Sailing Speed Optimization in Passenger Ships with Proportion-based and Threshold-based Hypothetical Carbon Tax

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Abstract: With the ongoing climate change crisis brought about by global warming, several efforts against excessive carbon dioxide CO_2 emission has been initiated. One of the measures to discourage CO_2 emission is carbon taxing. However, this heavily affects the maritime industry. This study investigates the effect of imposing carbon tax on the ship owner's revenue, as well as the CO_2 emission of a passenger ferry on a simple two-port system. Several assumptions were made to simplify the model initially proposed by Wang and Xu. A simple brute-force sailing-speed optimization program written in Python was used to find the optimal revenue. Under these assumptions, the revenue follows a downward parabolic trend while carbon emission increases in a quadratic manner. In addition, imposing a carbon tax results in a 4%-5% decrease in optimal revenue with corresponding 11%-13% decrease in carbon emission, making the carbon tax effective in this case.

Keywords: Ferry, Carbon Taxation, Optimization

1. INTRODUCTION

Curbing Carbon Dioxide (CO_2) emissions is one of the main concerns when it comes to slowing down global warming. In lieu with this objective, one of the measures that some governments started to implement is carbon taxation. This policy aims to disincentivize economic activities that produce carbon emissions by increasing their costs, as well as directing innovation towards cleaner energy (World Bank). As a consequence, industries that mostly rely on carbon like the maritime and aviation industry will be affected by this policy. As of now, the Philippine government does not impose any form of carbon tax.

Given that the Philippines is an archipelago, intra-country marine transportation is vital when it comes to delivering goods, as well as providing a viable alternative to increasingly congested land transportation. With this, carbon emission from maritime activities will start to become a concern in the country.

This paper explores the feasibility of implementing a carbon pricing policy or carbon taxation in a Philippine setting. Section 2 explores some related works. Model formulation is the discussed in Section 3. Section 4 described the algorithm and Section 5 discusses the results of the simulation. Section 6 summarizes the outcomes and insights.

2. RELATED WORKS

There are several studies that looked at carbon emissions of cargo ships over longer distances. Corbett, et al. looked at speed reduction being a viable option under a CO_2 trading system. Prpic-Orsic and Faltinsen (2012) looked at estimating CO_2 emissions on various sea states. Wang and Xu (2015) presented an analysis of a ship owner's revenue model under chartering system for cargo ships under various carbon taxation systems.

Among these different works, the model presented by Wang and Xu is the most applicable in implementing a carbon pricing policy in the Philippines. Therefore, this paper will look at an analysis of ship owner's revenue model under a passenger ferry system under short distances using a modified model presented by Wang and Xu (2015), and a model will be derived for passenger ferries.

The resulting model will use brute-force algorithm to find the optimal sailing speed. Brute force algorithm has been used to solve adjacent optimization problems (Mahoor, et al. 2017)

3. MODEL FORMULATION

3.1 Passenger Ferry System

Consider a simple two-port passenger ferry system in which passengers board and alight the ship at each of the ports A and B. Figure 1 shows the graph representation of the two-port passenger ferry system.

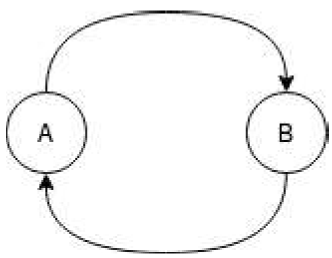

Fig. 1: Simple Two-port Passenger Ferry System

In the two-port system described earlier, there are multiple passenger ferries that dock each port. For simplicity, assume that each of these ferries are uniform and have the same characteristics (i.e.: passenger capacity, maximum sailing speed, weight, etc.). This study will focus on one particular ferry with passenger capacity denoted by n and maximum sailing speed denoted by v_{max}. In addition, it is also assumed that the ports have enough berthing space, hence any delays that would be caused by port congestion would be negligible.

