SPEED MANAGEMENT FOR ENERGY EFFICIENT SHIPPING

Ruihua Lu, Tong Cui, Osman Turan, Evangelos Boulougouris

Department of Naval Architecture and Marine Engineering, University of Strathclyde, 100 Montrose Street, Glasgow G4 0LZ, UK, r.lu@strath.ac.uk

ABSTRACT

Energy efficiency improvements and low carbon emissions in the shipping industry have drawn much attention in recent research activities. Speed management, one important fuel-efficient ship operation, has been carried out in two case studies for oil tanker and container ship within this paper. The objective of this paper is to illustrate the effect of speed management for energy efficient shipping and present the approach to estimate the optimum speed set for minimum fuel consumption while keeping the estimated time of arrival (ETA) fixed in actual commercial trade routes. Based on the semi-empirical ship operational performance prediction model, the relation between the required main engine power and ship speed under varying sea state is established for specific commercial ship. The correction factor including fouling effect and main engine aging condition is also included in ship performance prediction. When the optimum main engine output range, for example 60% - 85% Maximum Continuous Rating (MCR) has been determined, the corresponding optimum speed range under each specific Beaufort Number (BN) will be provided to ship masters as a reference for ship operation. With the fixed ETA, the optimum speed set with minimum fuel consumption is generated by utilizing a speed optimization programme written in house. This paper also looks into the ship operational performance with optional speed sets, which enables the ship masters to easily investigate the accurate relation between main engine fuel consumption, voyage time, speed settings and varying sea conditions. The results will also support the ship management with regards to ship scheduling whilst improving energy efficiency.

Keywords: Energy efficiency, Speed management, Speed optimization, Fuel-efficient ship operation

1. INTRODUCTION

Reducing Greenhouse Gas (GHG) emissions from shipping is a key drive for energy efficient shipping. According to the International Maritime Organization (IMO) GHG Study, shipping in 2012 was estimated to have emitted 949 million tonnes of CO_2. The average shipping CO_2 emissions growth by 2020 will amount to 7% of 2012 emissions. For 2030 the average shipping emissions will increase by 29% and for 2050 95% (IMO, 2014).

Another primary drive towards energy efficient shipping is fierce shipping competition. Although merchant ship engines burn the cheapest ‘bunker fuel’, the cost of IFO 180 has risen sharply with other petroleum products, increasing from $170/t in 2002, to $230/t in 2005, and further to nearly $700/t in July 2014 (Bunker Index, 2014). With such high fuel prices, the bunker costs could account for 50%-60% of a ship’s total operating cost (Wang and Teo, 2013). The competition between shipping companies is becoming fiercer with the increasing fuel price. Even if the cost of IFO 180 drops to around $260/t today (Bunker Index, 2015), energy efficient shipping is still the primary goal of shipping companies.

As the main regulatory body for shipping, the IMO has been focusing on regulating shipping energy efficiency and thereby controlling the marine GHG emissions. For this purpose, a number of technical and operational measures have been developed by the IMO. These measures include:

- Energy Efficiency Design Index (EEDI);
- Energy Efficiency Operational Index (EEOI);
- Ship Energy Efficiency Management Plan (SEEMP).

The SEEMP, as part of MARPOL Annex VI, has been made mandatory since 1st January 2013, and is applicable to both new and existing ships of 400 tonnages and above. The SEEMP is a 'live' document, outlining a program that drives the continuous improvement of the energy efficiency of the ships. The fuel-efficient ship operations recommended by SEEMP (IMO, 2012) include:

- Improved voyage planning
- Weather routing
- Just in time
- Speed optimization
- Optimized shaft power

