[1]*Elyakim Ben-Hakoun., [2]Prof. Eddy Van De Voorde., [1]Prof. Yoram Shiftan.

[1]ebh@technion.ac.il, Technion - Israel Institute of Technology, Israel

[2]Antwerp University, Belgium

Marine Environmental Emission Reduction Policy in the Liner Shipping The Economic Impact from Trade Lane Perspective

Abstract

This study focuses on the economic impact of the IMO Sulfur air pollution marine emissions reduction policy on carriers, as well as on socio-economic factors in the international liner shipping field. Air pollution regulations of strict emission levels and the high cost associated with the emissions reduction effort, has the potential to shift freight away from its original port destination. Hence, this policy has the potential to affect all segments of society in terms of freight rates, emissions reduction (public health) and potential shifting in cargo movements. While the regulation is bound by a feasibility evaluation, the precise economic impact is not well understood. This policy, which is implemented in an unequal (selective, global cap 0.5% out ECA and 0.1 in ECA) way, will create a new market failure from an economic and health perspective ("pollution leakage"). This study will evaluate the economic impact by developing a Trade Lane (TL) Sulfur Emission Control Area (SECA) Cost Benefit Analysis (CBA) framework, based on the carrier problem, choosing an appropriate compliance action from a selection of alternatives, differentiated by compliance techniques. The input data for this study is based on a major trade lane of one of the leading liner shipping companies. Results indicate that the scrubber is the most mature technological solution today, nevertheless the expected impact on slot cost cannot be overlooked (expected increase of 6-13% to slot cost compare of 4-17% for fuel switch alt.). Furthermore IMO 2020 regulations perpetuate the gap between developing and developed countries, seeing as strong economic countries (developed) could handle the increase in the price of goods, whereas developing countries may still struggle to deal with the existing rate. Results indicate that alternative fuels with global Sulfur content of 0.1% in a 200NM shore area and HFO uses in high seas, were found to be more economic and less destructive to industry (both to port and carrier) and less harmful to society in term of health and pollutions.

Keywords: *Trade Lane SECA CBA, IMO 2020, International Liner Shipping, Economic Impact, Emission Reduction Policy.*

1 Introduction

International shipping is one of the main key figures in our world economy and has a significant role in the "globalization" effort. Thanks to increased growth in the emerging middle class population and expected growth in urbanization rate, the demand for seaborne trade (e.g. food, energy, raw materials and finished products) continues to expand (UNCTAD 2018).

In the last decade due to events such as: 2008 financial crisis, soaring oil prices, unsustainable demand, low freight rate (due to carriers overcapacity) and natural changes in world fleet (new building / breakdown), container-shipping industry profits have been exceptionally volatile (Alphaliner Monthly Monitor August 2016).

Pollution arising from vessels activity affects both climate change and the quality of health of one million people worldwide living along coastlines, according to study by the National Oceanic and Atmospheric Administration (NOAA). SOx and PM emission emitted from vessels activity is considered a serious health risk primarily in the Mediterranean, India and East Asia, where populations are highly dense (people per sq. km of land area) and commercial shipping activity is most common. According to NOAA study, shipping contributes to premature deaths of approximately 60,000 people per year worldwide (Lack et al. 2009).

While the precise economic impact of International Maritime Organization (IMO) air pollution Emission Control Area (ECA), emissions reduction policy[1] is still a subject to discussion, there is remarkably little evidence that this policy, which is implemented in an unequal (selective, global cap 0.5% out ECA and 0.1% in ECA) manner, will create a new market failure from the economic and health perspective ("pollution leakage"). It is important to highlight that ECA policy is more likely to affect all segments of society in an indirect way and will continue its emphasis on the gap between the developed and developing countries.

The purpose of this research is to evaluate the economic impact of the ongoing implementation of air pollution and Sulfur emissions reduction policy on the carrier (shipper, ship-owner, etc.) and its socio-economic implications in the international shipping field.

This objective will be achieved by developing a Trade Lane (TL) Cost-Benefit Analysis (CBA) for the liner shipping combined with emission TL inventory model (per vessel) with refence to global regulation of Sulfur Emission Control Area (SECA). The model framework structure as

[1] IMO Sulfur emissions reduction policy, main target is to reduce and limit the level of emission that occurring from international shipping activity in sea areas in which stricter controls were established to minimize airborne emissions.

a decision support tool, for assessment of it`s impact from environmental emission reduction policy and its potential economic and social effect on sea freight (liner cargo) transportation.

The TL SECA CBA model framework is calibrated with the key inputs regarding vessel characteristics (nominal and effective capacity, utilization ratio per direction, etc.), voyage and Fuel Consumption (FC) characteristics (transit time, distance, Port to Port (P2P) speed, FC in and out of ECA), inputs regarding any Exhaust Gas Cleaning Systems (EGCS) / Liquefied Natural Gas (LNG) characteristics (installation/retrofit time and cost, etc,.), SO2 emissions allowance prices and emission damage cost based on Clean Air Interstate Rule (CAIR) - interstate regional cap for SO2 & NOx actual performance and forecasted prices, fuel cost & deviation ratio (3.5% / 0.5% / 0.1%) based on fuel history prices and forecasted prices data. These and other parameters, generate an economic evaluation basing on multiple fuel price scenarios, allowing us to estimate the expected economic impact of "global SECA emission reduction policy" on the carrier (ship-owner) and its socio-economic implications on international shipping filed from the marginal private slot cost criteria (money coming in and out of the shipping company) and from the marginal social slot cost criteria (concerning not only the shipping company but concerning whether or not everyone is going to be better off with global SECA emission reduction policy in term of emission reduction) per alternative and fuel cost scenarios.

The empirical results acquired from this study will be regarded as a scientific basis for economic impact assessment, policies recommendations as well as a tool to identify barriers for the effectiveness of implementation while minimizing the emerging gap derived from IMO selective SECA and future Nitrogen Emission Control Area (NECA) policy.

This paper is structured as follows. Section 2 reviews the theoretical background and lays the foundation for the model. Section 3 explains key variables and assumptions used for the TL SECA CBA model. The results are presented in Section 4. Section 5 concludes with a discussion, summary, conclusions and contribution.

2 Theoretical Background

2.1 The MARPOL Annex VI – Air Pollution Prevention

International convention on the prevention of pollution from vessels, also known as MARPOL 73/78 ("MARPOL" is short for marine pollution and 73/78 short for the years 1973 and 1978) is IMO guideline for vessel pollution that includes engine and fuel sulfur limits. The MARPOL Annex VI, is a global treaty aim to reduced SO2 from current level of 3.50% to 0.50%, based on technological improvements and implementation experience gained in the marine industry. Set to be effective from 1 January 2020.

In 1997, under the Kyoto Protocol, the MARPOL convention has been revised to include Annex VI - Prevention of Air Pollution from Ships, which has regulated and set quantitative limits of exhaust emissions for only Sulphur dioxide (SO2) from marine engine and vessel exhausts. It will take more than a decade for the Marine Environment Protection Committee (MEPC) to be ratified by the required number of states (May 2005), only to enter into force on October 2008 during the assembly of 58th MEPC international convention. During the years, MARPOL Annex VI had been revised and extended by MEPC to include additional exhaust emissions such as; Nitrogen Oxides (NOx), Particulate Matter (PM) and the introduction of ECAs idea (Smith et al. 2014).

2.2 SECA Regulation

In order to control SOx, IMO have limited the level of SOx, that can be emitted inside and outside SECA, regulation 14.1 and 14.4. Vessel-owners operating in these areas are now facing a significant increase in operation cost due to local stringent regulation (additional port dues) and the expected increase in demand (bunker fuel surcharge) for cleaner fuel with ultra-low sulfur diesel content. The applicable SOx limit is based on caps on SOx content of fuel oil as a measure to control SOx emissions. Furthermore, alternative measures such as scrubbers, exhaust gas cleaning system or any other technological method or equipment are allowed to be used in the effort to reduce SOx emissions to ≤ 6 g/kWh. Fuel type is not regulated, therefore Heavy Fuel Oil (HFO) and distillate are allowed to be used as a main source of energy.

As from January 1 2015, operating vessels inside ECA will be limited to 0.1% m/m of SOx and PM emissions[2]. On 26 October 2018, in its 73th session MEPC decided that from January 1 2020, operating vessels outside ECA, will be limited to 0.50% m/m of SOx, a significant

[2] Sulphur oxides (SOx) – Regulation 14 - http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx - Retrieved August 29, 2014

reduction from the 3.5% m/m global limit currently impose. MEPC based its resolution on independent third-party report which concluded that in the coming years sufficient amounts of fuel oil will be available to meet international shipping low sulfur fuel oil demand, and if not reduced, an additional 570,000 premature deaths (between 2020-2025) are estimated due to air pollution arise from vessels activity worldwide. In order to achieved tight enforcement, as IMO itself cannot impose compliance and/or enforce of its regulation, the MEPC adopted a resolution regarding carriage ban, hence from March 2020, vessels without scrubber cannot carry HFO with high sulfur content [3].

3 Methodology – TL SECA CBA Model Description and Input Data

This chapter is based on CBA methodology and present its contribution of this research in the marine transportation filed.

