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A game theoretic approach on improving sulphur compliance

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ABSTRACT

The global sulphur cap is the final step in a series of regulations that aim to reduce SO_x emissions from shipping. It affects international shipping and requires all vessels to use fuel with a maximum of 0.5% sulphur content or use abatement technologies that achieve a similar reduction in SO_x emissions. The existing legislative framework poses several challenges, stemming mainly from a highly non-homogeneous and spatially differentiated system, with cases where the penalty fines are as low as the benefit that the violator enjoyed from non-compliances. The purpose of this paper is to develop a game theoretic modelling framework that improves the effectiveness of sulphur regulations enforcement and proposes a uniform violation fine system. A mixed strategy game with two players is formulated, representing the ship operator (who can either comply or not with the regulation), and an enforcement agency (that can opt to inspect or not inspect the ship) respectively. The proposed model can improve compliance rates and increase societal environmental benefits through reduced sulphur emissions. We also consider a new system with warnings issued for repeated violations of the regulation that would lead to a mandatory retrofit of the vessel with sulphur abatement technologies. Such models can ensure a level playing field for ship operators that currently have invested heavily in abatement options to comply with the sulphur regulations.

1. Background

1.1. Sulphur emissions abatement in shipping

International maritime shipping carries more than 80% of the worldwide trade by weight (UNCTAD, 2019), offering low cost and environmentally friendly transportation of goods. In recent years, however, ship operators have come under increasing regulatory pressure with a particular focus on further improving the environmental performance of the sector. Frequently, such initiatives manage to reduce emissions of pollutant species at increased operating costs for the affected ship operators and in turn leading to higher freight rates. The revised MARPOL Annex VI has set maximum limits on the sulphur content in fuel used by ship operators inside and outside sulphur emission control areas - SECAs (where stricter limits apply).

The SECA limit was lowered in 2015 from 1% to 0.1% putting significant pressure on ship operators in these areas. As of January 2020 the global sulphur cap of 0.5% content (down from 3.5%) now affects all ship operators. The global sulphur cap essentially means that:

- All shipping activities require use of very low sulphur fuel or use of abatement technologies with a similar reduction effect
- Sulphur emissions are reduced globally
- Higher operating costs
- A need to enforce compliance in newly affected regions
- A level playing field is necessary

1.2. Compliance

To secure compliance, ship operators can use more expensive fuels with sulphur content lower or equal to the prescribed limit (for example Marine Gas Oil – MGO, hybrid low-sulphur HFO, or by blending ultra-low sulphur fuel with regular HFO). LNG contains no sulphur while also emitting less PM and NO_x. There are however, barriers to the further implementation of LNG such as its higher methane emissions, the requirement for an engine compatible with the fuel, and the limited amount of bunkering ports for LNG globally. Alternatively, technologies such as scrubber systems that require significant capital and offer a permanent solution allowing the use of regular fuel. Scrubbers treat the exhaust gases with water (freshwater or seawater depending on the technology used) to absorb SO_x emissions.

During the last two decades, issues on sulphur emissions from international shipping have risen in popularity in academic research. The main research questions revolved around the selection of the most cost-

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effective abatement option (Jiang et al., 2014; Zis et al., 2021), routing decisions on where to cross into a SECA (Fagerholt et al., 2015) and at what speed to sail at segments with different sulphur limit requirements. We refer to the paper of Zis and Cullinane (2020) that presents a thorough literature review of these research themes. As shown by the authors, the existing penalties for violations of the sulphur limits are rather low, to the point that occasionally compliance with the sulphur limits may be more expensive than the penalty issued in case of non-compliance.

1.3. Enforcement

To ensure compliance, the port state control (PSC) can inspect visiting ships and check the bunker delivery notes, and logbooks detailing the time of fuel switching when entering a SECA. The PSC officer can additionally take a fuel sample if there is suspicion of non-compliance, and escalate further by asking for a detailed analysis of fuel at a laboratory.

The International Maritime Organization (IMO) adopted an amendment on October 2018 that came in force on March 2020, known as the carriage ban. Through it, ships that have not been equipped with scrubbers are forbidden to carry non-compliant fuel. Theoretically, this implies the ship operators cannot purchase and carry fuel with higher sulphur content, unless the ship is equipped with scrubbers. If a ship operator attempts to buy compliant fuel but there is no availability at the original port of bunkering, the ship operator can then fill in a "fuel oil non-availability report" (FONAR). It is then up to the discretion of the port authorities at the next port of call of whether or not the ship operator is liable to a penalty. A FONAR is not a "get out of jail" card, as the next port authority may request a de-bunkering of the ship and cleaning of the tanks. Thus causing a significant cost and loss of valuable service time for the ship.

While the carriage ban was a rational move in the right direction, ship operators can still use non-compliant fuel stored in secret tanks. Topali and Psaraftis (2019) have briefly described this "magic pipe" option. These are pipes not shown in the design of ships, typically used to discharge waste liquids in the sea, violating relevant marine pollution regulations. Magic pipes may be installed to provide non-compliant fuel to the ship's engines. Thorough inspections are therefore necessary despite the carriage ban, to ensure a level playing field amongst ship operators, and heavy penalties for violators can assist in increasing compliance rates.

However, there are limited resources at each port to inspect a vessel, while a malevolent ship operator could simply choose to comply in areas near the ports. With the global sulphur cap, ship operators should be using low-sulphur fuel even in the high seas, thousands of miles away from the shore. Monitoring compliance in remote areas can be enhanced through technologies that allow airborne monitoring of ship emissions with the deployment of so-called sniffers. Sniffers can be unmanned aerial vehicles (drones) that fly through the ship's plume and sample it for excess SO_x emissions. Such measures are only complementary and cannot prove a violation. However, these can signal PSC officer of a suspicious ship, thereby increasing the chance of successfully inspecting a non-compliant operator. There are also fixed stations that monitor passing ships. Their locations are known to ship operators as a list is available by the International Transport Forum. Therefore, a malevolent ship operator would be able to avoid being caught violating near these stations.

The European Commission (EC) reported that in the first three years since the 0.1% limit within SECAs, 28000 inspections were reported to THETIS (inspection data system hosted by the European Maritime Safety Agency – EMSA), with around 10% of ships inspected, and 4.79% of violations of the sulphur limit. The average rate of non-compliance incidents has slightly decreased in recent years, and the number of inspections has slightly increased. The existing penalties in case of a validated non-compliance to the regulation within SECAs were not uniform. For instance, the USA set a maximum penalty of $25000 per violation per day, without specifying how many days would be charged to a non-complying vessel. Within the European Union, each member state is responsible to set penalties for violations. The International Transport Forum (ITF) reports a list of maximum fines in different countries across Europe before the global cap (ITF, 2016) showing extreme diversity across. Zis and Cullinane (2020) show that for many cases the actual penalties are very low compared to the potential savings from non-compliances.

Considering the global cap, there is to date no universal penalty scheme for violations, nor exists an official list of inspections/violations. We have to note the impact of the current ongoing COVID-19 pandemic, which created a perfect storm with extremely low fuel prices. Certain countries announced plans to reduce inspections at the port due to the pandemic. The global cap signals the very first time that several ports (in previously unaffected countries) have to consider enforcement and inspection strategies. We also have to acknowledge that certain national states have chosen not to apply these limits within their national waters for ships carrying their flag. However, these ships would still be liable to the regulations when calling at ports of other countries.

This section briefly set the scene on sulphur abatement in shipping, and discussed the key issues of securing compliance and the vague legislative framework on penalties for violators and inspection practices. Section 2 formulates the problem using a game theoretical approach, in an effort to show quantitatively that compliance rates may improve through an appropriate penalty regime. We explore the merits of a different enforcement system where non-compliance instances are punished with a requirement to retrofit the vessel to ensure non-repetition of the offence. Section 3 discusses the main findings of the paper, and the importance of key parameters such as the inspection cost, and monetary penalties issued for violations. Section 4 concludes with a series of suggestions for further research.

