System Impulse Modeling of the Green Shipping Policies

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Abstract:

Shipping emissions has aroused significant attention along with the rapid growth of the international maritime transportation. There are plenty of policies and measures in practice in regulating the shipping emission and a lot of studies have investigated the significance and impacts of these policies and measures to the shipping industry. It is obvious that they are inter-determined. However, previous studies have analyzed these emission abatement measures separately instead of in a systematical way. Therefore, this study tries to investigate the shipping emission abatement polices and measures in a system model in which each polices and measures are correlated with others. When there is a change in a certain policy or measure, the impact will transmit to other polices and measures. Hence, we can analyze the dynamic movement of the system by imposing an impulse to certain polices or measures. By introducing the definition of the pulse process and its stability, this study discusses the evolvement and adjustment of the shipping emission system in detail. The dynamics of the system is then discussed when there is a pulse in each of the variable. The results suggest that the slow steaming practice of ships may decrease emissions under certain circumstances; it actually increases the total emissions in the shipping industry. It also suggests that although the implementation of the EEDI policy can promote the adoption of the EEOI policy, the EEOI actually relieve the demanding for the EEDI policy. It also reveals that the effect of bunker price on emission reduction is larger than other measures.

Keywords: Shipping emission, System impulse modeling, EEDI, EEOI, MBMs

1. Introduction

The shipping transportation is one of the most environmentally friendly modes in terms of energy efficiency (IMO, 2012), which carries over 80% of the global trade volume (UNCTAD, 2017). However, due to the huge trade volume carried and the large number of vessels sailing around the world, substantial quantities of emissions are produced from the shipping industry (Psaraftis & Kontovas, 2013; Sun, Yan, Wu, & Song, 2013; Yang, Lu, Haider, & Marlow, 2013). According to the 2009 GHG (Green House Gas) study by International Maritime Organization (IMO)(IMO, 2009a), carbon dioxide (CO2) emissions from shipping transport accounts for 3% of the global CO2 emissions. It is estimated that the emissions would increase by 150-250% by 2050 if there is no active countermeasure to control the amount of emissions(IMO, 2009a). For this reason, the IMO established a goal to reduce the amount of CO2 emissions by 20-50% by 2050 from existing vessels (IMO, 2009a).

Since ships move between different jurisdictions, there is a need for the IMO, a specialized agency of the United Nations, to be responsible for regulations on the prevention of maritime pollution by ships (Fagerholt, Gausel, Rakke, & Psaraftis, 2015). Therefore, the Energy Efficiency Operational Indicator (EEOI) and Energy Efficiency Design Index (EEDI) are developed for existing and new vessels separately (IMO, 2009, 2009a, 2010) to restrict emissions in which three strategies are suggested: vessel size enlargement, voyage speed reduction, and new technologies application. In addition to the operation and technical measures, various Market-based Measures (MBMs) have also been introducing such as a carbon tax and Emissions Trading Scheme (ETS)(Miola, Marra, & Ciuffo, 2011; Wang, Fu, & Luo, 2015). It aims to motivate industrial organizations to use up-to-date technological, operational and managerial practices in emission reduction (European_Commission, 2013; IMO, 2009a).

Among the above three types of polices in emission reduction, speed is a key variable in maritime transportation (Psaraftis & Kontovas, 2013). In general, ships travel slower than other modes and it usually lasts 1-2 months for long-distance trips. Therefore high speed is significant during boom periods as it entails the economic added value of faster delivery of goods, lower inventory costs and increased trade throughput (Psaraftis & Kontovas, 2013). However, slow steaming and optimizing ship speed are receiving increased emphasis these days because of increasing fuel prices, depressed market conditions and environmental issues of air emissions.

Figure 1 illustrates the bunker price trends from 1973 to May, 2018 for 180st, 380cst, Gas Oil, Marine Diesel Oil (MDO) and Marine Gas Oil (MGO) from different locations. The bunker price has witnessed a remarkable increase from the early 2000s and the price during 2010 to 2013 is almost six times higher than ten years ago. Currently, although there is a sharp decrease in 2014, it is still three times higher than that in1990s. As discussed by Stopford (2009) and Ferrari, Parola, and Tei (2015), the fuel cost accounts for almost half of the overall operational costs of a ship. In addition, the impact of speed on fuel consumption is nonlinear, i.e., a ship goes faster will emit much more than the same ship going slower.

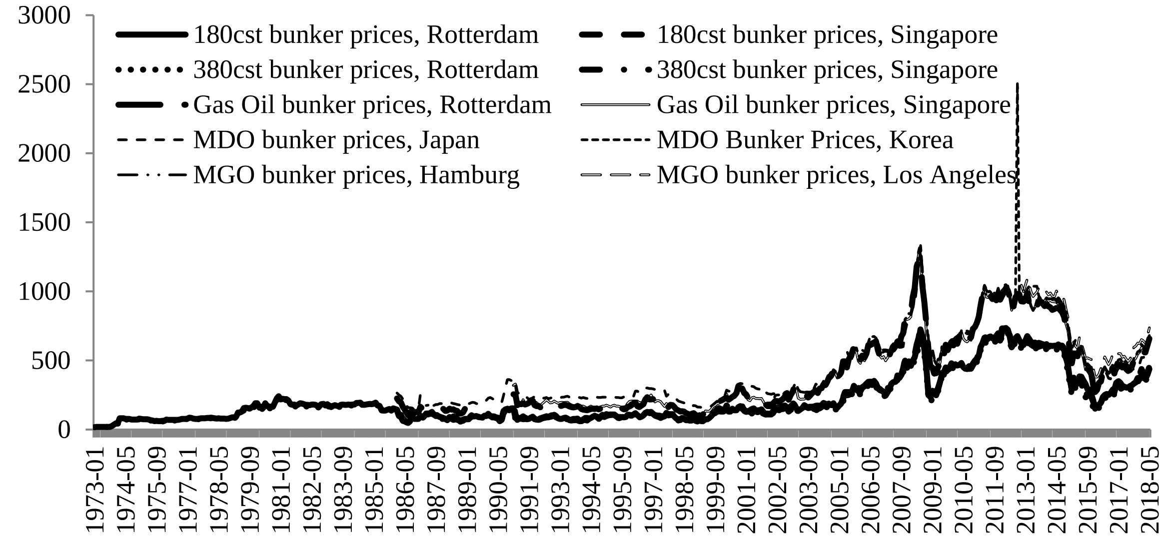

Figure 1. Trend in fuel prices (US$/tonne)
Source: Clarksons Shipping Intelligence Network (Clarksons, 2018).