Many studies on the optimization of shipping operations have assumed that ship speed is fixed during the voyage (Christiansen et al., 2004; Shintani et al., 2007; Gelareh et al., 2010; Wang and Meng, 2011, 2012). However, compared to the given speed, optimal speed for the voyage is very likely to contribute to energy efficient shipping. Some researchers (Corbett et al., 2010; Meng and Wang 2011a; Ronen, 2011) have investigated the optimal speed issue for container ships based on the third power relationship between speed and approximately proportional bunker consumption (Ronen, 1982). Besides the investigation of speed optimization for container ship, Norstad et al. (2011) also look into the bulk carrier. By utilizing the nine cases (as presented in Table 1) from bulk shipping companies, the effect of speed optimization using the multi-start local search heuristic was evaluated with five approaches, which include:

1. The speed of each case was fixed with service speed of 17 knots. This approach was taken as baseline solution.
2. Based on the baseline solution, the speed was optimized for each route separately, as proposed by Fagerholt et al. (2010).
3. The speed of each was fixed with maximum speed of 20 knots. Fuel consumption increases but additional spot cargoes may be carried for higher profits.
4. The maximum speed with speed optimization for each route, as proposed by Fagerholt et al. (2010).
5. Variable speed (in the range of 14-20 knots) for each case, where the speed on each route was optimized with fleet schedule.

Table 1: Characteristics of test cases for speed optimization (Norstad et al., 2011)

Case No.	1	2	3	4	5	6	7	8	9
No. of contracted cargoes	18	8	17	12	15	41	28	12	16
No. of spot cargoes	0	1	0	2	2	9	2	3	2
No. of vessels	6	3	6	7	13	13	13	4	6
Planning horizon (days)	23	75	75	40	35	150	20	35	90

Table 2: Speed optimization – profit and fuel cost differences (in percent) from fixed service speed (Norstad et al., 2011)

Approach	Case No.	1	2	3	4	5	6	7	8	9	Average
Service speed	Profit	0.4	0.5	2.0	4.0	1.7	6.8	0.8	0.4	8.7	2.7
+ speed opt (2)	Fuel	-2.4	-3.1	-14.0	-24.6	-9.7	-43.9	-10.4	-7.9	-11.1	-14.1
Max speed	Profit	-1.6	1.9	-7.0	-7.9	-6.1	-6.3	-1.9	-1.7	-25.6	-6.2
(3)	Fuel	31.7	53.7	45.6	46.2	35.4	40.1	24.9	31.8	74.7	42.7
Max speed +	Profit	1.8	6.4	2.0	4.0	2.0	7.2	1.1	0.4	26.3	5.7
speed opt (4)	Fuel	-15.3	27.6	-14.0	-24.4	-11.5	-45.2	-14.2	-7.9	8.5	-10.7
Variable speed	Profit	2.2	7.7	2.0	6.6	2.1	10.9	1.3	0.5	30.0	7.0
(5)	Fuel	-21.3	20.1	-14.0	-38.3	-12.4	-70.0	-18.0	-8.8	3.9	-17.6

Relative results of the last four approaches were compared with the baseline provided in approach 1, as presented in Table 2. Compared to the results generated with approach 1 and 3, speed optimization (approach 2, 4) contributes to profit increasing and fuel savings. The speed optimization with variable speed range achieves best profit and fuel savings. However, according to Fagerholt and Ronen (2013), the non-linearity of the bulk fleet scheduling problem with speed optimization is not able to find optimal solutions within any reasonable time frame for realistic size problems.

Lang and Veenstra (2010) have optimized sailing speed by assuming that fuel consumption varies linearly with the sailing speed to avoid nonlinearity, but the potential speed range must be very narrow. Golias et al. (2010) and Norstad et al. (2011) have taken a heuristic method to achieve speed optimization while the optimality cannot be guaranteed. Gelareh and Meng (2010) and Alvarez et al. (2010) have been discretizing the sailing speed range to address the nonlinearity. The benefits of this approach include:

- Widely applicable to continuous nonlinear functions
- Easily control approximation error by the number of discretization intervals

In an overview of the approaches for speed optimization, most studies are still using the third power relationship, which is not able to provide accurate ship operational performance prediction with varying sea conditions. Some studies have been using the historical operating data for regression. However, the ship fouling conditions, main engine aging conditions, and ocean currents are not involved. In the future studies, speed optimization for the commercial ship with wind-assisted technology (Kites and Rotors) will require a ship performance model sensitive to wind speed and wind direction.

