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Probabilistic Assessment Method of Hydrometeorological Conditions and their Impact on the Efficiency of Ship Operation

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Abstract

Among the most important ship operational characteristics, that determine the carrying capacity as well as the time of cargo delivery is speed. The speed depends on not only ship's main engine specification and design solutions in respect of hull form and general architecture, but also on cost and consumption of fuel, lubricants, level of freight rates, daily operating costs and a number of other variable factors. The issues concerning substantiation of ship operating speed are determined considering fuel consumption, cargo capacity and tonnage at the stage of ship designing. The efficiency of slow steaming ship operation is determined by the fact that the dependence of fuel consumption on speed is non-linear. The exact relation of fuel consumption dependence on ship speed can vary depending on, type of engine, current condition of vessel hull and weather conditions on the shipping route. Modern hydrometeorology successfully copes with tasks of forecasting of dangerous sea phenomena and protecting a vessel from getting into force-majeure navigation conditions and thereby providing safety of crew, passengers and a vessel as a whole. Ships of modern fleet possess excessive reserve capacity of main engines which reliable work allows the navigator to manoeuvre actively for prevention of flooding of the hull by a storm wave, and at inevitable occurrence of a dangerous pitching and rolling to recuperate the chosen operating mode.

Keywords: ship speed, weather conditions, ship operation efficiency;

1. Introduction

The search for an economical speed, which equally would provide the minimum cost of a ton-mile for cargo transportation and at the same time would be optimal in view of prevention of main engine damages, in other words the combination of optimal commercial speed with consideration of economic indicators of the ship and its technical capabilities is an actual task. A decrease in speed not only reduces fuel consumption, but also significantly reduces the operating costs of the vessel. But at the same time it is necessary to consider the fact that the question of justification of economically feasible ship speed and its reduction leads to a significant reduction in the number of voyages in the calendar period and, consequently, to the reduction of income from freight. Therefore, practically important and actual task is to justify a ship speed at which a balance between fuel economy and profit from ship operation will be provided.

The efficiency of ship operation, as it is known, can be carried out with the help of various tools. However, from the point of view of specifics of process of transportation of project cargoes, their directions and length of a shipping route, one of key mechanisms for maintenance of efficiency of vessel operation is clarification of optimum speed mode considering influence of meteorological factors. Other features of project cargo shipments are also distances between ports, the duration of the voyage and conditions on the time of arrival of the vessel in port, which are reflected in modern publications in the form of the proposed approach for speed mode optimization, which is based on daily profits of ship operation or time-charter equivalents.

The above-mentioned specifics of the process of project cargo transportation requires a comprehensive study, the need to accumulate an appropriate theoretical framework and indicates the existing potential for its development.

Considerable attention is devoted to issues of heavy and oversized cargo transportation, including the specifics of the transportation process, risk management assessment, the conditions of optimal operation of means of transport and the creation on this basis of a comprehensive approach to the theoretically sound strategies for the development of such transportation in studies [1-3, 16]. Routing decision support system and methods of average navigation risk assessment reviewed in [4, 6, 7]. In [5, 8, 10] weather routing optimization and weather hazard avoidance in modelling safety of motor-driven ship for multicriteria weather routing and probabilistic models for predicting ship besetting in ice in Arctic waters. A simplified method of forecasting ship's speed in determining ETA studied in [9, 17]. Significant emphasis on the optimization of ship speed is given in the works of [11-15]. Safety risk assessment on different modes of transport and studying of potential negative impact of the system of factors are in works [15-20].

Thus, a review of previous papers on the selected topic of research indicates an unequivocal academic gap in the issues of ensuring the speed mode of ship operation using the method of optimizing the efficiency of ship operation, taking into account the impact of weather conditions during shipping route. Hence, an approach consisting of a local examination of the speed mode of the passage sections during the voyage,

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taking into account the limits of each section under different weather conditions, which gives a reliable result that meets the logic and practice of ship operation, is proposed.

2. Methods and materials

Project cargo transportation is geographically specific in that it is carried out over significant distances. One of the main suppliers of this category of cargo (e.g., industrial equipment, machinery, parts of support towers for oil and gas production; wind generators, etc.) is China. European ports are the final destination for such cargoes.

Since this study considers the use of dry cargo ships for transportation of this type of cargo, the main objective of the ship operation under these conditions is to ensure the efficiency of operation while maintaining the safety of navigation.