As mentioned above, the technical, operational, and market based policies and the ship speed and fuel price measures all impact the shipping emissions. It is obvious that they are inter-determined. There are many studies discussed the EEDI and EEOI policies in restraining emissions (Acomi & Acomi, 2014; Ančićn & Šestan, 2015). Meanwhile, lots of studies investigated the feasibility of implementing the market-based polices (Heitmann & Khalilian, 2011; Lee, Chang, & Lee, 2013; Miola et al., 2011; Shi, 2016; Wang et al., 2015). In addition to these, plethora of studies have analyzed the role of slow steaming in emission abatement and discussed the optimal ship speed for different types of ships or routes under different scenarios (Corbett, Wang, & Winebrake, 2009; Doudnikoff & Lacoste, 2014; Fagerholt et al., 2015; Ferrari et al., 2015; Woo & Moon, 2013). However, these emission abatement measures are analyzed separately instead of systematically. A systematic analysis is significant as there are mountains of strategies in emission abatement in the shipping industry and most of them are inter-correlated. For example, the implement of the EEOI policy will lead to slow steaming which in turn will decrease emissions. Meanwhile the EEOI policy will also motivate the implement of the EEDI strategy, which also results in speed reduction.

Therefore, this study tries to investigate the shipping emission abatement polices and measures in a system model in which each polices and measures are correlated with others. When there is a change in a certain policy or measures, the impact will transmit to other polices and measures. Hence, we can analyze the dynamic movement of the system by imposing an impulse to certain polices or measures.

The remains of this study are arranged as follows. Section 2 presents the systematic model of emission polices. Section 3 illustrates the systematic model of the pulse process. Section 4 discusses the dynamics of the pulse process. Section 5concludes the study.

2. System Modeling of Emission Polices and Measures

Since we are aiming to investigate the structural inter-correlations among various emission abatement policies and measures, the bivariate correlations are used as inputs to the systematic model (Figure 2). In practice, there are dozens of polices or measures restricting shipping emissions. We just focused on seven key measures that are discussed a lot recently.

As the focus of the systematic model is to restrict emissions from the shipping industry, we denote V_1 as the shipping emission volume, which is put in the middle of the system diagram. Since shipping emission is serious concerned by the public, we include the environmental quality as variable V_2. It is obvious that V_1 impacts V_2 negatively. So, there is a "-" sign on the line from V_1 to V_2.

As mentioned above, shipping speed is one of the most important measures to reduce emissions (Corbett et al., 2009; Doudnikoff & Lacoste, 2014; Fagerholt et al., 2015; Woo & Moon, 2013), especially under the current depressed economic situation. Therefore, many shipping companies have chosen to slow down their shipping speed instead of laying up some of the vessels. In Figure 2, the slow steaming measure is denoted as V_3. It is obvious that the current emission situation has motivated the shipping company to slow down ship speed. Therefore V_1V_3 is positive. This down slowing ship speed can help improve the environmental quality in turn. So, V_3V_2 is positive.

Currently, the most discussed polices in shipping emission restriction are the EEDI and EEOI, which are denoted as V_4 and V_5 separately. As they are designed to reduce emissions, the paths of V_4V_1 and V_5V_1 are both negative. Meanwhile, they are also connected with other factors. It is obvious that the slow steaming activities can facilitate the implementation of the EEOI requirements (V_3V_4 is positive). Meanwhile, the implement of EEOI will lead to a condition improvement for the implement of EEDI, so V_4V_5 is positive.

As bunker consumption is one of the most important parts in operating a vessel. Bunker price is also considered in this model, which is denoted as V_6. It is naturally derived that the bunker price negatively impacts shipping emissions according to economics theory. So, V_6V_1 is negative. It is naturally derived that the increase of the bunker price will positively motivate the enforcement of the EEDI as which can be achieved by decreasing the fuel consumption of the engine in the ship building period. Therefore, V_6V_5 is positive.

Finally, although there is no consensus on how to carry out the MBMs policy yet, many researchers agreed on the significance of MPMs policy on emission abatement (Heitmann & Khalilian, 2011; Lee et al., 2013; Shi, 2016; Wang et al., 2015). Then V_7V_1 is negative. It is also revealed that a MBM is necessary for the shipping industry as the adopted technical and operational measures alone would not be sufficient in achieving absolute emissions reduction (Shi, 2016). Therefore, we propose a negative impact of environmental quality on the implement of the MBMs policy (V_2V_7 is negative), i.e., the keep deteriorating of the environment will urge various institutions and governments to compromise on the adoption of the most suitable MBMs to make its proportionate contribution to addressing global climate change.

Figure 2 is an illustration of the structural direct connections between various policies and measures, which is used as an input to the impulse analysis in the next section.