2. MODELLING APPROACH

This section introduces the modelling approach of ship operational performance with different speed sets and based on the results to find optimum speed set for a given ETA. The analysis diagram of the modelling approach is presented in Figure 1.

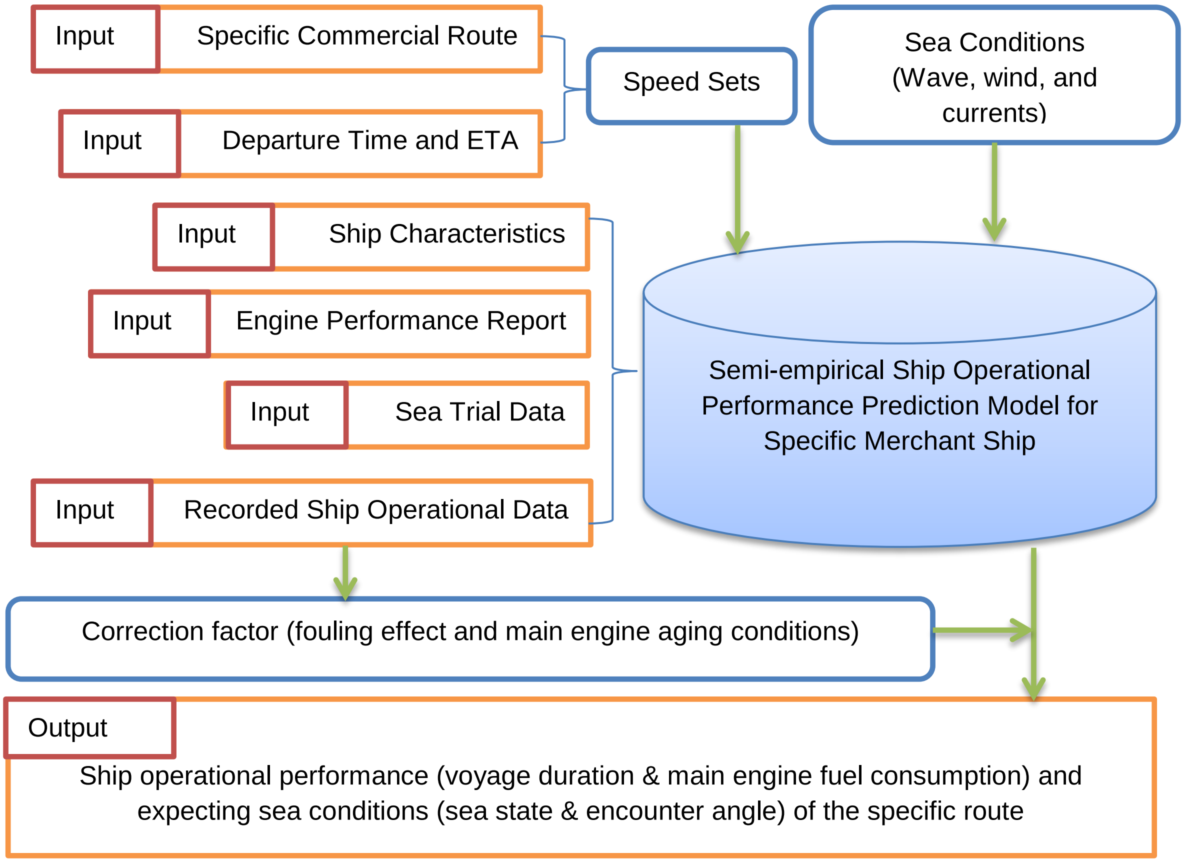

Figure 1: Analysis Diagram of the Modelling Approach

As the objective of this paper is to study the effect of speed management for energy efficient shipping, for the given route, departure date and time, and ship's loading conditions, the encountering sea state ocean currents and encounter angle between sea direction and ship heading direction are assumed to be fixed. Based on the semi-empirical ship operational performance model proposed by Lu et al. (2015), the relation between the required main engine power and ship speed under varying sea state can be extracted for specific commercial ship, as presented in Figure 2. By utilizing the Specific Fuel Oil Consumption (SFOC) diagram in the main engine performance report, the relation between Fuel Consumption Rate (FCR) and engine load is determined, and therefore the relation between required engine power and speed under varying sea states is converted into the relation between FCR and speed under varying sea conditions.