So why CBA? There are several methods that can be used for evaluation of economic methods for environmental policies, such as: Direct Compliance Cost Method, which assumes no behavioral response from players and is mostly appropriate when compliance cost and elasticities demand are small.

General Equilibrium Analysis, which divides the economy into sectors of Input-Output (I/O) and uses data as input for Computable General Equilibrium (CGE) model, while assuming fixed prices with and no behavioral response.

Least Cost Method, which prioritizes minimum cost with a feasible solution (not necessarily the best solution) while assuming no behavioral response is needed from players (Garrod and Willis 1999; Hawkins 2003).

Therefore, when addressing government policies and its impact on society (economics and environment), we should remember that shipping is driven by sentiment and not only by economics, as it serves different targets, such as: consolidation and cooperation purpose, support increase in demand, support the need for feeding capacity, support increase in brand awareness, function as trade / transport corridor (gateway), open additional targets markets (i.e. local and inland destinations), network effect: customers readily available, potential to realize rate premium for transit time and serve the trade interest between neighboring countries.

In conclusion, to incorporate externalities benefits and cost/damages of IMO SECA global cap regulation, we will use CBA approach.

[3] Implementation of sulphur 2020 limit - carriage ban adopted - http://www.imo.org/en/MediaCentre/PressBriefings/Pages/19-Implementation-of-sulphur-2020-limit-.aspx - Retrieved November 2, 2018

3.1 Cost-Benefit Analysis (CBA)

CBA, is widely used for comparing government policies (van Wee 2012; Whitmarsh 1997). In the marine environment, CBA is commonly used in the coastal and marine waters policy pollution abatement (Bertram et al. 2014).

3.2 Model assumptions

The TL SECA CBA model makes several key assumptions:

a. For each voyage between United States East Coast (USEC) to Asia Far East (F.East), utilization rates (full/effective capacity) stand on 71% while on return voyage utilization stand on 100%.
b. Carrier vessel ownership cost can be reflected by vessel daily charter Rate (vessel rent cost, crew cost, etc.).
c. At port (berth, operation time) FC is based only on auxiliary engine performance (one out of three/four), while maneuvering FC may be significant in the total voyage FC but due to lack of data is omitted from calculation.
d. Economic vessel life span of each vessel is assumed to be 12 years, as the existing fleet average age stands on 12-15 years old.
e. All vessel assign trade lane are Tier-2 type and equipped with Main Engine (ME) with 2-Stroke engine type and Auxiliaries engines (Aux) with 4-Stroke engine type.

3.3 Description of the Model Structure

The TL SECA CBA model, based on the carrier problem, choosing the method of emission reduction from different alternatives from existing methods of compliance, while considering hypothetical and futuristic alternative methods. Each method differing in capital and operational expense (i.e. CAPEX and OPEX), emission levels emitted/reduced and external socio-cost it provides.

The research consists of two phases divided into several stages, briefly described below.
Phase I: TL cost analysis (fixed and variable) and alternative development. This phase consists stages of data collection, analysis of trade lanes and vessel performance in each port, stretch, analysis of fuel, charter rate, port dues and externalities price history, etc. The purpose of this stages is to better understand the factors that may influence the carrier decisions on choosing a method of compliance. After "data cleaning"[4] based on the insights gained, this study starts to

[4] "data cleaning" – The investigated TL have change over the years (ports were added and/or removed according to market demand), therefore unrelated stretch were removed from TL preformence.

develop a TL SECA CBA model (alternative and scenarios) with more realistic parameters (cost and vessel performance - FC, time, etc.) and methods of compliance.

Phase II: Economic analysis and development of an emissions model. In this phase the study continues developing the model to examine the carrier response under different scenario of cost parameters, such as: HFO and Marine Gas Oil (MGO) fuel, vessel charter rate, different discount rate, scrubber premia charter rate and more, thus preforming Net Present Value (NPV) analysis for each alternative to better understand the private perspective (carrier profit viewpoint without including externalities), subject to sensitivity analysis. The study then investigates the implications of alternative specifications to capture the environmental impact of vessel assignment and voyage, thus calculating emissions emitted and emissions reduced, while including the estimated externalities price to calculate the effect of the air pollution and Greenhouse Gas (GHG) emissions reduction policy implementation from the socio-economic perspective.

3.4 Description of the Model Alternatives

In order to define a general framing of TL SECA CBA model, this study define six alternatives. The first two alternatives, functioning as a base / reference alternative, describe a past period (2010-2015 and 2015-2020) before IMO global cap SECA regulation. The third and fourth alternatives refer to a more realistic scenario of compliance to IMO global cap SECA regulation in a competitive environment and the fifth and sixth alternatives refer to a more hypothetical and futuristic alternative scenario.

First alternative, before SECA Regulation: reflects a situation before SECA regulations were ever implemented (before 2008) hence, for this alternative we assume that there were no reduction efforts, i.e, global use of HFO with high sulfur content up to 3.4% without any limitation uses.

Second alternative, after SECA Regulation (Selective); reflects a situation after SECA regulation were first imposed (2008-2020), hence describe the common method of fuel switch technic, between bunker HFO with sulfur content up to 3.4% out SECA zones and uses of MGO fuel with sulfur content of 0.1% within SECA zones (200NM shore area in ECA zones and while berth, first to last rope procedure, in ports with designated SECA zones).

Third alternative, Scrubber (EGCS): reflects a situation where a carrier succeeds to install / retrofit one scrubber (ECGS) system to be used for all main and auxiliary engines (1 for all), thus allowing vessels to operate and consume HFO with high sulfur content up to 3.4%, hence Business as Usual (BAU).

Fourth alternative, Fuel switch: reflects a situation where a carrier did not succeed to install / retrofit a scrubber before 2020 and/or choose not to, instead the carrier chose to comply with IMO global cap SECA regulation by use of fuel switch techniques, hence switching between bunker MGO fuel with a sulfur content of 0.5% out SECA (global use, hence will be referred to as IMO 0.5%) and MGO fuel with sulfur content of 0.1% within SECA (200NM shore area and/or ports with designated SECA while berth or first to last rope procedure), hence operating on MGO only, 100% of all voyages.

Fifth alternative, Hypothetical: reflects a hypothetical situation (not on IMO agenda) where a different regulation was implemented, global 0.1% SECA use in the 200NM shore area worldwide (WW), alongside no limitations while on the high seas (BAU - HFO). For simplicity, a carrier choosing to comply by fuel switch technics, could switch between bunker HFO fuel in the high seas (high sulfur content up to 3.4%) without any reduction effort and MGO fuel with sulfur content up to 0.1% in the 200NM shore area worldwide, hence global 0.1% SECA.

Sixth alternative, Futuristic: reflects a futuristic situation where technology technically available and allows use of LNG engine fuel (installation and retrofit) for all existing auxiliary and main engines (as vessel only source of power) while LNG is considered a reliable and safe alternative for the vessel, ports and sailing crew and where LNG fuel is accessible WW.

All alternatives are compared to the first two alternatives for fully comprehensive economic and environment impact on the slot cost structure of the IMO Sulfur air-pollution emissions reduction policy.

3.5 Data sources

The input data for the TL SECA CBA model is based on reported data (shipping records) from one of the major shipping companies in the field. The Shipping records data (statistics operational database) contain information regarding vessel movements on one of the major trade lanes and consists of records data from 2010-2017, before and after the implementation of IMO MEPC SECA regulations, 14.1 and 14.4.

Collected records data contains information such as port time performance data (pilot in/out, first to last rope – hence working time, waiting time records, sailing time in and out of ECA, sailing distance in and out of ECA, FC HFO and MGO in and out ECA, vessel speed in and out ECA, assign vessel profile (age, capacity, etc.,). All shipping records data was found to be reliable as they are collected automatically and monitored on a day-to-day basis (with breakdown between stretches, ports and voyage direction east and west) by assign trade lane operational analyst, carrier H/O.

The support data used in the model can be described as secondary sources: Netpas Distance for P2P distance table includes new and/or updated information regarding existing trade lanes to bypass the ECA regulation. Alphaliner and Drewry publications (specialized in liner shipping) for P2P freight rate, vessel charter rate history, port dues and more. Bunkerworld for fuel prices, history database for oil prices. Support data regarding externalities cost based on The International Energy Agency (IEA), United States Environmental Protection Agency (EPA) statistics database which includes information such as: emission trends and factors, oil prices, etc. Support data regarding emission factors for ME and AUX in berth or at sea are based on GHG3 IMO study report and Prof. Hans Otto Kristensen's work. Supporting data regarding EGCS, technical performance, CAPEX and OPEX are based on public and private information provided by one of the major shipping companies in the field. Support data regarding externalities cost estimation are based on Congestion Assessment and Resource Integration Study (CARIS) Phase 2 Base Case results, 2017. For simplicity the horizon time of analysis was limited to year 2030, as the fleet in study is expected to be completely replaced with new vessels, that will meet TIER 3 criteria with implemented Selective Catalytic Reduction (SCR) and EGCS.

