factors, obtained when these are held at their nominal values (tabulated in Table 6.3) one by one, while others are allowed to vary.

According to the main effect sensitivity indices (S_i) shown in Table 6.9, it is clear that the annual VKT of all vehicle-fuel categories has the greatest contribution to the reduction of overall variability of the output. If the annual VKT of all the vehicles can be fixed at some nominal values, about 88% of variability for the change in global emissions and about 77% of variability for the total climate cost will be reduced. Numerically, the second most important parameter is SCC, the valuation parameter having around 10% contribution to variability reduction of climate cost. Among the transport specific model factors, the emission factors are found to have less influence than VKT, i.e. S_i is about 0.09 altogether for the change in global emissions. It can be seen from Table 6.9 that emission factors of CO_2 have the greatest influence among all the pollutants having S_i of about 0.08 which represents approximately

92% of the whole variance of the model output and hence about 8% of variability reduction when the CO_2 emission factors from all the vehicle-fuel types are constant.

According to GSA results for climate impacts discussed above, rest of the ordering of the significant factors may be listed serially as the emission factors of methane, SO_2, and finally black and organic carbon. Since contribution of annual VKT is comparatively larger to the overall variance reduction, GSA for vehicle-specific VKT is conducted and it is found that most of the reduced output variability is due to Trucks (S_i is about 0.81). These influential factors' contribution to overall variance can be qualitatively shown as in Figures 6.10 through 6.13. These histograms show excel snapshots of the simulation runs for frequency distribution of climate impacts for the influential model factors held at their respective nominal values.

Among these distributions from Figure 6.10 to Figure 6.13, the most important observation is that when all the VKTs are kept constant, both for pre and post conversion cases, the overall climate impact is negative, i.e. only climate cost (no benefits) is evident from all the positive values in the resulting distribution. But for all other model factors including emission factors or SCC, there are always some possible combinations (due to uncertainties) that lead to climate benefits. This observation leads to two major findings. Firstly, climate results are the most sensitive to the VKTs. Since the nominal values of VKTs are chosen here as the (higher) present (post-conversion) VKTs obtained from survey, all the outcomes are positive implying climate costs because the true comparison between before and after policy cases is not made. Secondly, equally important are the nominal values at which the factors will have to be kept fixed for desired variability reduction. The results may show completely different scenario with lower (or different choices of) nominal values. These findings can be investigated in a more disaggregated level (vehicle-fuel wise distribution) among possible scenario options through LSA. The results from LSA regarding climate impacts are discussed in the following section 6.3.4.2.

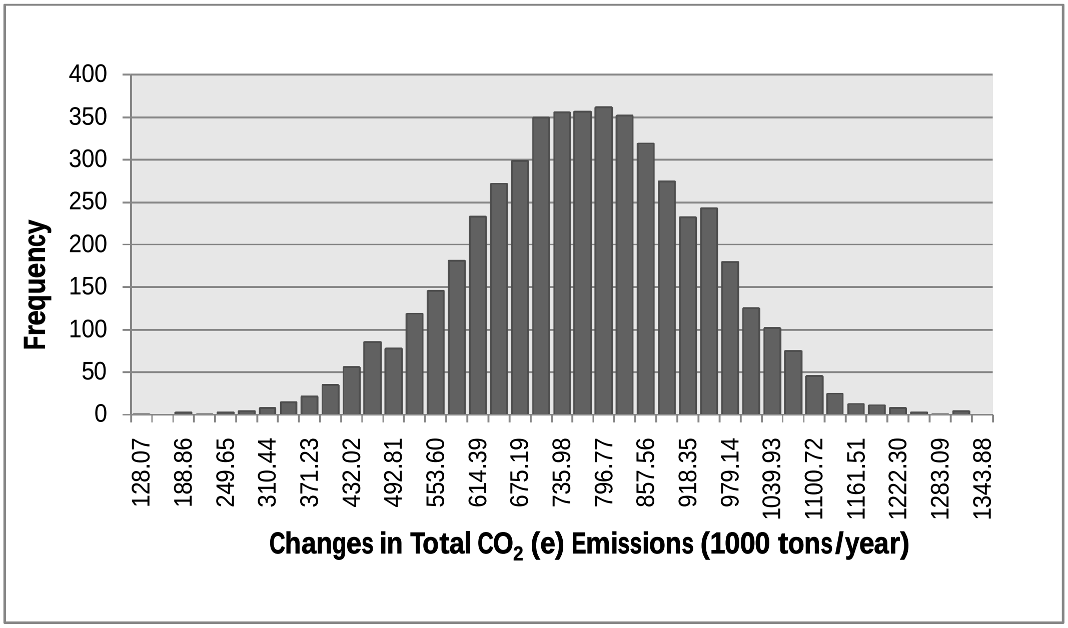

Figure 6.10: Histogram of Climate Impacts for Nominal VKTs of all the Vehicles

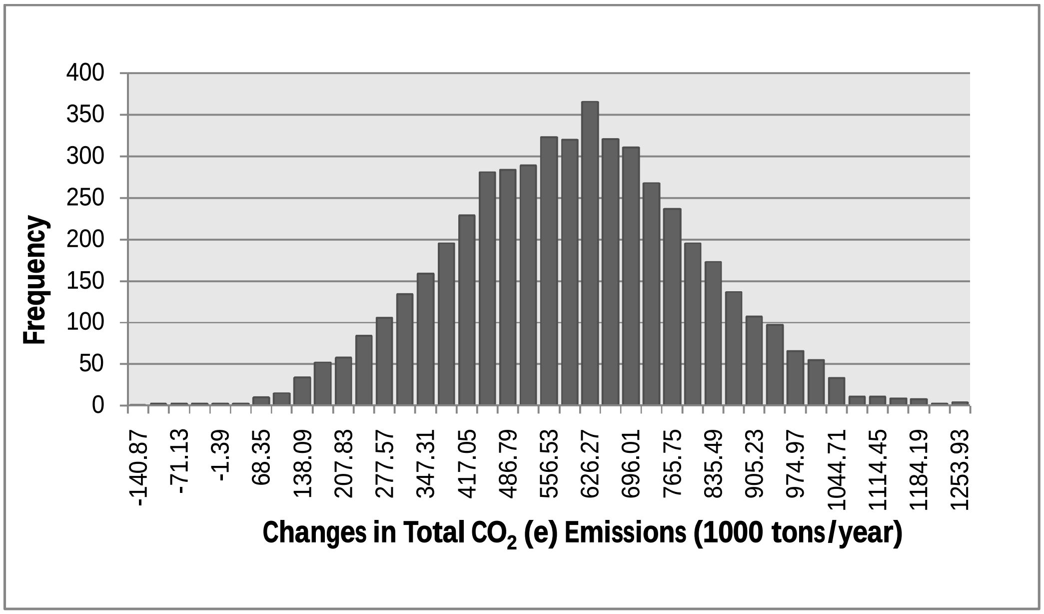

Figure 6.11: Histogram of Climate Impacts for Nominal VKT of Trucks

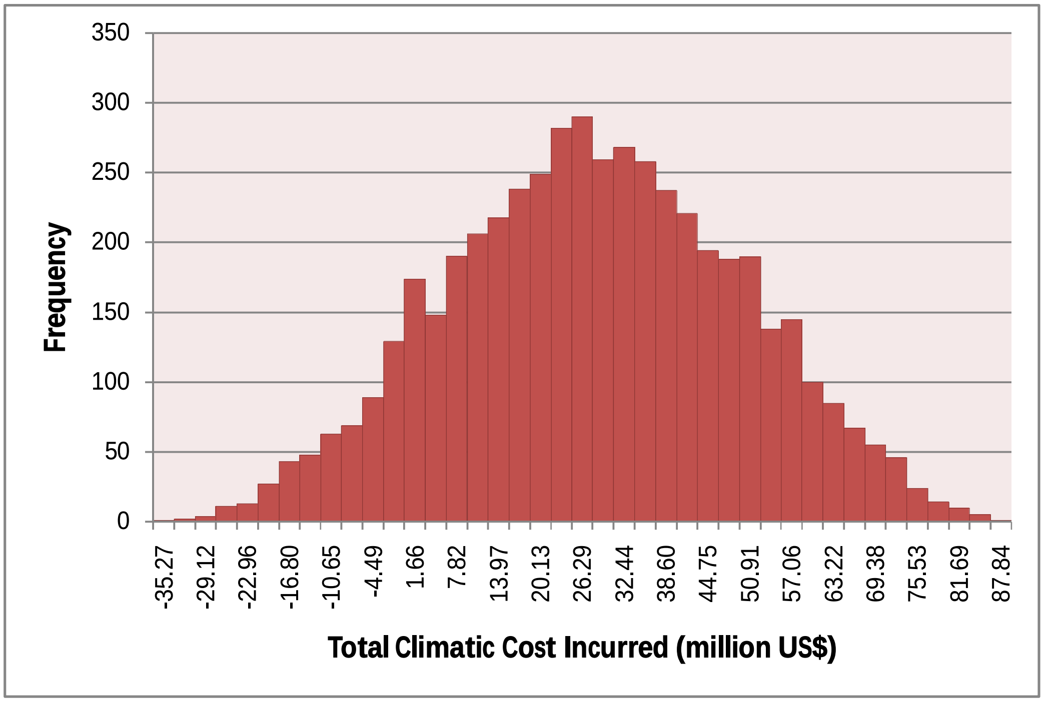

Figure 6.12: Histogram of Climate Cost/Benefits for Nominal SCC Values

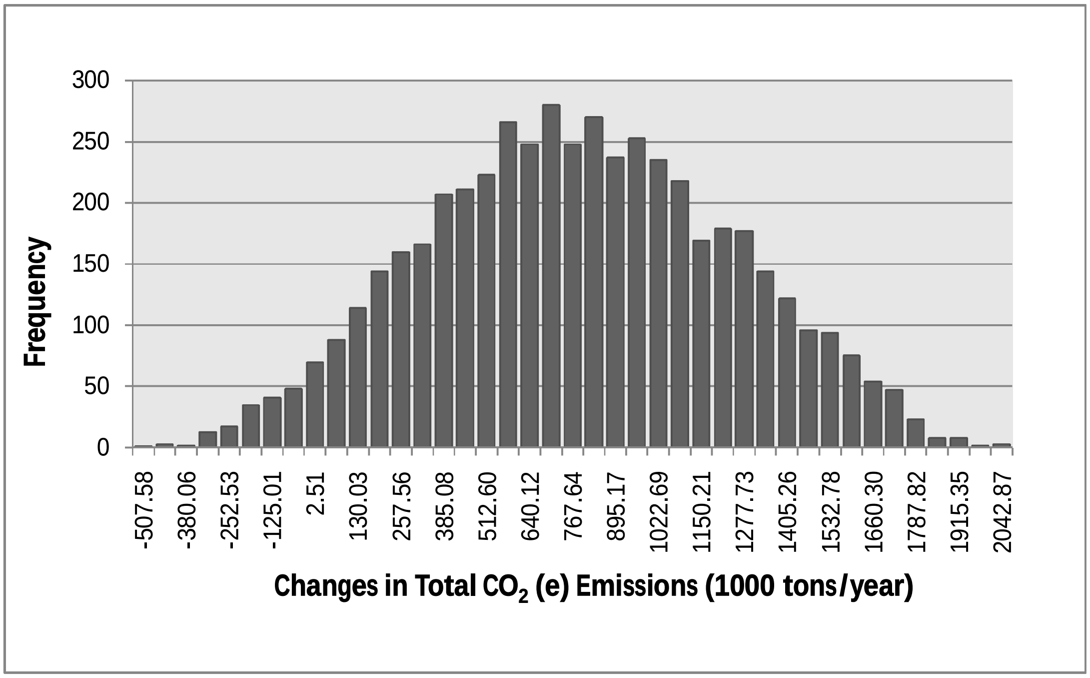

Figure 6.13: Histogram of Climate Impacts for Nominal Emission Factors

6.3.4.2 Results from Local Sensitivity Analysis regarding Climate Impacts

In LSA, annual VKT and all the emission factors for each type of existing vehicle-fuel combination are taken as model factors from transport sector and SCC as the impact valuation parameter. Of them, only the important factors are summarized in Table 6.10 along with their respective nominal values, possible extreme values and nominal climate model results.

Since the number of vehicles or the fraction of respective vehicle-fuel split is taken to be constant in the model, this factor has an influence over the model results. As such, for a given VKT or emission factor value, the vehicle-fuel combinations having greater fractions mostly show larger variations from the nominal result. For example, cars, gasoline and CNG micro-buses, buses, diesel trucks etc. Therefore, while considering transport specific factors, the vehicle-fuel combinations are selected based on the respective numbers of vehicles and/or larger VKTs.

As found from GSA results, the most influential factor is VKT which is also in agreement with the facts discussed in uncertainty results regarding climate costs arising from increased global emissions due to policy. VKT is an input factor which affects emissions from all global pollutants whereas a particular pollutant’s emission factor affects only a particular region for a given vehicle-fuel type. This is another reason why the results are more sensitive to changes in VKT values. Along with annual VKTs of selected vehicle-fuel types, all the emission factors are also taken into account for LSA, but only the selected results are given in Table 6.10.

From Table 6.10, ranges of climate model outputs may be obtained from the extreme (minimum and maximum) values of factors, varied one by one, from the respective nominal values. These ranges of outputs help the policy-maker to see the different policy scenario with changing options. This also reveals the importance of the choice of locations of model data. In this study, the choice of data locations for the model factors is based on an approach which is known as paired-sampling strategy wherever applicable. In such cases, uncertainty due to one factor is observed to affect another related factor and hence when the uncertainties are considered, effects of both the factors are taken into account.