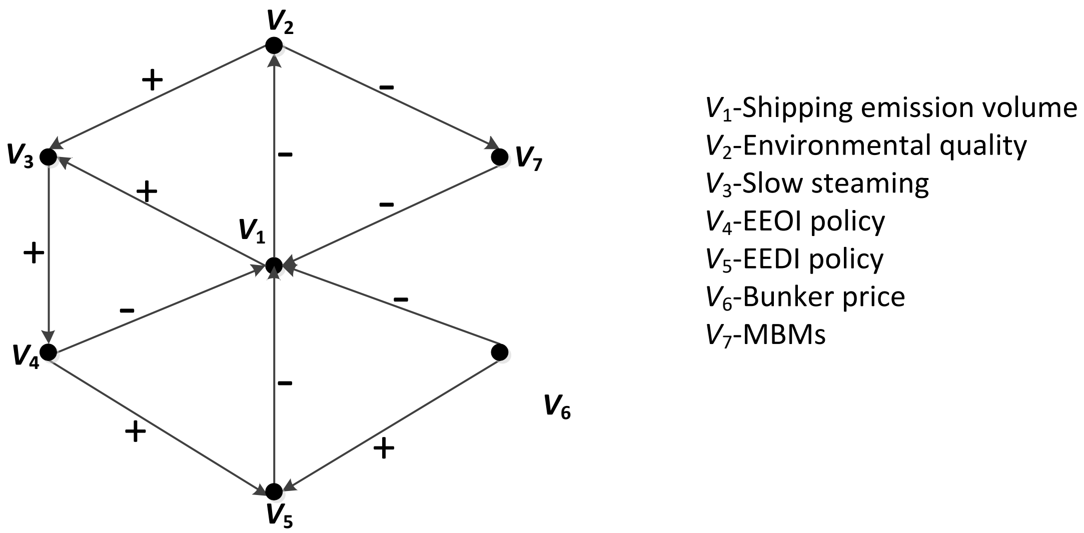

Figure 2: Structural connections of measures impacting shipping emissions.

3. Impulse Analysis of the System and Discussion

To analyze the inter-correlations between variables, we denote matrix A==(a_{ij}) as:

$$a_{ij} = \begin{Bmatrix} 1, & if\ V_iV_j\ is\ positive \\ -1, & if\ V_iV_j\ is\ negative \\ 0, & if\ V_iV_j\ is\ zero \end{Bmatrix} \quad (1)$$

Then the adjacency matrix of Figure 2 can be represented by the matrix in Equation 1. Actually, it will be more significant if we can calculate the actual effect of each variable on other variables. For example, V_1V_3=0.1 suggests a 10% (or 1 unite) decrease of the ship speed if the emission increase 1% (or 1 unit). However, the effect values are relatively difficult to obtain currently. So, we just focus on the directional adjacency matrix, A, in this study.

$$A = \begin{vmatrix} 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 1 & 0 \end{vmatrix} \quad (2)$$

3.1 The Pulse Process

To investigate the impact of a variable's sudden change on the dynamic evolvement of the system, $V_i(t)$ is denoted as the value of variable V_i at time t, and $P_i(t)$ is denoted as the change of V_i at time period t, which is called a **pulse**. It is obvious that,

$$V_i(t+1) = V_i(t) + P_i(t+1),\ i = 1,2,\ldots,7,\ \ t = 0,1,2,\ldots \quad (3)$$

$$P_j(t+1) = \sum_{i=1}^{8} A_{ij} P_i(t)\,,\ j = 1,2,\ldots,7,\ \ t = 0,1,2,\ldots \quad (4)$$

Denote $V(t)=(V_1(t),V_2(t),\ldots,V_n(t))$ and $P(t)=(P_1(t),P_2(t),\ldots,P_n(t))$, then Equation (3) and (4) can be illustrated as,

$$V(t+1) = V(t) + P(t) \quad (5)$$

$$P(t+1) = P(t)A, \; t = 0,1,2,\ldots \quad (6)$$

Without loss of generality, we suppose

$$V(0)=P(0) \quad (7)$$

If we impose a pulse at the initial time, the values of $P(t)$ and $V(t)$ at any t can be calculated using Equation (5) to (7). This system evolvement caused by imposing one or more pulses at the beginning is called a **Pulse Process**. It is called **Simple Pulse Process** if there is only one variable is 1 (or -1) in $P(0)$.

3.2 Stability of the Pulse Process

As discussed in Jiang, Xie, and Ye (2013), when there is a pulse at t=0 (a variable is changed), if all the values of the variables in the system do not increase (or decrease) infinitely at any time, the pulse process is stable. More precisely, for all the i (variables) at any time t, if $|P_i(t)|$ is finite, it is called **Pulse Stable,** and if $|V_i(t)|$ is finite, it is called **Value Stable**.

Because $P(t)$ and $V(t)$ are calculated by Equation (5) and (6), it is obvious that the stability of the system is determined by the eigenvalue (λ) of matrix A. Lucas (1996) has proposed the following theorems to ensure the stability of the pulse process.

Theorem 1: the necessary condition for the pulse process to be pulse stable is $|\lambda| \leq 1$.

Theorem 2: the sufficient condition for the pulse process to be pulse stable is $|\lambda| \leq 1$ and the characteristic roots are all single roots.

Theorem 3: the necessary and sufficient condition for the pulse process to be value stable is that the process is pulse stable and $\lambda \neq 1$.

Then, the characteristic polynomial for matrix A can be derived:

$$f(\lambda) = \lambda^4(\lambda^3 + 2) \quad (8)$$

Because $f(-1)=1$, $f(-2)=-96$, there is a root within (-2,-1). According to Theorem 1, there must be an instable pulse in some certain simple pulse process.

3.3 Adjustment of the Pulse Process

To convert an unstable process to a stable one so that it satisfies Theorem 1 and 2, the values in matrix A must be adjusted. Although there is no general conclusion to help transform an adjacent matrix system to a stable pulse process, there are some methods that can be applied to some special matrix systems. Among them, one is called **Advanced Rosette**, in which there are bi-directional connections in a diagram and a central vertex exits on all closed circuits just like the diagram in Figure 2. Here, a closed circuit is a path from a vertex to other points along their directional edges without repeating and finally goes back to the starting vertex.

