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EXTEDNED ABSTRACT
Title: A TAXONOMY OF CARBON EMISSION REDUCTION MEASURES IN WATERBORNE FREIGHT TRANSPORTATION

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INTRODUCTION

A wide range of measures has been proposed to improve vessel efficiency, reduce fuel consumption and lower emissions (1, 2). The classification of such measures is the subject of several publications. The Second GHG Study (3) of the International Maritime Organisation (IMO) is the most influential among them and identifies three fundamental categories of carbon emission reduction options: (i) energy efficiency improvements, which are further, sub-divided into the areas of ship design and operations; (ii) renewable energy sources; and (iii) fuels with lower lifecycle emissions per unit of work. Variations of this scheme have been proposed by Balland et al. (4) and Calleya, Pawling, and Greig (5).

Classification schemes like the ones mentioned above are simple and practical but lack rigid theoretical foundations. On the other hand, schemes that attempt to capture the multiplicity of interrelations among all factors affecting emission volumes are often of low practical value due to their high level of complexity. IMO (3) provides such an example. Although it clearly acknowledges that, by definition, the CO_2 emissions for most ships depend on the operational efficiency of the fleet and the transport work performed, when it comes to identifying the principal factors affecting the volume of emissions, the study presents a rather complex model including external and internal parameters that influence transport demand, modal split and fleet operations among others. McKinnon's analytical framework for green logistics falls into this category, too (6).

The objective of this paper is to address these weaknesses. More specifically, it aims to develop a simple and practical framework for classifying emission reduction measures in the shipping industry, which, however, is sufficiently supported by theory. Such a framework would put available options into a better perspective and serve as guidance in assessing their effectiveness and compatibility. The paper does not intend to provide an exhaustive list of potential carbon emission reduction measures in waterborne transport. Instead, it refers to the most important practices and policies in the field in order to demonstrate the applicability of the proposed taxonomy.

METHODOLOGY

Among the three types of sustainability frameworks suggested by Jeon and Amekudzi (7) - impacts-based, linkages-based, and influence-oriented - the linkages-based ones have been selected for the purpose of this paper due to their ability to capture relationships between the causal factors, impacts and the corrective actions that have been selected to achieve sustainability. The decomposition of CO_2 emissions into a number of influences is a special type of such frameworks. The first decomposition of this sort, known as the Kaya identity, was published by the UN in 1997 (8). Since then, decomposition has been used widely as a method for analyzing CO_2 emissions but has not been applied explicitly in classifying shipping-related emission reduction measures.

The extended Kaya identity used in this paper is:

$$CO2e = \sum_{vessel} \sum_{fuel} \frac{CO2e}{MJ} \times \frac{MJ}{vkm} \times \frac{vkm}{tkm} \times tonnes \times km \qquad (1)$$

where:
CO2e   = total GHG emissions produced by waterborne transport (gCO$_2$e)

CO2e/MJ   = carbon intensity of the fuel mix used (gCO$_2$e/MJ)

MJ/vkm   = energy efficiency of the vessels employed (MJ/vkm)

vkm/tkm   = vessel traffic required to handle a given amount of freight movement

tonnes   = freight tonnes lifted by seagoing and inland waterway vessels, and

km   = average length of haul resulting from dividing tkm by tonnes.

If the payload capacity C of a ship (in tonnes) and its capacity utilization rate (CUR), defined as the metric comparing actual to potential output, are introduced into Eq. (1), the framework for the classification of carbon emission reduction measures takes its final form:

$$CO2e = \sum_{vessel} \sum_{fuel} \frac{CO2e}{MJ} \times \frac{MJ}{vkm} \times \frac{1}{C} \times \frac{1}{CUR} \times tonnes \times km \qquad (2)$$

FINDINGS

The carbon intensity factor (CO2e/MJ) of Eq. (2) reflects the fuel mix used. Liquefied natural gas offers a cost-efficient alternative to the heavy fuel and marine diesel/gas oils used for all waterborne activities. Second-generation liquid biofuels, liquefied petroleum gas and hydrogen have also been proposed (9). Cold ironing, the shore-side electricity used by ships berthed at ports, is another measure gaining popularity (10).