3.6 Case Study - Trade Lane - Asia (Far East) to North America

This scenarios trade lane provides a service from north/central China (areas that are not included in MEPC SECA and NECA regulation, hence representing the developing countries) to the Caribbean, USEC (SECA and NECA areas, hence representing the developed, developing countries). The fleet chosen is based on actual trade lane and its characterized by 11 vessels with different types of engine and age profile, nevertheless all vessels are subject to a same tier policy (Tier 2), with a carrying capacity of 5,000 TEU, and weekly schedules with a frequency of an estimated Round Trip (RT) of 75 days.

The trade lane includes ports in: Savannah - Norfolk - New York - Halifax - Kingston - Slavyanka (Via Panama Canal) - Qingdao - Ningbo - Shanghai - Pusan - Balboa (Via Panama Canal) - Kingston – Savanna, as illustrated in Figure 1:

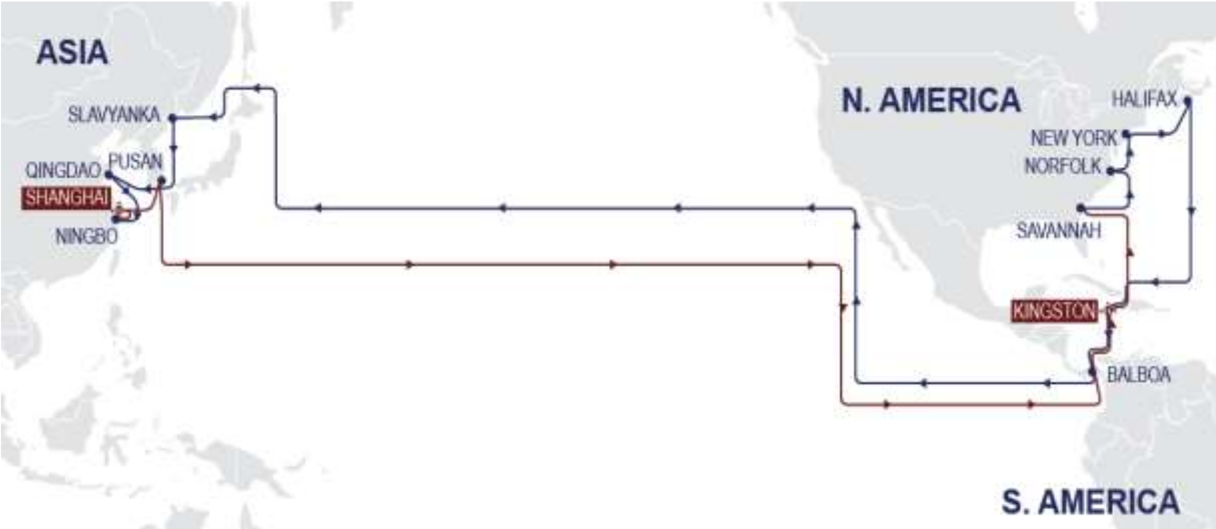

Figure 1: Trade lane - Asia Far East to North America and Canada Route map

Source: Leading liner shipping companies - Trade lane map.

From analaysis of seven years of historical vessel movments, voyages and port performance, it can be seen that a vessel spends less time out of her voyage (hrs) in ECA, as illustrated in Figure 2. These finding are suported by port performence analysis, as illustrated in Figure 3. High efficiency was found in the busiest ports, which can be explained by the fact that TEU loading and discharge is relative to the working hours, nevertheless waiting time on the Asia F.East port was found to be relativity high, compared to waiting time on the USEC ports. These findings can be explained by the fact that on west bound voyage journeys, vessels are likely to be loaded mainly with empty containers (as Asia is commonly described as a more underbalanced area from a 'logistic balancing procedure' standpoint). This is supported by the fact that FC on the Asian area mostly relay on HFO with high Sulfur content, which is significant less expensive then MGO (0.1%), up to half the price.

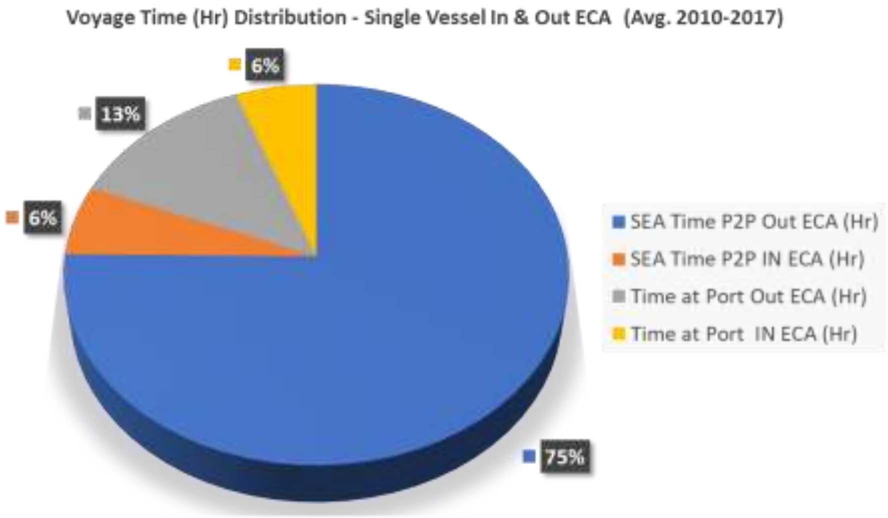

Figure 2: Voyage Time (Hr) Distribution - Single Vessel In & Out ECA (Avg. 2010-2017).
Source: This work, based on historical vessels movements (major trade lane – 2010-2017).

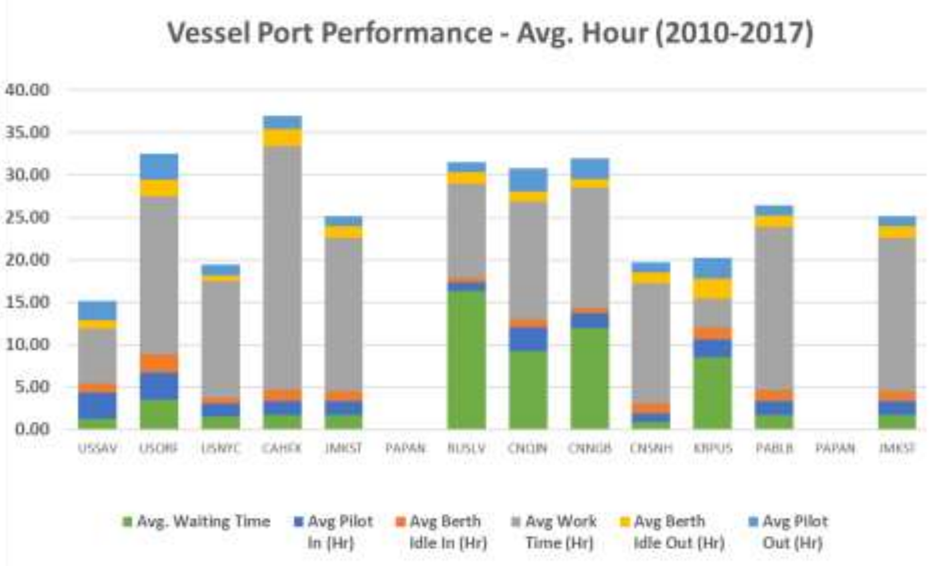

Figure 3: Vessel Port Performance - Avg. Hour (2010-2017)
Source: This work, based on historical vessels movements (major trade lane – 2010-2017).

3.6.1 Vessel characteristics input data

In order to evaluate the expected economic global cap SECA emission reduction policy's impact on the carrier (ship-owner) in the international shipping field and its socio-economic implications on society (partial view), the structure of slot cost needs to be well defined. To gain as realistic and accurate a slot cost analysis as possible, the study starts with current situation, BAU.

The following vessel characteristics were used in the BAU slot cost analysis: vessel nominal capacity - 5000 TEU (4050 effective), vessel economic life span - 12 years, utilization ratio 71% and 100% west and east bound respectively. Fuel type HFO (400$/t) use out ECA and MGO (640$/t) in use in ECA, port expenses per call (port dues) and vessel daily charter cost were based on public tariff and/or Alphaliner Monthly Monitor published reports. Time at port and time to next port, distance P2P, call frequency, vessel speed P2P, FC per knots level, etc. were based on historical vessel movements from the trade lane analysis, years 2020-2017. Fuel prices were based on Bunkerworld's historical analysis prices and an average container (A4-A3) freight rate of 1,800 USD/TEU (per voyage) were based on Drewry's historical freight database. The analysis horizon was limited to a fleet economic life span (12 years), hence 2030.

From the slot cost analysis (Round trip), three cost factors were found to be significant: vessel daily charter cost (26%), fuel expenses sailing out of the ECA (~40%) and port dues (28%), as illustrated in Figure 4. Hence, as expected, fuel expenses tend to play a significant rule in the TL SECA CBA regulation. Vessel daily cost, i.e. charter cost was found to have high fluctuation, as describe in Figure 5, since leasing contracts are signed for a period time of at least one year if not longer, the average charter rate of 16,000 USD/day was chosen for the analysis.