In Figure 2, V_1 is the vertex, V_1V_2, V_2V_7 and V_7V_1 comprised a closed circuit, $V_1V_2V_7V_1$. The number of the directed edges is called the **length** of the closed circuit. So, the length of closed circuit, $V_1V_2V_7V_1$, is 3. If the number of negative directed edges is an odd number, then the **sign** of this closed circuit is -1, otherwise it is +1. Let us denote a_k as the summation of all the k-edges closed circuits. Then, r is the largest number that satisfies $a_r \neq 0$. Therefore, the stability of an advanced rosette diagram can be determined by $\{a_1, a_2, \ldots, a_r\}$ with the following theorem (Lucas, 1996):

Theorem 4: the necessary condition for an advanced rosette diagram system to be pulse stable is

$a_r = \mp 1$ (9)

$a_k = -a_r a_{r-k}, \quad k = 1,2, \dots, r-1.$ (10)

Theorem 5: the necessary and sufficient condition for an advanced rosette diagram system to be value stable is

$\sum_{k=1}^{r} a_k \neq 1$ (11)

Theorem 4 can be used to find the violations in the system, so that the unstable system can be transformed to a stable one. Seeing from Figure 2, there is no circuit with one and two edged paths, so a_1=0 and a_2=0. There are two 3-edges closed circuits, which are $V_1V_3V_4V_1$ and $V_1V_2\ V_7V_1$. As the signs of these two circuits are both –1, so a_3=-2. Similarly, there is one 4-edges closed circuits, which are $V_1V_3\ V_4\ V_5V_1$. Since the sign this closed path is -1, so a_4=-1. Because a_k=0 for all the k>4, so r=4. We finally get the serial of {a_1, a_2, a_3, a_4}={0, 0, -2, -1}.

According to Equation (9) and (10), it must satisfies the following equations to be stable:

$a_1 = -a_4 a_3$ (12)

$a_2 = -a_4 a_2$ (13)

$a_1 = -a_4 a_3$ (14)

Obviously, Equation (13) is satisfied. To meet the requirements of Equation (12) and (14), we can only change a_3 to 0. Seeing from Figure 2, the signs along the 3-edges closed circuit of $V_1V_2\ V_7V_1$ cannot be changed. Similarly, the signs of paths V_1V_3 and V_4V_1 are determined according to reality. The only path we can change is V_3V_4. A negative impact of slowing steaming on the implementation of EEOI is more reasonable, as it will motivate public agencies to consider of the enforcement of EEOI if the ship speed cannot be slow down. Then, a_3 is 0 now. Since the sign of the path from V_3 to V_4 has been changed, the sign of the 4-edges circuit is also change to +1, i.e., a_4=1. The serial of {a_1, a_2, a_3, a_4} is changed to {0, 0, 0, 0, 1} and Equation (12) and (14) are all satisfied.

Above analysis can only ensure this advanced rosette diagram system to be pulse stable. According to Theorem 5, the summation of the a_is should not equal to 1 for the system to be value stable. Seeing from Figure 2, there is only one 4-edges closed circuits, which is $V_1V_3V_4V_5V_1$. The only path that can be changed is V_4V_5 without influencing the system too much. By changing the positive sign from V_4V_5 to negative, the serial of a_i changes to {0, 0, 0, -1} and all the Theorems are satisfied.

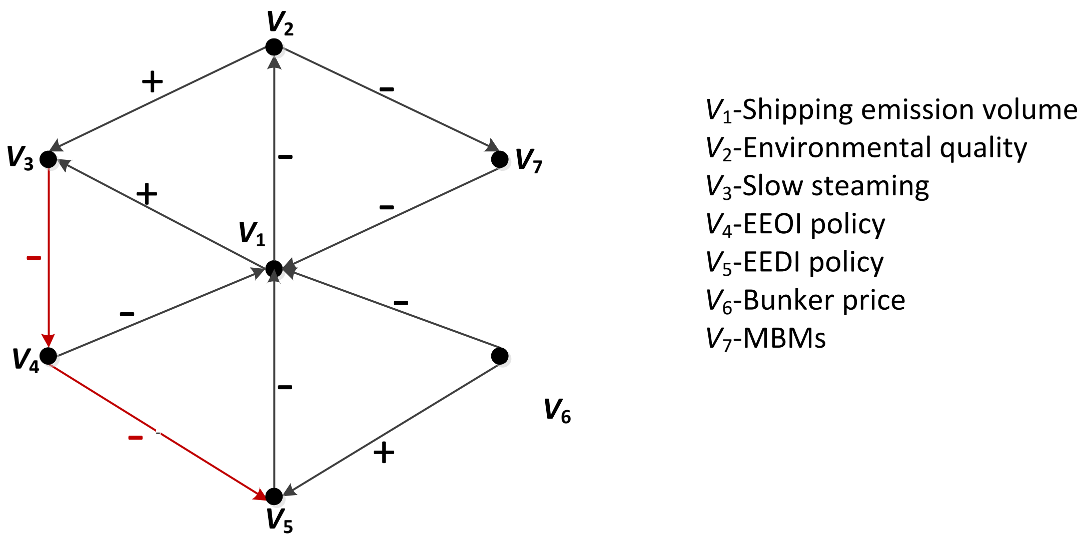

Figure 3: Adjusted structural connections of measures affecting shipping emissions.

According to above Theorems, the shipping emission system illustrated in Figure 3 is a stable pulse process, i.e., under any sudden changes of any variables in the system, the values changes of all the variables in the following periods are finite.