Table 6.10: Summary of LSA Data & Results for Climate Impacts

Transport Specific Model Factors	**Chosen Points of Model Factors**				**Climate Model Outputs**			
					Change in Global Emissions (1000 tons/year) at extreme points of			
Selected Vehicle-Fuel	EF_{CO2} (gm/km)	EF_{CH4} (gm/km)	EF_{BC} (gm/km)	VKT (10^4 km/year)	EF_{CO2} (gm/km)	EF_{CH4} (gm/km)	EF_{BC} (gm/km)	VKT (10^4 km/year)
Car-Gasoline	150, 300	_	0.026, 0.16	1.46, 1.825			951, 810	
Car-CNG	138, 275	2.5, 7.5	_	1.825,2.195	913, 949	688, 1007		887, 941
Microbus-Gasoline	150, 400	_	0.015, 0.16	1.825, 2.19			945, 906	
Microbus-CNG	138, 367	2.5, 7.5	_	2.19, 3.65	855, 973	823, 971		704, 902
Bus-Diesel	_	_	1.19, 1.52	3.65, 5.475			960, 919	
Bus- CNG	_	_	_	3.65, 5.475				951, 926
Minibus-Diesel	_	_	1.14, 1.52	3.65, 5.475			960, 903	
Minibus-CNG	_	8.5, 13	_	3.65, 5.475		915, 949		952, 924
Truck-Diesel				2.19, 4.745				
Truck-CNG				2.19, 4.745				960, 941
Others-Gasoline			0.015, 0.16	1.825, 2.19			944, 914	
Others-CNG		2.5, 7.5		2.19, 3.65		852, 964		763, 910
Valuation Factor, SCC	22.5, 73.5				**Climate Costs (USD million)** 21.2, 69			
Nominal Climate Model Results (USD million, 2010)					**941,000 tons/year (USD 42million)**			

For example, the converted CNG vehicles' CO_2 emission factors are directly dependent on the respective base fuel (diesel or gasoline) from which it is converted (the estimation method is described in chapter 5 in section 5.3.1.1). Thus if the gasoline car's CO_2 emission factor is varied, the CNG car's emission factors will change accordingly and hence the paired-sampling approach is applied. The resulting outputs at those points for a particular factor are calculated following a pair of two points, either minimum or maximum. Similarly, the choice of values for other CO_2 emission factors of considered vehicle-fuel types, i.e. gasoline and CNG microbuses, and the VKTs is based on this consideration. Like other factors, appropriate distributions are assigned for VKTs with respective minimum and maximum points. Here the pair is composed of the respective minimum and maximum points, i.e. when minimum VKT of gasoline car is applied (for pre and post conversion case); corresponding assigned minimum VKT is used for CNG cars in post conversion case and vice versa. In such cases, one output pair is obtained for each vehicle type considering its fuel-wise split. For instance, in Table 6.10, changes in global emissions vary from a minimum of 704,000 to a maximum of 902,000 tons/year for micro-buses where the variation is accounted for changes in VKTs of both gasoline and CNG micro-buses. Thus for micro-buses, the pair (gasoline VKT, CNG VKT) of the minimum values is (18250, 21900) and that of maximum values is (21900, 36500) for the two types of fuel applied at a time to estimate the extreme outputs given above. All such outputs are shown in the middles of the fuel types under a particular vehicle in Table 6.10. Non-significant outputs are not tabulated in the Table and marked by ‘hyphens’ (-).

It can be observed from Table 6.10 that for emission factors of BC and for VKTs of bus, mini-bus and trucks, for the minimum values, the outputs are on the larger side (greater that the nominal output value) or vice versa. BC emission factors are not encountered with paired sampling and these affect the model outputs independently. The observation of results for BC emission factors implies that less BC emissions from gasoline vehicles is associated with less benefits or more adverse impacts and vice versa when all other factors are constant. Similar observation for VKTs of bus, mini-bus and trucks under paired-sampling approach, implies that all others being the same, the more these vehicles run, the smaller will be the climate cost, although the model results are not very sensitive to these factors.

The tabulated results can be better represented and explained by graphical means, i.e. tornado charts, which also enable to find out the ranking of the important model factors more easily. Figure 6.14 (a) and Figure 6.14 (b) present tornado charts which show respectively the scenario analysis or LSA results for change in global emissions and total climate cost encountered due to policy.

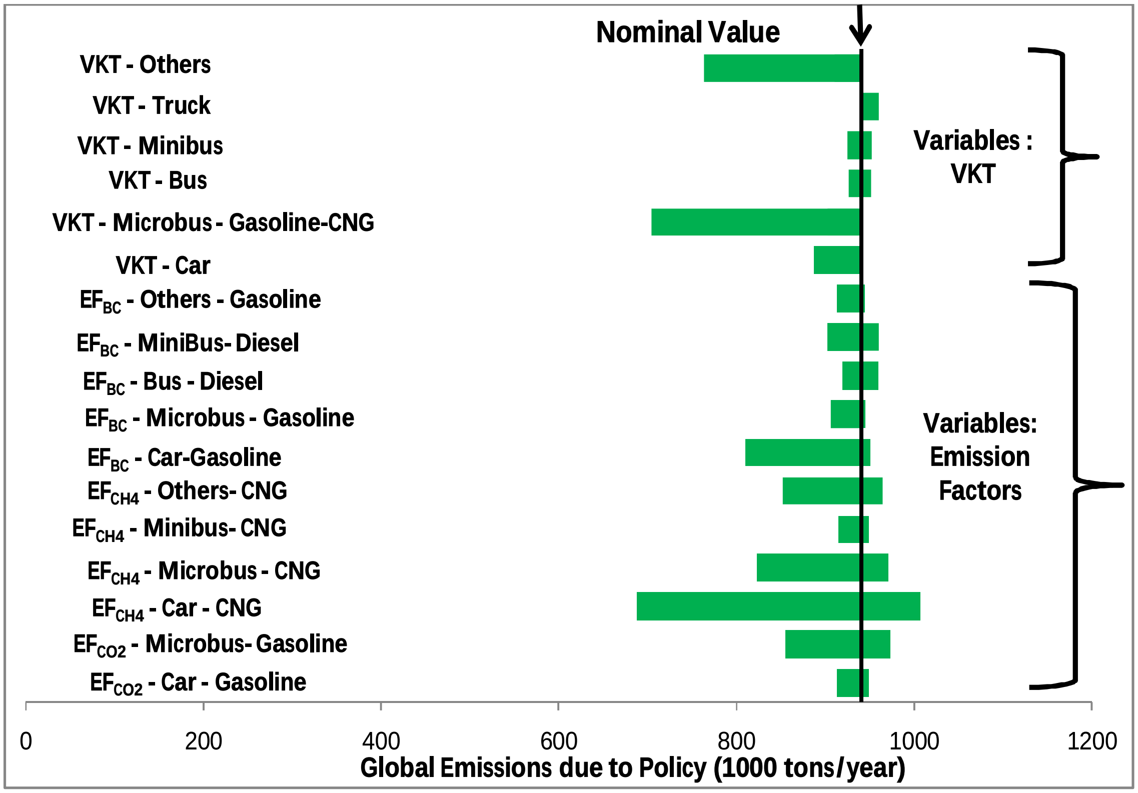

Figure 6.14 (a): Scenario Analysis of Changes in Global Emissions due to Policy

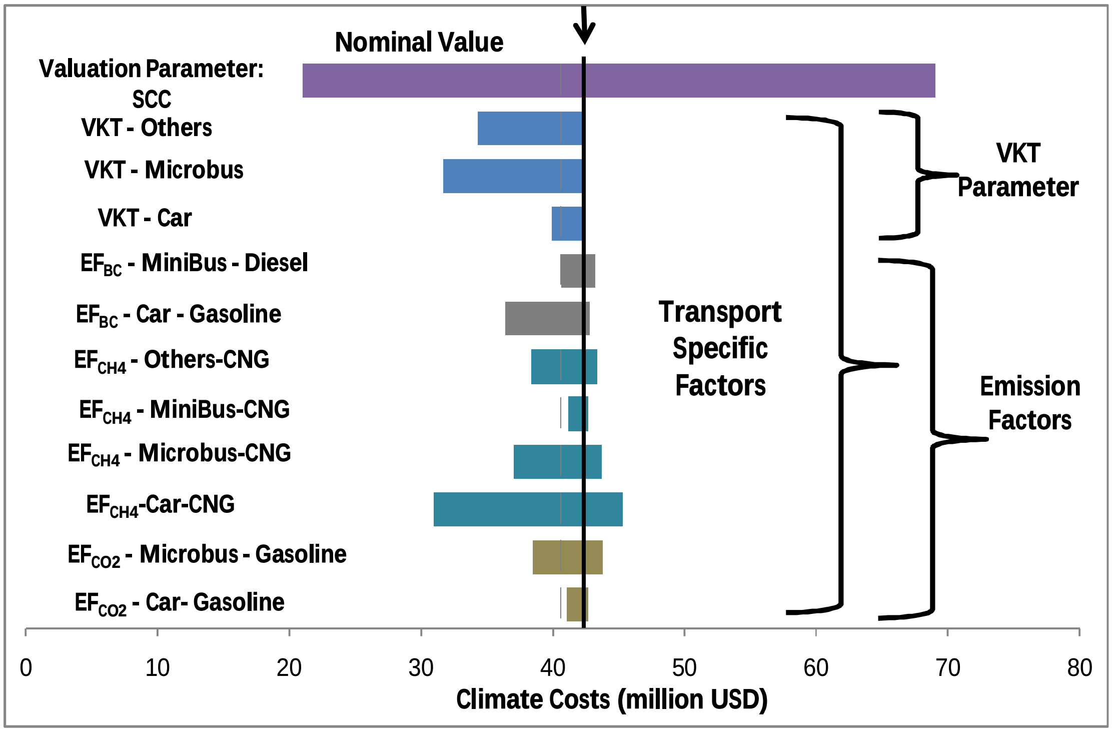

Figure 6.14 (b): Scenario Analysis of Climate Costs due to Policy

These tornado charts are similar to those prepared for LSA of air-quality results shown in Figures 6.7 (a) and 6.7 (b) and are based on the values tabulated in Table 6.10. Figure 6.14 (a) plots the deviation of the output from the nominal value, marked by the arrow, due to transport-specific model factors only. It is clear from the Figure 6.14 (a) that CH_4 emission factors from CNG cars is the most influencing factor for which the variation is the maximum from the nominal value. It is found to vary from a minimum of 27% less and a maximum of 7% greater than the nominal value. This result turns attention to the choices of the extreme points within which the factor is perturbed from its nominal value and hence to the amount of uncertainty associated. Same finding is also obtained in the uncertainty analysis in the section 6.3.4 where it is shown that it is due to the higher CH_4 emissions from CNG vehicles for which the policy is affecting the climate adversely. Therefore, more research is required for this particular emission factor that can mostly decide the climate benefits or costs from the policy.

Next important factor in Figure 6.14 (a), very close to CH_4 emission factors, is the VKT of micro-buses where both the gasoline and gasoline to CNG converted VKTs are considered as per the paired-sampling approach. The variations in the values of the stated VKT is found to have lower values of outputs than the nominal one and the minimum value is about 25% less than the nominal output implying lower climate costs. However, as per the discussion in section 6.3.4.1, the true comparison should be between the equal VKTs of CNG and unconverted vehicles, since the conversion is being made with the intention to run more and as a result the increased VKTs' effects from unconverted vehicles should be taken into consideration. Although such hypothetical data is neither analyzed nor the true VKTs before the conversion is available, it can be easily inferred from the data that for the equal VKT comparisons, there will be certainly less global emissions and hence less climate cost or possibly benefits.

Other significant influential model factors can be listed serially as the VKT of 'others' category vehicles, BC emission factors from gasoline cars and CH_4 emission factors from CNG micro-buses. The important factors obtained from Figure 6.14 (a) are summarized in Figure 6.14 (b) for the accrued climate costs along with the effect of the valuation parameter, SCC. Variation of SCC from its nominal value is observed to have the maximum influence over the model output among all the model factors. The associated climate cost varies from about USD 21 to 69 million with the nominal value being USD 42 million. Similar trend is observed for VSL in air-quality model as the policy valuation parameter regarding health impacts. Since, like VSL, SCC is also an impact monetizing parameter, associated uncertainty is relatively larger and requires further investigations from related studies. In this study, the focus is toward the transport specific model factors among which CH_4 emission factors from CNG cars are observed to have the maximum impacts followed by the VKT of micro-buses, others, BC emission factors from gasoline cars and CH_4 emission factors from CNG micro-buses. It can be inferred from the data that the impacts are in general higher for cars, because of the largest fractions within the entire converted vehicle fleet.

Therefore, the order of allocation of the research efforts and resources on different factors should correspond to the types of vehicles with higher proportions along with those with higher uncertain ranges of emission factors for the most important pollutants, i.e. CH_4. Nevertheless, the possible discrete values assigned for the factors in LSA are also subject to uncertainty as to which values should be used and this uncertainty is the lowest for lower ranges and increases with the widening of ranges.

6.4 Summary

This chapter summarizes the policy results for both urban-air and climate changes from their respective models, discussed in chapters 4 and 5 respectively, along with the uncertainty assessment results. The detail results of policy intervention are discussed and analyzed and from this, the major findings of the study are summarized in the following chapter.

CHAPTER 7

CONCLUSION

7.1 Introduction

This chapter is the concluding chapter of this thesis. The detail model results and analysis for the policy impacts from the uncertainty assessment as the major findings of this study is discussed in this chapter in section 7.2. Also some recommendations will be enlisted arising from the sensitivity analysis regarding the factors' further research and also those from limitations of the current study. Section 7.3 discusses on the limitations of the study and recommendations are listed in section 7.4.

7.2 Major Findings of the Study

The major findings of the study include the uncertainty assessment results of the CNG conversion of vehicles policy. The policy is primarily concerned with the improvement of urban air quality but at the same time such road transport policy also affects the overall climate.

For the policy related impacts, the respective model results can be summarized as below:

- The mean health benefits based on the valuation of the number of premature deaths avoided from reduced $PM_{2.5}$ emissions from CNG vehicles is obtained as about USD 1227 million or 17.62 million BDT computed from all the grids within Dhaka City Corporation (DCC). Within 95% confidence interval, the statistically significant range of health benefits varies from about USD 1213 to 1241 million or 17.41 to 17.82 million BDT.

- For the whole greater Dhaka (GD) region, the health benefit is certainly greater than that of DCC. From uncertainty analysis, the quantified health benefit for GD is obtained as USD (1490±8.54) million or (21.4±0.12) million BDT and the corresponding 95% confidence interval boundary is found to vary between USD 1473 to 1506 million or 21.14 to 21.62 million BDT. The major portion (around 82%) of the benefits accrues from DCC within the entire GD.

- Without any uncertainty consideration, based on the nominal values, the air-quality model gives lower health benefits of about USD 937 and 1134 million (13.45 and 16.28 million BDT) for DCC and GD respectively and the corresponding numbers of premature deaths avoided due to policy are about 4690 and 5673. The nominal results are about 23% lower than the results from uncertainty analysis.