An example of the ship's voyage on the route China - the Black Sea, when transporting project cargoes and its division into conditional sections is shown in (Fig. 1). It should be noted that, as a rule, for such voyages will not be correct to determine the optimal speed of the ship on the entire route, as is suggested in the current theoretical basis, without taking into account both environmental and meteorological factors of influence.

Fig. 1. Example of the ship's voyage on the route China - the Black Sea

It should be noted that the proposed approach is based on the most probable weather scenario during the voyage, i.e. the probability of occurrence of particular weather conditions in a specific region is determined by the season and can be assessed on the basis of statistical data, taking into account the weather forecast for the upcoming voyage. Thus, especially during stormy periods, when preparing the passage plan and assessing the level of its efficiency, the impact of weather conditions on the ship's operation in terms of speed mode must be considered.

The weather conditions affecting the ship operation are proposed to be divided into three categories (situations):
1) A - sea passage is under good weather conditions (1-5 Beaufort scale);
2) B - sea passage is under average weather conditions (7-8 Beaufort scale);
3) C - sea passage is under adverse weather conditions (9-11 Beaufort scale).

For further research, the following approach will be used. Suppose there are several such scenarios, and they are based on the relevant probabilities (given events) for each section of the passage, denote them: $P_i(A), P_i(B), P_i(C)$.

Naturally that:

$$P_i(A) + P_i(B) + P_i(C) = 1, i = \overline{1, n}. \quad (1)$$

Considering the multitude of sections and three variants of weather conditions for each section, the number of combinations of conditions during the passage can be quite significant and it does not make sense to consider them all. The scenario of weather conditions during a passage is given by the following combination of probability distributions:

Table 1. Probabilistic characteristics of weather conditions scenarios at the passage sections

Weather conditions type	Section 1	Section 2	…	Section n
A	$P_1(A)$	$P_2(A)$		$P_n(A)$
B	$P_1(B)$	$P_2(B)$		$P_n(B)$
C	$P_1(C)$	$P_2(C)$		$P_n(C)$

The calculations propose to take as the first weather scenario the following weather conditions at the sections that are characterized by the maximum probability, i.e. $k \in U_A$ if $P_k(A) = max\{P_k(A), P_k(B), P_k(C)\}$, similar for U_B, U_C.

For example, scenarios can be formed as accepted for consideration from the following after maximum probable weather conditions. Thus, three scenarios are presented for consideration C_1, C_2, C_3 . In this case, the probability of the first scenario:

$$P(C_1) = \prod_{i=1}^{n} max\{P_i(A), P_i(B), P_i(C)\}. \quad (2)$$

And the scenario itself is a combination of weather conditions of the type:

$$C_1 = \langle A, A, B, A, \ldots, C, B \rangle. \quad (3)$$

Probabilities of the remaining scenarios $P(C_2), P(C_3)$ are calculated similarly as probabilities of products of independent events. Since the scenarios in question do not form a complete group, then $P(C_1) + P(C_2) + P(C_3) < 1$.
As a result, sets of weather conditions are produced in the form of L_A, L_B, L_C values of the ship's operating efficiency - time-charter equivalent: TCE_s, calculated on the basis of the optimal speed $V_s{}^o$ and the relevant probability $P(C_s)$:

$$\langle P(C_s), L_A, L_B, L_C, V_s{}^o, TCE_s \rangle, s = 1,2,3. \quad (4)$$

Determine the average value of ship operation efficiency for different weather scenarios during the passage; we propose an approach similar in nature to the calculation of the mathematical expectation when conditionally considering three weather scenarios as a complete group of events:

$$\overline{TCE} = \sum_{s=1}^{3} \frac{P(C_s)}{P(C_1)+P(C_2)+P(C_3)} \cdot TCE_s. \quad (5)$$

$\frac{P(C_s)}{P(C_1)+P(C_2)+P(C_3)}$ is the probability of the event C_s conventionally accepted as a complete group of events C_1, C_2, C_3.

The averaged time-charter equivalent (5) takes into account different weather scenarios during ship passage and their probabilities, as well as different values of optimal speed modes of ship operation under different weather scenarios.
Thus, in contrast to existing approaches, the proposed method for optimizing the ship operation efficiency through her speed mode during transportation of project cargoes considers the structure of ship passage and various weather scenarios, which together provide the compliance of the proposed method with the actual conditions of ship operation.