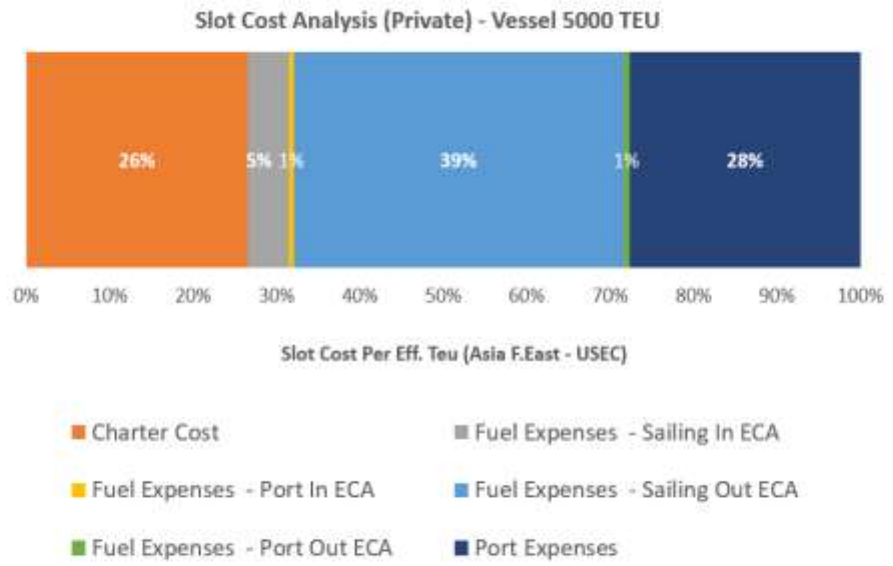

Figure 4: Slot Cost Analysis (Private perspective) - Vessel 5000 TEU
Source: This work, based on historical vessels movements (major trade lane – 2010-2017).

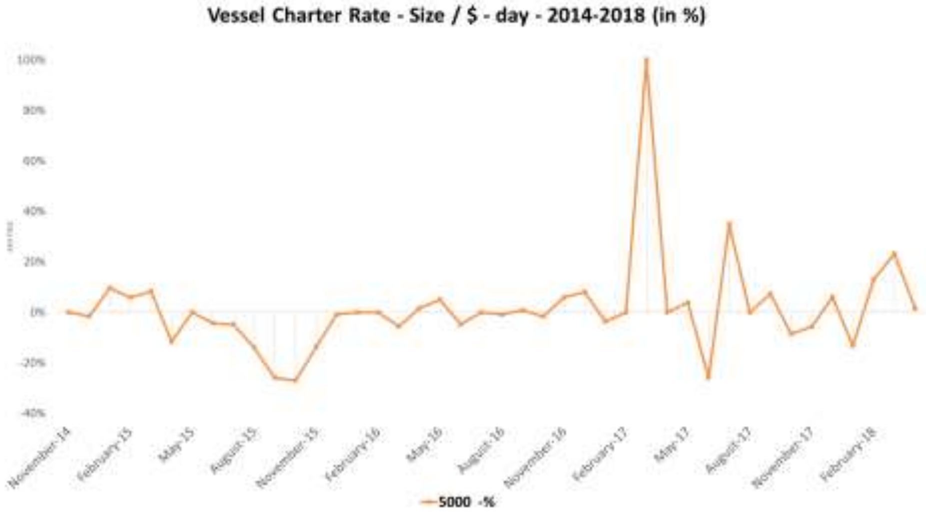

Figure 5: High fluctuation in Vessel Charter Rate - Size / $ - day - 2014-2018 (%)
Source: This work based on Alphaliner Monthly Monitor reports for 5000 TEU Vessel - 2014-2018.

3.6.2 Voyage Fuel Consumption (FC) input data

Base on port performance and historical vessels movements analysis - time, distance, speed P2P, FC per knots level, etc. An esitmated amount of 5000 Ton/Voy of HFO and MGO fuels was found to be consumed for a single vessel round trip voyage. As expected, high FC was observed in the high seas stage, sailing out of ECA (~4580 HFO Ton/Voy), as illustrated in Figure 6.

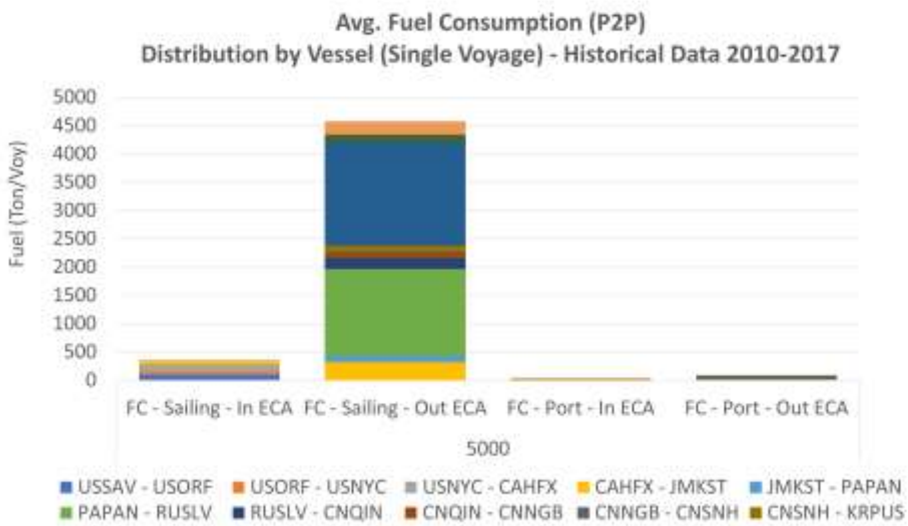

Figure 6: Avg. Fuel Consumption (P2P) Distribution by Vessel (Single Voyage) - Historical Data 2010-2017
Source: This work, based on historical vessels movements (major trade lane – 2010-2017).

3.6.3 Compliance with Exhaust Gas Cleaning System (EGCS) input data

EGCS systems are commonly used as Sulphur removal machinery, that can be implemented in a wet or dry method. The scrubber solution is considered highly to be an effective technique with high removal level of SO_2 emission (~98% success removal) and high removal level of harmful airborne sulphate particles (PM ~30-60% success removal) (Schnack and Kristensen

2009; Smith et al. 2014; Winther 2007). The scrubber portfolio is based on three main techniques of SO2 removal: Open Loop (OL), Close Loop (CL) and Hybrid, each one using different raw materials in the removal processes. OL uses seawater, CL uses caustic soda and Hybrid combines between the techniques. Based on information accepted from the fleet technical manager of one the major liner shipping companies, only OL and Hybrid systems were taken in consideration in TL SECA CBA model, with the following assumption regrading installation time, FC and expected increase in OPEX and CAPEX of EGCS system.

From a CAPEX perspective system price range can go up to one or two million, the difference depending on the manufacturer and dock demand (availability)[5]. Equipment price and installation cost are estimated (jointly) at rate of 7.5 MUSD[6]/Vessel (for 5000 TEU) which includes system components, auxiliary systems, spare parts, installation, testing, certification and crew training.

Based on information accepted from the fleet technical manager, no loss in cargo space (due to scrubber installation, generally true for 5000 TEU vessel and above) was taken in consideration. Only one scrubber is used for main and all auxiliary engines, where auxiliary engines/boilers are expected to continue burn MGO or other low-Sulphur fuels. From an OPEX perspective, two significant variable cost were observed; electric load (increase due to scrubber operation which is translated to increase in FC (t/day) in / out ECA zones and stand on 2% increase) and planned and unplanned maintenance (maintenance, i.e. - engine repair frequency, alternative vessel, scrubber Repair, crew training, alkali consumption, etc.). Scrubber installation and retrofit time, may last between 50-80 days per system, therefore 80 days standard per vessel was taken in consideration, thus a carrier faces two decisions; lease an additional vessel (at rate 16,000 USD/day) for the entire period of the absence (Off-Hire) for the entire fleet, or increase vessel speed to keep trade lane schedule reliability. For simplicity the first option (Off-Hire) was chosen.

[5] Scrubbers in the mist - https://safety4sea.com/cm-scrubbers-in-the-mist-the-egcs-quiz-show/ - Retrived Novmber, 2 2019

[6] MUSD - Million United States Dollars

3.6.4 Compliance fuel switch techniques input data

This method describes a compliance option where a carrier chooses to comply with IMO global cap SECA regulation by use of fuel switch technics, hence switching between bunker MGO fuel with sulfur content of 0.5% out SECA and MGO fuel with sulfur content of 0.1% within SECA, hence operating on MGO only, 100% all voyages.

Although not taken in consideration in terms of cost but worth mention, technical analysis on marine engine damage found that low Sulphur bunker fuel (mandatory for use in vessels trading in ECA zones) contain high catalytic fines (cat fine) in high concentration content, which may lead to a significant increase in rate of wear on critical machinery parts (i.e - rubbing surfaces of cylinder and fuel system), as illustrated in Figure 7. In addition, the technical analysis found that there is significant evidence that increase in engine damage cases today, are in direct correlation to increase in prevalence of fuel switch procedure (i.e – low Sulphur regulation compliance) (JHC Report 2013).