4. Discussion of the Pulse Process

To illustrate the evolvement of the variables in the system, we draw the variables at different periods when there is a simple pulse in each of the variables (Figure 4-9). Figure 4 is the pulse process of V_2 (Environmental quality). When the environmental quality deteriorates in time 0 (P_2 (0) = -1), it will bring some pressure to the implement of the MBMs policy directly, which will reduce the shipping emission in turn. The pulse will then transmit to the implementation of slow steaming, EEDI and EEOI gradually. Finally, all the variables will be stable at 1 or -1. The pressure on the implementation of the MBMs and EEOI policies are stable at 1, while, the value of emission, slow steaming, environmental quality and EEDI will be stable at -1. The bunker price will not be impacted under this pulse.

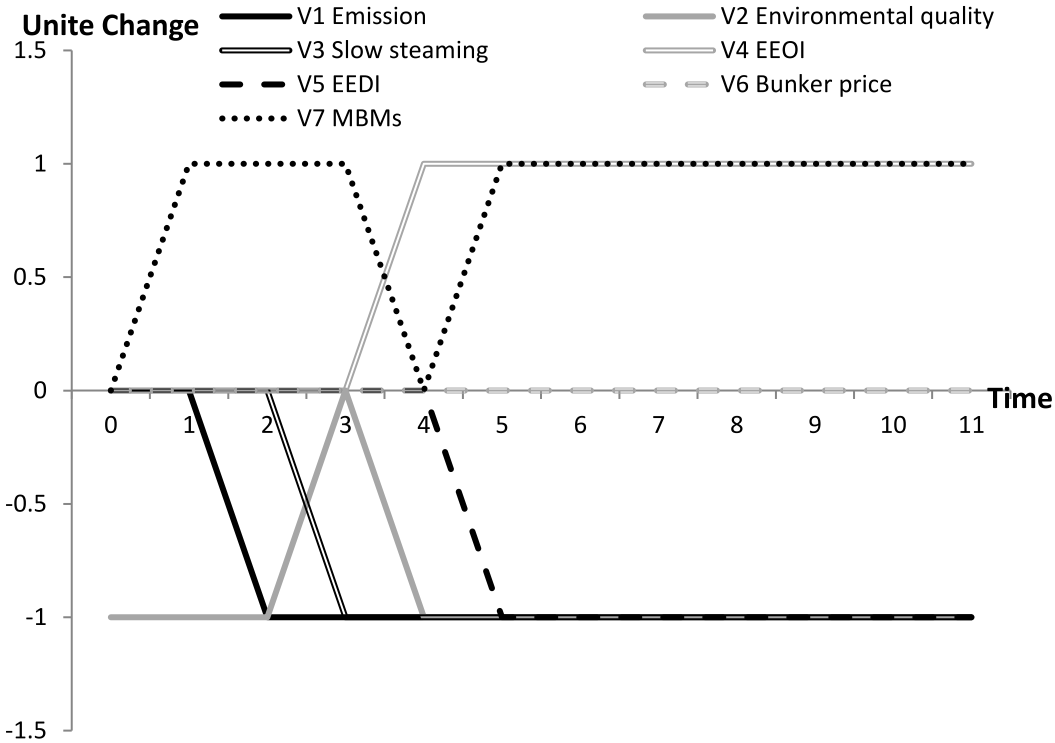

Figure 4: System evolvement with a pulse in V_2 (Environmental quality).

When there is a pulse in V_3 (slow steaming), the system will move dynamically as illustrated in Figure 5. As analyzed above, the active slow steaming practice may relieve the pressure on imposing the EEOI policy and it in turn impact the implementation of the MBMs policy negatively. On the other hand, it positively impacts the implementation the EEDI policy and the environmental quality. It is worth noting that, under current shipping transportation scales, this slow steaming practice actually increases the shipping emission volume. This result is similar to the results in Doudnikoff and Lacoste (2014), where the authors found that the total emissions are increased through slowing down within SECA and speeding up outside SECA for shipping companies to maintain a fixed service frequency.

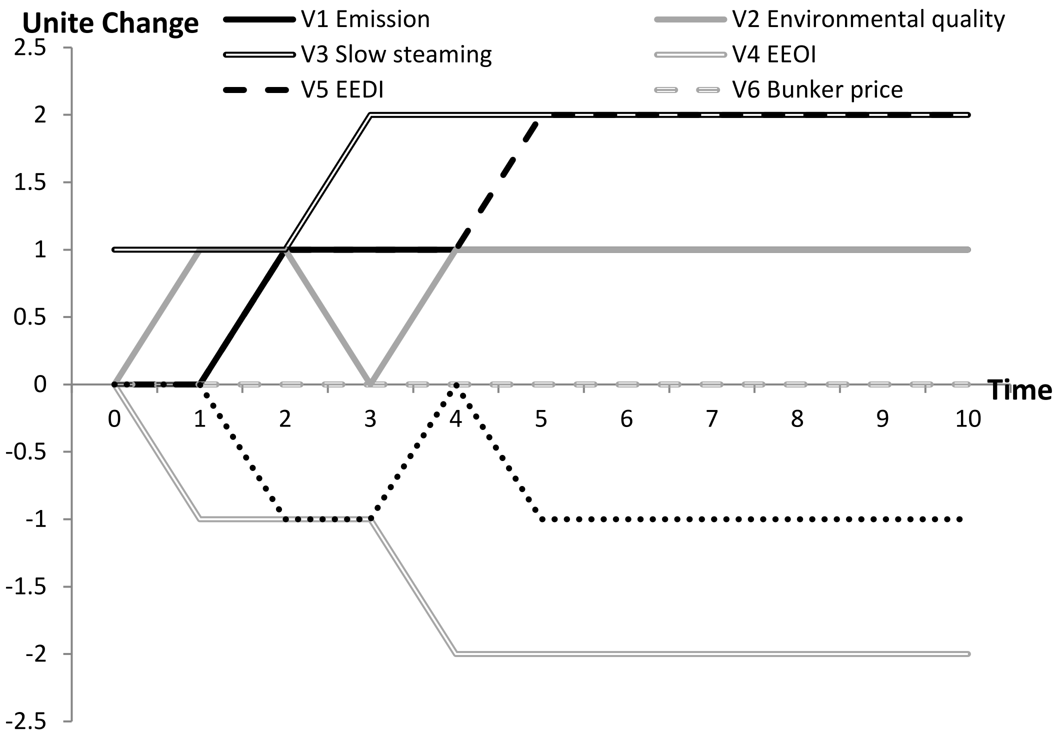

Figure 5: System evolvement with a pulse in V_3 (Slow steaming).