2. Using game theory to improve compliance rates

Game theory concepts in maritime shipping, port operations and management have been increasingly used by researchers. Pujats et al. (2018) consider different cooperation policies among terminals in order to balance profit for individual terminals and efficiency in terms of capacity. Cui and Notteboom (2018) also examine port cooperation strategies and list relevant literature of game theory applications in ports. Zavitsas et al. (2018) consider the relaxation of sulphur limits to improve the resilience of the global oil supply network following attacks in a game. Inspection games applied between ship operators and PSC have been examined by Yang et al. (2018). In their work the PSC can inspect or not a vessel, and the ship owner can either have a high intensive or low intensive effort in the vessel's overall maintenance status. We consider game theory for the improvement of the enforcement of sulphur regulations specifically. The proposed game is considering two players that seek to maximize their utility. This belongs to the family of inspection games, described in detail by Avenhaus et al. (2002).

There have been similar applications in public transport that inspired this paper. Bell (2000) uses game theory to assess the reliability of a transport network when one player (individual network user) aims to minimize their expected trip costs, while an "evil entity" imposes link costs on the network user to maximize the expected trip cost. Barabino et al. (2014) examine the optimum inspection level of passengers in Proof-of-payment transit systems. Troncoso and de Grange (2017) develop an econometric model to explain fare evasion through a case study in a bus system in Chile, and show the impacts of higher fares on evasion probability. More relevant to our work is the seminal paper of Sasaki (2014) who used an inspection game formulation to compare the installation of barriers versus random ticket inspections in a metro system. The issue of sulphur enforcement shares some similarities. The installation of barriers is essentially equivalent to a mandatory installation of abatement technology (e.g. scrubbers), and the ticket inspections is equivalent to PSC inspections of vessels at berth. However, there are significant differences that do not allow a direct application of Sasaki's model in the sulphur enforcement case. In Sasaki's case, the transport users were following the decision of the transport authority to use barriers or deploy ticket inspectors. In the sulphur case, the ship operator decides between using a permanent solution (scrubbers) and paying the extra price each time (use low-sulphur fuel). Therefore, the formulation of Sasaki is not directly applicable here.

In the context of enforcement of sulphur regulations, the first application of game theory is documented in Zis (2019), where it was shown that the existing monetary penalties were too low to ensure compliance from ship operators. In this paper, we construct a comprehensive inspection game framework with various subcases. This can assist regulatory bodies and ports decide on the frequency of inspections, and appropriate monetary fines to deter non-compliance.

2.1. Setting up a game between ship operator and an inspecting agency

The proposed game consist of two players that decide and play simultaneously with no recourse action. The first player (i.e. player 1) is the ship operator seeking to minimize their operating costs, and the second player is an inspecting agency (assumed to be the PSC) seeking to ensure compliance from the visiting ship operators, by performing inspections. These inspections come at a certain cost, but can also raise revenues from penalties issued to non-complying ship operators. The ship operator has two options: i) invest in scrubbers (if they also own the vessel), or charter a vessel that has been equipped with scrubbers, or ii) do not install scrubbers and either comply or not at each voyage with the low sulphur use. The inspection agency (i.e., player 2) decides on whether to inspect for compliance a vessel or not. Fig. 1 presents the options schematically.

2.1.1. The ship Operator's strategies

We only consider ship operators that have opted to rely on fuel switching and we do not include retrofitted ships whose owners have invested in scrubbers or other abatement options. In theory, a ship could have scrubbers but the operator chooses not to use them, as the scrubbers slightly increase fuel consumption (up to 3%). If the ship owner is also the ship operator, we expect that they would always use the technology they invested heavily in acquiring. If the ship operator is only chartering the scrubber-equipped vessel, we assume that the ship operator would not follow this practice of switching the scrubber off for such low savings. While technically feasible, there will be a log of the hours that the scrubber was running, that should match the operating hours of the ship. There might also be a clause stipulating that the charterer must operate the scrubber. Therefore, in our model we only focus on non-retrofitted ships where the operator needs to switch to low-sulphur fuels. The ship operator can therefore choose to comply with the regulation and use the more expensive fuel, or not comply and use regular HFO. For the remainder of the paper we refer to the compliance/non-compliance strategies as *S1* and *S2* respectively.

- If player 1 adopts strategy *S1*, the ship will emit less SO_x, but the player will have an increased operating cost due to the higher fuel price, regardless of whether the ship is inspected or not.
- If player 1 adopts strategy *S2*, the ship will emit more SO_x, and the player will have lower operating costs. However, player 1 will have to pay the monetary fine for the violation if the ship is inspected.

2.1.2. Inspecting agent strategies

Player 2 has the capability of inspecting any ship that calls at its berths. We assume that player 2 is aware of all ships equipped with scrubbers, and therefore only inspects for sulphur compliance the ships that should use low-sulphur fuel. This is realistic as there are publicly available lists of scrubber-retrofitted vessels, and it is in the interest of the shipowner to publicly announce such investments. In the baseline scenario, player 2 has no information on non-compliance for the incoming ships (e.g., through UAV sniffers). Player 2 knows the previous port of call, and the voyage duration. Player 2 can therefore select to inspect a ship or not. Let *I1* be the strategy of inspecting a ship, and *I2* the strategy of not inspecting.

- If player 2 chooses *I1 strategy*, they will incur a cost for performing the inspection, but might receive a compensation if the inspected vessel is found to be non-compliant.
- If player 2 chooses *I2 strategy*, there will be no cost or gain to the inspecting agency.

2.1.3. The third stakeholder

In the game described herein, we did not include a third player that exists; namely the society or regulator that has set the sulphur limits. The reason for not including this, is that the third player's decisions are at the strategic or planning level as opposed to this game where the decisions are made at the operational/real time level. The third player's objective is to minimize sulphur emissions (maximization of the compliance of all ship operators at all times) from the game played between the inspection agencies and the ship operators. Nevertheless, impacts on the third player are accounted for by different versions of the game proposed herein.

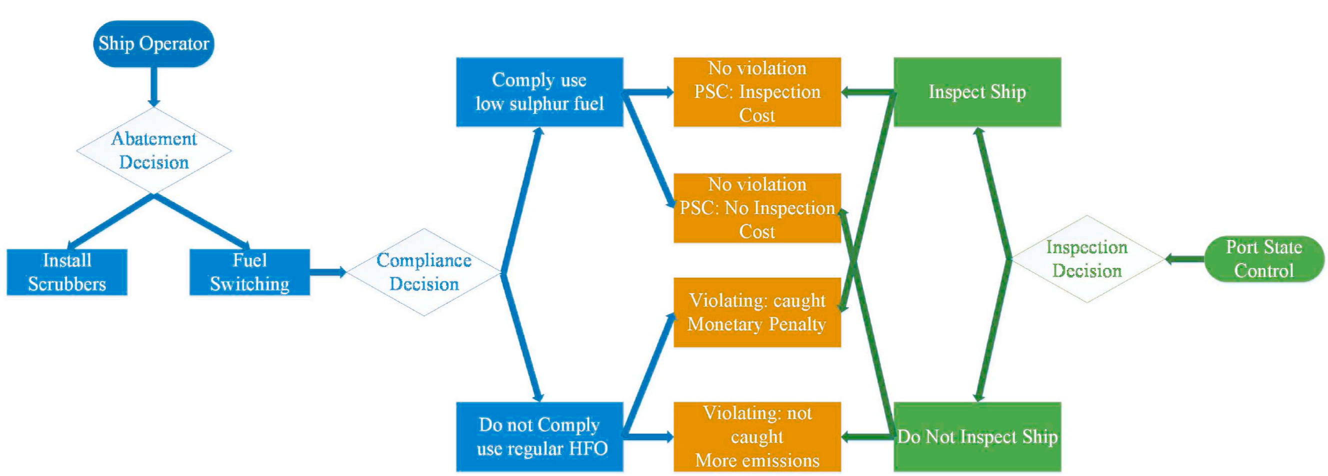

Fig. 1. The available decisions for each player.