The optimum speed range is generated with the pre-determined optimum main engine output range. With the given sea conditions during each route leg, the potential speed sets along the route is developed with all possible speed combinations. By utilizing a speed optimization programme written in house and taking fixed ETA as constraint, the optimum speed set for minimum fuel consumption is developed by evaluating the predicted ship operational performance (voyage duration and main engine fuel consumption) with all potential speed sets. Therefore, the ship masters are able to manage the optimum speed within specific ETA.

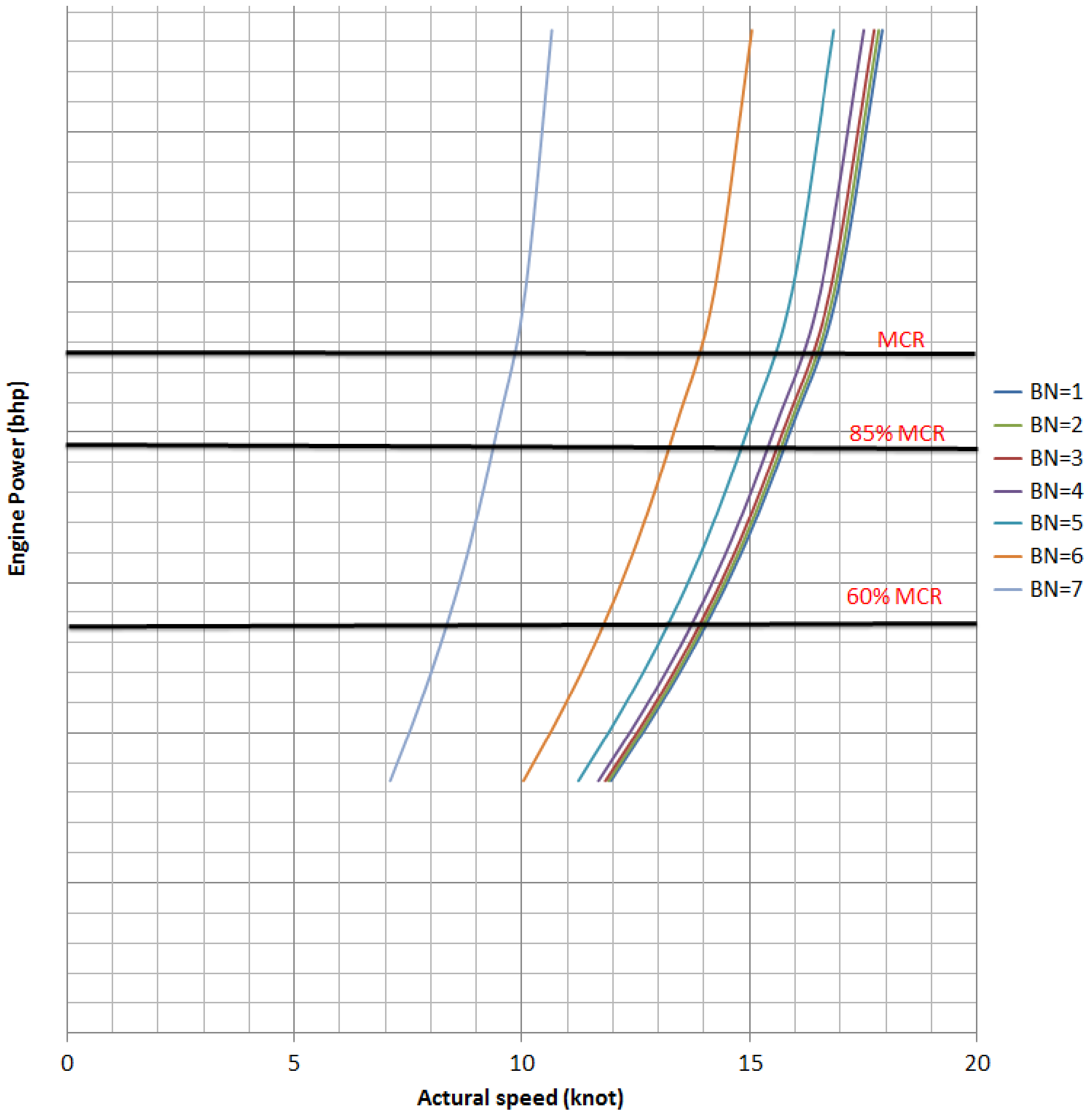

Figure 2: Relation between required main engine power and ship speed under varying sea state

With given route, departure date and time, loading condition, the encountering sea state and encounter angle are assumed to be constant, the total fuel consumption and voyage time under different speed sets are compared as following:

- Speed Set A - Actual voyage speed as recorded in ship noon report
- Speed Set B - Optimum speed with identical ETA in actual voyage
- Speed Set C – 0.5 knot increase on recorded daily voyage speed
- Speed Set D - 1 knot increase on recorded daily voyage speed
- Speed Set E – 0.5 knot decrease on recorded daily voyage speed
- Speed Set F - 1 knot decrease on recorded daily voyage speed

By evaluating the ship performance with varying speed sets, the ship masters are also able to balance the weight between fuel consumption and voyage time. If the extra voyage time is available, the corresponding amount of fuel savings can be easily presented to ship masters. In the following section, two case studies have been carried out, and the results will clarify the effect of speed management for energy efficient shipping.