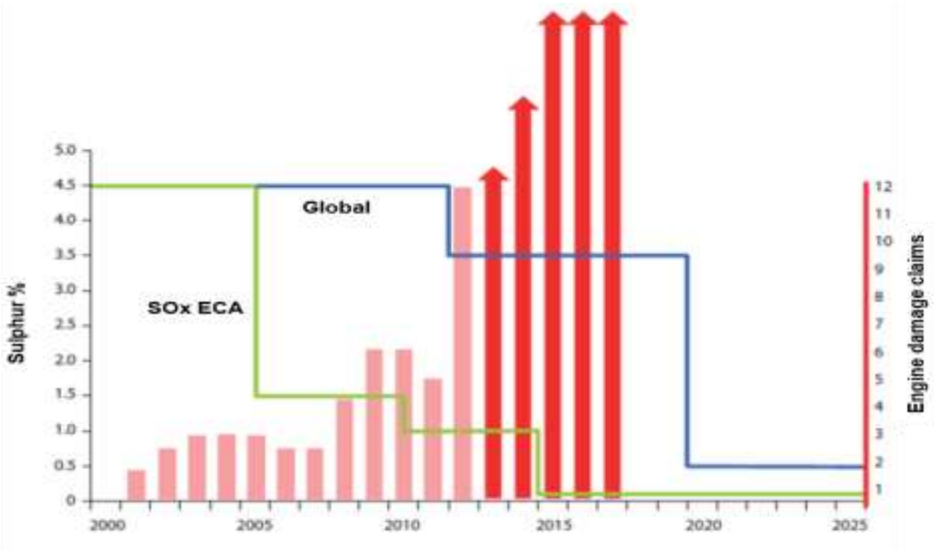

Figure 7: Significant evidence for correlation between low Sulphur legislation and engine damage (JHC Report 2013).

3.6.5 Compliance LNG input data

A futuristic situation where LNG technology is considered a reliable and safe alternative for the vessel, ports and sailing crew and where LNG fuel is accessible WW and used for all existing auxiliary and main engines.

Due to the lack of information, harsh assumptions were made from CAPEX perspective. System price and installation cost were estimated (jointly) at rate of 10 MUSD/Vessel (for 5000 TEU and were assumed to include the same types of expenses as for EGCS (i.e. - system components, spare parts, installation, testing, certification and crew training), with small losses in cargo space (up to 12 TEU slots) and no expected change in existing electric load demand.

In addition, harsh assumptions were made from an OPEX perspective, thus, only one variable cost was considered, i.e. maintenance cost, estimated at a rate of 32,000 USD/Vessel/Voyage[7]. LNG installation and retrofit time is unknown, therefore for simplicity 80 days standard per vessel was taken in consideration. Thus, as in the case of the scrubber, the carrier faces two decisions: lease an additional vessel or increase vessel speed. For simplicity, the same assumptions as in the case of scrubber installation were taken. Based on information accepted from a fleet technical manager for LNG TIER 2 vessel, ME were assumed equipped with 4-Stroke engine.

3.6.6 Emission Factor data – AUX and ME

Fuel related emission factor (g/kg fuel) were derived per engine and fuel type, and were based on the exist ratio g/kWh of NOx, CO, HC, PM emission factors for an average FC per voyage regarding to ME (sailing in and out ECA zones - 4.398 Ton/Hr) and Aux (port in and out ECA zones - 0.474 Ton/Hr) engines, the results are illustrated in Table 1 and

[7] Retrofitting scrubber and LNG technologies to existing ships - http://www.kmtp.lt/old//uploads/Inovaciju%20prizas%202012/Marchain%20workshop%202012_2.pdf - Retrieved September 2, 2018

Table **2** (Schnack and Kristensen 2009; Smith et al. 2014; Winther 2007). Key Assumptions regarding sulfur content in oil (%) for HFO was assumed 2.64 (pct.), as for MGO, LNG and DUAL 1 (pct.)

Table 1: Emission Factors for Main Engine (Schnack and Kristensen 2009; Smith et al. 2014; Winther 2007)

TIER 2 **Emission (g/kg fuel)**	2-Stroke **HFO**	2-Stroke **MGO**	4-Stroke **LNG**	2-Stroke **DUAL**
CO_2 emissions	3114	3206	2750	2780
NOx emissions	3.10	3.10	0.30	2.73
CO emissions	0.08	0.08	0.07	0.07
HC emissions	0.11	0.11	0.11	0.11
PM emissions	0.39	0.10	0.01	0.02
SOx emissions	75.28	20.95	0.00	0.06
Calorific value (MJ/kg fuel)	40.5	42.8	50	49.6
Calorific value (MJ/kg oil)	40.5	42.8	42.8	42.8
Calorific value (MJ/kg LNG)	50	50	50	50

Table 2: Emission Factors for Auxiliary Engine (Schnack and Kristensen 2009; Smith et al. 2014; Winther 2007)

TIER 2 **Emission (g/kg fuel)**	2-Stroke **HFO**	2-Stroke **MGO**	4-Stroke **LNG**	2-Stroke **DUAL**
CO_2 emissions	3114	3206	2750	2780
NOx emissions	20.25	20.25	2.74	20.25
CO emissions	1.05	1.05	2.74	2.74
HC emissions	1.05	1.05	1.05	1.05
PM emissions	3.64	0.94	0.06	0.21
SOx emissions	75.28	20.95	0.00	0.59
Calorific value (MJ/kg fuel)	40.5	42.8	50	49.6
Calorific value (MJ/kg oil)	40.5	42.8	42.8	42.8
Calorific value (MJ/kg LNG)	50	50	50	50

* Emission factor above are function of FC (for 5000 TEU vessel)

3.6.7 Emissions Prices input data

From the Socio-cost perspective, the TL SECA CBA model uses harsh assumptions regarding emissions prices (i.e. - CO2, SO2 and NOx). All social and damage cost were based on the Benefit Transfer (BT) approach and rely on Congestion Assessment and Resource Integration Study (CARIS) results (NYISO 2018).

US EPA/CAIR studies show significant decrease in the emission level for SO2 and NOx, and an emission level reduction in the US from ground level sources. The massive reduction is estimated to be around 99% and correlated to massive scrubber installations (as CAIR introduce regional cap was introduced in 2005/6), which later reflected a major reduction in SO2 emission, a ~+70% decrease between 1980-2008 period time (Burtraw and Szambelan 2009; Schmalensee and Stavins 2012).

As illustrated in Figure 8 and Figure **9**, an increase in damages and the social cost of CO2 (Global pollutant) is expected for the following years, as the COP 21 Paris, France (United Nations Climate Change Conference) agreement is set to be effective from 1 January 2020 with participation of all UN members. The agreement was adopted by 196 countries (the US is expected to withdrawal as early as November 2020[8]). Social cost estimation was regarded in the model as cost parameters for the CBA analysis, while damage cost was regarded in the model as benefit parameters for the avoided/reduction level of achieved emission per year.

[8] On the Possibility to Withdraw from the Paris Agreement: A Short Overview - https://unfccc.int/news/on-the-possibility-to-withdraw-from-the-paris-agreement-a-short-overview, - Retrieved September 2, 2017

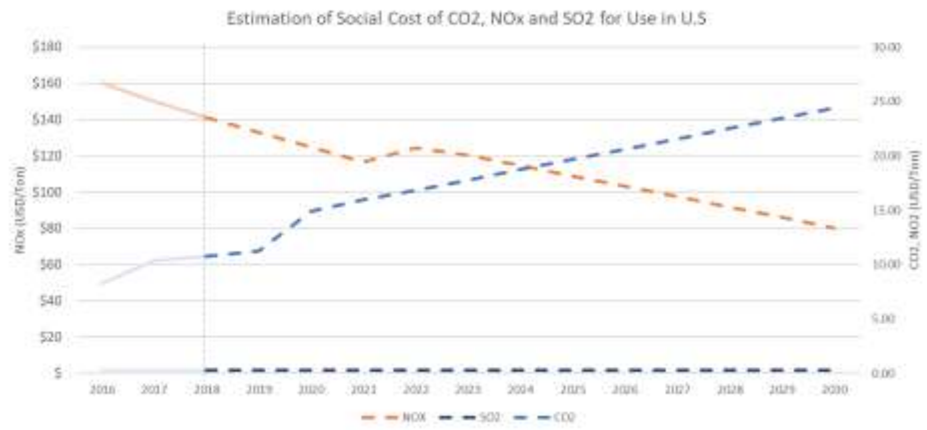

Figure 8: Estimation of Social Cost of CO2, NOx and SO2 for Use in U.S

Source: This work, based CARIS results (NYISO 2018)