The energy efficiency factor (MJ/vkm) includes both technological and operational measures. Numerous energy efficiency enhancement technologies exist in relation to ship design, construction materials, main/auxiliary machinery, and other energy-saving devices (2). Slow steaming, the sailing at lower than the design speed on the legs of the voyage that the schedule allows, is a common operational practice. Weather routing, trim/draft optimization and condition management of the ship's hull and propeller are other practices of this type. The IMO's Energy Efficiency Management Plan is a mechanism fostering improvements in this regard.

The inverse relationship of Eq. (2) between the payload capacity (C) of a ship and the emissions produced highlight the positive effect that the employment of larger capacity vessels can have on emissions through economies of scale, which also affect costs in the same direction. Vessel utilization (CUR) acts in the same way. Cabotage rules that restrict domestic maritime trade to national fleets and various administrative restrictions that apply in inland navigation to protect local, national and regional interests have a negative impact on emissions. Collaborative business strategies like mergers and alliances improve ship utilization. Shippers can also achieve environmental (in addition to financial) gains by selecting the appropriate packaging solutions, by employing more space-efficient handling equipment and, where applicable, by optimizing the cargo mix (heavy and light cargoes) for exploiting both the weight and volume capacity of a container/vehicle.

Transport demand management is the subject of the last two factors of Eq. (2). McKinnon (11) identifies four developments that may 'dematerialize' international trade in the short term: miniaturization, digitization, 3D printing and postponement, the act of adding value as late as possible in a production process. In addition, many argue that the recent trend of technologically driven disintermediation is causing a global shift away from the economic value of

manufacturing to the value of human capital (12), thus reversing the lengthening of the average distances observed during the last decades.

In addition to measures targeting a single factor of the right-hand side of Eq. (2), a variety of measures exists that target a combination of these factors. The operational research (OR) applications that aim at minimizing the distance sailed (in vkm), which is the product of the last four factors of Eq. (2), is a family of such measures (13). Market-based measures in the form of a tax/levy on fossil fuel, a tax rebate/subsidy on renewable energy sources or a 'cap and trade' scheme on CO_2 emissions is another family of measures (14).

All measures mentioned above target CO_2 emission reductions within shipping. This excludes gains associated with shifting freight from a mode of high carbon intensity like air and road to a low-carbon mode like rail and shipping. Given the significant differences in carbon intensities, as they have been documented in IMO (3), such gains can be substantial. Eq. (2) can capture the effects of modal shifts if the formulation is expanded by adding a summation operator over all transport modes.

CONCLUSIONS

The paper briefly reviews the main types of frameworks employed in assessing transport sustainability and selects an extended Kaya identity for the classification of CO_2 emission reduction measures. The carbon intensity of the fuels used, the energy efficiency of the vessels employed, the vessel capacity and utilization rate, as well as the transport activity expressed by cargo volumes and average haul lengths are identified as the most important factors affecting emissions.

A wide range of CO_2 reducing practices and policies, albeit by no means exhaustive, are examined and classified on the basis of these factors. The main contribution of this classification framework is that it provides a wider perspective on possible measures and their effectiveness. Many studies in the literature have concluded that pursuing single policies or initiatives is not sufficient for reaching the ambitious goals set by the international society with regard to climate change, as they tend to have a rather modest effect on CO_2 reduction (1, 15). Instead, the objective of sustainable mobility requires the employment of packages of complementary instruments.

The classification framework can also help in assessing the compatibility and side effects of the various carbon reduction measures proposed. As is the case with any political initiative, sufficient care should be given to the 'push-down/pop-up principle'. Undesirable results of the substitution and income effects of political interventions are not uncommon in the transport field.

An additional use of the classification framework relates to the sometimes heated discussion on economy versus environment. All measures addressing the five last factors in the right-hand side of Eq. (2) result in lower fuel consumption and, thus, savings in terms of both costs and emissions. In the search for win-win solutions, therefore, we should not overlook the environmental benefits derived indirectly by many profit-maximizing measures.

A final comment relates to the scope of this paper, which is restricted to waterborne transport. It should be kept in mind that shipping is only one of the transport modes involved in freight logistics. Sustainable ships need to be served by sustainable ports, and together they have to interact with sustainable trains and trucks through sustainable intermodal terminals. Even the sustainability of the entire supply chain might prove misleading in cases of great differentiations in the sustainability of the production processes. A life-cycle assessment methodology is suggested for such occurrences.

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