- The associated sensitivity analysis results are derived from both global and local sensitivity analysis (GSA and LSA). Regarding health benefits accrued from reduction of vehicular $PM_{2.5}$ emissions, around 50% of the model output variability can be reduced by fixing only the values of $PM_{2.5}$ emission factors in which about 88% of the contribution is carried by gasoline car alone. On the other hand, keeping the VSL value constant, the overall output variability is reduced to about 85% while the emission factors vary.
- From LSA analysis, in general it is found that VSL is the most important model factor which requires the most research before they are fixed followed by the mortality risk factors of the associated diseases. These are the non-transport related factors. Among the transport specific model factors, $PM_{2.5}$ emission factor from gasoline cars is found to have the most important variability from the nominal result while other factors do not affect the model output significantly due to their shifting to other data locations rather than the nominal data points.
- Another impact analysis of the stated policy is the overall climate impacts through change in global emissions. From uncertainty analysis with the currently available data, it is observed that the policy is not beneficial for the overall climate changes; rather it adds to the climate costs. The amount of total climate cost accrued from the policy is about USD (26±0.318) million or (3,73,295±4565) BDT resulting from a total change (increase) in global emissions of about (592±6.71) in 1000 tons/year. Within 95% confidence interval, the values vary from a minimum of USD 25.4 to a maximum of 26.6 million (3,64,680 to 3,81,909 BDT, all 2010 prices) and from 579,000 to 605,000 tons/year respectively.
- The climate results from uncertainty analysis are found to be 37% lower than the nominal result which gives a total change in emissions of about 941,000 tons/year and a climate cost of about USD 42 million or 6,03,015 BDT. While computing for climate impacts, the VKT is found to be as an important variable which might reverse the current result.
- Among the uncertain climate model factors, GSA presents VKT as the most important model factor by contributing to maximum of the output variability. The second most important transport-specific factor is the emission factors, more specifically emission factors of CO_2. Moreover, it is observed from the nominal results and uncertainty analysis

of the climate models that it is due to the higher CH_4 emissions from CNG vehicles for which the overall climate impact is adverse. On the other hand, climate impact valuation factor, i.e. social cost of carbon (SCC) is another important model factor due to the wide range of assigned uncertainty.

- From LSA, in a disaggregated level for individual vehicle-fuel combinations, it is usual to find that the larger the fractions of a particular vehicle-fuel category, the more the variations of output from its nominal value while considering the transport related model factors. Ranking of important transport specific factors affecting climate model results as found from LSA is firstly the emission factors of CH_4 for CNG cars followed by the annual VKT of micro-buses, VKT of ‘others’ category vehicles, BC emission factors from gasoline cars and CH_4 emission factors from CNG micro-buses. The LSA ordering may seem to be different from those of GSA but it is important to remember that VKT of all vehicle-fuel combination contributes to significant output differences when varied from the nominal values but the CO_2 and black carbon emission factors only from certain vehicle-fuel combinations are significant.

Combining the analysis of two types of impacts of the CNG conversion policy, it can be concluded from the current study that this policy will be beneficial in urban-air quality sector; the ultimate accuracy of results may be reached with the future research on the important model factors as obtained from the study. But for climate changes, the scenario can be different. The increased carbon di-oxide and methane emissions and reduced SO_2 and organic carbon emissions from CNG vehicles are mainly responsible for the increased equivalent CO_2 emission and hence climate costs. It is found that these changes in emissions are again dependent on the VKT factors which are larger for the CNG vehicles in policy case than the base VKTs of the unconverted vehicles in pre-policy case. Hence, the annual VKT comparison before and after the policy is critical to the policy impact analysis and may reverse the scenario. Therefore, besides the CH_4 emission factors from certain CNG vehicles, the climate results are also very sensitive to VKT factors and it requires more concentrated research on this model factor, particularly for climate impact estimation.

7.3 Limitations of the Study

This study proposes first ever a detail methodology to estimate and analyze the impacts of such a wide-scale transport policy. The study has the greatest success in application of uncertainty assessment of the specified road transport policy which is done in such large scale for the first time in Dhaka or Bangladesh as per the latest knowledge. Uncertainty assessment is a key to any policy in order to facilitate the decision making processes by approaching precision of final outputs and also by providing different scenario analysis. Another remarkable feature of the study is that the estimation of health impacts from policy using Impact-pathway approach, is done for the grid-wise distributed Dhaka city (for both DCC and entire greater Dhaka) along with the uncertainty consideration of the model factors, in a matrix form. This study has developed a model in C++ program for estimating health impacts arising from such a policy which can directly yield modified results with further updated input data. The grid-wise distribution also informs the policy-maker the grid-specific output of a particular area. Also this study has combined the source-receptor model developed for Dhaka city to relate the change in emissions to the change in concentration of $PM_{2.5}$ and also most recent data and methodology for estimating the valuation related parameters like VSL and/or SCC. However, this study certainly has some limitations in different sectors of data and methods of computation or comparison. These limitations are broadly divided into two groups and are discussed below.

7.3.1 Limitations regarding Model & Model Factors

Every model has its own limitations and boundaries within which it estimates the intended results. These limitations usually affect the overall results and the final results will be confined within this boundary with the known sources of uncertainty. The individual steps of the impact-pathway approach (sub-models, i.e. emissions model, concentration model, SRM etc) and some of the computed model factors are based on some assumptions which raise the limitations of the study.

1. Limitations related to grid-distribution method followed from Arjumand (2010), i.e. study area, techniques of division into grids, measurements of major/minor road lengths, lack of updated data on vehicle numbers, VKT computation procedure etc, do apply for the current model.

2. The impact pathway model is limited by the capabilities of underlying source-receptor model.

3. Vehicle numbers are collected from BRTA (2010) with negligible information on scrappage and cumulative numbers of all registered vehicles up to the year 2010 which are not given fuel-wise. Although the field survey provides information on fuel-split, it may

also contain some error. Also, the assumption of ratio-wise split of fuel for different vehicles in gridded data may not be always practically valid.

4. Daily VKT, used as a model factor for estimation of health benefits, is not considered as a random variable in order to avoid the complexity of the model computation methodology and for convenience to understanding. However, the VKTs are used at the maximum values for both before and after the conversion cases and hence the calculated result is on the safe side. If the precise values were used, the health benefits would be more and hence only the accuracy of the final quantity is affected, not the impact itself.

5. There are some assumptions related to calculation of some of the pollutants' emission factors, i.e. size-fractions of particulates to derive emission factors of $PM_{2.5}$, limited data on super-emitters' fractions in the vehicle fleet of Dhaka, less reliable data on fuel penalty, carbon efficiency etc to estimate emission factors of CO_2. Also the differences in emission factors between dedicated and converted CNG vehicles, variation depending on different conditions of driving etc may add to the uncertainty level and affect the ultimate precision.

   It is assumed that the boundary values defining the associated uncertainty distributions have included these variations and uncertainty analysis is not required in a disaggregated level, yet more specific sources of data or detail uncertainty analysis in a more disaggregated level considering all the conditions may reach the extreme accuracy level.

6. Due to lack of reliable sources of data on mortality rates for Dhaka, the only available data from WHO (2009) is used. No uncertainty due to this factor is taken into the analysis assuming negligible contribution to overall uncertainty of results from this factor.

7. The secondary particulates formations from SO_2 are ignored which may be important. It is observed that SO_2 emissions are reduced in conversion case, implying rise in global temperature. However, SO_2 is associated with secondary $PM_{2.5}$ formation and hence its reduction can be added to the health benefits and further reduction in more black carbon emissions which also affect the climate system. These are not considered in the study which can even increase the obtained benefits.

8. Regarding climate impacts, vehicular kilometers travelled annually (annual VKT) is a very important model factor. It should be more specific. The former or base case VKT should be precisely known and compared with the current converted vehicles' VKT in order to determine the increased VKT and hence the emissions that would be in absence of the

conversion. Including this factor into uncertainty analysis merely generate the distributions within the same boundary values assigned for both before and after the conversion. As a result, the underlying error is not overcome rather may give an erroneous result.

7.3.2 Limitations regarding Uncertainty Assessment

1. One of the most important underlying uncertainties within the climate model arises from climate science related uncertainty, i.e. global warming/cooling potentials of different global pollutants considered. Since this study is more focused to the overall impacts from vehicular emissions, this purely environmental or climate related factor is not taken into uncertainty analysis; rather specific values are directly used from Reynolds & Kandlikar (2008). But it should be mentioned here that these types of parameters usually vary within a considerably wide range of values leading to wider ranges of results given other factors are constant.

2. In sensitivity analysis, GSA permits to determine the output variance apportionment among the model factors by fixing a particular factor at a nominal value while others vary. But again, the nominal values of the factors at which they would be fixed is not definite which can lead to a variety of different variance apportionments depending on how the factors are fixed, and can even at times lead to situations where fixing a given factor increases output variability. This can also lead to inappropriate allocation of resources. This drawback of GSA is overcome by an original method referred to as *Distributional Sensitivity Analysis*. The method focuses on determining which factors would on average cause the greatest reduction in output variance, given that the portion of a particular factor's variance that can be reduced is a random variable. However, this study introduces uncertainty assessment approaches to support decision-making processes and confines the sensitivity studies within the global sensitivity analysis not including the detail of overcoming the inherent limitations. Also such errors of GSA are assumed to be overcome by LSA where different possible data locations (or at least the extreme data points) are investigated to check the influential factors according to the maximum deviations from the nominal output.

3. The results of a global sensitivity analysis permit a ranking of model factors known as factor prioritization for future research and factor fixing, for which the goal is to identify non-influential factors that may be fixed without substantially affecting model outputs (Allaire 2009). While the main effect sensitivity indices may be used for factor

prioritization, the total effect sensitivity indices may be used for factor fixing. In this research work, initially the factor prioritization is more important and hence only the main effect sensitivity analysis has been applied here. Determination of Total effect sensitivity indices would be more informatory and would complete the global sensitivity analysis.

7.4 Recommendations and Future Scope of the Study

The recommendations, which may be made from the current study, emerge from both its analysis and its limitations. Both types of recommendations can identify the future scope of the studies, allocate the resources efficiently and may bring more precision to the results with more sophisticated data or modified model assumptions.

7.4.1 Recommendations from Present Analysis

1. The sensitivity analysis conducted in the current study has identified in accordance with health benefits that emission factors of $PM_{2.5}$ (from gasoline car) are the most important model factor specific from transport-only factors. Furthermore, in any case, the emission factors, particularly for the larger proportions of vehicle-fuel combinations are critical to the analysis. Therefore, future research should focus on such factors and particularly on emission factors of $PM_{2.5}$ from gasoline car.

2. In case of climate impact valuation, VKT estimation is crucial to the overall model approach. Since the true comparison of VKT between pre and post conversion cases may cause changes even in the estimated current result, it should be taken into future scope of the study to overcome the limitation. This can be addressed by endogeneity analysis, an econometric modeling.

3. VKT is also found as one of the most important model factor from the local sensitivity analysis preceded by CH_4 emission factors (for CNG cars). The stated transport specific factors require further research and may be recommended for more detail sensitivity analysis, i.e. distributional sensitivity approaches.

4. There are also impact valuation related parameters, i.e. VSL used for estimating health benefits and SCC for determination of climate cost. These parameters usually hold very important position in the overall ranking among all the model factors altogether since they vary within a wide range. Hence the valuation factors are always critical to any policy valuation and obviously require more research efforts.

7.4.2 Recommendations from Limitations of the Study

1. The modification in model assumptions in the different components of methodology, may overcome the limitations related to models and hence more precision can be reached. The referred models in the impact-pathway approach, intended to determine the health benefits, are the only means to generate systematic grid-wise calculations for Dhaka as per the latest available knowledge under their respective limitations or validity. With progress in further related attempts to overcome the associated limitations, the current model will require only the incorporation of latest updates to reach the ultimate accuracy. This part of the study can be a wide future scope of related studies.

2. A large-scale vehicle inventory or most recent data on the current estimate of vehicle-fuel split actually plying on the street of Dhaka can increase the accuracy of the calculation. More specifically, this can be done grid-wise considering all the major and minor roads of the city (which is a limitation of the study conducted by Arjumand 2010). As a result, more practical approach, either from direct survey or modified calculation, may be proposed to compute the fuel-split of vehicles in each grid rather than using a merely ratio-based concept.

3. If vehicle emission testing facilities can be introduced in Dhaka, under different driving conditions for different types of vehicles and fuels, it may remove the uncertainty associated with emission factors of both regular and super-emitting fractions in the vehicle fleet.

4. Development of C-R functions for finer fractions of particulates specifically for Dhaka is very important because it affects the overall analysis as is also found from the sensitivity analysis. Although there is one research by Aktar and Shimada on the C-R function for PM_{10}, in general, this part of research is till now very limited in Bangladesh and may be recommended for future studies.

5. Determination of Total effect sensitivity index in GSA can give directly the non-influential factors that can be fixed without significant changes in the results and hence this can also help to allocate future research efforts and resources more efficiently

6. Research should focus on secondary particulates formation from SO_2, as a result, the health benefits can be even more than that calculated now and more importantly it may change the climate impacts estimated under currently available data.

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APPENDIX A

Derivation Method of Fuel-split of Grid-wise distributed Composite VKTs

Step 1: Composite VKTs, for both pre and post-conversion cases, are calculated separately for each vehicle-fuel type following the formula:

$$\mathrm{VKT}_{\mathrm{comp}\ i,j} = \mathrm{N}_{ij} \times \mathrm{VKT}_{ij} \tag{A.1}$$

where, $\mathrm{VKT}_{\mathrm{compi},j}$ is composite VKT for vehicle type i and fuel type j;

N_{ij} and VKT_{ij} represent the numbers and average daily VKT of vehicle i and fuel type j

Step 2: For a particular vehicle type, total composite VKT is obtained from Arjumand (2010) by summing up the values of all the grids and denoted as $\mathrm{VKT}_{\mathrm{total}}$. Then the composite VKTs per grid of the given vehicle (as calculated by Arjumand 2010) are divided by $\mathrm{VKT}_{\mathrm{total}}$. Finally the composite VKTs of the given vehicle type calculated in current study are summed up and multiplied with the obtained ratio per grid. This can be easily understood by the following equation:

$$\mathrm{VKT}_{\mathrm{comp-grid},i} = \mathrm{VKT}_{\mathrm{comp-total},i} \times \frac{\mathrm{VKT}_{\mathrm{grid},i}}{\mathrm{VKT}_{\mathrm{total},i}} \tag{A.2}$$

where, $\mathrm{VKT}_{\mathrm{comp-grid},\ i}$ is the composite VKT of vehicle type i in a grid;

$\mathrm{VKT}_{\mathrm{comp-total},\ i}$ is the summation of all the composite VKTs under current study over all the prevailing fuel types of vehicle type i;

$\mathrm{VKT}_{\mathrm{grid},\ i}$ is the VKT of vehicle i from Arjumand (2010) for the grid under calculation;

$\mathrm{VKT}_{\mathrm{total},\ i}$ is the summation of all VKTs given by Arjumand (2010) for vehicle i over all the 252 grids.

It is important to mention here that the grid-wise data from Arjumand (2010) is considered to correspond to the current policy case whereas the base case grid-wise VKTs are derived from the given values. The total numbers of vehicles are the same for both cases and the dedicated CNG vehicles are distributed as diesel and/or gasoline vehicles in the base case according to the fuel-split as obtained from the field survey.