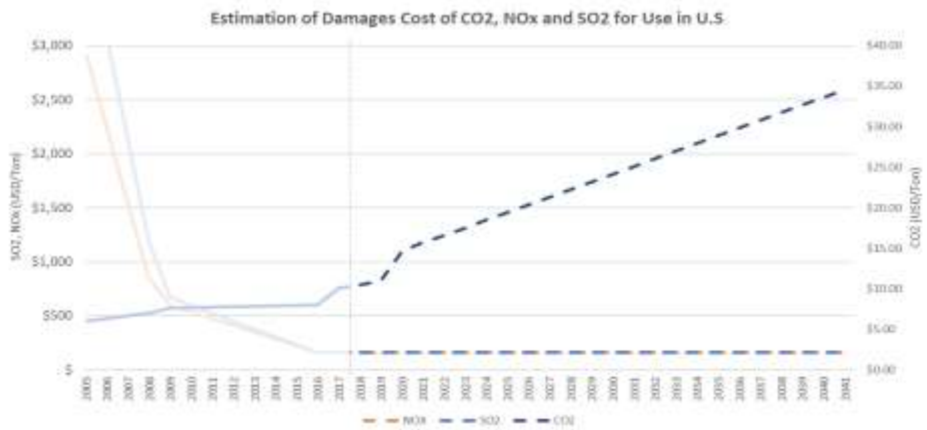

Figure 9: Estimation of Damages Cost of CO2, NOx and SO2 for Use in U.S

Source: This work, based CARIS results (NYISO 2018)

3.6.8 Fuel Prices Scenarios

The slot cost analysis (Figure 4**Error! Reference source not found.**) shows that fuel expense is the most significant cost parameter with a share of ~40% of the slot structure cost and is the main cost parameter that is expected to change drastically. For this reason, the TL SECA CBA model defined three main fuel cost frames scenarios (Low, Sustainable and High).

- The Low bound: reflects the minimal recorded fuel prices.
- The Sustainable bound: reflects the natural (the average of last 2016-2017 prices).
- The High bound: reflects the maximum recorded fuel prices (years 2014-2015)

The scenarios branch out to a wide range of fuel price possibilities, as describe in Table 3, thus supporting the model with a bounded economic estimation. Consider fuel types described as: HFO with Sulfur content of 2.64%, ULSMGO[9] with S. content of 0.1%, IMO 2020 with Sulfur content of 0.5% and LNG.

[9] ULSMGO – Ultra Low-Sulfur Marine Gas Oil

Table 3: Frames Scenarios and fuel prices

Based on historical fuel prices 2010-2017. Source: Bunkerworld

	Low bound **(USD/Ton)**	Sustainable **(USD/Ton)**	High bound **(USD/Ton)**
HFO	100	400	760
ULSMGO	220	640	1100
IMO2020	200	620	1080
LNG	80	240	360

3.6.9 Reduction Rate data according to alternative

Scrubber, Fuel Switch, LNG effectiveness in reduction of emission levels, as described in Table 4.

Table 4: Method of Compliance and Emission Reduction Potential

Table 2 (Schnack and Kristensen 2009; Smith et al. 2014; Winther 2007)

	Scrubber **(HFO)**	Fuel Switch **(MGO 0.1%)**	LNG[10] **(4-Stroke)**
CO_2 emissions	+2%	+3%	-25-30%
NOx emissions	-7%	0%	-85%
CO emissions	0%	0%	0%
HC emissions	0%	0%	0%
PM emissions	-40-60%	-74%	-95-100%
SOx emissions	-97%	-97%	-100%

3.6.10 Level of accuracy and reliability of results

The volatility in fuel price cost plays a main role in the model, as it enables us to receive the model with a bounded economic estimation for the economic impact assessment of IMO global cap SECA policy. Nevertheless from the private perspective, the TL SECA CBA model demonstrate high certainty and high accuracy as it based on real data that contains statics regarding vessel operational port performance and historical vessels movements analysis, therefore , based on the existing data we can say that the model is sufficient to provide a glimpse of an economic estimation for the expected impact of the global cap SECA regulation implementation in the international shipping industry mainly from the aspect of the carrier (vessel owner) and the Beneficial Cargo Owner (BCO.) From the Socio-cost perspective the TL SECA CBA model may suffer from a high level of uncertainty and small accuracy, due to the fact that social and damage cost are based on the Benefit Transfer (BT) approach and rely on the US EPA/CAIR market, hence, being subject to a large number of external parameters and regulations (local, regional, national, federal, etc.) that may radically change the estimation of social cost. From a sensitivity analysis perspective, the model makes use of two levels of a discounted rate for the NPV calculation. Lower levels, at a rate of 3.5% demonstrate a situation where the model tips more to the benefit of the future generation, where the higher level, at a rate of 7.5% demonstrates a situation where the model tends to benefit the current generation, as it assumed that this generation is bearing most of the cost while future generations are expected to gain the benefit (greener transportation, advance in technology, health improvement, etc.).

All factors, parameters and results where share, presented with one of the major shipping companies in the field and were validated with its operational team and Israel Administration of Shipping and Ports Chief Engineer Office.

4 Results

4.1 Alternative Empirical Work Analysis

4.1.1 Scrubber

[10] Lng – a cost-efficient fuel option? – https://www.sjofart.ax/sites/www.sjofart.ax/files/attachments/page/oceaneballand2014.pdf - Retrived September, 2 2018.

From the model results, it seems that scrubber result show "best performance" for the realistic alternative as expected increase in OPEX is estimated between 7-12% annually only. ROI achievement is possible in less than two years, depending on fuel availability (IMO 0.5 and LSHFO fuel price) in 2020. Nevertheless, the fuel price deviation/gap (IMO 0.5 to HFO 3.5%) is expected to erode over the years as market reach new equilibrium, thus reducing the attractiveness of this alternative.

4.1.2 Fuel Switch (MGO)

High expected increase in OPEX is estimated between 15-22% annually. Nevertheless, a flexible solution for adjusting business atmosphere / technology changes as it requires a "small investment" while considering IMO 2020 regulation compliance. Better fit for short "economic life" vessels and for small / mid vessels as no cargo loss is required. High sensitivity for low sulphur fuel availability as of 2020 is expected to show shortage in the short run. However, this method of compliance shows a high increase in CO2 emission levels, contrary to the legislator's intent (i.e. 2023 regulation) and exposed the carrier to additional expenses of CO2 emission reduction effort.

4.1.3 Hybrid (Fuel Switch)

Expected increase in OPEX is estimated between 2-3% annually only. A flexible solution for adjusting business atmosphere / high technology changes – i.e – the shipping industry. Fuel supply problems are insignificant. Requires a small investment (compared to scrubber alternative) and has minimum impact on the slot cost calculation. High NPV (with minimum investment), however, does not exist on IMO agenda therefore not IMO 2020 compliant.

4.1.4 LNG

High NPV (private and social with minimum investment). Minimum Impact on the environment and society in terms of health and pollution (emission reduction; SO2 ~99%, CO2 – 25-30%, Nox – 85%). High tolerance to IMO 2020, NECA 2021 and 2023 CO2 future regulation, with a small OPEX / Slot Cost expected. Cons: fuel availability, high investment in supplement infrastructure needed from port and carrier, technology still premature.

4.2 Slot Cost (Private) - Additional Expected Cost Per Alternative

Findings from the model for a container vessel size of 5,000 TEU, as illustrated in Figure 10 shows: For the scrubber alternative the additional cost expected in the private slot cost structure is estimated at a rate of $123 - $128 per TEU (for Low, Sustainable, High fuel price scenarios respectively). For Fuel Switch (MGO) alternative the additional expected cost is estimated at a rate of $115 - $369 per TEU (for Low, Sustainable, High fuel price scenarios respectively). For the hybrid alternative the additional expected cost is estimated at a rate of $2 - $7 per TEU (for Low, Sustainable, High fuel price scenarios respectively) and For Hybrid alternative the additional expected cost is estimated at a rate of -$480 - $17 per TEU (for Low, Sustainable, High fuel price scenarios respectively). All finding was compared to the private slot cost in the second alternative, which reflects a situation after SECA regulation were first imposed (2008-2020).

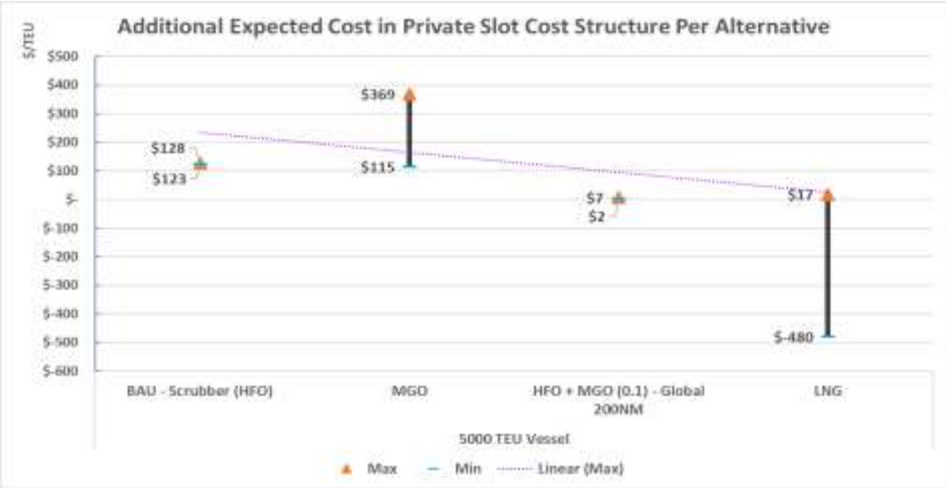

Figure 10: Additional Expected Cost in Private Slot Cost Structure Per Alternative

Source: This work, based on historical vessels movements (major trade lane, years 2010-2017).