3. CASE STUDIES

3.1 CASE STUDY OF AFRAMAX OIL TANKER

For an Aframax Oil Tanker, a case study regarding speed management has been carried out. A range of optimum speed is determined with 60% - 85% Maximum Continuous Rating (MCR) of the main engine. In this case study, the range of optimum speed under specific BN has been concluded in Table 3.

Figure 3: Selected commercial trade route (Lagos, Nigeria – Barcelona, Spain) for an Aframax oil tanker (Google map API, 2015)

Table 3: The range of optimum speed under specific BN for an Aframax oil tanker

	Optimum speed range (knots)	
BN	60%MCR	85%MCR
1¬3	13.9	15.6
4	13.8	15.4
5	13.2	14.8
6	11.7	13.2

For the selected 12 days voyage route, as presented in Figure. 3, the ship operational performances of an Aframax oil tanker with different speed set have been compared, as presented in Table 4. While keeping the same sea states and ETA, 2.52% of total Heavy Fuel Oil (HFO) consumption is saved by utilizing the optimum speed set. When the recorded daily voyage speed is increased by 0.5 knot and 1 knot, extra 6.92% and 13.63% of total HFO consumption are required. The time saving is estimated to be 10 hours for 0.5 knot speed increase and 20 hours for 1 knot speed increase respectively. When the recorded daily voyage speed is decreased by 0.5 knot and 1 knot, 7.13% and 13.42% of total HFO consumption can be saved. However, voyage duration is increased by 11 hours and 23 hours for 0.5 knot speed decrease and 1 knot speed decrease respectively.

Table 4: Comparison of ship operational performance with different speed sets for an Aframax oil tanker