The calculation described in Step 2 gives the grid-wise composite VKT distribution for the current study on day basis including contributions of all the fuels within a particular vehicle type.

Step 3: One of the fuels (diesel/gasoline in base case and diesel/gasoline/CNG for current case) of a given vehicle is taken as a reference fuel with respect to which other fuels' proportions are calculated. Gasoline is taken as the reference fuel for both base and current cases for the vehicles which run by gasoline, diesel and/or CNG. For taxis and auto-rickshaws, both the cases consider only CNG vehicles and no impact due to conversion policy is associated with these vehicles (same thing is applicable for gasoline fuelled motor-cycles which are not converted in current case, hence no such reference fuel is required). For buses, mini-buses and trucks, there are only diesel vehicles in base case requiring no such proportions and in current case (for CNG buses) these are expressed with respect to diesel vehicles. The ratios are denoted as follows:

Notations:

1. Whenever composite VKTs of diesel vehicles are expressed with respect to gasoline, the ratio is denoted as R_1.
2. Whenever composite VKTs of CNG vehicles are expressed with respect to gasoline, the ratio is denoted as R_2.
3. Whenever composite VKTs of gasoline vehicles are expressed with respect to diesel, the ratio is denoted as R_3.
4. Whenever composite VKTs of CNG vehicles are expressed with respect to diesel, the ratio is denoted as R_4.

R_1 is necessary for most of the vehicles in base case and R_2 for current case. On the other hand, to find out the fuel-wise split, for non-gasoline vehicles in current cases, R_4 is important. The following steps of derivation show the equation to compute the fuel-wise composite VKT of a vehicle from the composite VKTs obtained per grid in step 2.

Total composite VKT in a grid for a vehicle,

$$\mathrm{VKT_{comp-grid,i}} = \mathrm{N_D} \times \mathrm{VKT_D} + \mathrm{N_G} \times \mathrm{VKT_G} + \mathrm{N_{CNG}} \times \mathrm{VKT_{CNG}}$$

$$\Rightarrow \mathrm{VKT_{comp-grid,i}} = \mathrm{N_G} \times \mathrm{VKT_G}\,(1 + \mathrm{R_1} + \mathrm{R_2})$$

$$\Rightarrow \mathrm{N_G} \times \mathrm{VKT_G} = \frac{\mathrm{VKT_{comp-grid,i}}}{(1+\mathrm{R_1}+\mathrm{R_2})} \tag{A.3}$$

Here, N_D, N_G & N_{CNG} and VKT_D, VKT_G and VKT_{CNG} are the numbers and VKTs of diesel, gasoline and CNG fuelled vehicles respectively of a given vehicle type. In product form, these represent the composite VKTs for each fuel type. For base case, since there are no CNG vehicles, $R_2 = 0$.

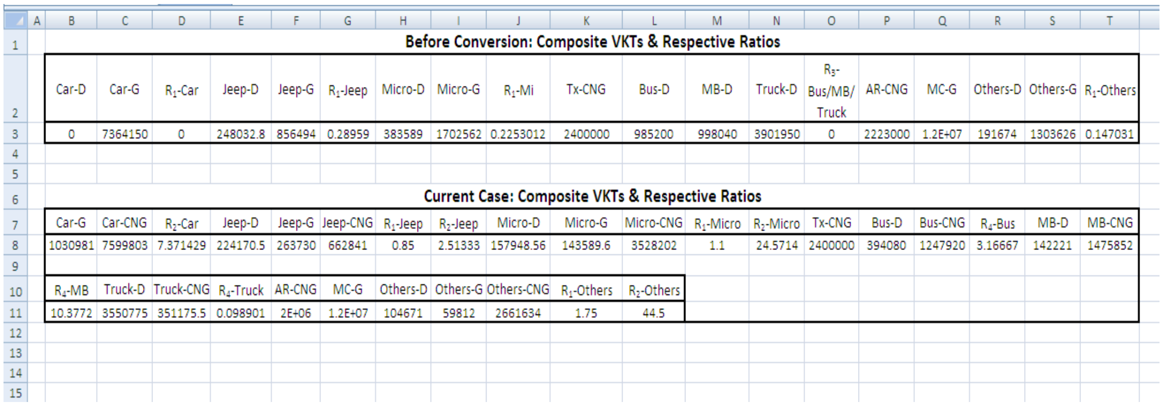
Using equation (A.3), gasoline split can be determined for a vehicle type and then other remaining fuel splits of the considered vehicle (in terms of composite VKTs) can also be determined by similar ratios or directly by deducting from the total composite VKT.

Similarly, for non-gasoline vehicles, in current case, using the ratios, it can be deduced that

$$\Rightarrow N_D \times VKT_D = \frac{VKT_{comp-grid,i}}{(1+R_3+R_4)} \tag{A.4}$$

Here $R_3 = 0$ for non-gasoline vehicles.

Therefore, composite VKTs for diesel fractions can be calculated from equation (A.4) per grid and others from similar ratios or from the total. Figure A.1 shows a snapshot showing composite VKTs and the ratios for desired fuel-split for all the types of vehicles for before and after the conversion.



Before Conversion: Composite VKTs & Respective Ratios

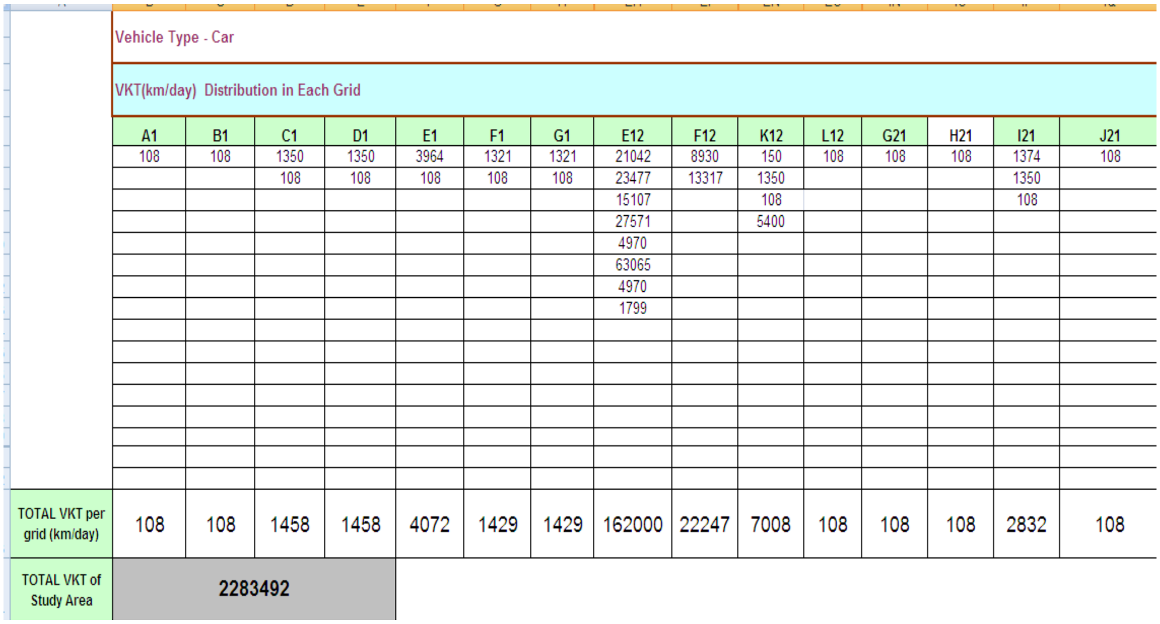
Car-D	Car-G	R_1-Car	Jeep-D	Jeep-G	R_1-Jeep	Micro-D	Micro-G	R_1-Mi	Tx-CNG	Bus-D	MB-D	Truck-D	R_3-Bus/MB/Truck	AR-CNG	MC-G	Others-D	Others-G	R_1-Others
0	7364150	0	248032.8	856494	0.28959	383589	1702562	0.2253012	2400000	985200	998040	3901950	0	2223000	1.2E+07	191674	1303626	0.147031

Current Case: Composite VKTs & Respective Ratios

Car-G	Car-CNG	R_2-Car	Jeep-D	Jeep-G	Jeep-CNG	R_1-Jeep	R_2-Jeep	Micro-D	Micro-G	Micro-CNG	R_1-Micro	R_2-Micro	Tx-CNG	Bus-D	Bus-CNG	R_4-Bus	MB-D	MB-CNG
1030981	7599803	7.371429	224170.5	263730	662841	0.85	2.51333	157948.56	143589.6	3528202	1.1	24.5714	2400000	394080	1247920	3.16667	142221	1475852

R_4-MB	Truck-D	Truck-CNG	R_4-Truck	AR-CNG	MC-G	Others-D	Others-G	Others-CNG	R_1-Others	R_2-Others
10.3772	3550775	351175.5	0.098901	2E+06	1.2E+07	104671	59812	2661634	1.75	44.5

Figure A.1: Snapshot of Spreadsheet showing Estimation Procedure of Composite VKTs and required Ratios for Fuel-split

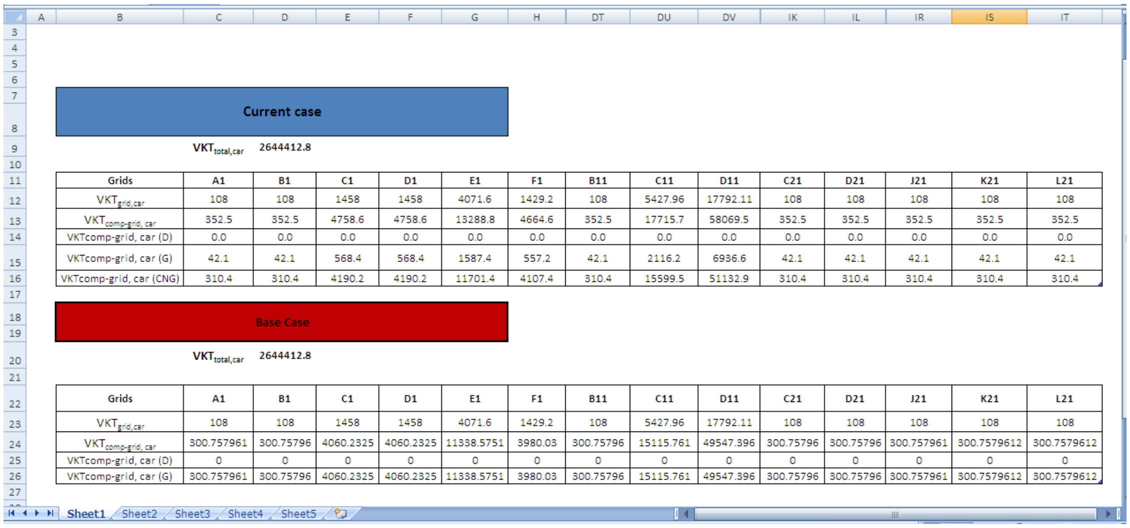


Vehicle Type - Car

VKT(km/day) Distribution in Each Grid

	A1	B1	C1	D1	E1	F1	G1	E12	F12	K12	L12	G21	H21	I21	J21
	108	108	1350	1350	3964	1321	1321	21042	8930	150	108	108	108	1374	108
			108	108	108	108	108	23477	13317	1350				1350	
								15107		108				108	
								27571		5400					
								4970							
								63065							
								4970							
								1799							
TOTAL VKT per grid (km/day)	108	108	1458	1458	4072	1429	1429	162000	22247	7008	108	108	108	2832	108
TOTAL VKT of Study Area	2283492														

Figure A.2: Snapshot of Excel Worksheet showing Estimation of Grid-wise VKT of Car (Arjumand 2010)



Current case

$VKT_{total,car}$ 2644412.8

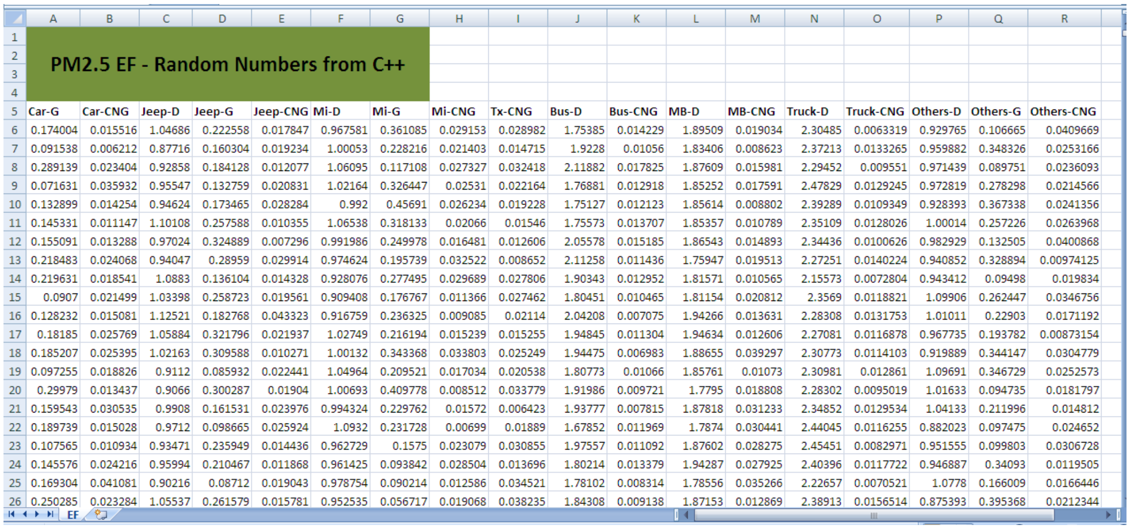
Grids	A1	B1	C1	D1	E1	F1	B11	C11	D11	C21	D21	J21	K21	L21
$VKT_{grid,car}$	108	108	1458	1458	4071.6	1429.2	108	5427.96	17792.11	108	108	108	108	108
$VKT_{comp\text{-}grid,\ car}$	352.5	352.5	4758.6	4758.6	13288.8	4664.6	352.5	17715.7	58069.5	352.5	352.5	352.5	352.5	352.5
VKTcomp-grid, car (D)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VKTcomp-grid, car (G)	42.1	42.1	568.4	568.4	1587.4	557.2	42.1	2116.2	6936.6	42.1	42.1	42.1	42.1	42.1
VKTcomp-grid, car (CNG)	310.4	310.4	4190.2	4190.2	11701.4	4107.4	310.4	15599.5	51132.9	310.4	310.4	310.4	310.4	310.4