2.1.4. The main form of the games and key assumptions

We assume that all versions of the game examined are of mixed strategy with complete information. In that sense, the ship operator is aware of the potential monetary penalty (*MP)* if caught not complying. Player 2 could choose not to disclose the *MP* in the case of violation, but that would not help towards a level playing field. Ship owners that chose to invest in scrubbers are adamant that the regulation is strictly enforced. If certain ports would not disclose the potential penalties of non-compliance this could result in ships preferring other ports of call. We also consider that player 1 is also aware of the inspection cost (*IC)* that player 2 endures. In reality, there is a vague picture on the expected penalties in case of a violation (see section 1), but it is vital to have a concrete penalty scheme known to all stakeholders.

Player 2 knows the fuel benefits (*ΔFC)* that player 1 enjoys when not complying. At the very minimum, a non-compliant vessel will have been using the cheaper fuel for the last leg before the port of inspection. This is a straightforward calculation based on the fuel price differential, the voyage duration from the previous port, and high-level data on the ship's technical specifications. A further extension could assume that a non-complying ship operator had been doing so in all voyages since the last bunker delivery of low-sulphur fuel. This should thus increase significantly the penalty; however, in this work we only assume a liability for the preceding voyage alone

2.2. Game I – ship operator vs port state control

We start with the simplest formulation where we consider only the two players (ship operator and inspecting agent) that are playing against each other. This game is similar to the current state of practice with random checks in certain ports, and known penalties at each geographical location. Table 1 presents the payoff matrix for the two players in each strategy combination.

$$E_s(p,q) = p\%q\%(-\Delta FC) + p\%(1-q)\%(-\Delta FC) + (1-p)\%q\%(-MP) + (1-p)\%(1-q)\%(0) = = -p\Delta FC + (1-p)q(-MP) \quad (1)$$

$$E_I(p,q) = p\%q\%(-IC) + p\%(1-q)\%0 + (1-p)\%q\%(MP-IC) + (1-p)\%(1-q)\%(0) = p\%q\%(-IC) + (1-p)\%q\%(MP-IC) \quad (2)$$

- *ΔFC* represents the additional costs that the ship operator will pay by using low sulphur fuel. *ΔFC* depends on the voyage (distance and duration), and the fuel price differential.
- *IC* represents the cost per inspection that player 2 performs. We assume that there are no capital costs involved, and it is only the hours of existing staff members assigned with the inspection. We assume that this cost is the same for all ships and independent of the particular voyage and ship.
- *MP* is the monetary penalty that the ship operator will pay if caught not complying. It is set by the third player. We assume that this is paid to player 2, so it is essentially a revenue for player 2. This revenue can be used to enhance efforts of player 2 to ensure compliance of ship operators and thus reduce emissions from non-compliant operators. As we will show later on, we suggest that the *MP* should be ship and voyage specific.

Table 1
The payoff matrix for Game I.

Ship operator/Port State Control	I1: Inspect ship	I2: Do not Inspect ship
S1: Use clean fuel	*-ΔFC, -IC*	*-ΔFC, 0*
S2: Use high sulphur fuel	*-MP, MP-IC*	*0, 0*

Based on this formulation some observations can be made. If $\Delta FC > MP$ then the ship operator would have a pure strategy to never comply (*S2*), as the penalty is less than the benefits enjoyed by not complying. If $IC > MP$ then player 2 would have a pure strategy to never inspect (*I2*), as the costs of inspection are higher than the revenue collected in case of a successful inspection of a non-compliant ship. Considering low fines in certain countries, it is evident that in some cases there is no motivation for the ship operator to comply with the regulation. There is however the angle of the potential moral damage to the ship operator (loss of clients due to poor reputation if caught) that could be included in the payoff matrix.

If the previous two inequalities do not stand, then it is in the best interest of each player to randomize and thus use a mixed strategy.

- Let p be the probability of complying with the regulation for player 1 (playing *S1*) in a given voyage, it follows that player 1 would violate with probability *1-p* (playing *S2*)
- let q be the probability of player 2 inspecting a ship (playing *I1*), and *1-q* the probability of not inspecting (playing *I2*)

The expected payoffs $E_S(p,q)$ and $E_I(p,q)$ for the ship operator and the inspector respectively are given by the following equations:

The mixed strategy Nash equilibrium consists of finding the probabilities p^* and q^* as functions of *MP, IC* and *ΔFC* such that each player does not change their selected strategy (Nash, 1950). We can also estimate p^* and q^* on the following premise. The inspecting agency should be inspecting with a probability q^* that would make the ship operator indifferent on complying or not.

Proposition. *Player 2 has a best response of inspecting with probability q^*, that is independent of the actual IC.*

Proof: Player 1 would be indifferent when their payoff of compliance (E_{S1}) is equal to the payoff of non-compliance (E_{S2}). That is:

$$E_{S1}(q^*) = E_{S2}(q^*)$$

$$-\Delta FC\%q^* + (-\Delta FC)(1-q^*) = -MP\%q^*$$

$$-\Delta FC = -MP\%q^*$$

$$q^* = \begin{cases} \dfrac{\Delta FC}{MP}, \ for\ IC < MP \\ 0, \ for\ IC \geq MP \end{cases} \quad (3)$$

This means that the best response strategy for player 2 should be to inspect a visiting vessel with a probability equal to the ratio of the potential fuel benefits from non-compliance over the prescribed MP, independent of the *actual cost of inspection. It follows that if the MP is lower or equal to the fuel savings from not complying, player 2 should always inspect (as in that case player 1 would always use high-sulphur fuel). We can work in a similar manner to deduce the optimal response of player 1, to constitute player 2 indifferent between inspecting or not.*

Proposition. *The ship operator has a best response of complying with probability p*, that is independent of ΔFC.*

Proof: Player 2 would be indifferent when their payoff of inspecting (E_{I1}) is equal to the payoff of not inspecting (E_{I2}). That is:

$$E_{I1}(p^*) = E_{I2}(p^*)$$

$$-p^* \% IC + (1-p^*)\%(MP - IC) = 0$$

$$-p^* \% IC + MP - IC - p^* \% MP + p^* \% IC = 0$$

$$p^* = \begin{cases} 1 - \dfrac{IC}{MP}, & for\ IC < MP \\ 0, & for\ IC \geq MP \end{cases} \tag{4}$$

This means that the ship operator's best response strategy should be to violate with a probability equal to the ratio of the cost of inspection over the monetary penalty. This is independent of the fuel savings, but it is evident that with a higher MP the compliance probability increases. If the IC is greater or equal to MP then the ship operator equation (4) *confirms that the ship operator would never comply (in that case player 2 has a pure strategy I2).*

2.2.1. Numerical examples

We illustrate the ineffectiveness of current enforcement (similar to Game I) with some numerical examples of calculating the resulting equilibria. The following numerical examples are considering cases with illustrative values for *MP*, *ΔFC* and *IC*.

2.2.1.1. Case of relatively low fines. In the first example, we consider a relatively low *MP* that is equivalent to 4.5 times the fuel savings of not complying. The payoff matrix is shown in Table 2.