As for the Socio-economic model, the marginal social slot cost (in terms of emission reduction) findings were found quite similar (minor cost differences) to the results that were received from the marginal private slot cost model, as illustrated in Figure 11. Findings from alternatives three to six were compared to the private and slot cost social cost in the second alternative, whereas the second alternative was compared only to the first one for better understanding of the economic impact of SECA regulation compared to past performances, hence with no limitations on sulfur content while sailing on the high seas or ports of call (HFO only - with current fuels prices).

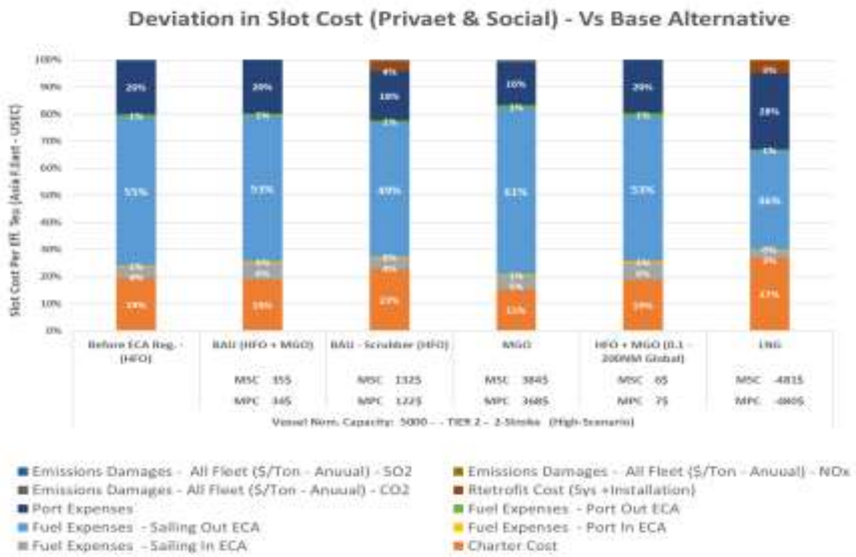

Figure 11: Deviation in Slot Cost (Private & Social) - Vs Base Alternative - (ratio in %)

Source: This work, based on historical vessels movements (major trade lane – 2010-2017).

4.3 Emission Deviation – Single Vessel Vs Entire Fleet (One Voy. Vs 52 Voy.)

Findings from the TL SECA model, as illustrated in Figure 12 show the that potential reduction for the scrubber alternative is higher in terms of SO2, PM and NOx while CO2 emission increases due to electric load originating from operation of the scrubber. While in the fuel switch alternative, small reductions were observed in SO2, PM, NOx emission level. Which can be explained as this alternative makes of use of 0.5% sulfur content fuel in the high seas and in ports outside SECA zones. While in the scrubber alternative the reduction achievement is higher as it reduced SO2 emission levels by ~97% regardless sulfur content level in fuel. Carbon emissions in fuel switch alternatives increase due to effective hydrocarbon burning which leads to higher CO2 emission factor.

4.4 NPV – Calculation

From the CBA study, as described in Figure 10, Figure **11** and Figure **13**, it can be seen that the scrubber alternative was found to be more economic in terms of price increase of slot cost than a fuel switch, but this finding can be described as the “Lesser of Two Evils”, as Return of Investment (ROI) for the scrubber alternative is expected to decrease if the completion of

Figure 12: Emissions Deviation Scrubber Vs Fuel Switch (MGO) - Single Vessel per One Voyage Vs All Fleet per 52 Voyages

Source: This work, based on historical vessels movements (major trade lane – 2010-2017).

From 2020 a “double funding”, an additional cost for fuel switch compliance and cost for an additional vessel leasing (off-hire)/increase of speed (schedule reliability shipping issues) is sure to occur as remaining fleets complete the retrofitting and installation effort. Moreover, an expected increase in CO2 prices is likely to happen as the COP 21 Paris agreement, starting in the year 2020, will potentially result in high volatility of slot cost for the scrubber and fuel switch alternatives, as scrubbers are expected to increase FC by ~2%. MGO with low sulfur content has a higher emission factor due to effective hydrocarbon burning, thus increasing the emission level and the CO2 marginal abetment cost. Furthermore, it seems that "Slow steaming", which functions as an emission level reduction procedure as well as an effort to reduce slot cost (economic burden) has already run its course, not to mention the unknown impact of IMO 2023, CO2 Market Based Method (MBM) regulation reform on the slot cost structure. In terms of NPV and ROI the futuristic alternative LNG and the hypothetical alternative Fuel Switch (Hybrid), were found economically promising.

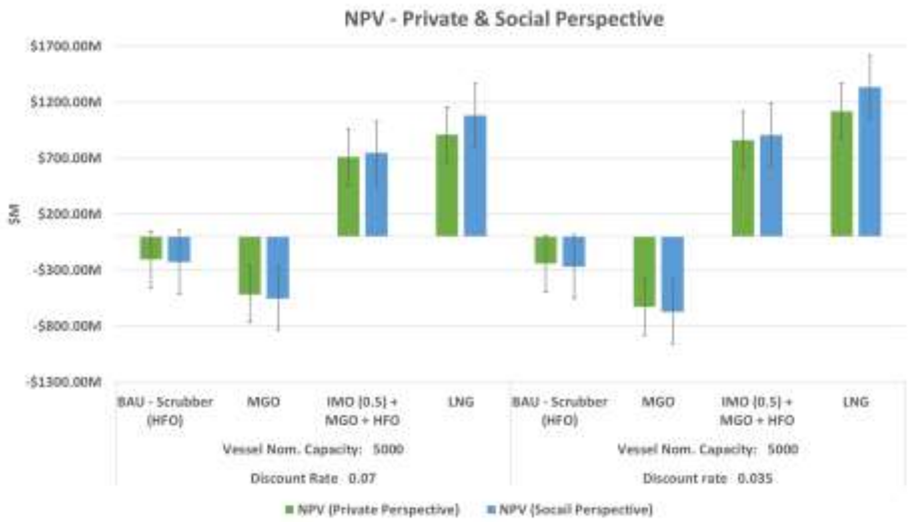

Figure 13: NPV analysis - Private & Social (Emission Reduction) Perspective
Source: This work, based on historical vessels movements (major trade lane – 2010-2017).

5 Discussion, Summary and Conclusions

The TL SECA CBA model framework, based on the carrier problem, chooses the method of emission reduction from different alternative existing methods of compliance. The model purpose is to evaluate the economic impact of the ongoing implementation of Sulfur air pollution emissions reduction policy on the carrier (shipper, ship-owner, etc.) and its socio-economic implications on international shipping, from the marginal private slot cost criteria (money coming in and out of the shipping company) and from the marginal social slot cost criteria (whether or not everyone is going to be better off with global cap SECA emission reduction policy).

The study started, with evaluation of the marginal private slot cost structure (fixed and variable), hence better understanding the factors that may influence the carrier decisions on choosing a method of compliance. The study then continues with economic analysis while developing an emissions model in order to evaluate the relative cost of the expected socio-economic impact on the liner shipping industry from an economic and environmental perspective.

The empirical results show that there is remarkably significant evidence that one of the potential economic impacts of the global cap (and selective) SECA zones reduction policy on cost of emission reduction effort will be divided on all the available slots (e.g. vessel effective capacity) as a result of companies' interest to stay competitive with the existing freight rates.

Therefore, in 2020 expected freight rates will tend to increase the direct cost consumers are expected to pay for freight services which may lead to a situation where developing countries (non SECA zones) pay a portion (high or small) of "cost of the subsidy" for emission reduction in the developed countries, e.g. – Asia/Africa for N. America and N. Europe. Furthermore, high rate of fuel prices may have the potential to increase unemployment in developing countries that tend to be with high import levels, thus leading to a decrease in money saving at a state capital level.

The results of this study show that the relative advantages of vessel equip with scrubber (i.e. burning cheaper fuel and thus will be able to sail faster than similar vessels, fuel price deviation/gap (IMO 0.5 to HFO 3.5%) is expected to erode over the years as market reach new equilibrium, thus reducing the attractiveness of this alternative. And when we examine things thoroughly, additional factors are arising, and may change Scrubber attractiveness. factors such as: an additional FC expenses (due to scrubber increase in energy load (2-3%), an increase of OPEX for the all fleet depend on the TL structure i.e. international / domestic areas, familiar or not with ECA regulation, vessel size, utilization ratio in each leg, frequency and Net operation revenue (NOR) and freight rates in the designated TL. An increase in GHG emission (e.g CO_2) as a result of increase in FC or as a result of increase in emission factor when fuel switch technique is being at use.