The dynamics of the system variables with a pulse in the EEOI (*V_4*) policy are different (illustrated in Figure 6). The implementations of the EEOI policy will negatively influence the practice of the EEDI policy as discussed previous. Although it impacts the emissions, environmental quality, slow steaming and MBMs policies shortly, in the long-run, the effects return to 0, i.e., these variables return to their initial level. This suggests the ineffectiveness of the EEOI policy if it is implemented alone.

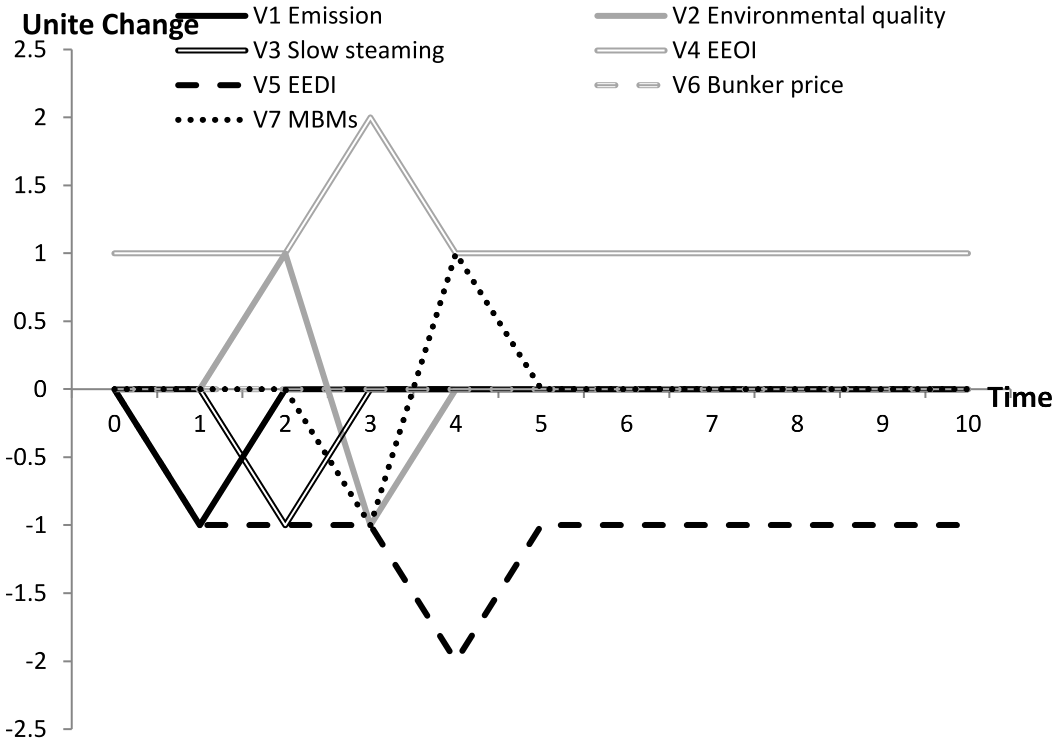

Figure 6: System evolvement with a pulse in V_4 (EEOI).

Figure 7 illustrates the dynamics of the system when there is a pulse in the EEDI policy. It will decrease the emission level at the first period and which will be kept in a stable level in the following periods. However, the improved shipbuilding technology motivated by the imposed EEDI policy will relax the demand for slow steaming. This is indicated by the lowered stable level of slow steaming variable. Similar to this, the improvement in shipbuilding will improve the operation of the ship and smooth the implementation of the EEOI policy. Different with these, the impacts of carrying on the EEDI on the environmental quality and MBMs are short-term. They will return to their original level after several periods because of the complicated dynamic system.

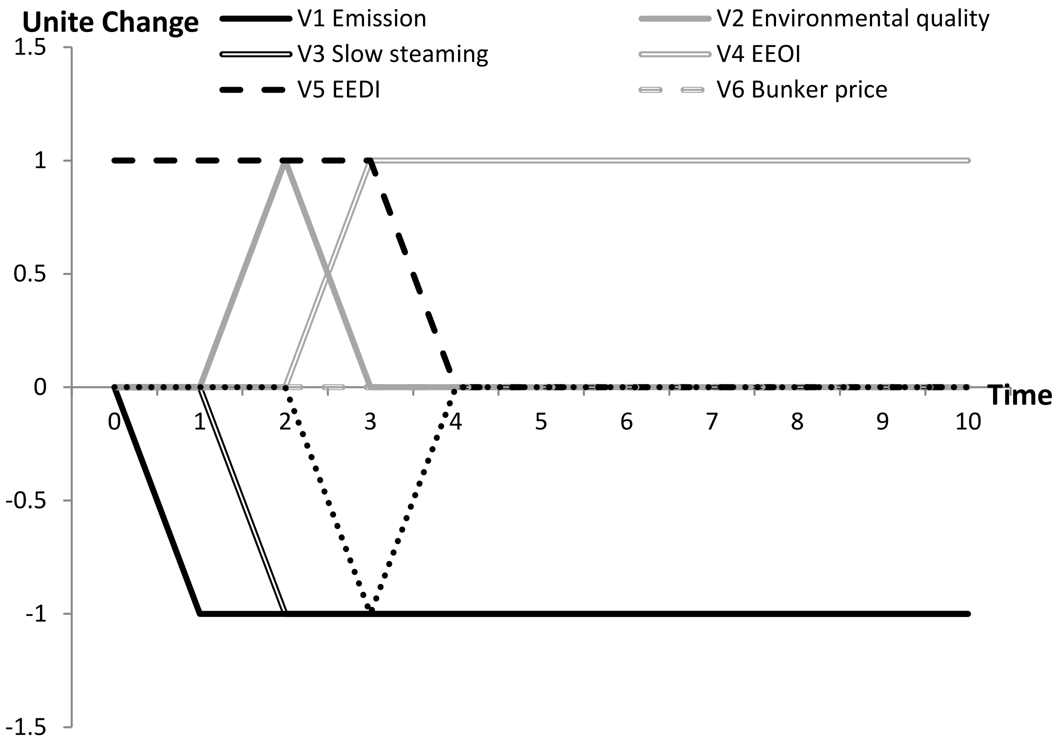

Figure 7: System evolvement with a pulse in V_5 (EEDI).