2. Results and Discussion

It is necessary to note, that as a rule, for similar transoceanic voyages it will be incorrect to define optimum ship speed throughout the whole route of passage as it is offered in existing theoretical base without taking into account both navigational and meteorological factors of influence. Therefore, unlike existing classical methods of speed mode analysis of ship operation during the voyage and methods and solutions for ship speed optimization proposed in [8,10,11-15,21], in the given work the approach that provides local consideration of speed mode on sections of ship passage taking into account restrictions of each section at different weather conditions is offered. To demonstrate the proposed method, consider the following input data (Table.2).

Table 2. Baseline data on the route and weather conditions on the sections of the passage China - Black Sea

Section of passage	L_i, NM	Probability of weather conditions		
		$P_i(A)$	$P_i(B)$	$P_i(C)$
1) Shanghai - Singapore	2887	0,85	0,1	0,05
2) Singapore – Galle	1366	0,9	0,08	0,02
3) Galle – Bab El Mandeb	1867	0,25	0,7	0,05
4) Bab El Mandeb – Suez	1561	0,8	0,18	0,02
5) Suez – Bosphorus	1214	0,18	0,8	0,02

The total passage distance L=8895 nautical miles.

Taking into account the accepted dependence y = 0,0104x3 - 0,1984x2 + 1,5098x - 2,73 fuel consumption (tons) on the speed for the considered ship was obtained the dependence $TCE(V)$ and the set value of the optimum speed $V^o = 12$ kn, that maximizes operational efficiency и $TCE(V^o) =$ 5429USD/days (Fig.2) excluding the influence of weather conditions on the ship's operation. Accept V^{max} knots, V^{max}knots, V^{max} knots.

Most probable weather scenario: $C_1 = \langle A, A, B, A, B \rangle$ with probability

$$P(C_1) = 0{,}85 \cdot 0{,}9 \cdot 0{,}7 \cdot 0{,}8 \cdot 0{,}8 = 0{,}343.$$

For a given weather scenario: $L_A = 2887 + 1366 + 1561 = 5814$ nautical miles;

$L_B = 1867 + 1214 = 3081$nautical miles.

For weather conditions ***B:*** V^{max^o} Therefore, in sections with weather conditions of the given type we accept $V = V^{max}$ Accordingly, we obtain the following pattern (Fig.3):

$$TCE(V) = \frac{F - R^{port} - c^b \cdot \left[\frac{5814}{V \cdot 24} \cdot r^b(V) + \frac{3081}{11 \cdot 24} \cdot r^b(11)\right]}{t^{st} + \frac{5814}{V \cdot 24} + \frac{3081}{11 \cdot 24}}. \quad (6)$$

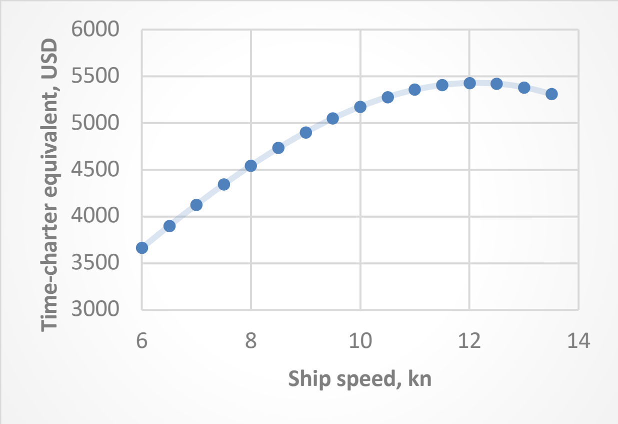

Fig. 2. Dependence $TCE(V)$ for the considered ship and passage from China to Black sea (port of Odesa)

Obviously, the value of the optimum speed remains the same, $V^o = 12$ kn, the value of efficiency has slightly decreased: $TCE(V^o) = 5403$USD/days. We note that the initial efficiency is higher, given the fact that the speed on part of the route has already been set, which is more economical in terms of fuel consumption and provides a shorter voyage time.

