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Uncertainty quantification of CO_2 emission reduction for maritime shipping

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HIGHLIGHTS

- We propose a systematic method to quantify uncertainty in emission reduction.
- Marginal abatement cost curves are improved to better reflect the uncertainties.
- Percentage reduction probability is given to determine emission reduction target.
- The methodology is applied to a case study on maritime shipping.

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ABSTRACT

The International Maritime Organization (IMO) has recently proposed several operational and technical measures to improve shipping efficiency and reduce the greenhouse gases (GHG) emissions. The abatement potentials estimated for these measures have been further used by many organizations to project future GHG emission reductions and plot Marginal Abatement Cost Curves (MACC). However, the abatement potentials estimated for many of these measures can be highly uncertain as many of these measures are new, with limited sea trial information. Furthermore, the abatements obtained are highly dependent on ocean conditions, trading routes and sailing patterns. When the estimated abatement potentials are used for projections, these 'input' uncertainties are often not clearly displayed or accounted for, which can lead to overly optimistic or pessimistic outlooks. In this paper, we propose a methodology to systematically quantify and account for these input uncertainties on the overall abatement potential forecasts. We further propose improvements to MACCs to better reflect the uncertainties in marginal abatement costs and total emissions. This approach provides a fuller and more accurate picture of abatement forecasts and potential reductions achievable, and will be useful to policy makers and decision makers in the shipping industry to better assess the cost effective measures for CO_2 emission reduction.

1. Introduction

With the rapid growth in international trade in recent decades, the shipping industry has grown dramatically, and this has led to significant increases in CO_2 emission from shipping each year. With the increasingly concern about the climate change and global warming, considerable attention has been given in recent years to improving the shipping efficiency in order to reduce the total greenhouse gas (GHG) (e.g. CO_2) emission.

In view of the current environmental concerns, many organizations have proposed and implemented various measures to reduce CO_2 emissions from shipping. For example, the European Commission has implemented a speed limit regulation for all ships entering European Union ports (Cariou, 2011; Cariou and Cheaitou, 2012). Slow steaming is also suggested by International Maritime Organization (IMO) since the bunker fuel consumption is positively related to the ship speed. Wartsila (2009) has proposed a comprehensive host of measures including lightweight construction and optimum main hull dimensions, and Psaraftis (2012) reviewed different types of reduction measures for GHG emissions from ships. However, not all of these measures can be retrofitted and some measures only apply to the new builds. More recently, the IMO MEPC 62 report (IMarEST, 2011) identified 50 possible operational and technical measures and conducted a comprehensive study on 22 measures.

However, some measures may not be economically feasible.

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Policy makers are then confronted with the challenge of searching for suitable and cost-effective ways to reduce carbon emission. For this purpose, marginal abatement cost curves (MACCs) have been widely used to illustrate the economic feasibility of the emission reduction measures (see e.g. Eide et al., 2009; Miola et al., 2011). MACCs represent the relationship between the cost-effectiveness (CE) of various abatement options and the amount of emission reduced. As MACCs examine the complex cost-effective emission reduction measures in a simplified manner, they have recently become a standard policy tool to prioritize mitigation options (Kesicki and Strachan, 2011). With MACCs to represent the economic feasibility of the measures to reduce emissions, all the measures can be ranked according to their CE. Then the total emission reduction can be evaluated for the selected economically feasible measures. Although MACCs are commonly applied for policy making, they have some limitations.

One significant shortcoming of MACCs is the lack of uncertainty assessment (Kuik et al., 2009; Kesicki and Ekins, 2012). One important type of uncertainty in relation to MACCs is the data uncertainty (Kesicki, 2012). Data uncertainty generally refers to uncertainties associated with input data, such as abatement potential and implementation cost related to various measures, fuel price projection, discount rate estimation, etc. As the marginal abatement cost (MAC) analysis relies on numerous highly uncertain input assumptions, MACCs and further evaluation of the total emission reduction are also inevitably highly uncertain. Therefore, to enable the better understanding and more confident use of the MACCs and emission evaluation, it is important to place emphasis on the uncertainty quantification related to the input assumptions, so that policy makers are more aware of them and account for them in their decisions.