In each port, the ship spends time (called dwell time) for passengers to alight and board the ship as well as to conduct maintenance on the ship. For simplicity, several assumptions have to be made with regards to the passenger ferry system. First, it is assumed that each passenger pays a uniform ticket price. Second, given that the local government are the ones running the ports, it is then assumed that part of the ticket price paid by the passengers go into the port. If p is the actual ticket price, then the amount that goes into the ship owner is denoted by p_{in}, where $p_{in} < p$. The determination of p_{in} is setup by an internal arrangement with the agency owning the port. In this case, since it is assumed that every passenger pays a uniform price p to the port, then it would also be reasonable to assume that the shipowner receives a uniform

p_{in} for each ticket sale. Third, it is assumed that the only source of revenue for the ship owner is the ticket sales.

In addition to the assumptions made about the passenger ferry system, there are also certain assumptions that can be made with regards to passenger behavior. First, it is assumed that passengers who board the ship on port A must alight port B, and vice versa. Second, it is assumed that the ship reaches full capacity before departing. Third, it is assumed that any cargo the passenger carries is minimal and does not affect the ship's capacity. With these, for a single trip, the ship owner's income is computed as:

$$In = np_{in} \tag{3.1}$$

where n is the passenger capacity of the ship.

Given that the ship owner's revenue in each trip is constant, the ship owner can increase profits by increasing the sailing speed since each trip would then becomes shorter. Assuming that uncertainties in travel time (due to external factors like weather) are negligible, a ship's travel time from one port to another can be estimated by

$$t_i = \frac{L}{v_i} \tag{3.2}$$

where L is the distance between Port A and Port B, and v_i is the ship's average sailing speed.

Hence, on a given time interval T, the number of trips (n_{trips}) a ship can make is given by

$$n_{trips} = \left\lfloor \frac{T}{t_i + t_{dwell}} \right\rfloor \tag{3.3}$$

where t_{dwell} is the ship's average dwell time in the port.

However, a faster sailing speed will lead to higher fuel costs and higher carbon tax. Hence, the optimal revenue tends to balance the increased revenue from more trips with the higher costs associated with fuel consumption and carbon tax.

3.2 Fuel Costs

On cargo ships, it has been shown that the ship's bunker consumption and sailing speed can be reasonably approximated by a cubic relationship provided the absence of enough historical data (Wang and Meng, 2015). Later on, a more accurate equation for the cargo ship's fuel consumption is described by the following equations (Wang and Xu, 2015):

$$N_e = 0.7355 \frac{D^{2/3} v^3}{C} \tag{3.4}$$

$$G = g_e N_e 10^{-6} \tag{3.5}$$

where,

G is the ship's hourly fuel consumption (in $tons/h$)
N_e is the cargo ship's power (in kW)
D is the ship's displacement (in tons)
v is the ship's sailing speed (in $knots$)

C is the ship's Admiralty constant (averages 200-300) which is the power required for the ship to attain the desired speed,

g_e is the ship's engine fuel consumption (in g/kWh).

The Environmental Protection Agency proposed the commercial marine vessels fuel consumption model (EPA, 2000). Assuming that the engine will not experience deterioration in the short run, it is reasonable to assume that the actual engine output is a constant. For this case, this study will assume that the engine is 100% efficient.

$$\begin{aligned} g_e &= \frac{14.1205}{E_e} + 205.7169 \\ &= \frac{14.1205}{1} + 205.7169 \\ &= 219.8374 \end{aligned} \tag{3.6}$$

where E_e is the actual engine efficiency (0%-100%)

Since the passenger ferry does not consume diesel fuel while docked, computing for the diesel cost of a single trip is simple. The ferry's total fuel consumption on a single trip, denoted by O_d is obtained by multiplying the ship's hourly fuel consumption (G) with its travel time (t_i). However using (3.2), O_d can be written as:

$$O_d = Gt_i = G\frac{L}{v_i} \tag{3.7}$$

The diesel fuel cost on a single trip is then obtained by multiplying the ship's fuel consumption (O_d) with the diesel fuel price per ton (p_d). Hence, the fuel cost is given by:

$$C_d = p_d O_d = p_d G\frac{L}{v_i} \tag{3.8}$$

Combining (3.5) and (3.6) gives the following:

$$\begin{aligned} C_d &= p_d(g_e N_e 10^{-6})\frac{L}{v_i} \\ &= p_d(219.8374)\left(0.7355\frac{D^{2/3}v_i^3}{C}\right)10^{-6}\frac{L}{v_i} \\ &= 161.69\, p_d\frac{D^{2/3}Lv_i^2}{C}\, 10^{-6} \end{aligned} \tag{3.9}$$

where,

L is the distance between Port A and Port B (in nmi) and

p_d is the price of diesel per gallon.

