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Paradox of international maritime organization's carbon intensity indicator

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\textbf{ABSTRACT}

The 76th session of the Marine Environment Committee (MEPC 76) of the International Maritime Organization adopted several mandatory measures in June 2021 to reduce carbon emissions from ships. One of the measures is the carbon intensity indicator (CII), which is the carbon emissions per unit transport work for each ship. Several options of CII\textsubscript{supply} are available and none of them is chosen to be applied yet. We prove that, at least in theory, requiring the attained annual CII of a ship to be less than a reference value, no matter which CII option is applied, may increase its carbon emissions. Therefore, more elaborate models, combined with real data, should be developed to analyze the effectiveness of each CII option and possibly to design a new CII.

\section{Introduction}

Maritime decarbonization has become a priority area for policymakers. The International Maritime Organization (IMO), which is the United Nations body for international shipping, adopted an initial strategy on the reduction of greenhouse gas emissions from ships in 2018 (IMO, 2018). The Initial IMO Strategy sets up to reduce carbon dioxide (CO\textsubscript{2}) emissions per transport work by at least 40\% by 2030 compared to 2008, and to reduce the total annual greenhouse gas (GHG) emissions from international shipping by at least 50\% by 2050 compared to 2008. The 76th session of the Marine Environment Committee (MEPC 76) of the IMO adopted several mandatory measures in June 2021 to reduce carbon emissions from ships, which will contribute to achieving the carbon emission targets set by the Initial IMO Strategy (IMO, 2021a). One of the measures is the carbon intensity indicator (CII), which measures the carbon emissions per unit transport work for each particular ship. Comparing the CII value of a ship over a year with the reference CII\textsubscript{supply} values determined by the IMO, the performance of the ship will be rated as ‘A’ (major superior), ‘B’ (minor superior), ‘C’ (moderate), ‘D’ (minor inferior), or ‘E’ (inferior). A rating of ‘A’, ‘B’, or ‘C’ is required for compliance, and corrective actions should be taken for ships receiving ‘D’ for three consecutive years or ‘E’ for one year. Ship owners should thus try to achieve a rating of ‘C’ or above for their ships. The reference CII\textsubscript{supply} values will decrease with time. MEPC 76 decided for each ship to achieve an annual reduction of 1\% until 2023 and 2\% from 2023 to 2026, leaving open the required reductions until 2030. Note that 2030 is the year of the intermediate target, which stipulates a reduction of CII of at least 40\% in 2030 versus the 2008 level.

\begin{equation}
\frac{\text{Annual carbon emissions of the ship (g)}}{\text{The ship's deadweight tonnage times the sailing distance in the year}} = \text{Supply based CII: CII\textsubscript{supply}}
\end{equation}
According to the Fourth IMO GHG Study carried out by the IMO (2020), there are at least four potential versions of CII, defined as follows:

\[
\text{Demand} = \text{based CII: } \frac{\text{Annual carbon emissions of the ship (g)}}{\text{Actual tonne – miles carried by the ship in the year}}
\]

(2)

\[
\text{Distance} = \text{based CII: } \frac{\text{Annual carbon emissions of the ship (kg)}}{\text{Actual sailing distance of the ship in the year}}
\]

(3)

\[
\text{Sailing time} = \text{based CII: } \frac{\text{Annual carbon emissions of the ship (tonne)}}{\text{Actual sailing time of the ship in the year}}
\]

(4)

The units of the four versions of CII are: g/dwt/nm² for supply-based CII, g/tonne/nm for demand-based CII, kg/nm for distance-based CII, tonne/h for sailing time-based CII (IMO, 2020). The IMO/MEPC 76 has not yet agreed on which version to use, but all are on the table (IMO, 2021b). Despite the intention of CII to reduce carbon emissions, the Baltic and International Maritime Council (BIMCO) has warned that the carbon emissions may increase due to the application of CII (Osler, 2021). In this paper, we prove that paradoxes can occur no matter which CII is used, that is, adopting the CII measure will increase carbon emissions in some situations. Combined use of different CII may also increase carbon emissions in some situations.

2 The dwt is the acronym for deadweight tonnage; nm is the acronym for nautical mile (1 nautical mile = 1.852 km).

2 The dwt is the acronym for deadweight tonnage; nm is the acronym for nautical mile (1 nautical mile = 1.852 km).

However, some new ships attracted by the program will cause extra emissions.