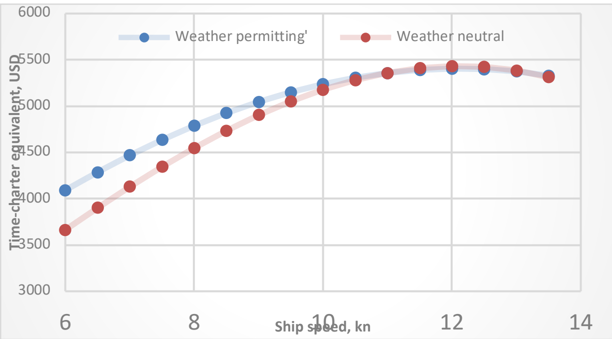

Fig. 3. Dependence $TCE(V)$ including weather scenario

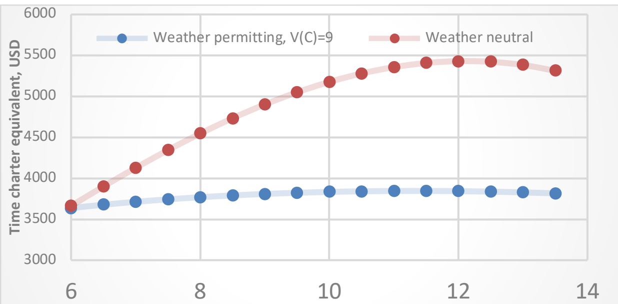

Fig. 4. Dependence $TCE(V)$ considering the "worsened" weather scenario

"Worst" weather conditions for the first section $P_1(C) = 0{,}9; P_1(A) = 0{,}05; P_1(B) = 0{,}05$ and for the second section$P_2(C) = 0{,}02; P_2(A) = 0{,}08; P_2(B) = 0{,}9$.. Then the weather scenario for this situation$C_1 = \langle C, B, B, A, B \rangle$. For a given weather scenario:

$L_A = 1561$nautical miles;

$L_B = 1366 + 1867 + 1214 = 4447$nautical miles;

$L_c = 2887$nautical miles.

For the weather conditions ***C:*** V^{max^o} Therefore, in sections with weather conditions of this type we accept $V = V^{max}$ Accordingly, we obtain the following pattern (Fig. 4):

$$TCE(V) = \frac{F - R^{port} - c^b \cdot \left[\frac{1561}{V \cdot 24} r^b(V) + \frac{4447}{11 \cdot 24} r^b(11) + \frac{2887}{9 \cdot 24} r^b(9)\right]}{t^{st} + \frac{1561}{V \cdot 24} + \frac{4447}{11 \cdot 24} + \frac{2887}{9 \cdot 24}}. \quad (7)$$

Apparently, the value of the optimum speed on the sections with weather type ***A:*** $V^o = 11$ kn, the value of efficiency has decreased: $TCE(V^o) = 3844$USD/days;

When we change the allowable speed under type C weather conditions for V^{max} kn, we get $V^o = 11{,}5$ kn, and $TCE(V^o) = 4050$USD per day, (Fig.5).

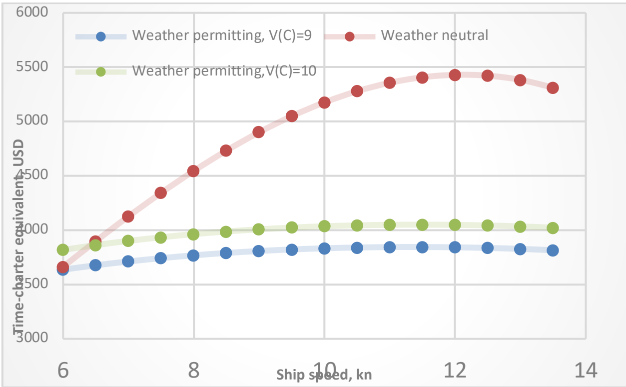

Fig. 5. Dependence$TCE(V)$ considering the "worsened" weather scenario for different values of maximum permissible speeds

4.Conclusion

Thus, after identifying sections of the route with adverse weather conditions of different types, a "refinement" (recalculation) of the optimal speed value that maximizes the performance indicator regardless of weather conditions in different sections of the route was carried out. It should be noted that this approach is adequate to the real processes of ship operation, and thus ensures reliable results - the optimal speed value and the level of the efficiency indicator - the time-charter equivalent. It is also worth noting that the suggested approach is based on the most probable weather scenario during the voyage, In other words, the probability of this or that weather scenario occurring in a particular region is determined by the season and can be evaluated on the basis of statistical data, considering the information available about the weather forecast for the intended voyage.

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