The results of this study indicate that the global cap SECA policy is more likely to affect all segments of society and will further contribute to the emerging gap between the developed, developing and developing countries. It has important implications for the shipping industry and society. IMO MEPC should promote equalitarian and a more realistic green sea freight transportation, thus, sustaining economic growth while promoting advancing technology and business atmosphere in the marine transportation field by other means. An additional research is needed to better understand the expected impact on large and small vessels in international liner shipping, hence better understanding the impact of the global cap SECA regulation on the economics of scale basis.

Bibliography:

Alphaliner Monthly Monitor August. 2016. *Monthly Monitor*. Retrieved (www.alphaliner.com).

Bertram, Christine, Thomas Dworak, Stefan Görlitz, Eduard Interwies, and Katrin Rehdanz. 2014. “Cost-Benefit Analysis in the Context of the EU Marine Strategy Framework Directive: The Case of Germany.” *Marine Policy* 43:307–12.

Burtraw, Dallas and Sarah Jo Fueyo Szambelan. 2009. *U.S. Emissions Trading Markets for SO2 and NOx*.

Garrod, G. and K. .. Willis. 1999. *Economic Valuation of the Environment: Methods and Case Studies*. illustrate. Edward Elgar. Retrieved (http://books.google.co.il/books/about/Economic_Valuation_of_the_Environment.html?id=5HId83pl2ikC&redir_esc=y).

Hawkins, Katherine. 2003. *Economic Valuation of Ecosystem Services*. Minneapolis , Minnesota , United States. Retrieved February 11, 2014 (http://www.environmentalmanager.org/wp-content/uploads/2008/04/valuation%2520of%2520ecosystems.pdf).

JHC Report, JHC. 2013. *Marine Engine Damage Due to Catalytic Fines in Fuel*. Retrieved (https://iumi.com/images/documents/JHC_Catfines_Pack.pdf).

Lack, Daniel A. et al. 2009. “Particulate Emissions from Commercial Shipping: Chemical, Physical, and Optical Properties.” *Journal of Geophysical Research Atmospheres* 114(4):1–16.

NYISO. 2018. *2017 Congestion Assessment and Resource Integration Study*. New York, NY. Retrieved (https://www.nyiso.com/documents/20142/1402648/05_CARIS2017_Report.pdf).

Schmalensee, Richard and Robert N. Stavins. 2012. *The SO2 Allowance Trading System: The Ironic History of a Grand Policy Experiment*.

Schnack, Søren and Hans Otto Kristensen. 2009. *Green Ship of the Future - Exhaust Gas Emission Reduction Concept Study*. Stockholm, Sweden.

Smith, T. W. P. et al. 2014. *Third IMO Greenhouse Gas Study 2014*. London, UK. Retrieved (http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third Greenhouse Gas Study/GHG3 Executive Summary and Report.pdf).

UNCTAD, United Nations Conference on Trade and Development. 2018. *Review of Maritime Transport 2018*. Geneva, Switzerland. Retrieved (https://unctad.org/en/PublicationsLibrary/rmt2018_en.pdf).

van Wee, Bert. 2012. “How Suitable Is CBA for the Ex-Ante Evaluation of Transport Projects and Policies? A Discussion from the Perspective of Ethics.” *Transport Policy* 19:1–7.

Whitmarsh, D. 1997. “Marine Pollution Policy in the UK.” *... FOR THE ECONOMICS AND MANAGEMENT OF ...*. Retrieved October 7, 2014 (http://portsmouth.ac.uk/research/cemare/publications/pdffiles/researchpaperspdf/filetodownload,182461,en.pdf).

Winther, Morten. 2007. *Fuel Consumption and Emissions from Navigation in Denmark from 1990-2005 – and Projections from 2006-2030*. University of Aarhus, Denmark. Retrieved (http://www.dmu.dk/Pub/FR650.pdf).

Appendix - Table of abbreviations

BAU	Business as Usual
BCO	Beneficial Cargo Owner
BT	Benefit Transfer
CAIR	Clean Air Interstate Rule
CAPEX	Capital expense
CARI	Congestion Assessment and Resource Integration
CBA	Cost-Benefit Analysis
CL	Close Loop
ECA	Emission Control Area
EGCS	Exhaust Gas Cleaning Systems
EPA	Environmental Protection Agency
FC	Fuel Consumption
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
IEA	International Energy Agency
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MARPOL	Marine Pollution
MBM	Market Based Method
ME	Main Engine
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MUSD	Million United States Dollars
NECA	Nitrogen Emission Control Area
NOAA	National Oceanic and Atmospheric Administration
NOx or NO2	Nitrogen Oxides
NPV	Net Present Value
OL	Open Loop
OPEX	Operational expense
P2P	Port to Port
PM	Particulate Matter
RT	Round Trip
SCR	Selective Catalytic Reduction
SECA	Sulfur Emission Control Area
SOx or SO2	Sulphur dioxide
TL	Trade Lane
ULSMGO	Ultra Low-Sulphur Marine Gas Oil
USEC	United States East Coast
WW	Worldwide

Appendix - Cost and benefits (alternatives)

In the liner shipping industry, the calculation of fixed cost takes into account that in the short term it is not possible to cancel a TL or change its route dramatically. Therefore, in calculating the fixed cost of operating a TL, the fuel expenses, for example, which are usually perceived as variable expenses, are recorded as fixed expenses. Where variable expenses are considered as expenses that can be assigned to a particular container box.

Total Cost (Private & Social - Annual)

Fixed cost

$$Fuel(Cost/Voy) = \sum FC_{High\_seas}\left(SP_{P2P}, ECA_{Y/N}, V_{Size}\right)\cdot T_{P2P}\cdot P_{Fuel} + FC_{port}\left(ECA_{Y/N}, V_{Size}\right)\cdot T_{Port}\cdot P_{Fuel}$$

$$CharterRate = V_{Num}\left(\left(\sum T_{P2P} + T_{port}\right)/Freq.\right)\cdot 365\cdot P_{Daily\_cost}$$

$$PortEX = \sum P^{i}_{PortDues}\left(V_{Nom.Size}, LOA\right)\cdot RT_{365/Freq.}$$

$$FixedCost = Fuel(Cost/Voy)\cdot AV + CharterRate + PortEX$$

Where,

- $Fuel(Cost/Voy)$ represents fuel expenses, as function of FC (by area (Tons/Voy)) multiply by $Time\cdot P_{Fuel}$;
- FC (by area - Tons/Voy) is a function of speed between ports in and out ECA as it effects speed and fuel type and vessel size;
- T_{P2P} is a vector of voyage sailing time between ports in and out ECA (Hr) and T_{Port} is vector of berth time at port (Hr) in and out ECA;
- P_{Fuel} is vector of fuel price as s function of fuel type in use when sailing/berth in and out ECA;
- V_{Num} is TL required vessel number as function of total voyage time divided by call frequency ($Freq.$);
- P_{Daily_cost} is a vessel charter rate ($/day), where for scrubber alt. scrubber premia was added;
- $PortEX$ represents port expenses, a function of accumulated port dues and canal fees per voyage (function of vessel nominal size ($V_{Nom.Size}$), Length Overall (LOA)) multiply by Round Trip (RT) (function of 365 days divided by call frequency ($Freq.$));
- $FixedCost$ represents total voyage cost (annual) of the trade lane (where AV represents the Annual Voyages); Imp

- $VCAPEX$ - represents Vessel CAPEX, system $\left(P_{sys}\right)$ and implementation cost (retrofit / installation - one-time cost $\left(P_{imp}\right)$

Additional cost for Scrubber and LNG alternative

CAPEX

$$TF_{CAPEX} = \underbrace{\left(P_{sys} + P_{imp}\right)}_{VCAPEX} \cdot V_{Num} + P_{Other}$$

Where,

- $VCAPEX$ - represents Vessel CAPEX, system $\left(P_{sys}\right)$ and implementation cost (retrofit / installation - one-time cost $\left(P_{imp}\right)$.
- TF_{CAPEX} represents total fleet CAPEX as a function of VCAPEX multiply by V_{Num} with P_{Other} (other cost represents alternative vessel cost and/or low sulfur fuel cost when retrofit operation continues after 2020).

OPEX - Ongoing Cost (Annual)

- $FC(ECA,Voy) \cdot Energy(\%) \cdot P_{Fuel}$ represents expected operation cost increase in electric load due to scrubber operation - in and out ECA.
- Loss Cargo – represents loss in cargo space function of vessel size, number of lost slot, vessel life span and freight rate in designated TL.
- Scrubber other cost - EGCS maintenance cost, Sludge disposal cost, Caustic soda (NaOH)

Damages Cost

- Total Fleet Emissions Damages ($/Ton - annual), represents by emission social cost, multiply by deviation of emission $\left(\Delta CO_2, \Delta SO_2, \Delta NO_X\right)$ compare to reference alternative

Total Benefits (Private & Social - Annual)

Hard & Soft Savings

- Total TL fleet fuel expense saving, Scrubber and LNG alternative ($/Anuual)
- IMO Compliance - Scrubber Retro Fit Saving, MGO and Hybrid alternative ($/Anuual)
- Avoided emissions allowance cost, represents by avoided emissions cost (damages), multiply by deviation of emission $\left(\Delta CO_2, \Delta SO_2, \Delta NO_X\right)$ compare to BAU (HFO/MGO) alternative.