Date	BN	Relative Angle	Speed Set A (Recorded)	Speed Set B (Optimum)	Speed Set C (+0.5 kn)	Speed Set D (+1 kn)	Speed Set E (-0.5 kn)	Speed Set F (-1 kn)
Day 1	4	Bow Sea	13.5	13.8	14	14.5	13	12.5
Day 2	4	Bow Sea	13.2	13.8	13.7	14.2	12.7	12.2
Day 3	4	Bow Sea	13.4	13.8	13.9	14.4	12.9	12.4
Day 4	4	Bow Sea	13.5	13.8	14	14.5	13	12.5
Day 5	3	Head Sea	13.6	14.2	14.1	14.6	13.1	12.6
Day 6	4	Bow Sea	13.4	13.8	13.9	14.4	12.9	12.4
Day 7	5	Head Sea	13.2	12.4	13.7	14.2	12.7	12.2
Day 8	6	Head Sea	13.2	10.3	13.7	14.2	12.7	12.2
Day 9	5	Head Sea	13.1	12.4	13.6	14.1	12.6	12.1
Day 10	4	Head Sea	13.3	13.8	13.8	14.3	12.8	12.3
Day 11	4	Head Sea	13.5	13.8	14	14.5	13	12.5
Day 12	3	Head Sea	13.2	14.2	13.7	14.2	12.7	12.2
Voyage Duration (h)			283	283	273	263	294	306
Main Engine Fuel Consumption (t)			477	465	510	542	443	413
Fuel savings compared to Speed Set A (%)			0	2.52	-6.92	-13.63	7.13	13.42

3.2 CASE STUDY OF POST-PANAMAX CONTAINER SHIP

For a Post-panamax container ship, a case study regarding speed management has been carried out. A range of optimum speed is determined with 60% - 85% MCR of main engine for each BN and the results are provided in Table 5.

Table 5: The range of optimum speed under specific BN for a Post-panamax Container ship

	Optimum speed range (knots)	
BN	60%MCR	85%MCR
1‒3	15.2	24.2
4	15	22.4
5	14.6	22.2
6	14.2	21.5

For the selected 5 day voyage, as presented in Figure. 4, the ship operational performances of the Post-panamax container ship with different speed set have been compared, as presented in Table 6. While keeping the same sea states and ETA, 1.03% of total HFO consumption is saved by utilizing the optimum speed set. When the recorded daily voyage speed is increased by 0.5 knot and 1 knot, extra 7.77% and 16.87% of total HFO consumption are required. The time saving is estimated to be 3 hours for 0.5 knot speed increase and 6 hours for 1 knot speed increase respectively. When the recorded daily voyage speed is decreased by 0.5 knot and 1 knot, 6.45% and 11.88% of total HFO consumption can be saved. The voyage duration is only increased by 3 hours and 6 hours for 0.5 knot speed decrease and 1 knot speed decrease respectively.