Base Case

$VKT_{total,car}$ 2644412.8

Grids	A1	B1	C1	D1	E1	F1	B11	C11	D11	C21	D21	J21	K21	L21
$VKT_{grid,car}$	108	108	1458	1458	4071.6	1429.2	108	5427.96	17792.11	108	108	108	108	108
$VKT_{comp\text{-}grid,\ car}$	300.757961	300.75796	4060.2325	4060.2325	11338.5751	3980.03	300.75796	15115.761	49547.396	300.75796	300.75796	300.757961	300.7579612	300.7579612
VKTcomp-grid, car (D)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VKTcomp-grid, car (G)	300.757961	300.75796	4060.2325	4060.2325	11338.5751	3980.03	300.75796	15115.761	49547.396	300.75796	300.75796	300.757961	300.7579612	300.7579612

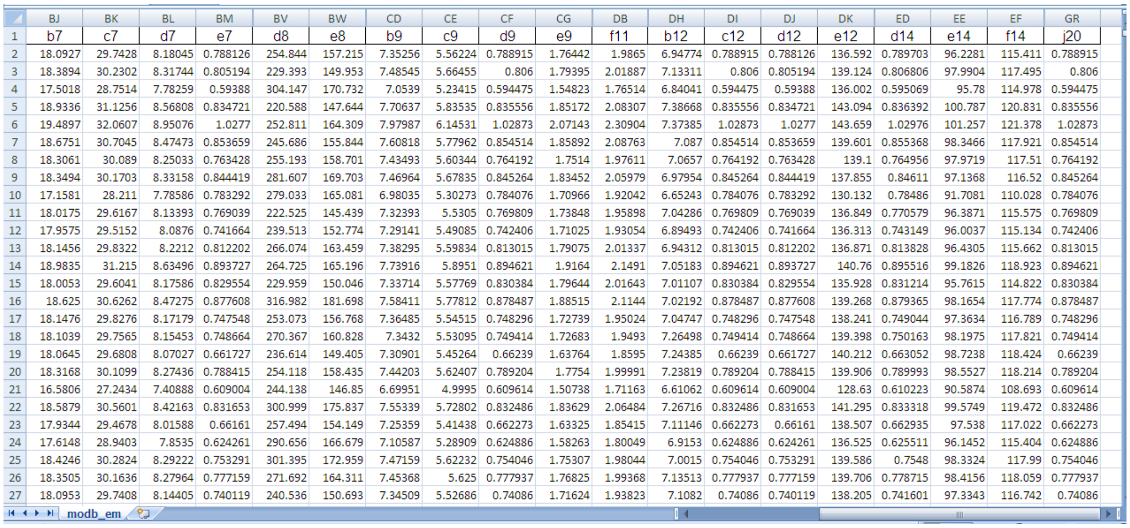
Figure A.3: Snapshot of Excel Worksheet showing Calculation of Grid-wise Composite VKT & corresponding Fuel-split of Car



PM2.5 EF - Random Numbers from C++

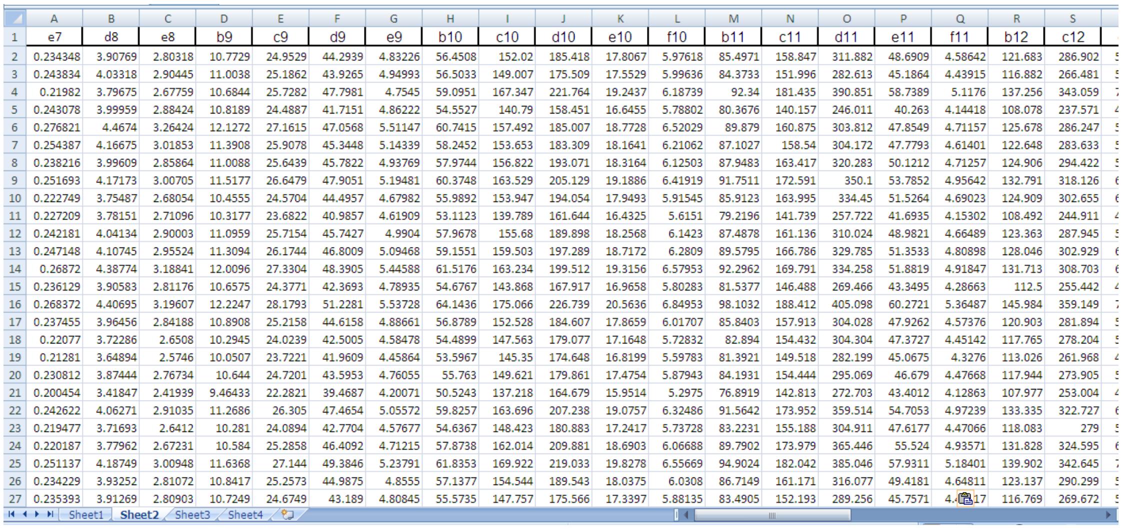
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
5	Car-G	Car-CNG	Jeep-D	Jeep-G	Jeep-CNG	Mi-D	Mi-G	Mi-CNG	Tx-CNG	Bus-D	Bus-CNG	MB-D	MB-CNG	Truck-D	Truck-CNG	Others-D	Others-G	Others-CNG
6	0.174004	0.015516	1.04686	0.222558	0.017847	0.967581	0.361085	0.029153	0.028982	1.75385	0.014229	1.89509	0.019034	2.30485	0.0063319	0.929765	0.106665	0.0409669
7	0.091538	0.006212	0.87716	0.160304	0.019234	1.00053	0.228216	0.021403	0.014715	1.9228	0.01056	1.83406	0.008623	2.37213	0.0133265	0.959882	0.348326	0.0253166
8	0.289139	0.023404	0.92858	0.184128	0.012077	1.06095	0.117108	0.027327	0.032418	2.11882	0.017825	1.87609	0.015981	2.29452	0.009551	0.971439	0.089751	0.0236093
9	0.071631	0.035932	0.95547	0.132759	0.020831	1.02164	0.326447	0.02531	0.022164	1.76881	0.012918	1.85252	0.017591	2.47829	0.0129245	0.972819	0.278298	0.0214566
10	0.132899	0.014254	0.94624	0.173465	0.028284	0.992	0.45691	0.026234	0.019228	1.75127	0.012123	1.85614	0.008802	2.39289	0.0109349	0.928393	0.367338	0.0241356
11	0.145331	0.011147	1.10108	0.257588	0.010355	1.06538	0.318133	0.02066	0.01546	1.75573	0.013707	1.85357	0.010789	2.35109	0.0128026	1.00014	0.257226	0.0263968
12	0.155091	0.013288	0.97024	0.324889	0.007296	0.991986	0.249978	0.016481	0.012606	2.05578	0.015185	1.86543	0.014893	2.34436	0.0100626	0.982929	0.132505	0.0400868
13	0.218483	0.024068	0.94047	0.28959	0.029914	0.974624	0.195739	0.032522	0.008652	2.11258	0.011436	1.75947	0.019513	2.27251	0.0140224	0.940852	0.328894	0.00974125
14	0.219631	0.018541	1.0883	0.136104	0.014328	0.928076	0.277495	0.029689	0.027806	1.90343	0.012952	1.81571	0.010565	2.15573	0.0072804	0.943412	0.09498	0.019834
15	0.0907	0.021499	1.03398	0.258723	0.019561	0.909408	0.176767	0.011366	0.027462	1.80451	0.010465	1.81154	0.020812	2.3569	0.0118821	1.09906	0.262447	0.0346756
16	0.128232	0.015081	1.12521	0.182768	0.043323	0.916759	0.236325	0.009085	0.02114	2.04208	0.007075	1.94266	0.013631	2.28308	0.0131753	1.01011	0.22903	0.0171192
17	0.18185	0.025769	1.05884	0.321796	0.021937	1.02749	0.216194	0.015239	0.015255	1.94845	0.011304	1.94634	0.012606	2.27081	0.0116878	0.967735	0.193782	0.00873154
18	0.185207	0.025395	1.02163	0.309588	0.010271	1.00132	0.343368	0.033803	0.025249	1.94475	0.006983	1.88655	0.039297	2.30773	0.0114103	0.919889	0.344147	0.0304779
19	0.097255	0.018826	0.9112	0.085932	0.022441	1.04964	0.209521	0.017034	0.020538	1.80773	0.01066	1.85761	0.01073	2.30981	0.012861	1.09691	0.346729	0.0252573
20	0.29979	0.013437	0.9066	0.300287	0.01904	1.00693	0.409778	0.008512	0.033779	1.91986	0.009721	1.7795	0.018808	2.28302	0.0095019	1.01633	0.094735	0.0181797
21	0.159543	0.030535	0.9908	0.161531	0.023976	0.994324	0.229762	0.01572	0.006423	1.93777	0.007815	1.87818	0.031233	2.34852	0.0129534	1.04133	0.211996	0.014812
22	0.189739	0.015028	0.9712	0.098665	0.025924	1.0932	0.231728	0.00699	0.01889	1.67852	0.011969	1.7874	0.030441	2.44045	0.0116255	0.882023	0.097475	0.024652
23	0.107565	0.010934	0.93471	0.235949	0.014436	0.962729	0.1575	0.023079	0.030855	1.97557	0.011092	1.87602	0.028275	2.45451	0.0082971	0.951555	0.099803	0.0306728
24	0.145576	0.024216	0.95994	0.210467	0.011868	0.961425	0.093842	0.028504	0.013696	1.80214	0.013379	1.94287	0.027925	2.40396	0.0117722	0.946887	0.34093	0.0119505
25	0.169304	0.041081	0.90216	0.08712	0.019043	0.978754	0.090214	0.012586	0.034521	1.78102	0.008314	1.78556	0.035266	2.22657	0.0070521	1.0778	0.166009	0.0166446
26	0.250285	0.023284	1.05537	0.261579	0.015781	0.952535	0.056717	0.019068	0.038235	1.84308	0.009138	1.87153	0.012869	2.38913	0.0156514	0.875393	0.395368	0.0212344

Figure A.4: Snapshot of Random Numbers for Emission Factors (gm/Km) of $PM_{2.5}$ for Different Vehicle-Fuel Combinations (obtained from Triangular Distribution)



	BJ	BK	BL	BM	BV	BW	CD	CE	CF	CG	DB	DH	DI	DJ	DK	ED	EE	EF	GR
1	b7	c7	d7	e7	d8	e8	b9	c9	d9	e9	f11	b12	c12	d12	e12	d14	e14	f14	j20
2	18.0927	29.7428	8.18045	0.788126	254.844	157.215	7.35256	5.56224	0.788915	1.76442	1.9865	6.94774	0.788915	0.788126	136.592	0.789703	96.2281	115.411	0.788915
3	18.3894	30.2302	8.31744	0.805194	229.393	149.953	7.48545	5.66455	0.806	1.79395	2.01887	7.13311	0.806	0.805194	139.124	0.806806	97.9904	117.495	0.806
4	17.5018	28.7514	7.78259	0.59388	304.147	170.732	7.0539	5.23415	0.594475	1.54823	1.76514	6.84041	0.594475	0.59388	136.002	0.595069	95.78	114.978	0.594475
5	18.9336	31.1256	8.56808	0.834721	220.588	147.644	7.70637	5.83535	0.835556	1.85172	2.08307	7.38668	0.835556	0.834721	143.094	0.836392	100.787	120.831	0.835556
6	19.4897	32.0607	8.95076	1.0277	252.811	164.309	7.97987	6.14531	1.02873	2.07143	2.30904	7.37385	1.02873	1.0277	143.659	1.02976	101.257	121.378	1.02873
7	18.6751	30.7045	8.47473	0.853659	245.686	155.844	7.60818	5.77962	0.854514	1.85892	2.08763	7.087	0.854514	0.853659	139.601	0.855368	98.3466	117.921	0.854514
8	18.3061	30.089	8.25033	0.763428	255.193	158.701	7.43493	5.60344	0.764192	1.7514	1.97611	7.0657	0.764192	0.763428	139.1	0.764956	97.9719	117.51	0.764192
9	18.3494	30.1703	8.33158	0.844419	281.607	169.703	7.46964	5.67835	0.845264	1.83452	2.05979	6.97954	0.845264	0.844419	137.855	0.84611	97.1368	116.52	0.845264
10	17.1581	28.211	7.78586	0.783292	279.033	165.081	6.98035	5.30273	0.784076	1.70966	1.92042	6.65243	0.784076	0.783292	130.132	0.78486	91.7081	110.028	0.784076
11	18.0175	29.6167	8.13393	0.769039	222.525	145.439	7.32393	5.5305	0.769809	1.73848	1.95898	7.04286	0.769809	0.769039	136.849	0.770579	96.3871	115.575	0.769809
12	17.9575	29.5152	8.0876	0.741664	239.513	152.774	7.29141	5.49085	0.742406	1.71025	1.93054	6.89493	0.742406	0.741664	136.313	0.743149	96.0037	115.134	0.742406
13	18.1456	29.8322	8.2212	0.812202	266.074	163.459	7.38295	5.59834	0.813015	1.79075	2.01337	6.94312	0.813015	0.812202	136.871	0.813828	96.4305	115.662	0.813015
14	18.9835	31.215	8.63496	0.893727	264.725	165.196	7.73916	5.8951	0.894621	1.9164	2.1491	7.05183	0.894621	0.893727	140.76	0.895516	99.1826	118.923	0.894621
15	18.0053	29.6041	8.17586	0.829554	229.959	150.046	7.33714	5.57769	0.830384	1.79644	2.01643	7.01107	0.830384	0.829554	135.928	0.831214	95.7615	114.822	0.830384
16	18.625	30.6262	8.47275	0.877608	316.982	181.698	7.58411	5.77812	0.878487	1.88515	2.1144	7.02192	0.878487	0.877608	139.268	0.879365	98.1654	117.774	0.878487
17	18.1476	29.8276	8.17179	0.747548	253.073	156.768	7.36485	5.54515	0.748296	1.72739	1.95024	7.04747	0.748296	0.747548	138.241	0.749044	97.3634	116.789	0.748296
18	18.1039	29.7565	8.15453	0.748664	270.367	160.828	7.3432	5.53095	0.749414	1.72683	1.9493	7.26498	0.749414	0.748664	139.398	0.750163	98.1975	117.821	0.749414
19	18.0645	29.6808	8.07027	0.661727	236.614	149.405	7.30901	5.45264	0.66239	1.63764	1.8595	7.24385	0.66239	0.661727	140.212	0.663052	98.7238	118.424	0.66239
20	18.3168	30.1099	8.27436	0.788415	254.118	158.435	7.44203	5.62407	0.789204	1.7754	1.99991	7.23819	0.789204	0.788415	139.906	0.789993	98.5527	118.214	0.789204
21	16.5806	27.2434	7.40888	0.609004	244.138	146.85	6.69951	4.9995	0.609614	1.50738	1.71163	6.61062	0.609614	0.609004	128.63	0.610223	90.5874	108.693	0.609614
22	18.5879	30.5601	8.42163	0.831653	300.999	175.837	7.55339	5.72802	0.832486	1.83629	2.06484	7.26716	0.832486	0.831653	141.295	0.833318	99.5749	119.472	0.832486
23	17.9344	29.4678	8.01588	0.66161	257.494	154.149	7.25359	5.41438	0.662273	1.63325	1.85415	7.11146	0.662273	0.66161	138.507	0.662935	97.538	117.022	0.662273
24	17.6148	28.9403	7.8535	0.624261	290.656	166.679	7.10587	5.28909	0.624886	1.58263	1.80049	6.9153	0.624886	0.624261	136.525	0.625511	96.1452	115.404	0.624886
25	18.4246	30.2824	8.29222	0.753291	301.395	172.959	7.47159	5.62232	0.754046	1.75307	1.98044	7.0015	0.754046	0.753291	139.586	0.7548	98.3324	117.99	0.754046
26	18.3505	30.1636	8.27964	0.777159	271.692	164.311	7.45368	5.625	0.777937	1.76825	1.99368	7.13513	0.777937	0.777159	139.706	0.778715	98.4156	118.059	0.777937
27	18.0953	29.7408	8.14405	0.740119	240.536	150.693	7.34509	5.52686	0.74086	1.71624	1.93823	7.1082	0.74086	0.740119	138.205	0.741601	97.3343	116.742	0.74086