2.2.1.2. Case of high fines. In the second example we increase the *MP* to be ten times the fuel savings of non-compliance, while the IC remains as high as before. The resulting payoff matrix is shown in Table 4.

The resulting equilibrium is for $p = 0.9091$ and $q = 0.0909$. This shows that increasing the fine leads to a higher compliance rate among ship operators (a violation of approximately one out of ten times), and a lower need for inspection for ports. This can be seen in more detail in Fig. 2 where the probabilities p and q are plotted as functions of MP.

In the first graph the assumption is that the *IC* is equal to *ΔFC* (as in Tables 3 and 4), whereas in the second graph the assumption is that the *IC* is much lower and equal to one tenth of *ΔFC*. We note the symmetry in the first graph, where because IC and ΔFC are equal, *p* and *q* sum up to 1.

Table 2
Payoff matrix with relatively low fines.

Ship operator/Port	P1: Inspect ship	P2: Do not Inspect ship
S1: Use clean fuel	*−2, -2*	*−2 0*
S2: Use high sulphur fuel	*−9, 7*	*0, 0*

The resulting equilibrium is for $p = 0.7778$ and $q = 0.2222$. Considering that with such low fines the ship operator would be violating approximately one out of five times is a very high result that would constitute the regulation ineffective in reducing SO_x emissions. We also note that the *IC* is relatively high, and equivalent to the *ΔFC*.

In each graph, the x-axis depicts the ratio of *MP* over *ΔFC*. For very high ratios, the ship operator quickly increases their probability of complying. For a very low *MP*, in the second graph the ship operator would always play *S2*.

An important weakness of the current game is that if player 2 does not inspect a non-complying vessel, there is no penalty for them (payoff is zero). This has a significant consequence, as assuming no penalty from not "catching" a violation would dissuade player 2 from checking as often. In the real world, this would actually make sense, as player 2 would inspect vessels not just for the sulphur limits compliance, but also for an array of issues spanning from ballast water treatment, to waste management onboard, as well as other severe misdemeanors. For this reason, we will see if it is possible to internalize the cost of not catching a violating ship.

2.3. Game II - internalizing the emissions penalty

If a ship violates the regulation, there is an environmental penalty associated with the increased sulphur emissions. These emissions are proportional to the sulphur content of the fuel used, and thus the result would be 7 and 35 times higher SO_x emitted during the previous voyage if the vessel sails outside and inside a SECA, respectively. In Game II we assume that this cost is internalized and equal to *c* monetary units per ton of fuel. The payoff matrix for Game II is shown in Table 2.

Similar to Game I, let *p* be the probability of compliance for the ship operator, and *q* the probability of inspection for the port state control. The expected payoff for each player is now:

$$E_S(p,q) = p\%q\%(-\Delta FC) + p\%(1-q)\%(-\Delta FC) + (1-p)\%q\%(-MP - c\%\Delta FC) + (1-p)\%(1-q)\%(0) = -pDFC - qMP - cq\Delta FC + pqMP + pqc\Delta FC \tag{5}$$

$$E_I(p,q) = p\%q\%(-IC) + p\%(1-q)\%0 + (1-p)\%q\%(MP - IC) + (1-p)\%(1-q)\%(-c\%\Delta FC) = p\%q\%(-IC) + (q-pq)\%(MP-IC)$$
$$+ (1-p-q+pq)(-c\Delta FC) = p\%q\%(-IC) + qMP - qIC - pqMP + pqIC + (1-p-q+pq)(-c\Delta FC) = q\,MP - qIC - pqMP + (1-p-q+pq)(-c\Delta FC) \tag{6}$$

Proposition. *Player 2 has a best response of inspecting with probability q*, that is independent of the actual IC.*

Proof: Player 1 is indifferent when their payoff of compliance is equal to the payoff of non-compliance. That is:

$$E_{S1}(q^*) = E_{S2}(q^*)$$

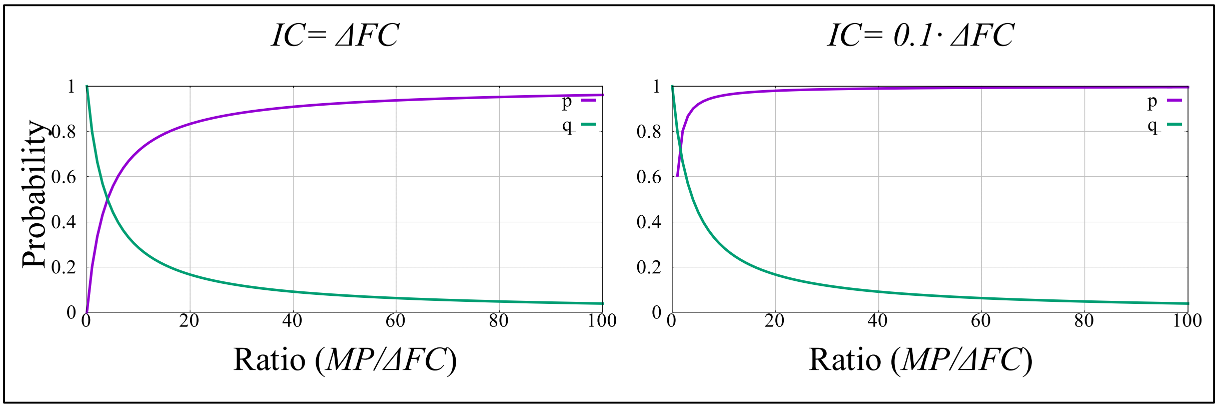

Fig. 2. Comparison of Mixed Strategy Equilibria for different monetary fines *MP* as function of *ΔFC*.

Table 3
Payoff matrix with relatively high fines.

Ship operator/Port	P1: Inspect ship	P2: Do not Inspect ship
S1: Use clean fuel	*−2, -2*	*−2 0*
S2: Use high sulphur fuel	*−22, 20*	*0, 0*

Table 4
Payoff matrix for Game II.

Ship operator/Port State Control	I1: Inspect ship	I2: Do not Inspect ship
S1: Use clean fuel	*-ΔFC, -IC*	*-ΔFC, 0*
S2: Use high sulphur fuel	*-MP-c•ΔFC, MP -IC*	*0, -c•ΔFC*

Table 5
Payoff matrix for Game III.

Ship operator/Port State Control	I1: Inspect ship	I2: Do not Inspect ship
S1: Use clean fuel	*-ΔFC,0*	*-ΔFC, 0*
S2: Use high sulphur fuel	*-MP-c•ΔFC, MP*	*0, -c•ΔFC*

$$-\Delta FC\% q^{*} + (-\Delta FC)\%(1-q^{*}) = (-MP - c\%\Delta FC)\% q^{*} + 0\%(1-q^{*})$$

$$q^{*} = \frac{\Delta FC}{MP + c\%\Delta FC} \tag{7}$$

From equations (7)–(9) *we observe that when c=0, Game II reduces to Game I. As c increases, the probability of inspection decreases. This is a counterintuitive conclusion, as one would expect that inspection rates would be proportional to the cost of pollution* (*i.e., not catching a violator*). *However, higher values of c, results in higher compliance rates that do not require high inspection rates.*

Proposition. *Player* 1 *has a best response of compliance with probability p*, that now depends on ΔFC enjoyed by not complying, the internalized cost of emissions, the IC, and the MP.*

Proof: Player 2 *would be indifferent when their payoff of inspecting is equal to the payoff of not inspecting. That is:*

$$E_{I1}(p^{*}) = E_{I2}(p^{*})$$

$$-p^{*}\% IC + (1-p^{*})\%(MP - IC) = p^{*}\%0 + (1-p^{*})\%(-c\%\Delta FC)$$

$$-p^{*}\% IC + MP - IC - p^{*}\% MP + p^{*}\% IC = -c\%\Delta FC + p^{*}\% c\%\Delta FC$$

$$MP - IC - p^{*}\% MP = -c\%\Delta FC + p^{*}\% c\%\Delta FC$$

$$p^{*} = \frac{MP - IC + c\%\Delta FC}{MP + c\%\Delta FC} \tag{8}$$

When c=0 then the game collapses to the form of game I, and the probability p^{*} is dependent on the ratio IC over MP. As with game I, the p moves closer to* 1 (*pure strategy*) *as the IC decreases. It is evident that p* will increase with a higher internalization variable c.*

2.4. Game III – the regulator subsidizes the inspecting agent

An alternative way to ensure a higher compliance would be to reduce the *IC* through subsidies provided to the inspecting agency by the regulator (e.g., the IMO). The payoff matrix for Game III is shown in Table 5.