In land transportation, the most well-known paradox is the Braess Paradox, which offers an example in which constructing a new road makes every private driver experience a longer travel time (Braess, 1968). In a two-mode transport system consisting of public transit services and a highway for private drivers, Downs (1962) and Thomson (1977) showed that the expansion of the highway may decrease the travel utility of all the travelers (both public transit users and private drivers). The rationale of the Downs–Thomson Paradox is that the expanded highway will attract some public transit users to become private drivers; then the transit authority may reduce the public transit service frequency in view of the reduced number of public transit service users. The reduction in frequency will shift more public transit service users to the highway, leading to a vicious circle. In the end, travelers of both modes may suffer from the highway expansion. To date, such paradox is still an important factor considered in optimization problems in land transportation (Schadschneider and Bittrih, 2020; Bittrih and Schadschneider, 2021; Huang and Chen et al., 2021).

Our research complements the existing literature of paradoxes in transportation management and sheds insights into shipping emission management.

3. Paradox of existing possible CII

3.1. Paradox of the supply-based CII

We use an example to show the paradox of the supply-based CII.

Example 1 (A ship sails empty to comply with the supply-based CII measure): A ship owner has a bulk cargo ship with a deadweight tonnage of \( Q = 80 \) 000 tonnes; we assume that the weights of fuel, ballast water, provisions, and crew make up a small proportion of \( Q \) and can thus be ignored. For simplicity, in our example we assume that the ship sails at a fixed speed \( v = 13 \) knots. The fuel consumption rate of the ship, denoted by \( f(w) \) (tonne/nm), is a monotonically increasing function of the cargo payload \( w \) (tonne). For this ship \( f(Q) = 0.1095 \) tonne/nm, \( f(0) = 0.8f(Q) \) tonne/nm. We also assume that the fuel cost is the dominant component of the total operational costs for the ship owner. The fuel used is heavy fuel oil (HFO) and burning one tonne of HFO will generate \( \alpha = 3.114 \) tonnes of carbon dioxide (CO₂). The ship owner has to transport cargo to payload equal to \( Q \) tonnes over a distance of \( L = 2.766 \) nm, between Jakarta, Indonesia, and Qingdao, China, each year. The ship completes \( N = 20 \) voyages each year. No ballast voyages will be involved.

In 2023, the total amount of carbon emissions will be \( 10^6Naf(Q)L \) (g) and the attained annual operational supply-based CII for the ship in the year will be \( \frac{10^6af(Q)}{L} = 4.26 \) g/tonne/nm. According to the tentative rule of the IMO, in 2023, a bulk carrier with a deadweight tonnage less than \( 279,000 \) tonnes will be rated as ‘C’ if its attained annual operational supply-based CII is between 3.78 and 4.26 g/tonne/nm (ClassNK, 2021). Therefore, the ship will receive a ‘C’ rating in 2023.

In 2024, to receive a ‘C’ rating, attained annual operational supply-based CII must be between 3.70 and 4.17 g/tonne/nm (ClassNK, 2021). Therefore, to achieve a rating of ‘C’, after transporting the cargo to the destination, the ship owner has to sail the empty ship over a distance of \( l_1 = 335.8 \) nm (maybe sail for \( l_1/2 \) away from the destination port and then return to it), and the actual supply-based CII for the ship will be \( \frac{10^6af(Q)L + l_1}{L} = 4.17 \), meeting the requirement of a ‘C’ rating. As a result, the amount of carbon emissions will increase by \( Naf(l_1) = 1.832 \) tonnes.

In Example 1, the ship sails empty to reduce the carbon intensity, which actually increases the carbon emissions. We can also design examples to show that in some situations two ships may be used to meet the supply-based CII requirement while one ship is enough to fulfill the transport work, and produce unnecessary carbon emissions.
3.2. Paradox of the demand-based CII

We use an example to show the paradox of the demand-based CII.

Example 2 (A ship sails full over a longer distance than necessary to comply with the demand-based CII measure): The basic setting is the same as that of Example 1, but the cargo trade is imbalanced and the ship has to sail back empty. It completes M = 10 laden voyages and M = 10 ballast voyages each year.

In 2023, the total amount of carbon emissions is \(10^6M(af(Q)L + af(0)L)\) (g). The attained annual operational demand-based CII for the ship will be \(10^6M(af(Q)L + af(0)L)\). Suppose that in 2023, the upper bound of the attained annual operational demand-based CII for a ‘C’ rating is equal to \(10^6M(af(Q)L + af(0)L)\), that is, the ship will receive a ‘C’ rating in 2023.