3.3 Carbon Taxing Methods

There are two different carbon taxation model that will be considered in this study; (1) threshold-based carbon tax and (2) proportion-based carbon tax, both of which have been formulated based on Wang and Xu (2015). Let Q be the amount of ship's carbon emission without imposition of carbon tax on a single trip. In the case of passenger ferries, $Q = \gamma_d O_d$, where γ_d is the carbon emission per ton of diesel fuel consumption.

The threshold-based carbon tax system is formulated as follows (Wang and Xu, 2015): A threshold expressed as proportion of Q is defined such that no carbon tax will be levied on emissions below ϵQ. If δ is the carbon emission tax rate and Q' is the amount of ship's carbon emission with awareness of the carbon tax, then the carbon emission tax under the threshold-based scheme is defined as:

$$B_{th} = \delta(Q' - \epsilon Q) \tag{3.10}$$

An average ferry ship emits $18gCO_2/passenger - km$ (BBC News, 2019). This will be used as the carbon emission threshold.

$$\epsilon Q = 18nl(10^{-6}) \tag{3.11}$$

where ϵQ is in tons CO_2, n is the ship's passenger capacity and l is the distance in km.

The proportion-based carbon tax system has a more simpler formulation. In this scheme, a carbon tax is levied on the ship in proportion to the amount of its carbon emission (Wang and Xu, 2015). Hence, the carbon emission tax under the proportion-based scheme is defined as:

$$B_{pr} = \delta Q' \tag{3.12}$$

Under a no-carbon tax scheme, the ship isn't taxed regardless of its carbon emission amount (Wang and Xu, 2015). Hence, the carbon emission tax under the no-carbon tax scheme is defined as:

$$B_0 = 0 \tag{3.13}$$

This study will use these carbon taxing schemes described for the ship owner's revenue analysis.

3.4 Revenue Model

The ship's revenue for a given trip can be obtained by deducting incurred costs per trip from the ship's income. The revenue model (Wang and Xu, 2015) for a passenger ferry on the i^{th} trip is given as:

$$R_i = In - C_d - B_j \tag{3.14}$$

where In is the ship's revenue defined in (3.1), C_d is the ship's diesel fuel cost, and B_j is the tax due to the carbon tax; $j = \{0, th, pr\}$.

The ship's total revenue over the time interval T is:

$$R = \sum_i R_i - C_{fixed} \tag{3.15}$$

where C_{fixed} is the total overhead cost incurred during time interval T (i.e. salaries, ship's maintenance cost, etc.). Since the ship's profit will be compared among different taxation methods using the same time interval, then C_{fixed} can be ignored. In addition, from the earlier assumptions imposed in the study, it can be said that each trip would be identical. Hence, the optimal sailing speed for the first trip (v_1) is the same as the optimal sailing speed for the i^{th} trip (v_i). With these, R can then be simplified as

$$R = n_{trips}R_i = n_{trips}(In - C_d - B_j) \tag{3.16}$$

Incorporating (3.1) into (3.16), the linear programming model for the ship owner's revenue model is as follows:

$$\begin{aligned} &\text{maximize:} && n_{trips}(np_{in} - C_d - B_j) \\ &\text{subject to:} && v_i \le v_{max} \\ &&& v_i > 0 \\ &&& \sum_i (t_i + t_{dwell}) \le T \end{aligned} \tag{3.17}$$

where:

T is the planning time horizon
n_{trips} is the number of trips made on time interval T
p_{in} is the amount received by the ship owner per ticket sales
n is the ship's passenger capacity
t_i is the travel time of the i^{th} trip
C_d is the ship's diesel fuel cost as described in (3.9)
B_j is the carbon tax using scheme $j = \{0, th, pr\}$

Control variables:

v_i is the sailing speed during the i^{th} trip

3.5 Parameter Values

For the optimization, the following parameters and their values were as follows:

Parameter	Value	Parameter	Value
n	241	L	23.16415 nm
p_{in}	Php 300.00 / ticket	C	250
v_{max}	50 knots	p_d	Php 51,579.50 / ton
D	543.48 tons	E_e	1
t_{dwell}	0.3 hour	δ	Php 2.50/kg CO_2 (OECD, 2018)
T	8760 hours (1 year)	γ_d	3,209 kg CO_2/ton (Krantz, 2016)
l	42.9 km	η	0.2

Table 1: Parameters and Values

The passenger capacity (n), maximum velocity (v_{max}), displacement (D), dwell time (t_{dwell}) were obtained through the data provided by MARINA (Maritime Industry Authority). For the Admiralty's constant (C), the average of the typical range was used. The price of diesel per gallon (p_d) was based on its market price in Philippines in December 2019. Finally, it is assumed in this study that the ship was perfect enging efficiency ($E_e = 1$).

4. ALGORITHM

Since the optimization involves optimizing a single variable (i.e.: sailing speed), a brute-force technique can be used to find the sailing speed that will optimize the revenue. The linear program is evaluated for $v_i \in (0, v_{max}]$ using increments of size 0.2. A simple Python program was written to solve for the optimal sailing speed. Algorithm 1 shows the pseudocode used for computing the optimal sailing speed for each carbon tax scenario.

Algorithm 1 Simple Optimization Algorithm in Python

```
import numpy as np
def main(η):                                                    η ← step size
    params ← setParameters()
    arr ← initializeArrays()
    velArr ← np.arange(η, params[v_max]+η, η)
    for vel in velArr:
        fuelUsed ← computeFuelUse(vel)
        Q' ← params[δ]*fuelUsed
        arr[emission].append(Q')

        # No Carbon Tax
        B_0 ← 0
        rev ← computeRevenue(fuelUsed, B_0)
        arr[R_0].append(rev)

        # Threshold-based Carbon Tax
        B_th ← params[δ]*(Q' − params[ϵ]*Q)
        rev_th ← computeRevenue(fuelUsed, B_th)
        arr[R_th].append(rev_th)

        # Proportion-based Carbon Tax
        B_pr ← params[δ]* Q'
        rev_pr ← computeRevenue(fuelUsed, B_pr)
        arr[R_pr].append(rev_pr)

    ## Get the max revenue and optimal sailing speed
    maxRev_0, maxRev_th, maxRev_pr ← max(arr[R_0]), max(arr[R_th]), max(arr[R_pr])
    index_0, index_th, index_pr ← arg max(arr[R_0]), arg max(arr[R_th]), arg max(arr[R_pr])
    vel_0, vel_th, vel_pr ← velArr[index_0],velArr[index_th],velArr[index_pr]

    return maxRev_0, maxRev_th, maxRev_pr, vel_0, vel_th, vel_pr
```

5. RESULTS

Figures 2 and 3 shows the graph of the trends of the ship's revenue and CO_2 emissions (in kg) with respect to its sailing speed (in knows).