We observe that *I1* strategy dominates *I2*, since when the ship operator abides by the regulation the payoff is zero for both *I1* and *I2*, but if the ship operator plays *S2*, then the payoff of *I1* is positive (*MP*) whereas for *I2* it would be negative (the additional emissions also harm the port). Player 1 knowing that player 2 would now always inspect, would have to comply as now *S1* dominates *S2* if the column player always plays *I1*. We can draw the same conclusion by equating *IC* to zero in equation (4), which gives a *p** equal to 1.

In reality, it would not be feasible to inspect every ship even if all *IC* were subsidized, due to insufficient staff resources, time limitations and ship delays. However, it could be feasible that a minimum number of inspections per vessel calls is set by the third stakeholder to provide a compensation for player 2. This strategy would effectively dictate the probability *q* of inspection, and, assuming that this information was known to the ship operators, would also control the probability of compliance.

2.5. The third player's perspective for each game

In this section, we examine the impact of the previous games on the environment/third stakeholder. We assume that 100 vessels are calling at one port in a given time period, and we will examine the total emissions for the different games during the Nash equilibria of each formulation. To facilitate comparisons, we display the result for different ratios of *MP* over *ΔFC*. As our key performance indicator, we consider the percentage increase in sulphur emissions ΔSO_x in excess of what would have been a full compliance. This is can be estimated as follows:

$$\Delta SO_x = (1-p^{*})\%(6\%\Delta FC_{out} + 34\%\Delta FC_{in}) \tag{9}$$

Where ΔFC_{out} refers to the additional fuel consumption when the ship sails outside a SECA using 3.5% sulphur content instead of 0.5%. This means seven times higher SOx emissions compared to the full compliance, which explains the value of 6 in equation 11. ΔFC_{in} refers to the extra fuel consumption inside a SECA using 3.5% sulphur content instead of 0.1%. This is 35 times higher SOx emissions when not complying, which justifies the 34 value in equation 11. Equation 11 is correct under the assumption that when an operator is not complying they are using fuel with a sulphur content of 3.5% (which is the main

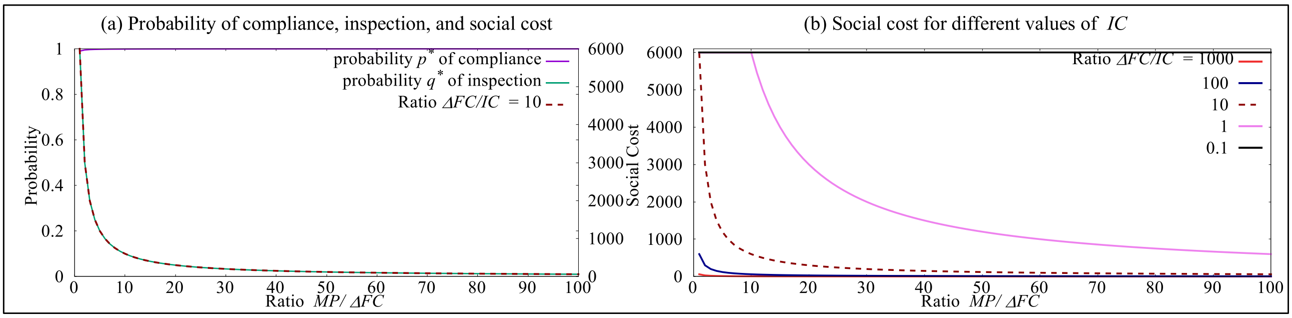

Fig. 3. Probability of compliance and social costs for Game I.

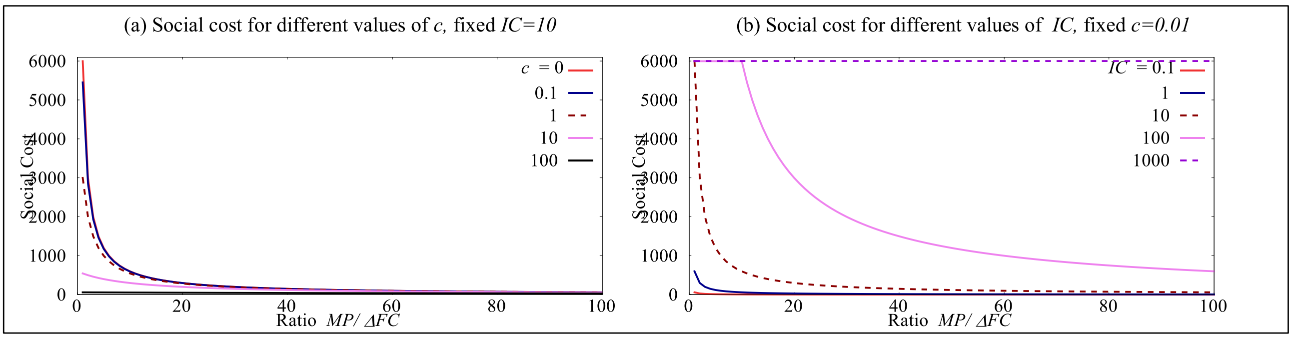

Fig. 4. Probability of compliance and social cost for Game II.

type of HFO sold to operators that have invested in scrubbers). In reality, there might be differences in these numbers depending on the actual sulphur content in the fuel used by the non-complying operator. The social cost decreases with higher level of compliances, and is independent of whether a violator is caught and subsequently pays the damage (for games II, III). Alternatively, we could consider the economic cost of these excess emissions by multiplying ΔSO_x with the unit cost *c*.

2.5.1. Social cost for game I

For Game I the social cost is proportional to the probability of inspection. From equation 11 if we substitute p^* from equation (4), it follows that the social cost is proportional to *1/MP*, as is q^* from equation (3). In Fig. 3a we show the impact of the relative value of *MP* over the *ΔFC*. Fig. 3b shows the social cost for different *IC*.

We observe that for high relative values of *IC* that the social cost increases, and unless a very high *MP* is issued, the players choose a pure strategy combination n of *I2*, *S2*.

2.5.2. Social cost for game II

In Game II we consider that the inspecting agent would pay for the environmental cost of non-complying ships (regardless of these getting inspected or not). We show the social cost in Fig. 4.

In Fig. 4a we keep the *IC* fixed at 10 units (equal to *ΔFC*), and we conduct a sensitivity analysis on the values of *c*. For very high *c* values the game moves to a pure strategy equilibrium (*S1, I1*) with a zero social cost. For other values of *c*, we notice a small reduction in the social cost (the curves for c = 0.1 the curve is lower than for c = 0.01). In Fig. 4b we maintain a low *c* at 0.01, and we observe that as the *IC* is increasing the social cost increases (Similar to Game I), leading to a pure strategy of non-compliance for very high values.