Suppose that in 2024, the upper bound of the attained annual operational demand-based CII for a ‘C’ rating is equal to 0.98 \(10^6M(af(Q)L + af(0)L)\). To achieve a rating of ‘C’, instead of transporting the cargo over a distance of \(L\), the ship owner has to intentionally detour \(^3\) for a distance of \(l_2 = \frac{Q f_1}{Q f_2}f_1 f_2\), and the actual demand-based CII for the ship will be \(10^6M(af(Q)L + af(0)L)\). Evidently, the amount of carbon emissions will increase by \(Naf(0)l_3 = M f_1 f_2 f_3 f_4 f_5 f_6 f_7 f_8 f_9 f_{10}\) (tonne).

In Example 2, instead of sailing empty back, the ship may try to secure some cargo when sailing back so that it does not have to detour on the laden leg, and the freight rate of the back-haul cargo can be truly negative if the extra fuel consumption for carrying the back-haul cargo is less than the extra fuel consumption during detour on the laden leg.

3.3. Paradox of the distance-based CII

We use an example to show the paradox of the distance-based CII.

Example 3 (A ship sails empty to comply with the demand-based CII measure): The basic setting is the same as that of Example 1.

In 2023, the total carbon emissions equal \(10^6Naf(Q)L(\text{kg})\), and the attained annual operational distance-based CII for the ship will be \(10^6Naf(Q)L\). Suppose that in 2023, the upper bound of the attained annual operational distance-based CII for a ‘C’ rating is equal to \(10^6Naf(Q)L\), that is, the ship will receive a ‘C’ rating in 2023.

Suppose that in 2024, the upper bound of the attained annual operational distance-based CII for a ‘C’ rating is equal to 0.98 \(10^6Naf(Q)L\). To achieve a rating of ‘C’, besides transporting the cargo over a distance of \(L\) in each voyage, the ship owner has to sail empty for a distance of \(l_2 = \frac{Q f_1}{Q f_2}f_1 f_2\). Then the actual distance-based CII for the ship will be \(10^6Naf(Q)L + Naf(0)l_3 = M f_1 f_2 f_3 f_4 f_5 f_6 f_7 f_8 f_9 f_{10}\) (tonne).

In Example 3, the ship sails empty for an extra distance to reduce the carbon intensity, which actually increases the carbon emissions.

3.4. Paradox of the sailing time-based CII

We use an example to show the paradox of the sailing time-based CII.

Example 4 (A ship sails empty to comply with the demand-based CII measure): The basic setting is the same as that of Example 1.

In 2023, the total carbon emissions equal \(10^6Naf(Q)L(\text{kg})\), and the attained annual operational distance-based CII for the ship will be \(10^6Naf(Q)L\). Suppose that in 2023, the upper bound of the attained annual operational demand-based CII for a ‘C’ rating is equal to \(10^6Naf(Q)L\), that is, the ship will receive a ‘C’ rating in 2023.

Suppose that in 2024, the upper bound of the attained annual operational sailing time-based CII for a ‘C’ rating is equal to 0.98 \(10^6Naf(Q)L\). To achieve a rating of ‘C’, besides transporting the cargo over a distance of \(L\) in each voyage, the ship owner has to sail empty for a distance of \(l_4 = \frac{Q f_1}{Q f_2}f_1 f_2\). Then the actual sailing time-based CII for the ship will be \(10^6Naf(Q)L\). Evidently, the amount of carbon emissions will increase by \(Naf(0)l_3 = M f_1 f_2 f_3 f_4 f_5 f_6 f_7 f_8 f_9 f_{10}\) (tonne).

In Example 4, the ship sails empty for an extra distance to reduce the carbon intensity, which actually increases the carbon emissions.

In this section, we have discussed the paradox of four existing CII, and the paradox of combinations of these CII will be displayed in Section 4.

4. Paradox of combined CII

4.1. Paradox of weighted sum of existing CII

A weighted sum of the aforementioned forms of CIIs can be used as a new form. We consider the case in which all the four CIIs have the same weight as an example, and the weighted sum is defined as follows:

\[
\text{Weighted sum CII} = \frac{\text{CII}_{\text{supply}} + \text{CII}_{\text{demand}} + \text{CII}_{\text{distance}} + \text{CII}_{\text{sailing time}}}{4}.
\]

We use an example to show the paradox of the weighted sum CII in Eq. (5).

Example 5 (A ship sails empty to comply with the weighted sum CII): The basic setting is the same as that of Example 1. In this section, due to the complexity of Eq. (5), we will prove that the ship can obtain a lower weighted sum CII by sailing empty, and the total carbon emissions will increase.