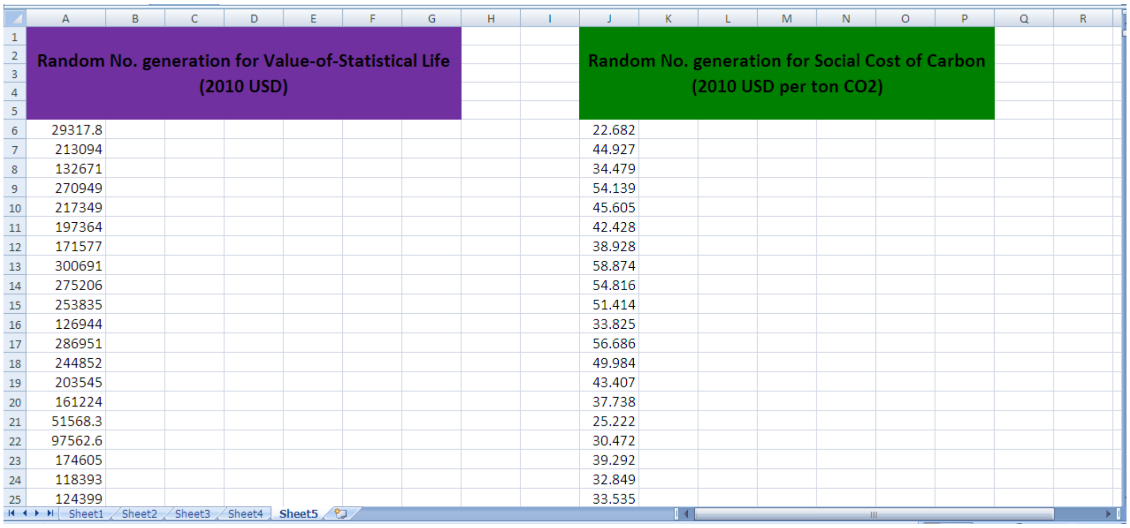
Figure A.5: Snapshot of Modified Base $PM_{2.5}$ Emissions Matrix Result from C++ Program to Excel File



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	e7	d8	e8	b9	c9	d9	e9	b10	c10	d10	e10	f10	b11	c11	d11	e11	f11	b12	c12
2	0.234348	3.90769	2.80318	10.7729	24.9529	44.2939	4.83226	56.4508	152.02	185.418	17.8067	5.97618	85.4971	158.847	311.882	48.6909	4.58642	121.683	286.902
3	0.243834	4.03318	2.90445	11.0038	25.1862	43.9265	4.94993	56.5033	149.007	175.509	17.5529	5.99636	84.3733	151.996	282.613	45.1864	4.43915	116.882	266.481
4	0.21982	3.79675	2.67759	10.6844	25.7282	47.7981	4.7545	59.0951	167.347	221.764	19.2437	6.18739	92.34	181.435	390.851	58.7389	5.1176	137.256	343.059
5	0.243078	3.99959	2.88424	10.8189	24.4887	41.7151	4.86222	54.5527	140.79	158.451	16.6455	5.78802	80.3676	140.157	246.011	40.263	4.14418	108.078	237.571
6	0.276821	4.4674	3.26424	12.1272	27.1615	47.0568	5.51147	60.7415	157.492	185.007	18.7728	6.52029	89.879	160.875	303.812	47.8549	4.71157	125.678	286.247
7	0.254387	4.16675	3.01853	11.3908	25.9078	45.3448	5.14339	58.2452	153.653	183.309	18.1641	6.21062	87.1027	158.54	304.172	47.7793	4.61401	122.648	283.633
8	0.238216	3.99609	2.85864	11.0088	25.6439	45.7822	4.93769	57.9744	156.822	193.071	18.3164	6.12503	87.9483	163.417	320.283	50.1212	4.71257	124.906	294.422
9	0.251693	4.17173	3.00705	11.5177	26.6479	47.9051	5.19481	60.3748	163.529	205.129	19.1886	6.41919	91.7511	172.591	350.1	53.7852	4.95642	132.791	318.126
10	0.222749	3.75487	2.68054	10.4555	24.5704	44.4957	4.67982	55.9892	153.947	194.054	17.9493	5.91545	85.9123	163.995	334.45	51.5264	4.69023	124.909	302.655
11	0.227209	3.78151	2.71096	10.3177	23.6822	40.9857	4.61909	53.1123	139.789	161.644	16.4325	5.6151	79.2196	141.739	257.722	41.6935	4.15302	108.492	244.911
12	0.242181	4.04134	2.90003	11.0959	25.7154	45.7427	4.9904	57.9678	155.68	189.898	18.2568	6.1423	87.4878	161.136	310.024	48.9821	4.66489	123.363	287.945
13	0.247148	4.10745	2.95524	11.3094	26.1744	46.8009	5.09468	59.1551	159.503	197.289	18.7172	6.2809	89.5795	166.786	329.785	51.3533	4.80898	128.046	302.929
14	0.26872	4.38774	3.18841	12.0096	27.3304	48.3905	5.44588	61.5176	163.234	199.512	19.3156	6.57953	92.2962	169.791	334.258	51.8819	4.91847	131.713	308.703
15	0.236129	3.90583	2.81176	10.6575	24.3771	42.3693	4.78935	54.6767	143.868	167.917	16.9658	5.80283	81.5377	146.488	269.466	43.3495	4.28663	112.5	255.442
16	0.268372	4.40695	3.19607	12.2247	28.1793	51.2281	5.53728	64.1436	175.066	226.739	20.5636	6.84953	98.1032	188.412	405.098	60.2721	5.36487	145.984	359.149
17	0.237455	3.96456	2.84188	10.8908	25.2158	44.6158	4.88661	56.8789	152.528	184.607	17.8659	6.01707	85.8403	157.913	304.028	47.9262	4.57376	120.903	281.894
18	0.22077	3.72286	2.6508	10.2945	24.0239	42.5005	4.58478	54.4899	147.563	179.077	17.1648	5.72832	82.894	154.432	304.304	47.3727	4.45142	117.765	278.204
19	0.21281	3.64894	2.5746	10.0507	23.7221	41.9609	4.45864	53.5967	145.35	174.648	16.8199	5.59783	81.3921	149.518	282.199	45.0675	4.3276	113.026	261.968
20	0.230812	3.87444	2.76734	10.644	24.7201	43.5953	4.76055	55.763	149.621	179.861	17.4754	5.87943	84.1931	154.444	295.069	46.679	4.47668	117.944	273.905
21	0.200454	3.41847	2.41939	9.46433	22.2821	39.4687	4.20071	50.5243	137.218	164.679	15.9514	5.2975	76.8919	142.813	272.703	43.4012	4.12863	107.977	253.004
22	0.242622	4.06271	2.91035	11.2686	26.305	47.4654	5.05572	59.8257	163.696	207.238	19.0757	6.32486	91.5642	173.952	359.514	54.7053	4.97239	133.335	322.727
23	0.219477	3.71693	2.6412	10.281	24.0894	42.7704	4.57677	54.6367	148.423	180.883	17.2417	5.73728	83.2231	155.188	304.911	47.6177	4.47066	118.083	279
24	0.220187	3.77962	2.67231	10.584	25.2858	46.4092	4.71215	57.8738	162.014	209.881	18.6903	6.06688	89.7902	173.979	365.446	55.524	4.93571	131.828	324.595
25	0.251137	4.18749	3.00948	11.6368	27.144	49.3846	5.23791	61.8353	169.922	219.033	19.8278	6.55669	94.9024	182.042	385.046	57.9311	5.18401	139.902	342.645
26	0.234229	3.93252	2.81072	10.8417	25.2573	44.9875	4.8555	57.1377	154.544	189.543	18.0375	6.0308	86.7149	161.171	316.077	49.4181	4.64811	123.137	290.299
27	0.235393	3.91269	2.80903	10.7249	24.6749	43.189	4.80845	55.5735	147.757	175.566	17.3397	5.88135	83.4905	152.193	289.256	45.7571	4.4[illegible]17	116.769	269.672

Figure A.6: Snapshot of Grid-wise No. of Premature Deaths Avoided due to Policy

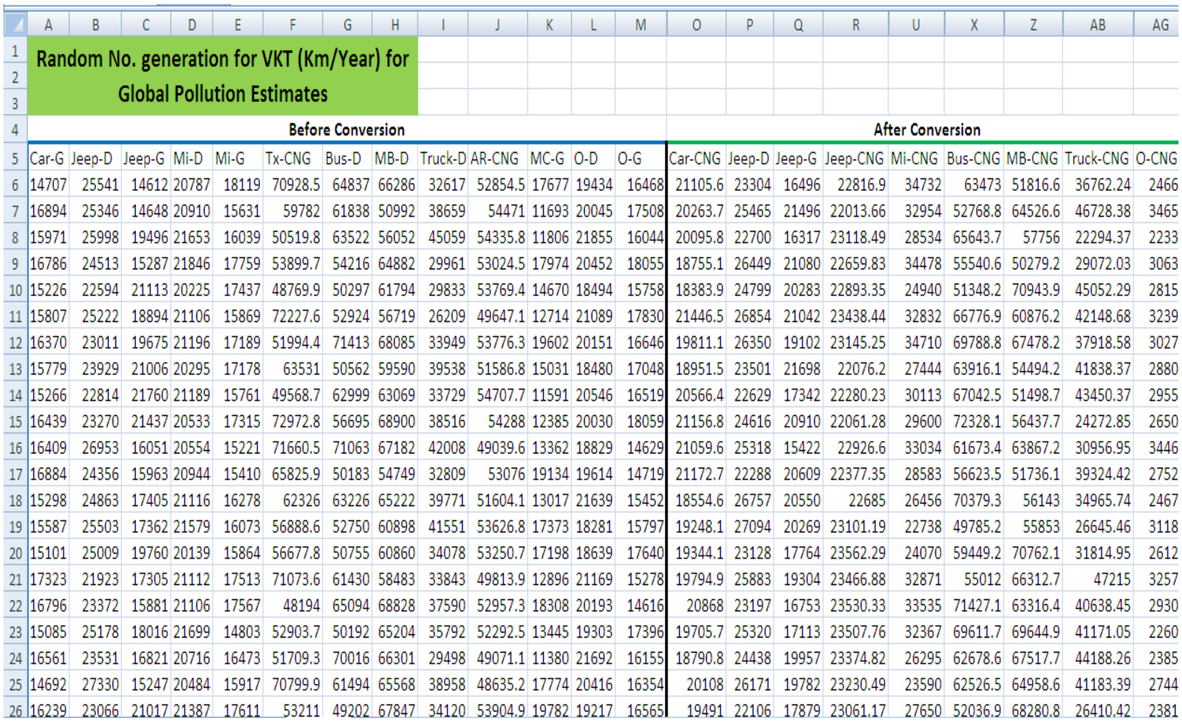
APPENDIX B



Random No. generation for Value-of-Statistical Life (2010 USD)	Random No. generation for Social Cost of Carbon (2010 USD per ton CO2)
29317.8	22.682
213094	44.927
132671	34.479
270949	54.139
217349	45.605
197364	42.428
171577	38.928
300691	58.874
275206	54.816
253835	51.414
126944	33.825
286951	56.686
244852	49.984
203545	43.407
161224	37.738
51568.3	25.222
97562.6	30.472
174605	39.292
118393	32.849
124399	33.535

Figure B.1 Snapshot of Random Numbers for Impact Valuation Parameters (2010 USD)

(Obtained from Triangular Distributions)