2.5.3. Social cost for game III

In Game III player 1 pays for the environmental cost if caught not complying, and player 2 pays for environmental costs of not-inspected violating vessels. As stated in section 2.4, Game III would result in a pure strategy of full compliance for the ship operators if the *IC* were reimbursed to player 2 (who would now always play *I1* due to the zero cost per inspection). Therefore, the social cost in that case would be zero as there would not be any violations. More interesting is the actual economic cost for the regulator to subsidize all inspections. It might be that there is a limit on the number of inspections that can be performed by player 2. As we showed in Games I and II, the equilibrium would consist of finding the p^* and q^* that would not make the players change their strategy, or make each player indifferent by changing their

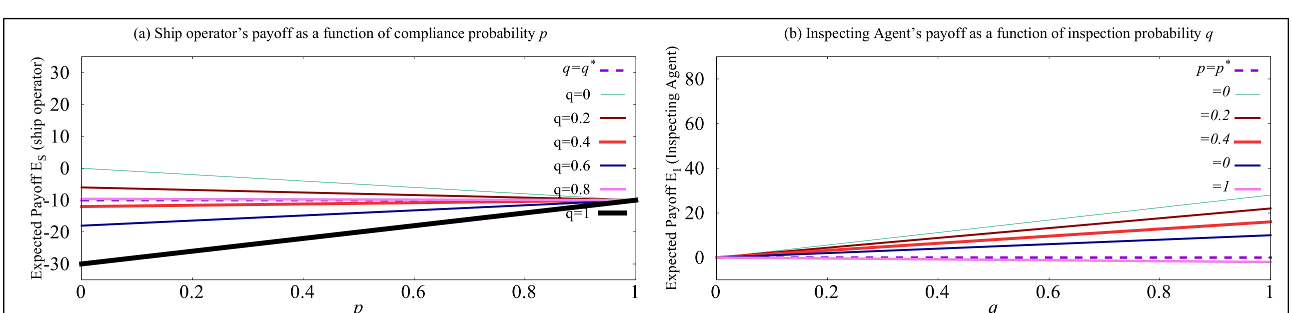

Fig. 5. Expected payoffs for the two players as functions of inspection and compliance probabilities.

strategy. In other words, there is a $q*$ inspection probability that would give the ship operator the same payoff no matter how often the ship operator complies or not. This is depicted schematically in Fig. 5 for several different inspection rates q, considering an illustrative case were ΔFC is equal to 10 units, IC is equal to 2 units, and MP is equal to 30 units.

In Fig. 5a, the dashed line represents the payoff when player 2 plays $q*$. The payoff of player 1 is constant regardless of their strategy (always comply, never comply, mixed strategy). In Fig. 5b, we observe the inspecting agent's payoff for different strategies of the ship operator. The dashed line (ship operator plays optimal strategy p*) is a horizontal line. However, if a third player (the regulator as in Game III) compensates the *IC*, then we would have the situation depicted in Fig. 5a. If a full compensation was paid, and there was enough supply of inspecting staff, then the optimal strategy for the ship operator would be always play *S1*.

How does this information translate into our Game III? Considering that the third player sets the *MP*, now pays for the *IC*, and wants to minimize the social cost (zero violations) it is in their best interest to set an *MP* where the $q*$ is low enough that these inspections can be performed (at each port which will be subsidized for the inspections). We also note that in Fig. 5b we assumed that $c=0$ (which makes sense as the purpose of Game III is to have zero violations). However, if c was included in the calculations the only difference would be the payoffs of each player (lower payoff for ship operator, higher for inspecting agents).

That raises an interesting follow-up question; is it not in the best interest of the regulator to set as high an *MP* as possible? In line with Becker's (1968) work that suggests a maximum punishment for a crime to reduce the probability of crime and the requirement to spend resources in catching perpetrators. In our work, setting a very high *MP* would result in a very small number of inspections (under Game III), and thus reduce the actual costs of enforcement for player 3, given that for level playing field reasons compensations should be given to all ports. This question is beyond the scope of this paper, but we can assume that there would be legal repercussions that would set a limit on the maximum *MP* for violations.

2.6. Alternative enforcement schemes

The form of punishment is another point of discussion. For example, keeping a non-compliant ship in port (time penalty for a few days) could prove more effective than issuing a monetary penalty that can take ages to be settled in court. An alternative approach would be to change the repercussions of a non-compliance. One option is a hefty fine, and the additional damage to the violator (time delays, cost of de-bunkering, moral damage in company's reputation). Here we propose a different enforcement scheme under consideration. Through it, after n occurrences of non-compliances the ship is forced to get retrofitted with a scrubber system or an engine capable of using alternative fuels complying with the regulation (for example LNG, methanol, or other non-HFO bunkers), where n could be as low as one violation. Such a mechanism would have the benefit that it would limit the number of inspections in the future, while also send a clear message that while fuel switching is allowed, non-compliance is not tolerated. The proposed scheme is hypothetical for maritime shipping; however, it borrows elements from other transportation modes. Similar to point penalty systems in several countries where drivers accumulate points for various traffic offenses or infringements, and can lose their driving license when they exceed a limit in points. There is still a penalty for each infringement, but through the point system repetition of the offence is further punished. In the context of sulphur compliance, we will examine a similar system.

Table 6
Sensitivity analysis on MP and number of warnings before forced conversion. Where IC is 2 monetary units, and ΔFC is 10 monetary units.

n (number of warnings)	*MP*	p	Q	Time periods until all vessels converted	
				Exclude from reinspection after conversion	Continue reinspection after conversion
1	20	0.9	0.5	20	102
	50	0.96	0.2	125	635
	100	0.98	0.1	500	2541
	200	0.99	0.05	2000	11165
	400	0.995	0.025	8375	41890
3	20	0.9	0.5	61	180
	50	0.96	0.2	376	1118
	100	0.98	0.1	1499	4785
	200	0.99	0.05	5990	20950
	400	0.995	0.025	23947	67050
5	20	0.9	0.5	101	247
	50	0.96	0.2	626	1567
	100	0.98	0.1	2502	6442
	200	0.99	0.05	10056	23942
	400	0.995	0.025	39909	83844

We will show a brief illustrative example on how this system could work. We assume that there are 100 vessels sailing between two ports, currently relying on low-sulphur fuel to comply with the regulation. The ship operators would occasionally randomize and choose to not comply with the regulation. Depending on the *MP*,*IC*, and ΔFC, it is possible to find the Nash Equilibrium with the probabilities $p*$ and $q*$ of complying and inspecting. In this example, we will show how quickly the 100 vessels would be retrofitted under that rule.

Each time a vessel is converted, it is excluded from possible future inspections for sulphur compliance. Therefore, in our illustrative example the probability of a non-converted vessel to be inspected is increasing since the population of said vessels is being reduced with each conversion. We show in Fig. 6 how quickly the 100 vessels would get converted by performing a sensitivity analysis on the *MP*, and on the number n of warnings. This is an illustrative example where all vessels

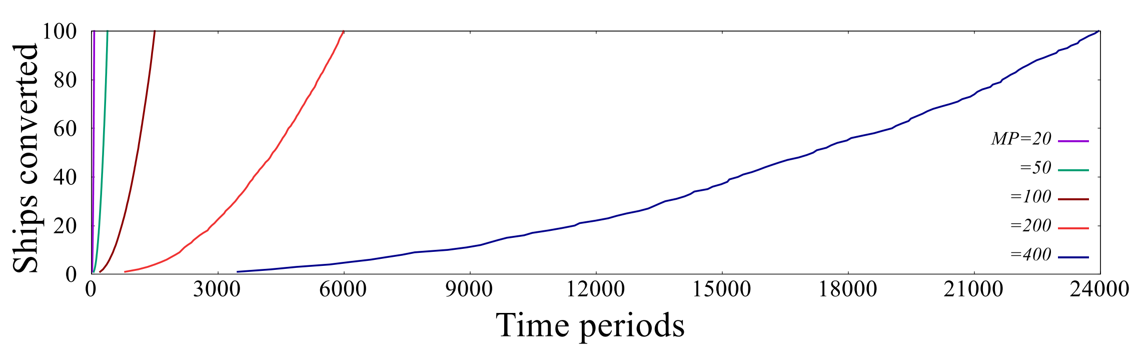

Fig. 6. Number of Ships converted for different values of MP as a function of time periods.