When there is a pulse in V_6 (bunker price), the dynamics of the system is more significant than other variables, which is drew in Figure 8. First, it decreases the shipping emissions gradually in the first two periods and keeps in this lower emission level afterwards. Before period 4, this increased bunker price motivates the progress in shipbuilding technology as suggested by the increased value of EEDI. However, its impact on the EEOI starts at period 2 and which gradually increases to a stable higher level. After period 4, the impact on EEDI decreases to a negative level. Different with our perception, the increased bunker price lowers down the demand for slowing steaming as which has been digested by impacting the implementation of the EEDI and EEOI policies.

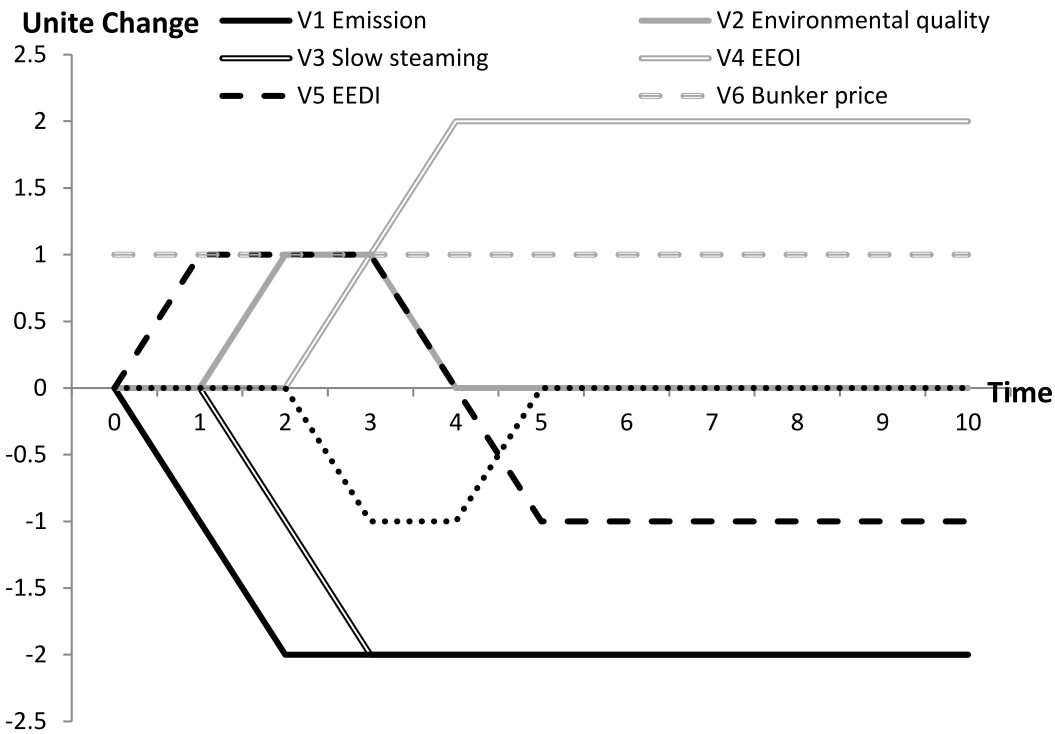

Figure 8: System evolvement with a pulse in V_6 (Bunker price).

The effects of an impulse in the MBMs policy are illustrated in Figure 9. First of all, it decreases the shipping emission and which is kept stable afterwards. Similar with other pulses, the impacts on the EEDI and EEOI policies are opposite. The effect on slow steaming is also negative.