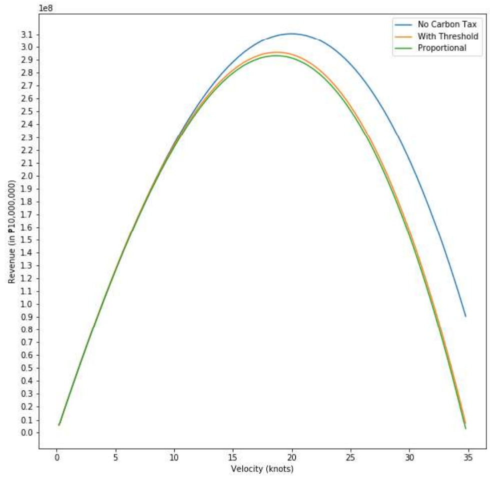

Fig. 2: Revenue vs Velocity

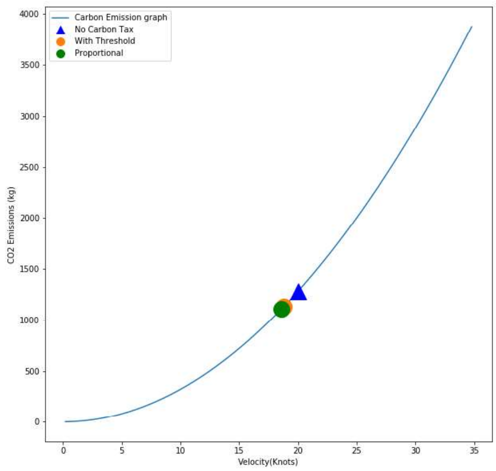

Fig. 3: CO_2 Emission vs Velocity

In this scenario, the revenue graph is a downward parabola, hence the global maximum can easily be determined. Meanwhile, the graph of the CO_2 emission follows a quadratic trend with the level of emission at optimal revenue marked on the graph. Imposing a carbon tax caused the revenue graph to shrink, showing an overall decrease in revenue. It can also be seen from the graph that the higher the ship's sailing speed, the higher the decrease in revenue is due to taxation. Beyond a sailing speed of 35 knots, the shipowner's revenue will already be negative due to the combined diesel fuel costs and carbon tax outweighing the shipowner's profits.

Table 2 describes in detail the ship's optimal sailing speeds and their corresponding annual revenue (R) and CO_2 emissions across three different carbon taxation schemes (no carbon tax, threshold and proportion-based tax)

Scheme	v_i	R (in Php)	% change In R	CO_2 emission (in tons)	% change in CO_2 emission	R/CO_2 Ratio
B_0	20	310,667,950.86	–	1,280.54	–	242,607.00
B_{th}	18.8	295,854,675.00	4.7 %	1,131.48	11.64 %	261,475.60
B_{pr}	18.6	293,202,756.58	5.6 %	1,107.54	13.51 %	264,734.53

Table 2: Ship's annual revenue and CO_2 emission between different schemes

As can be seen, imposing carbon tax caused a slight decrease in the ship owner's annual revenue due to having overall lower number of trips due to decrease in the ship's optimal velocity. Moreover, the ship's annual CO_2 emission also decrease. In addition, the proportion-based scheme caused slightly more decrease to the ship's annual CO_2 emission compared to threshold-based emission.

In order to determine which scheme is the most efficient, the revenue to CO_2 emission ratio will be the metric used. In this case, the proportion-based taxation scheme gives the most amount of revenue per ton of CO_2 emission. Hence, it is the more efficient carbon tax scheme for this setup.

6. CONCLUSION

This paper used a simplified version of Wang and Xu (2015) model made to fit a simple two-port passenger ferry system. This paper also investigated the effect of implementing a threshold and proportion-based carbon tax to the ship owner's revenue and the ship's CO_2 emission on a given time horizon T by formulating a simple linear programming model. In order to simplify the model, several assumptions were made.

From the results, it can be concluded that a carbon tax scheme in ferry boat system is feasible. A 4.7-5.6% decrease in revenue can result to a 11.64-13.51% decrease in CO_2 emission respectively without sacrificing the optimal speed of the ferries.

The model used in this study is simplified and ignores a lot of factors in actual port networks that might have a significant effect on the results of the model. For instance, this model is reliant on the ship's sailing speed to compute the travel time, hence the number of trips. There might be uncertainties on the ship's travel time due, as well as uncertainties on the ship's dwell time on the port. In addition, ship scheduling is also ignored in this model since it is assumed that each time the ship departs, the ship will be fully occupied and it is also assumed that the ship will be able to dock instantly into each port without consideration of berthing.

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