have the same ΔFC (i.e. perform the same trip in order to call at our port). We consider that a time period has passed when all 100 vessels have visited the port (some have randomly been inspected). To estimate this, we perform a Monte-Carlo simulation of 1000 runs for each scenario and we present the average results in Table 6. We show the total time periods until all ships have been converted, considering two sub-scenarios. In the first case, a vessel that has been retrofitted after n violations is no longer inspected. This increases the chance of a non-retrofitted vessel to be inspected in the next time period. Under this case, we assume that the PSC will be performing the same number of total inspections, and that the ship operators are not aware that their probability of being inspected is increasing over time. In the second case, the probability of being inspected is not changing regardless of how many vessels have been retrofitted. This can be conceived as if we are examining a sample of the vessels that are visiting the ports. As expected, in the second scenario it takes a longer period for all 100 vessels to be retrofitted.

The results in Table 6 show that when the *MP* is high, it takes a longer time until the vessels are caught not complying and are forced to retrofit. This is due to the higher probability p of compliance, and low probability q of inspection. The time periods are increasing proportionally as the number of warnings is increased. To compare the impact of removing ships from the "inspection pool" in the first sub-scenario, we plot in Fig. 6 the evolution of the vessels being converted considering that a conversion is mandatory at the third violation ($n = 3$).

As expected, each curve follows a convex shape and ships are converted faster as previously converted ships are removed from the pool. The main benefit of such a system is that it would still provide an incentive for inspections early on, but over time, the number of violations would decrease. In addition, it would allow for a lower *MP* as a means to make the move to scrubber equipped (or other abatement technology) vessels faster. One of the disadvantages of this scheme is that it might be perceived as advantageous for constructors of scrubber systems at the expense of refineries producing low-sulphur fuel.

How could such a system work in reality? Going back to the point penalty system for drivers, we can observe that the probability of being inspected for violations (say illegal parking, speeding, driving under the influence etc.) remains the same for the driver. In a similar manner, a ship can be inspected in different ports of call, with the same probability regardless of whether they had been violating in previous voyages. Each violation would still be penalized with the MP, but in addition to that, a warning (or points) would also be awarded each time in an international registry. When the inspected ship reaches the upper limit n of warnings, then the ship would have to be retrofitted in order to continue being used. An important question is whether the ship operator or the ship owner would be penalized (when they are not the same). In the point penalty system, the driver loses the license while the car in which the violation was registered is unaffected. For our case in shipping, we could propose that the ship itself is penalized (e.g. needs to be retrofitted after n violations in a given timeframe), but then the ship operator would have to cover the costs on behalf of the ship owner.

A final comment on this hypothetical scheme is necessary concerning the game played itself. Player 2 should in theory be indifferent to the information on how many warnings player 1 has amassed in previous voyages. Player 2 would still randomize whether to inspect each arriving speed, with a probability that depends on the specific voyage. However, player 1 might change their behavior when getting near the final warning, and change to a pure strategy of always complying (or at least until previous warnings are cleared). This has been observed in the equivalent penalty point system for traffic violations. Sagberg and Ingebrigtsen (2018) find that the probability of a new offence is decreased when drivers approach the limit to lose their license. In our results, we showed in Table 6 and Fig. 6, we did not change the behavior of player 1 as they neared the final warning, and thus a worst case scenario (from a societal perspective) is presented in our work. To incorporate the impact of the final warning, it would be possible to replay the game and increase substantially the *MP* (to include the cost of the forced retrofit and the time lost), which would then change the probability p of complying with the regulation. Further extensions of this research could consider the impact of these warnings in the game, and on whether player 2 is aware of how many warnings player 1 has left prior to each voyage.

3. Discussion

Due to the unprecedented times with the COVID-19 pandemic and the extreme disruptions in maritime transport, as well as the very low fuel prices in the first months of 2020, the picture regarding the enforcement of the global cap is not clear. So far, we only have the first five years of the 0.1% limit in the SECAs to rely on in understanding the enforcement of such regulations. Game I is the closest approximation to the existing enforcement efforts of this regulation. In this section, we will discuss some important aspects in implementing the proposed games.

3.1. *Defining a level playing field*

This is one of the most important questions as regards the enforcement and implementation of environmental regulations. It has been an issue in maritime transport, and typically, before the IMO decides on a course of action to reduce emissions, a consensus is required amongst participating IMO member states (Psaraftis and Kontovas, 2020). In fact, when the first SECAs were introduced there were some vocal reactions by affected ship operators (particularly in Northern Europe) that were considering that the lower limits would harm their business more than ship operators in Southern Europe would. Ship operators that chose to invest in scrubbers need to be assured that there will be active control and inspection of ships that chose to use low sulphur fuel. In our view, a level playing field would mean that all ships (that do not have scrubbers) would have an equal chance of getting inspected and that the potential *MP* would not be the same for each violation, but it would be proportional to the offence. With the proposed game formulations we actually achieve that, as the inspection probability q^* would be the same at each port for all visiting vessels. In addition, the *MP* is higher for ship operators that benefit more (saving more fuel costs) from non-compliance, and it is a function of fuel prices. The potential fuel savings from non-complying can be estimated based on the sailing distance, total voyage time, and ship technical specifications, given the fuel price differential. These fuel savings can be slightly more complicated if the effect of weather are factored in, or the behavior of the ship operator. In rough weather, the overall fuel consumption is increasing, and thus the savings from using cheaper fuel grow. In previous years, and particularly during 2015–2020, ship operators would benefit from speed optimization and optimal path when entering and leaving a SECA (speeding up outside, reducing speed outside, deciding at which point to cross) as shown in the seminal paper of Fagerholt et al. (2015). However, the economic benefits from this practice are now extremely limited due to the very low fuel price differential between fuel with 0.5% and 0.1% sulphur content, and only applicable in voyages crossing a SECA.

3.2. *The MP should be uniform in different ports*

In section 3, we showed that the *MP* should be ship and voyage specific. The actual justification is to ensure a level playing field amongst participating ship operators, but also port authorities. For Game I, we saw that the inspection probability solely depends on the ratio of the ΔFC over the *MP*. Let us consider that the ship operator is designing their network and route itinerary. For one particular geographical area, there are two options of ports in different but neighbouring countries, with an almost equal distance from the preceding port and the next port of call. The fuel consumption for the leg until reaching one or the other port, and the fuel consumption in the leg after thus port call would be approximately the same. However, if one of the two ports has a very different *MP*, the probability of inspection would be different, as well as the repercussions of getting caught not complying.

3.3. The importance of IC

Lowering the *IC* would result in a higher number of inspections and a better overall performance of the system (lower social cost). Considering also the importance of having a level playing field, we concluded that the *MP* should be dependent on the *ΔFC*, so that all vessels would have the same probability of inspection, but also in such a manner that the penalty is harsher for higher polluters. From the PSC point of view, if the *IC* is the same regardless of the vessel type, the PSC may prefer to spend their resources at larger ships that would reward the PSC with a higher *MP* (due to the higher *ΔFC*). After all, the probability of non-compliance would be the same for all vessels. This could be avoided if the regulator requires a documentation of the vessels inspected to ensure that there is no "preferential" treatment and selection of vessels to be inspected each time.