In 2023, the total carbon emissions equal \(Naf(Q)L(\text{tonne})\), and the attained annual operational weighted sum CII for the ship will be \(0.98 Naf(Q)L + 10^6Naf(Q)L\), which will be positive when \(Q f_1 f_2 f_3 f_4 f_5 f_6 f_7 f_8 f_9 f_{10}\). In that case, the upper bound for the attained annual operational weighted sum CII for a ‘C’ rating is equal to \(0.98 Naf(Q)L + 10^6Naf(Q)L\), that is, the ship will receive a ‘C’ rating in 2023.

Suppose that in 2024, the upper bound of the attained annual operational weighted sum CII for a ‘C’ rating is equal to \(0.98 Naf(Q)L + 10^6Naf(Q)L\), that is, the ship will receive a ‘C’ rating in 2023.

In the basic setting of Example 1, we assume that \(f(0) = 0.8f(Q)\), and therefore the right-hand side of Eq. (6) can be rewritten as \(0.2 \frac{Q f_1 f_2 f_3 f_4 f_5 f_6 f_7 f_8 f_9 f_{10}}{L} - 0.8\), which will be positive when \(l_5 < \frac{1}{2}(10^6 + 0.98 Naf(Q)L - 0.8)\). In that case, the upper bound for a ‘C’ rating in 2024 is lower than that in 2023.

In conclusion, in Example 5, the ship sails empty to meet the rating requirement, which actually increases the carbon emissions.
4.2. Paradox of meeting at least one existing CII

Another combined form of CII is to regulate that the ship should have the ‘C’ rating in at least one of the four existing CII. We use an example to show the paradox of this regulation on CII.

Example 6 (A ship sails empty or full over a longer distance than necessary to comply with this regulation on CII): The basic setting is the same as that of Example 1. Suppose that in 2023, the ship will obtain a rating of ‘C’ or above in at least one of the CIs. Then in 2024, due to the decline of the upper bounds of the attained annual operational CII, the ship will fail to obtain a rating of ‘C’ or above in any of the CIs. Considering the operating cost, the ship is likely to make operational amendments to obtain a ‘C’ rating in one of the CIs to abide by the regulation. If the ship operator decides to lower its annual operational supply-based CII, distance-based CII, or sailing speed-based CII by sailing empty for a longer distance than necessary, the total carbon emissions will increase according to Examples 1, 3, and 4. If the ship operator decides to lower its annual operational demand-based CII by sailing full for a longer distance than necessary, the total carbon emissions will increase according to Example 2.

In conclusion, in Example 6, the amendments adopted by the ship to reduce the carbon intensity will actually increase the total carbon emissions.

4.3. Paradox of meeting multiple existing CII simultaneously

On top of Example 6, consider a more strigent regulation that stipulates ships should obtain ‘C’ rating or above in at least 2 CII. We use an example to show the paradox of this regulation on CII.

Example 7 (A ship sails empty over a longer distance than necessary to comply with this regulation on CII): The basic setting is the same as that of Example 1. Suppose that in 2023, the ship will obtain a rating of ‘C’ or above in distance-based CII and sailing time-based CII, and ‘D’ or ‘E’ in the other CIs. Then in 2024, due to the decline of the upper bounds of the attained annual operational CII, the ship will fail to obtain a rating of ‘C’ or above in any of the CIs. Considering the operating cost, the ship is likely to make operational amendments to obtain a ‘C’ rating in two of the CIs to abide by the regulation. Suppose that the ship needs to sail empty for at least 1t, 1s, and 1t to obtain a ‘C’ rating in supply-based CII, distance-based CII, and sailing time-based CII, respectively. And we have 1t > 1s > 1t. Then the ship operator will choose to sail empty for 1t to obtain a ‘C’ rating in distance-based CII and sailing time-based CII. As a result, the total carbon emissions will increase according to Examples 3 and 4.

In conclusion, in Example 7, the amendments adopted by the ship to reduce the carbon intensity will actually increase the total carbon emissions.

5. Concluding remarks

The seven simple examples described above prove the paradox that, at least in theory, the CII requirement may increase carbon emissions of some ships in some situations. More elaborate models, combined with real data, can and should be developed to analyze, for each CII option, the proportion of ships whose carbon emission will increase, the average amount of increase for these ships, and the average amount of decrease for the other ships. The design of indicators to achieve utmost carbon emissions reduction, for example, a function of the four existing CII metrics, or requiring the average carbon intensity of ships owned by a company to comply with the CII rather than each individual ship, is also worth exploring.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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5 This option was proposed by Denmark to the IMO (Adamopoulos, 2021) but did not receive support at MEPC 76.
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