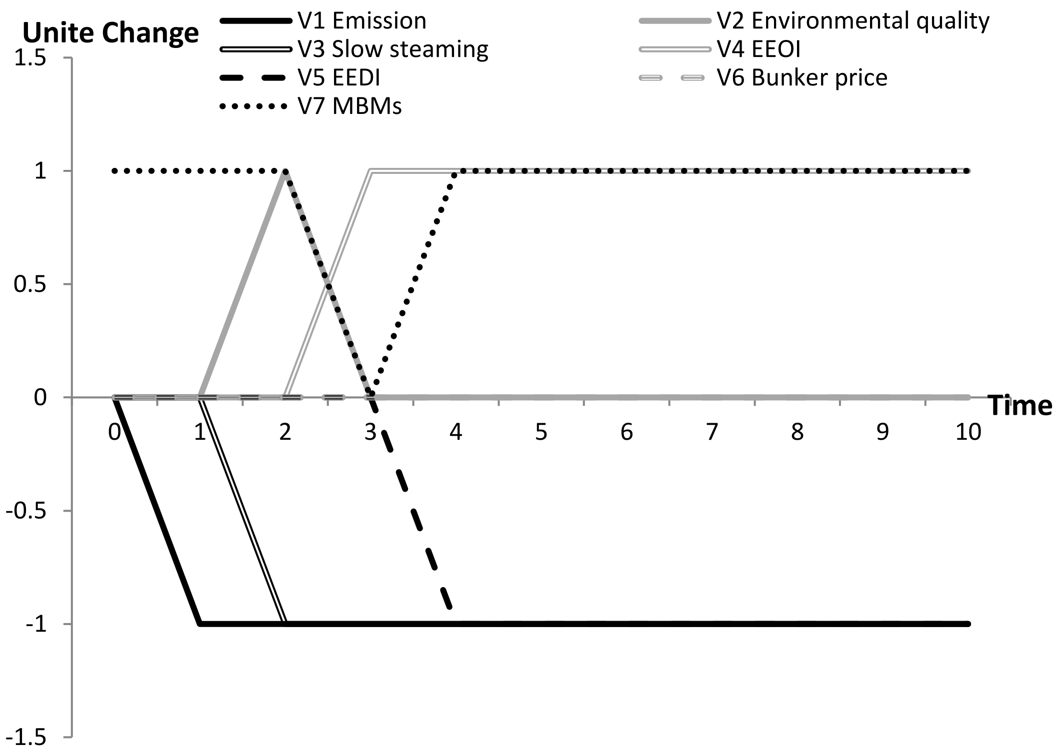

Figure 9: System evolvement with a pulse in V_7 (MBMs).

To summarize, we draw the emissions from each pulse in Figure 10. It is obvious that all the pulses have positive influence on shipping emissions except the slow steaming practice and the EEOI policy. The increase of bunker price has the biggest impact on decreasing emissions.

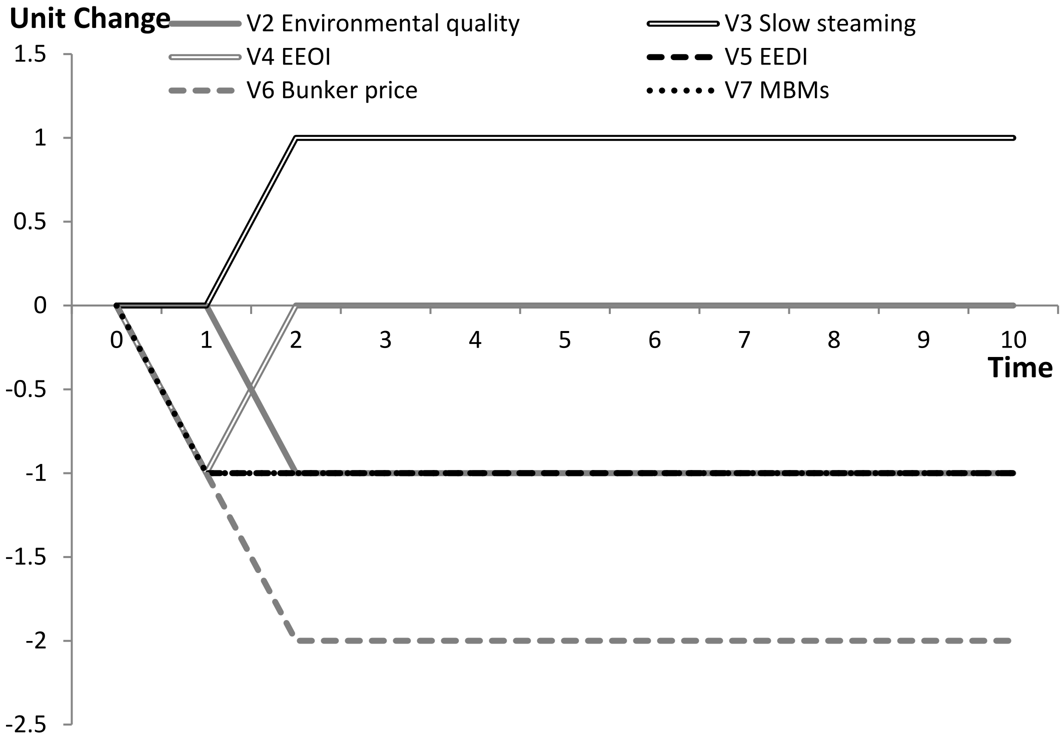

Figure 10: Emission dynamics under various pulses.

5. Conclusion

With the rapid growth of the international maritime transportation, the shipping emission has aroused a significant attention from international communities, maritime authorities, trade associations and academic scholars recently. Broadly saying, there are two types of policies and measures in the shipping industry. The most important one relates to policies issued by IMO, such as the several amendments of MARPOL 73/78/97 (IMO, 1997). It was revised again in 2008 with some specified approaches and phases to stringently control shipping emissions in the revised Annex IV (IMO, 2008). The IMO also established a goal of reducing the amount of CO2 emissions by 20-50% by 2050 (IMO, 2009a). The other type of policies and measures are those issued by port authorities or related associations. Such as the requirements of using shore power facilities for berthing ships.

As a result, there are plenty of policies and measure in practice in regulating the shipping emission and a lot of studies have investigated the significance and impacts of these policies and measures to the industry (Acomi & Acomi, 2014; Ančićn & Šestan, 2015; Corbett et al., 2009; Doudnikoff & Lacoste, 2014; Fagerholt et al., 2015; Ferrari et al., 2015; Lee et al., 2013; Miola et al., 2011; Shi, 2016; Wang et al., 2015; Woo & Moon, 2013). However, all of these policies and measures are analyzed separately without considering the mutual effects among them. Therefore, this study tries to investigate the inter-correlation of the emission abatement policies and measures in a systematic model by considering their structural correlations. By introducing the definition of the pulse process and its stability, this study discusses the adjustment of the shipping emission system in detail in section 3. Finally, the dynamics of the system is then discussed when there is a pulse in each of the variable. The results suggest: 1) the slow steaming practice of ships may decrease emissions under certain circumstances, it actually increases the total emissions in the shipping industry. 2) although the implementation of the EEDI policy can promote the adoption of the EEOI policy, the EEOI actually relieve the demanding for the EEDI policy. 3) the effect of bunker price on emission reduction is larger than other measures.

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