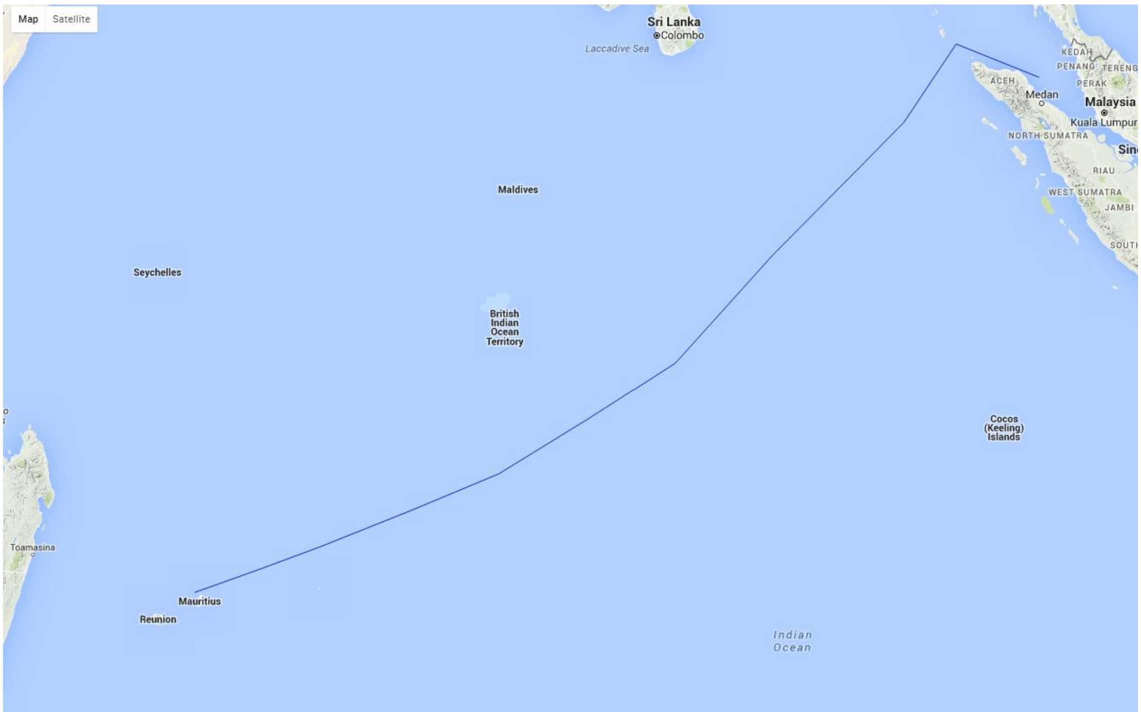

Figure 4: Selected commercial trade route (Penang, Malaysia – Port Louis, Mauritius) for a Post-panamax container ship (Google map API, 2015)

Table 6: Comparison of ship operational performance with different speed sets for a Post-panamax container ship

Date	BN	Relative Angle	Speed Set A (Recorded)	Speed Set B (Optimum)	Speed Set C (+0.5 kn)	Speed Set D (+1 kn)	Speed Set E (-0.5 kn)	Speed Set F (-1 kn)
Day 1	5	Head Sea	21.2	19.8	21.7	22.2	20.7	20.2
Day 2	3	Beam Sea	20.9	21.9	21.4	21.9	20.4	19.9
Day 3	4	Beam Sea	21.3	21.7	21.8	22.3	20.8	20.3
Day 4	4	Following Sea	21.4	21.7	21.9	22.4	20.9	20.4
Day 5	5	Beam Sea	21.4	21	21.9	22.4	20.9	20.4
Voyage Duration (h)			128	128	125	122	131	134
Main Engine Fuel Consumption (t)			681.7	674.7	734.7	796.7	637.7	600.7
Fuel savings compared to Speed Set A (%)			0	1.03	-7.77	-16.87	6.45	11.88

4. DISCUSSIONS AND CONCLUDING REMARKS

Based on the case studies of one 12 day voyage for an Aframax oil tanker and one 5 day voyage for a Post-panamax container ship, 2.52% and 1.03% of total HFO consumption can be saved respectively by utilizing optimum speed set while keeping recorded ETA and sea conditions. Between 2010 and 2012, the Aframax oil tanker voyages around 263 days annually, 263.4 t HFO is potential to be saved per year by utilizing optimum speed set. The Post-panamax container ship voyages around 180 days annually, 252.8 t HFO is potential to be saved per year by utilizing optimum speed set.

Since the voyage speed set has been pre-determined for a specific route, the four optional speed sets, 0.5 knot increase/decrease on daily speed and 1 knot increase/decrease on daily speed, are generated. For the Aframax oil tanker, 11 and 23 hours delay on ETA will save 7.13% and 13.42% HFO consumption respectively; 10 and 20 hours earlier arrival than ETA will cause extra 6.92% and 13.63% HFO consumption respectively. For the Post-panamax container ship, 3 and 6 hours delay on ETA will save 6.45% and 11.88% HFO consumption respectively; 3 and 6 hours earlier arrival than ETA will cause extra 7.77% and 16.87% HFO consumption respectively.

Within this paper, the approach of modelling the ship operational performance with different speed sets and based on the results to select optimum speed set has been proposed. With identical ETA and sea conditions, 1 - 3% of fuel consumption can be saved by utilizing optimum speed set for oil tanker and container ship. By evaluating the ship operational performance with optional speed sets, large amount of fuel savings, can be achieved with small delay on ETA. Conversely, a large amount of extra fuel is consumed by earlier arrival than ETA. The energy efficiency of ship scheduling is very likely to increase by investigating the relation between different ETA and corresponding fuel consumption for specific commercial ships.