The quantification of the emission estimation uncertainty has been previously studied. The National Research Council (NRC) of the United States has recommended the quantification of the emission estimation uncertainty including NRC (1991) report, the NRC (1994) report and the NRC (2000) report. The NARSTO emission inventory assessment has provided an extensive literature of the quantitative methods to uncertainty and sensitivity analysis of emissions (NARSTO, 2005). The Environmental Protection Agency (EPA) Office of the Inspector General has developed the methods of how to quantify the emission estimation uncertainty (EPA, 2006). The Intergovernmental Panel on Climate Change (IPCC) has proposed guidance on the uncertainty quantification of the national GHG emissions, including the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC, 2000) and IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Among these uncertainty quantification methods, there are some non-probabilistic methods such as interval analysis and fuzzy numbers. Interval analysis can be used to set bounds on the assessment. However, it becomes uninformative when the bounds are very wide. Fuzzy numbers has been applied in many areas. However, fuzzy numbers represent vagueness rather than uncertainty. Instead of the non-probabilistic methods, probability seems to be a natural way to describe the uncertainty. As stated in IPCC (2006), the quantitative methods typically specify the probability distributions of the input factors to the emission estimation, and then propagate the input uncertainty to the overall emission estimation uncertainty. This uncertainty “propagation” can be done analytically for a simple model form with specific assumptions of the input distributions (e.g. Johnson et al., 2009). However, in many practical applications, the uncertainty propagation cannot be done analytically due to the complexity of the model and the probability distribution of the input factors. In this situation, more widely applicable numerical methods such as Monte Carlo (MC) methods (e.g. Zhao et al., 2012) and bootstrap simulation methods (e.g. Tong et al., 2012) can be applied.

Despite a voluminous literature on the uncertainty quantification for emission estimation, little attention has been paid to quantifying the uncertainty of MACCs and its subsequent use to prioritize mitigation options and to estimate target emission reductions. To quantify the uncertainty of MACCs and emission reduction, a simple way provided by the IMO MEPC 62 report (IMarEST, 2011) is to compute cost-effectiveness and emission reduction for “optimistic” and “pessimistic” cases, where in optimistic case the maximum emission reduction is obtained and in pessimistic case the minimum emission reduction is obtained with different settings of all input assumptions. Eide et al. (2011) also discussed the similar uncertainty quantification approach to estimate the CO_2 emissions reduction based on some specified scenarios of the input parameters. However, this approach only provides limited scenarios for the MACCs and, assumes equal likelihood of the extreme cases and throughout the entire region, resulting in a wide range for the estimation of total emission reduction. It only snapshots a broad picture of the worst and best case scenarios without giving any implication where the likely-happened scenario will occur. Thus, it leaves a big challenge to policy makers in deciding which level of emission abatement can be achieved. Besides, this method also does not provide any precise insights into the uncertainty assessment. In this paper, we provide a systematic way to quantify the MACCs uncertainty and the total emission reduction estimation uncertainty from a set of mitigation measures, where the maritime industry is analyzed as a case study. The proposed approach takes into account the input uncertainties and the resulting measures selection uncertainty. We further compare the different uncertainty quantification methods to illustrate the accuracy and efficiency of the proposed method. In addition, we also propose improvements to the typical MACCs which better reflect the uncertainties in MACCs and the emission reduction for decision making.

The rest of the paper is organized as follows: the cost effectiveness and the emission reduction formulation are given in Section 2. Section 3 provides a general uncertainty quantification method for the total emission reduction. A case study is given in Section 4 to illustrate the proposed method. Section 5 describes the improvements to the MACC plot. Major findings and conclusions are provided in Section 6.

2. Emission reduction model

Marginal Abatement Cost (MAC) analysis has been widely applied in various economic sectors as a realization tool for economic appraisal of different GHG emission reduction measures (Bockel et al., 2012; CCS, 2012; Holland et al., 2011; IMarEST, 2011). The MAC of a measure depicts the cost of eliminating an additional unit of emissions, and can be interpreted as the cost-effectiveness (CE) of that measure since it indicates potential amount of emission reduction with its associated cost. Similar to IMO MEPC 62 report (IMarEST, 2011), CE is used to represent MAC here. To estimate the total emission reduction, there are three general steps. In the first step, CEs are computed. In the second step, the measures are ranked from the most cost-effective measures (lowest cost per metric tonne of CO_2 equivalent emissions abated) to the least cost-effective measures (highest cost-effectiveness value). Here all the measures are ranked according to the CE values However, noted that it may be inappropriate to rank negative CE measures based on CE values as the ranking for negative CE measures can be misleading, alternative ranking approaches for negative CE measures suggested by Taylor (2012) and Ward (2014) can be applied. In this paper, as we focus on the uncertainty quantification of the emission reduction, and not the ranking procedure, the ranking based on CE values is adopted as an example to illustrate the proposed uncertainty quantification