3.4. Liability for violations

Another important issue is who has the liability to pay in case of an inspected non-compliance. In section 2, the assumption is that the ship operator is the one paying the *MP*. In reality, the situation may be more complicated. Occasionally the ship owner and the ship operator are different. The owner may charter the vessel to the ship operator, and depending on the contract, the one paying for the fuel should be the one held responsible if the fuel is not compliant. At the same time, the ship owner has to decide of whether to invest in a scrubber system, and not the operator. In such cases, the ship owner may find it profitable to retrofit the vessel with the scrubber, as it could allow a higher charter rate that will pay back the investment. The ship operator may prefer to charter a retrofitted vessel (yet a higher charter rate) as this could allow sailing at faster speeds due to the lower fuel cost of HFO. We therefore suggest that it should be very clear that the *MP* should burden the party that decides (and pays) for the fuel used in the affected voyages. There is the issue of proving intent in the case of a non-compliance, which depending on the country where the PSC may require taking the ship operator to court. We have to note that if an inspection with a fuel sample shows a very small exceedance of the sulphur limit, this may not have been on purpose and could be attributed to the fuel supplier. However, with the current global cap or with the 0.1% limit inside SECAs, using a fuel with a sulphur content between 2 and 3.5% (theoretically only sold to scrubber-equipped vessels) would not be at the fault of the bunker supplier. If the bunker supplier admitted to knowingly sell high-sulphur fuel for the price of low-sulphur fuel, the damage to their reputation would far exceed the potential benefits. The ship operator could claim compensation for the damage caused in the engine from the use of high-sulphur fuel (due to the different lubrication requirements). It is our understanding that the moral damage to an established shipping firm would be graver than any potential fuel saving, and associated fiscal penalties for non-compliances. However, the need for proper inspections and enforcement is important to dissuade poor practices from some operators. Finally, due to the potential delays from court proceedings until the intent to a non-compliance was proven, we can suggest that the PSC has the power to hold the ship at the port until a deposit equal to the *MP* is paid. If the ship operator proves at the court that they were not intentionally using high-sulphur fuel, then that deposit should be returned to them.

3.5. The value of c and other external costs

A small commentary here is necessary to clarify how the value of *c* could actually be estimated in the real world. In essence, *c* would represent the value of the external costs of transportation, or of the environmental damage due to increased SO_x. Typically, a monetary value is used for each ton of emissions to be internalized which can then be used in conjunction with either the fuel consumed, or the emissions generated based on the transport activity. Regarding maritime transportation, Tichavska and Tovar (2017) review methodologies for the estimation of external costs from vessel emissions near ports. The EU has produced a list of estimates through its external cost calculator for the EU Marco Polo programs (Brons and Christidis, 2012). Such calculators tend to differentiate depending on the area of pollution (for example the North Sea has a higher value than the Baltic Sea) and provide a range of values based on impact. For SO_x in particular, the external cost estimates range from 1.4€ to €167 per kg of emissions. This of course raises the question on whether compliance with the regulation is more important near areas with a higher cost, or near residential centers (coastlines, ports) rather than in the middle of the Pacific Ocean (where enforcement is much more difficult). We note that enforcing the internalization of external costs (pollutant emissions in our case) is outside the capability of bodies such as the IMO. In theory, this internalization could only be done on a country (or a block of countries such as the EU) level through the passing of relevant regulation.

For illustrative purposes, a value of *c* equal with $15,000 per ton of SO_x, would result in an environmental cost of $71,400 per day for a typical Ro-Ro ship operating within a SECA (0.1% limit), and $153,000 per day for a transpacific service outside SECAs (0.5% limit). These costs amount only to impact of the additional SO_x emissions in the case of a non-compliance. In reality, all emissions species should be internalized in the calculation. It is well known that sulphur abatement results in increased CO_2 emissions due to either the use of scrubbers (higher energy consumption), or the higher CO_2 emission factor of low-sulphur fuels.

4. Conclusions and further work

The paper formulated a game theoretical framework that can propose monetary fines for violations in order to minimize incidents of non-compliance. We showed that a very heavy fine compared to potential fuel savings could increase levels of compliance among ship operators, and decrease the requirement of the port to inspect. The *MP* should be a function of the *ΔFC* to ensure a fair treatment. Then the probability of inspection is the same for all vessels regardless of their size, owner, charterer, or affiliation with the port. At the same time, it is extremely important that the penalties are using the same mechanism in every port that has inspection capabilities to ensure a level playing field not only amongst ship operators, but also amongst port authorities. We propose that the *MP* should be very clearly stated, and the same in all geographical areas, calculated as a function of the specific ship and voyage. The MP could then be set in such a way to ensure that each PSC has the capacity to perform the required number of inspections in the resulting Nash equilibrium. Setting an extremely high *MP* would be infeasible for practical reasons, and we expect that the cost for a violation should not be higher than the cost of a scrubber retrofit. However, we do propose an alternative enforcement mechanism where a scrubber (or alternative technology guaranteeing compliance) retrofit is mandatory after repeated violations.

The paper has also shown how important it is to minimize the *IC* in order to reduce the social cost (minimize violations). By achieving a reduction in the *IC*, the PSC will be able to both minimize its costs and maximize compliance from the ship operators (assuming that the *MP* will not change). We believe that this will be possible in the future due to the economies of scale of having dedicated staff performing inspections. The *IC* can also be reduced through the following concept. The port inspecting agency can decide to invest in UAV or fixed stations at specific crossings that can alert on the possibility of a non-compliant vessel. In the game, such an investment would require some capital costs, but would raise the probability of catching a non-compliant ship operator.

For example, unsuspecting vessels that had been "sniffed" and were shown to be clean would be removed from the pool of possible inspections when arriving at the port, and thus increase the probability of catching non-compliant vessels. Other indications of a non-compliance could be a very high sailing speed for a ship that is not equipped with scrubbers compared with ships of the same size and type, since the optimal speed would depend on the fuel price of the fuel used.

An interesting extension in this line of work would be to consider that the PSC may be tempted to "turn a blind eye" at certain violators. This could either be at the expense of a bribe in order to avoid inspecting a particular ship, or simply in order to appease a strong client that regularly visits the port (reducing delays due to bureaucracy when inspecting the ship). To draw parallels with other inspection games, this would be similar to offering a bribe to a tax inspector. When the PSC assumes the responsibility for checking for compliance, it might be in the interest of the port to be less thorough in its investigations. The port authority may on purpose never inspect visiting ships for compliance to the regulations in a way to entice more ships to call at their port. For example, the port authority may value more the increased volumes than the *MP* received when catching a non-compliant ship. If on the other hand the inspection is conducted by a dedicated service from the regulator (e.g. the IMO) at all ports of call, then it can be expected that the inspections would be fair. Other extensions include more complicated versions of these games. For example formulating the problem as a repeated game and selecting an appropriate discount factor in the payoff specification to account for future actions. A repeated game has the additional the complexity that the ship operator does not reveal their strategy at each game, unless inspected by the PSC.

A final extension in this line of work that we intend to consider is the issue of the optimal deployment of UAVs and sniffers. The idea here is that this may allow a stealthy inspection of a vessel at the high seas, so that the ship operator is not aware of that occurrence. Xia et al. (2019) considered the drone-scheduling problem to monitor vessels inside ECAs, assuming a fixed station from where to launch the UAV sniffer. However, due to the limited range and autonomy of such vehicles, sampling plumes far from the shore and other fixed stations is infeasible. We propose the deployment of vessels that serve as a mobile base of operations for the launch of sniffers as an interesting subject for further work. Either using dedicated vessels, or through cooperation with operators wanting to ensure their competition is not cutting corners. It is important to ensure that the environmental cost of such practices is lower than the environmental costs of non-compliances.

Author statement

Thalis P.V. Zis: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – Original Draft, Funding acquisition.

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