Voyage optimization combining weather routing and speed management can potentially generate significant savings and this provides a good mission for the authors to combine both energy efficiency measures and present the results in future papers.

ACKNOWLEDGEMENTS

The study presented in this paper was carried out as part of the research project: Shipping in Changing Climate - funded by UK Research Council (EPSRC Grant no. EP/K039253/1)

REFERENCES

Alvarez, J.F., Longva, T. and Engebrethsen, E.S. (2010) ‘A methodology to assess vessel berthing and speed optimization policies’. Maritime Economics & Logistics 12, 327–346.

Bunker Index (Accessed July 2014 and November 2015) IFO 380 price in Port Singapore, Rotterdam and Fujairah. Website: http://www.bunkerindex.com/

Christiansen, M., Fagerholt, K. and Ronen, D. (2004) ‘Ship routing and scheduling: status and perspectives’. Transportation Science 38 (1), 1–18.

Corbett, J.J., Wang, H. and Winebrake, J.J. (2010) ‘The effectiveness and costs of speed reductions on emissions from international shipping’. Transportation Research 14D, 593–598.

Fagerholt, K., Laporte, G. and Norstad, I. (2010) ‘Reducing fuel emissions by optimizing speed on shipping routes’, Journal of the Operational Research Society, 61(3), 523-529.

Fagerholt, K. and Ronen, D. (2013) ‘Bulk ship routing and scheduling: solving practical problems may provide better results’, Maritime Policy & Management, 40:1, 48-64.

Gelareh, S. and Meng, Q. (2010) ‘A novel modeling approach for the fleet deployment problem within a short-term planning horizon’. Transportation Research 46E, 76–89.

Gelareh, S., Nickel, S. and Pisinger, D. (2010) ‘Liner shipping hub network design in a competitive environment’. Transportation Research 46E, 991–1004

Google maps API. Website: https://developers.google.com/maps/documentation/javascript/tutorial [Accessed November 2015]

IMO (2012). ‘Guidelines for the development of a SEEMP’, MEPC 63/23, Annex 9.

IMO (2014). ‘Third IMO GHG Study 2014 – Final Report’, MEPC 67/INF, pp. 13 -161.

Lang, N. and Veenstra, A. (2010) ‘A quantitative analysis of container vessel arrival planning strategies’. OR Spectrum 32, 477–499.

Lu, R., Turan, O., Boulougouris, E., Banks, C. and Incecik, A. (2015) ‘A semi-empirical ship operational performance prediction model for voyage optimization towards energy efficient shipping’. Ocean Engineering doi:10.1016/j.oceaneng.2015.07.042

Meng, Q., Wang, S. (2011a) ‘Optimal operating strategy for a long-haul liner service route’. European Journal of Operational Research 215, 105–114.

Norstad, I., Fagerholt, K. and Laporte, G. (2011) ‘Tramp ship routing and scheduling with speed optimization’, Transportation Research Part C: Emerging Technologies, 19, 853-865.

Ronen, D. (1982) ‘The effect of oil price on the optimal speed of ships’. Journal of the Operational Research Society 33, 1035–1040.

Ronen, D. (2011) ‘The effect of oil price on containership speed and fleet size’. Journal of the Operational Research Society 62, 211–216.

Wang, S. and Meng, Q. (2011) ‘Schedule design and container routing in liner shipping’, Transportation Research Record 2222, 25–33.

Wang, S. and Meng, Q. (2012) ‘Liner ship fleet deployment with container transshipment operations’, Transportation Research Part E 48, 470–484

Wang, X., Teo, C., 2013. ‘Integrated hedging and network planning for container shipping’s bunker fuel management’. Maritime Economics & Logistics, pp. 172-196.

Shintani, K., Imai, A., Nishimura, E., Papadimitriou, S. (2007) ‘The container shipping network design problem with empty container repositioning’. Transportation Research 43E, 39–59.