Random No. generation for VKT (Km/Year) for Global Pollution Estimates

Before Conversion													After Conversion								
Car-G	Jeep-D	Jeep-G	Mi-D	Mi-G	Tx-CNG	Bus-D	MB-D	Truck-D	AR-CNG	MC-G	O-D	O-G	Car-CNG	Jeep-D	Jeep-G	Jeep-CNG	Mi-CNG	Bus-CNG	MB-CNG	Truck-CNG	O-CNG
14707	25541	14612	20787	18119	70928.5	64837	66286	32617	52854.5	17677	19434	16468	21105.6	23304	16496	22816.9	34732	63473	51816.6	36762.24	2466
16894	25346	14648	20910	15631	59782	61838	50992	38659	54471	11693	20045	17508	20263.7	25465	21496	22013.66	32954	52768.8	64526.6	46728.38	3465
15971	25998	19496	21653	16039	50519.8	63522	56052	45059	54335.8	11806	21855	16044	20095.8	22700	16317	23118.49	28534	65643.7	57756	22294.37	2233
16786	24513	15287	21846	17759	53899.7	54216	64882	29961	53024.5	17974	20452	18055	18755.1	26449	21080	22659.83	34478	55540.6	50279.2	29072.03	3063
15226	22594	21113	20225	17437	48769.9	50297	61794	29833	53769.4	14670	18494	15758	18383.9	24799	20283	22893.35	24940	51348.2	70943.9	45052.29	2815
15807	25222	18894	21106	15869	72227.6	52924	56719	26209	49647.1	12714	21089	17830	21446.5	26854	21042	23438.44	32832	66776.9	60876.2	42148.68	3239
16370	23011	19675	21196	17189	51994.4	71413	68085	33949	53776.3	19602	20151	16646	19811.1	26350	19102	23145.25	34710	69788.8	67478.2	37918.58	3027
15779	23929	21006	20295	17178	63531	50562	59590	39538	51586.8	15031	18480	17048	18951.5	23501	21698	22076.2	27444	63916.1	54494.2	41838.37	2880
15266	22814	21760	21189	15761	49568.7	62999	63069	33729	54707.7	11591	20546	16519	20566.4	22629	17342	22280.23	30113	67042.5	51498.7	43450.37	2955
16439	23270	21437	20533	17315	72972.8	56695	68900	38516	54288	12385	20030	18059	21156.8	24616	20910	22061.28	29600	72328.1	56437.7	24272.85	2650
16409	26953	16051	20554	15221	71660.5	71063	67182	42008	49039.6	13362	18829	14629	21059.6	25318	15422	22926.6	33034	61673.4	63867.2	30956.95	3446
16884	24356	15963	20944	15410	65825.9	50183	54749	32809	53076	19134	19614	14719	21172.7	22288	20609	22377.35	28583	56623.5	51736.1	39324.42	2752
15298	24863	17405	21116	16278	62326	63226	65222	39771	51604.1	13017	21639	15452	18554.6	26757	20550	22685	26456	70379.3	56143	34965.74	2467
15587	25503	17362	21579	16073	56888.6	52750	60898	41551	53626.8	17373	18281	15797	19248.1	27094	20269	23101.19	22738	49785.2	55853	26645.46	3118
15101	25009	19760	20139	15864	56677.8	50755	60860	34078	53250.7	17198	18639	17640	19344.1	23128	17764	23562.29	24070	59449.2	70762.1	31814.95	2612
17323	21923	17305	21112	17513	71073.6	61430	58483	33843	49813.9	12896	21169	15278	19794.9	25883	19304	23466.88	32871	55012	66312.7	47215	3257
16796	23372	15881	21106	17567	48194	65094	68828	37590	52957.3	18308	20193	14616	20868	23197	16753	23530.33	33535	71427.1	63316.4	40638.45	2930
15085	25178	18016	21699	14803	52903.7	50192	65204	35792	52292.5	13445	19303	17396	19705.7	25320	17113	23507.76	32367	69611.7	69644.9	41171.05	2260
16561	23531	16821	20716	16473	51709.3	70016	66301	29498	49071.1	11380	21692	16155	18790.8	24438	19957	23374.82	26295	62678.6	67517.7	44188.26	2385
14692	27330	15247	20484	15917	70799.9	61494	65568	38958	48635.2	17774	20416	16354	20108	26171	19782	23230.49	23590	62526.5	64958.6	41183.39	2744
16239	23066	21017	21387	17611	53211	49202	67847	34120	53904.9	19782	19217	16565	19491	22106	17879	23061.17	27650	52036.9	68280.8	26410.42	2381

Figure B.2 Snapshot of Random Numbers for Annual VKTs (Km/Year) of different Vehicle-Fuel Combinations before and after the Conversion (obtained from Uniform Distribution)

APPENDIX C

C++ Codes of the Model Developed to Compute Health Impacts from the Policy

```
#include<iostream.h>
#include<stdlib.h>
#include<stdio.h>
#include<math.h>
#include<iomanip>
# include<fstream.h>
//FUNCTION DEFINED FOR GENERATING 5000 RANDOM NUMBERS FOR EMISSION FACTORS OF
PM2.5 WITH TRIANGULAR DISTRIBUTION
double triang_EF (double a, double b, double m)

{
        double min=0, max=1, u, temp;

        u=min+(rand()*(max-min))/RAND_MAX;

        if (u<=((m-a)/(b-a)))
        {
                temp=a+ sqrt(u*(b-a)*(m-a));
        }
        else if (u>((m-a)/(b-a)))
        {
                temp=b-sqrt((1-u)*(b-a)*(b-m));
        }
                return temp;
}

main()
{
        int i, j, k, l, m, n, p, q, trans_row=200, trans_col=200;

      const int row=5000, col=252, mod_col=200;

      double pop_dcc[200], pop_GD[200]; // gridwise popualation in DCC and in GD
// Declaration of Emission Factors' Arrays for Different Vehicle-Fuel combination
double Car_D[5000][1], Car_G[5000][1], Car_C[5000][1], Jeep_D[5000][1], Jeep_G[5000][1],
Jeep_C[5000][1], Micro_D[5000][1], Micro_G[5000][1], Micro_C[5000][1], Tx_C[5000][1];
double Bus_D[5000][1], Bus_C[5000][1], MB_D[5000][1], MB_C[5000][1], Truck_D[5000][1],
Truck_C[5000][1], AR_C[5000][1], MC_G[5000][1],Others_D[5000][1], Others_G[5000][1],
Others_C[5000][1];
// Inputs of the Defining Values for Emission Factors of PM2.5 for all V-F Types
double C_D_a=0.33, C_D_b=0.85, C_D_m=0.748, C_G_a=0.065, C_G_b=0.37, C_G_m=0.0814,
C_C_a=0.0045, C_C_b=0.045, C_C_m=0.02, J_D_a=0.86, J_D_b=1.14, J_D_m=0.978, J_G_a=0.0476,
J_G_b=0.5, J_G_m=0.09, J_C_a=0.0045, J_C_b=0.045, J_C_m=0.01;
```

```
double M_D_a=0.86, M_D_b=1.14, M_D_m=0.978, M_G_a=0.0476, M_G_b=0.5, M_G_m=0.09,
M_C_a=0.0045, M_C_b=0.045, M_C_m=0.01, Tx_C_a=0.0045, Tx_C_b=0.045, Tx_C_m=0.02,
B_D_a=1.58, B_D_b=2.14, B_D_m=1.89, B_C_a=0.0054, B_C_b=0.018, B_C_m=0.01, MB_D_a=1.714,
MB_D_b=2.015, MB_D_m=1.85, MB_C_a=0.0054, MB_C_b=0.045, MB_C_m=0.01, T_D_a=2.144,
T_D_b=2.538, T_D_m=2.36, T_C_a=0.0054,T_C_b=0.018, T_C_m=0.01, AR_C_a=0.0045,
AR_C_b=0.09, AR_C_m=0.05, MC_G_a=0.024, MC_G_b=0.09, MC_G_m=0.05, O_D_a=0.86,
O_D_b=1.14, O_D_m=0.978, O_G_a=0.0476, O_G_b=0.5, O_G_m=0.09, O_C_a=0.0045,
O_C_b=0.045, O_C_m=0.01;

//Calling 'triang_EF' Function defined before to Generate 5000 Random Numbers for PM2.5
Emission Factors

for (i=0; i<5000; i++)
{
	for (j=0;j<1;j++)
	{
	Car_D[i][j]=triang_EF (C_D_a, C_D_b, C_D_m);
	Car_G[i][j]=triang_EF (C_G_a, C_G_b, C_G_m);
	Car_C[i][j]=triang_EF (C_C_a, C_C_b, C_C_m);
	Jeep_D[i][j]=triang_EF (J_D_a, J_D_b, J_D_m);
	Jeep_G[i][j]=triang_EF (J_G_a, J_G_b, J_G_m);
	Jeep_C[i][j]=triang_EF (J_C_a, J_C_b, J_C_m);
	Micro_D[i][j]=triang_EF (M_D_a, M_D_b, M_D_m);
	Micro_G[i][j]=triang_EF (M_G_a, M_G_b, M_G_m);
	Micro_C[i][j]=triang_EF (M_C_a, M_C_b, M_C_m);
	Tx_C[i][j]=triang_EF (Tx_C_a, Tx_C_b, Tx_C_m);
	Bus_D[i][j]=triang_EF (B_D_a, B_D_b, B_D_m);
	Bus_C[i][j]=triang_EF (B_C_a, B_C_b, B_C_m);
	MB_D[i][j]=triang_EF (MB_D_a, MB_D_b, MB_D_m);
	MB_C[i][j]=triang_EF (MB_C_a, MB_C_b, MB_C_m);
	Truck_D[i][j]=triang_EF (T_D_a, T_D_b, T_D_m);
	Truck_C[i][j]=triang_EF (T_C_a, T_C_b, T_C_m);
	AR_C[i][j]=triang_EF (AR_C_a, AR_C_b, AR_C_m);
	MC_G[i][j]=triang_EF (MC_G_a, MC_G_b, MC_G_m);
	Others_D[i][j]=triang_EF (O_D_a, O_D_b, O_D_m);
	Others_G[i][j]=triang_EF (O_G_a, O_G_b, O_G_m);
	Others_C[i][j]=triang_EF (O_C_a, O_C_b, O_C_m);

	}
}
// Declaration of Arrays of Base case VKTs':

double bVKT_C_G[1][252], bVKT_J_D[1][252],bVKT_J_G[1][252], bVKT_Mi_D[1][252],
bVKT_Mi_G[1][252], VKT_Tx_CNG[1][252], bVKT_B_D[1][252], bVKT_MB_D[1][252],
bVKT_T_D[1][252], VKT_AR_C[1][252], VKT_MC_G[1][252], bVKT_O_D[1][252],bVKT_O_G[1][252];

// Declaration of Arrays of Current case VKTs':

double VKT_C_G[1][252], VKT_C_C[1][252],VKT_J_D[1][252], VKT_J_G[1][252], VKT_J_C[1][252],
VKT_Mi_D[1][252], VKT_Mi_G[1][252], VKT_Mi_C[1][252], VKT_B_D[1][252], VKT_B_C[1][252],
VKT_MB_D[1][252], VKT_MB_C[1][252], VKT_T_D[1][252], VKT_T_C[1][252], VKT_O_D[1][252],
VKT_O_G[1][252], VKT_O_C[1][252];
```

```
//Dynamic Memory Allocation: PM2.5 - Grid Emissions for Base & Current Cases, Modified-grid

Base & Current Emissions, Concentrations, Change in Concentration y, pmf_area matrix (Transformation Matrix), Relative Risk (RR), Modified Mortality Risks (MMR) & Deaths Avoided (dA) corresponding to Cardiovascular and Respiratory
double **b_em = (double**)malloc(row * sizeof(*b_em));

double **em = (double**)malloc(row * sizeof(*em));

double **modb_em = (double**)malloc(row * sizeof(*modb_em));

double **modem = (double**)malloc(row * sizeof(*modem));

double **b_conc = (double**)malloc(row * sizeof(*b_conc));

double **conc = (double**)malloc(row * sizeof(*conc));

double **y = (double**)malloc(row * sizeof(*y));

double **pmf_area = (double**)malloc(trans_row * sizeof(*pmf_area));

double **RR_cnom = (double**)malloc(row * sizeof(*RR_cnom));

double **RR_rnom = (double**)malloc(row * sizeof(*RR_rnom));

double **dA_nom = (double**)malloc(row * sizeof(*dA_nom));

for(i=0; i<row; ++i)
{
b_em[i] = (double*)malloc(col * sizeof(*b_em[0]));
em[i] = (double*)malloc(col * sizeof(*em[0]));
modb_em[i] = (double*)malloc(mod_col * sizeof(*modb_em[0]));
modem[i] = (double*)malloc(mod_col * sizeof(*modem[0]));
b_conc[i] = (double*)malloc(mod_col * sizeof(*b_conc[0]));
conc[i] = (double*)malloc(mod_col * sizeof(*conc[0]));
y[i] = (double*)malloc(mod_col * sizeof(*y[0]));
RR_cnom[i] = (double*)malloc(mod_col * sizeof(*RR_cnom[0]));
RR_rnom[i] = (double*)malloc(mod_col * sizeof(*RR_rnom[0]));
dA_nom[i] = (double*)malloc(mod_col * sizeof(*dA_nom[0]));
}
for(i=0; i<trans_row; ++i)

{

pmf_area[i] = (double*)malloc(trans_col * sizeof(*pmf_area[0]));

}
//Reading Grid-wise derived Composite VKTs' from 'VKTinputdiff.txt' file
ifstream in("VKTinputdiff.txt");

for (i=0; i<1; i++)
```

```
{
	for(j=0; j<252; j++)
	{
		in>>bVKT_C_G[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>bVKT_J_D[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>bVKT_J_G[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>bVKT_Mi_D[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>bVKT_Mi_G[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>VKT_Tx_CNG[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>bVKT_B_D[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>bVKT_MB_D[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>bVKT_T_D[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>VKT_AR_C[i][j];
	}
	for(j=0; j<252; j++)
	{
		in>>VKT_MC_G[i][j];
	}

	for(j=0; j<252; j++)
	{
		in>>bVKT_O_D[i][j];
	}
```

```
for(j=0; j<252; j++)
{
            in>>bVKT_O_G[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_C_G[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_C_C[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_J_D[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_J_G[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_J_C[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_Mi_D[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_Mi_G[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_Mi_C[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_B_D[i][j];
}
for(j=0; j<252; j++)
{
            in>>VKT_B_C[i][j];
}

for(j=0; j<252; j++)
{
            in>>VKT_MB_D[i][j];
}
for(j=0; j<252; j++)
```

```
		{
				in>>VKT_MB_C[i][j];
		}
		for(j=0; j<252; j++)
		{
				in>>VKT_T_D[i][j];
		}
		for(j=0; j<252; j++)
		{
				in>>VKT_T_C[i][j];
		}
		for(j=0; j<252; j++)
		{
				in>>VKT_O_D[i][j];
		}
		for(j=0; j<252; j++)
		{
				in>>VKT_O_G[i][j];
		}
		for(j=0; j<252; j++)
		{
				in>>VKT_O_C[i][j];
		}
}
for (i=0; i<trans_row; i++)
{
		for (j=0; j<trans_col; j++)
		{
				in>>pmf_area[i][j];
		}
}

for (j=0; j<mod_col; j++)
{
		in>>pop_dcc[j];
}

for (j=0; j<mod_col; j++)
{
		in>>pop_GD[j];
}
//Base Case: Grid-wise PM2.5 Emission Generation (Tons/year)

for(i=0; i<row; ++i)
{
		for(k=0; k<col; ++k)
		{
				for (j=0,l=0; j<1 && l<1; j++,l++)
				{
```

```
    b_em[i][k]=(((Car_G[i][j]*bVKT_C_G[l][k]+Jeep_D[i][j]*bVKT_J_D[l][k]+Jeep_G[i][j]*bVKT_J_
    G[l][k]+Micro_D[i][j]*bVKT_Mi_D[l][k]+Micro_G[i][j]*bVKT_Mi_G[l][k]+Tx_C[i][j]*VKT_Tx_CN
    G[l][k]+Bus_D[i][j]*bVKT_B_D[l][k]+MB_D[i][j]*bVKT_MB_D[l][k]+Truck_D[i][j]*bVKT_T_D[l][
    k]+AR_C[i][j]*VKT_AR_C[l][k]+MC_G[i][j]*VKT_MC_G[l][k]+Others_D[i][j]*bVKT_O_D[l][k]+O
    thers_G[i][j]*bVKT_O_G[l][k])*365)/(pow(10,6)));
        }
    }
}
```

//Current Case: Grid-wise PM$_{2.5}$ Emission Generation (Tons/year)

```
for (p=0; p<row; ++p)
{
    for (q=0; q<col; ++q)
    {
        for (j=0,l=0; j<1 && l<1; j++,l++)
        {
        em[p][q]=(((Car_G[p][j]*VKT_C_G[l][q]+Car_C[p][j]*VKT_C_C[l][q]+Jeep_D[p][j]*VKT
        _J_D[l][q]+Jeep_G[p][j]*VKT_J_G[l][q]+Jeep_C[p][j]*VKT_J_C[l][q]+Micro_D[p][j]*VK
        T_Mi_D[l][q]+Micro_G[p][j]*VKT_Mi_G[l][q]+Micro_C[p][j]*VKT_Mi_C[l][q]+Tx_C[p][
        j]*VKT_Tx_CNG[l][q]+Bus_D[p][j]*VKT_B_D[l][q]+Bus_C[p][j]*VKT_B_C[l][q]+MB_D[
        p][j]*VKT_MB_D[l][q]+MB_C[p][j]*VKT_MB_C[l][q]+Truck_D[p][j]*VKT_T_D[l][q]+Tr
        uck_C[p][j]*VKT_T_C[l][q]+AR_C[p][j]*VKT_AR_C[l][q]+MC_G[p][j]*VKT_MC_G[l][q]+
        Others_D[p][j]*VKT_O_D[l][q]+Others_G[p][j]*VKT_O_G[l][q]+Others_C[p][j]*VKT_O
        _C[l][q])*365)/(pow(10,6)));
        }
    }
}
```

//Conversion Factors for Modified (SRM) Grids

```
doublemvalue[200][4]={0.000,0.000,0.000,0.000,0.454,0.009,0.527,0.010,0.364,0.007,0.618,0.012,0.273,0.005,0.709,0.013
,0.182,0.003,0.800,0.015,0.091,0.002,0.891,0.017,0.891,0.017,0.091,0.002,0.800,0.015,0.182,0.003,0.709,0.013,0.273,0.00
5,0.618,0.012,0.364,0.007,0.527,0.010,0.454,0.009,0.436,0.008,0.545,0.010,0.345,0.007,0.636,0.012,0.254,0.005,0.727,0.0
14,0.164,0.003,0.818,0.015,0.073,0.001,0.909,0.017,0.872,0.016,0.109,0.002,0.782,0.015,0.200,0.004,0.691,0.013,0.291,0.
005,0.600,0.011,0.382,0.007,0.000,0.000,0.000,0.000,0.446,0.017,0.517,0.020,0.357,0.014,0.606,0.023,0.267,0.010,0.695,
0.027,0.178,0.007,0.785,0.030,0.089,0.003,0.874,0.034,0.874,0.034,0.089,0.003,0.785,0.030,0.178,0.007,0.695,0.027,0.26
7,0.010,0.606,0.023,0.357,0.014,0.517,0.020,0.446,0.017,0.428,0.016,0.535,0.021,0.339,0.013,0.624,0.024,0.250,0.010,0.7
13,0.027,0.160,0.006,0.802,0.031,0.071,0.003,0.892,0.034,0.856,0.033,0.107,0.004,0.767,0.029,0.196,0.008,0.678,0.026,0.
285,0.011,0.588,0.023,0.374,0.014,0.000,0.000,0.000,0.000,0.437,0.026,0.507,0.030,0.350,0.021,0.595,0.035,0.262,0.015,
0.682,0.040,0.175,0.010,0.770,0.045,0.087,0.005,0.857,0.050,0.857,0.050,0.087,0.005,0.770,0.045,0.175,0.010,0.682,0.04
0,0.262,0.015,0.595,0.035,0.350,0.021,0.507,0.030,0.437,0.026,0.420,0.025,0.525,0.031,0.332,0.020,0.612,0.036,0.245,0.0
14,0.700,0.041,0.157,0.009,0.787,0.046,0.070,0.004,0.874,0.051,0.840,0.049,0.105,0.006,0.752,0.044,0.192,0.011,0.665,0.
039,0.280,0.016,0.577,0.034,0.367,0.022,0.000,0.000,0.000,0.000,0.429,0.034,0.497,0.040,0.343,0.027,0.583,0.047,0.257,
0.021,0.669,0.053,0.171,0.014,0.754,0.060,0.086,0.007,0.840,0.067,0.840,0.067,0.086,0.007,0.754,0.060,0.171,0.014,0.66
9,0.053,0.257,0.021,0.669,0.053,0.257,0.021,0.497,0.040,0.429,0.034,0.412,0.033,0.514,0.041,0.326,0.026,0.600,0.048,0.2
40,0.019,0.686,0.055,0.154,0.012,0.772,0.062,0.069,0.005,0.857,0.069,0.823,0.066,0.103,0.008,0.737,0.059,0.189,0.015,0.
652,0.052,0.274,0.022,0.566,0.045,0.360,0.029,0.000,0.000,0.000,0.000,0.420,0.043,0.487,0.050,0.336,0.034,0.571,0.058,
0.252,0.026,0.655,0.067,0.168,0.017,0.739,0.075,0.084,0.009,0.823,0.084,0.823,0.084,0.084,0.009,0.739,0.075,0.168,0.01
7,0.655,0.067,0.252,0.026,0.571,0.058,0.336,0.034,0.487,0.050,0.420,0.043,0.403,0.041,0.504,0.051,0.319,0.033,0.588,0.0
60,0.235,0.024,0.672,0.069,0.151,0.015,0.756,0.077,0.067,0.007,0.840,0.086,0.807,0.082,0.101,0.010,0.723,0.074,0.185,0.
019,0.639,0.065,0.269,0.027,0.555,0.057,0.353,0.036,0.000,0.000,0.000,0.000,0.412,0.051,0.477,0.060,0.329,0.041,0.560,
0.070,0.247,0.031,0.642,0.080,0.165,0.021,0.724,0.091,0.082,0.010,0.807,0.101,0.807,0.101,0.082,0.010,0.724,0.091,0.16
5,0.021,0.642,0.080,0.247,0.031,0.560,0.070,0.329,0.041,0.477,0.060,0.412,0.051,0.395,0.049,0.494,0.062,0.313,0.039,0.5
76,0.072,0.230,0.029,0.658,0.082,0.148,0.019,0.741,0.093,0.066,0.008,0.823,0.103,0.790,0.099,0.099,0.012,0.708,0.088,0.
181,0.023,0.626,0.078,0.263,0.033,0.543,0.068,0.346,0.043,0.000,0.000,0.000,0.000,0.403,0.060,0.467,0.070,0.322,0.048,
0.548,0.082,0.242,0.036,0.629,0.094,0.161,0.024,0.709,0.106,0.081,0.012,0.790,0.118,0.790,0.118,0.081,0.012,0.709,0.10
```

```
6,0.161,0.024,0.629,0.094,0.242,0.036,0.548,0.082,0.322,0.048,0.467,0.070,0.403,0.060,0.387,0.058,0.484,0.072,0.306,0.0
46,0.564,0.084,0.226,0.034,0.645,0.096,0.145,0.022,0.725,0.108,0.064,0.010,0.806,0.120,0.774,0.115,0.097,0.014,0.693,0.
103,0.177,0.026,0.612,0.091,0.258,0.038,0.532,0.079,0.338,0.050,0.000,0.000,0.000,0.000,0.394,0.069,0.457,0.080,0.316,
0.055,0.536,0.093,0.237,0.041,0.615,0.107,0.158,0.027,0.694,0.121,0.079,0.014,0.773,0.134,0.773,0.134,0.079,0.014,0.69
4,0.121,0.158,0.027,0.615,0.107,0.237,0.041,0.536,0.093,0.316,0.055,0.457,0.080,0.394,0.069,0.379,0.066,0.473,0.082,0.3
00,0.052,0.552,0.096,0.221,0.038,0.631,0.110,0.142,0.025,0.710,0.123,0.063,0.011,0.789,0.137,0.757,0.132,0.095,0.016,0.
678,0.118,0.174,0.030,0.599,0.104,0.252,0.044,0.521,0.091,0.331,0.058,0.000,0.000,0.000,0.000,0.386,0.077,0.448,0.090,
0.309,0.062,0.525,0.105,0.231,0.046,0.602,0.120,0.154,0.031,0.679,0.136,0.077,0.015,0.756,0.151,0.756,0.151,0.077,0.01
5,0.679,0.136,0.154,0.031,0.602,0.120,0.231,0.046,0.525,0.105,0.309,0.062,0.448,0.090,0.386,0.077,0.370,0.074,0.463,0.0
93,0.293,0.059,0.540,0.108,0.216,0.043,0.617,0.123,0.139,0.028,0.694,0.139,0.062,0.012,0.772,0.154,0.741,0.148,0.093,0.
019,0.664,0.133,0.170,0.034,0.586,0.117,0.247,0.049,0.509,0.102,0.324,0.065,0.000,0.000,0.000,0.000,0.377,0.086,0.438,
0.099,0.302,0.069,0.513,0.117,0.226,0.051,0.588,0.134,0.151,0.034,0.664,0.151,0.075,0.017,0.739,0.168,0.739,0.168,0.07
5,0.017,0.664,0.151,0.151,0.034,0.588,0.134,0.226,0.051,0.513,0.117,0.302,0.069,0.438,0.099,0.377,0.086,0.362,0.082,0.4
53,0.103,0.287,0.065,0.528,0.120,0.211,0.048,0.604,0.137,0.136,0.031,0.679,0.154,0.060,0.014,0.754,0.171,0.724,0.165,0.
091,0.021,0.649,0.147,0.166,0.038,0.573,0.130,0.241,0.055,0.498,0.113,0.317,0.072};

//Emissions for Base Case (Tons/year)

for (i=0; i<row; i++)
{
        for (m=0,n=1; m<mod_col,n<11; m+=20,n++)
        {
                for (l=m,j=n,k=0; l<(m+20); l++)
                {
                        if (l==(m+1))
                        {
                        k=2;
                        modb_em[i][l]=(mvalue[l][k]*b_em[i][j]+mvalue[l][k+1]*b_em[i][j+1]);
                        k=0;
                        }
                        else
                        {
                        if (l>=(m+3) && !(l==(m+6) || l==(m+16)))
                        {
                        j+=12;
                        }
                        if (l>=(m+3) && (l==(m+6) || l==(m+16)))
                        {
                        j+=24;
                        }

        modb_em[i][l]=(mvalue[l][k]*b_em[i][j]+mvalue[l][k+1]*b_em[i][j+1]+mvalue[l][k+2]
        *b_em[i][j+12]+mvalue[l][k+3]*b_em[i][j+13]);
                }
        }
}
//Conversion to Modified Grids: Emissions for Current Case (Tons/year)

for (i=0; i<row; i++)
        {
        for (m=0,n=1; m<mod_col,n<11; m+=20,n++)
                {
                for (l=m,j=n,k=0; l<(m+20); l++)
```

```
        {
        if (l==(m+1))
        {
        k=2;
        modem[i][l]=mvalue[l][k]*em[i][j]+mvalue[l][k+1]*em[i][j+1];
        k=0;
        }
        if (l>=(m+3) && !(l==(m+6) || l==(m+16)))
        {
        j+=12;
        }
        if (l>=(m+3) && (l==(m+6) || l==(m+16)))
        {
        j+=24;
        }
modem[i][l]=(mvalue[l][k]*em[i][j]+mvalue[l][k+1]*em[i][j+1]+mvalue[l][k+2]*em[i][j+12]+m
value[l][k+3]*em[i][j+13]);
        }
    }
}
```

//Calculation of PM$_{2.5}$ Concentration (Base year-micro gm/cubic meter)

```
double c=0;
for (i=0; i<row; i++)
{
    for (k=0; k<mod_col; k++)//k<mod_col
    {
        for (m=0,n=0; m<20,n<200; m++,n+=10)//m=20,n<200
        {
            for (j=m,l=n; (j<(m+181)) && (l<(n+10)); j+=20,l++)//j<m+181, l<n+10
            {
            c+=((modb_em[i][j]*pmf_area[l][k])/3000);
            }
        }
        b_conc[i][k]=c;
        c=0;
    }
}
```

//Calculation of PM$_{2.5}$ Concentration (Current Case-micro gm/cubic meter)

```
double d=0;
for (i=0; i<row; i++)
{
    for (k=0; k<mod_col; k++)
    {
        for (m=0,n=0; m<20,n<200; m++,n+=10)
        {
            for (j=m,l=n; j<(m+181) && l<(n+10); j+=20,l++)
            {
```

```
                                                d+=((modem[i][j]*pmf_area[l][k])/3000);
                                        }
                                }
                                conc[i][k]=d;
                                d=0;
                        }
                }
```

//Declaration & Initialization of Constant k corresponding to Cardiovascular and Respiratory

```
double k_cnom=0.00889, k_rnom=0.01266;
```

// Computation of Change in Concentration of $PM_{2.5}$ (y), Relative Risks and Total No. of Deaths Avoided

```
for (i=0; i<5000; i++)
{
        for (j=0; j<200; j++)
        {
                y[i][j]=b_conc[i][j]-conc[i][j];
                RR_cnom[i][j]=exp(k_cnom*y[i][j]);
                RR_rnom[i][j]=exp(k_rnom*y[i][j]);
        }
}
for (i=0; i<row; i++)
{
        for (j=0; j<mod_col; j++)
        {
//for DCC
dA_nom[i][j] = ((RR_cnom[i][j]*((RR_cnom[i][j])-1)*5.36/1000+RR_rnom[i][j]*((RR_rnom[i][j])-
1)*3.4/1000)*(pop_dcc[j]));

//for GD
dA_nom[i][j]=((RR_cnom[i][j]*((RR_cnom[i][j])-1)*5.36/1000+RR_rnom[i][j]*((RR_rnom[i][j])-
1)*3.4/1000)*(pop_GD[j]));        }
}
```

// Removing the Memory Spaces Allocated Dynamically

```
for(i=0; i<row; ++i)
{
free(b_em[i]);
free(em[i]);
free(modb_em[i]);
free(modem[i]);
free(b_conc[i]);
free(conc[i]);
free(y[i]);
free(RR_cnom[i]);
free(RR_rnom[i]);
free(dA_nom[i]);
```

```
}

for(i=0; i<trans_row; ++i)
{
free(pmf_area[i]);
}

free(b_em);
free(em);
free(modb_em);
free(modem);
free(b_conc);
free(conc);
free(y);
free(pmf_area);
free(RR_cnom);
free(RR_rnom);
free(dA_nom);

}
```