

A Comparison Study between Advance Transfer Technique and Advance Transfer Mathematical Model Using Bulk Carrier Ship: Cross-track Distance Validation by Percentage Change and Mann Whitney U Test

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ABSTRACT: One of the methods of efficient course alteration is through the accurate identification of the WOP by ATT. ATT is widely used by mariners worldwide, and recently, the technique has been restructured and enhanced into ATMM. To prove the efficacy of ATMM over ATT, a few types of ships have been used to carry out the manoeuvring analysis. This study extends the analysis by using a bulk carrier ship. A ship simulator was used for a manoeuvring simulation study, which was carried out to verify the differences between these two methods. Throughout the manoeuvring simulation study, XTD data for each simulation was monitored and verified by XTL compliance, percentage variation, and the Wilcoxon-Mann Whitney U Test via IBM SPSS. It was found that the ATMM can produce a significantly improved WOP compared to ATT and is suitable to be used onboard a bulk carrier ship. This research's finding is expected to contribute as evidence to strengthen ATMM's efficiency so that it can be accepted as an ECDIS algorithm for ship navigation.

1 INTRODUCTION

Wheel over point (WOP) is a term that refers to a point on a course line that reminds the navigator to initiate course alteration, which will ensure the ship stays on the planned course [1], [2]. Keeping the ship on its course helps to ensure the safety of ship navigation [3], [4]. Inadequate awareness of a ship's ability to turn and manoeuvre may result in a severe accident.

Other than that, WOP can be used to observe pilot behaviour since there have been several reports of pilot-related mishaps throughout the years [5], [6]. For instance, in one case, a vessel ran aground because the pilot slept [7]. In a subsequent event, a pilot made a late turning that the master subsequently overruled, but the vessel ended up running aground as a result of the late decision [8].

Then, in one instance, a vessel ran aground due to a pilot's judgement error during the turn's execution [9]. Another recorded incident occurred when navigating with the pilot on board; the navigation officer thought the pilot had everything under control despite the fact that the vessel was slightly off course, and the vessel ran aground due to inadequate course alteration [10]. Additionally, owing to inadequate turning, a cargo vessel ran aground during pilotage [11]. Then there was an instance in which a pilot repeatedly overshot a predetermined track before finally aground [12], and a vessel ran aground owing to the pilot's lack of expertise, and the navigation officer was unable to establish the chain of the pilot's error [13].

With WOP accurately indicated on the course line, it is possible to monitor the evolution of human error while turning. If the pilot initiates course alteration prior to WOP, the ship is safe; however, the ship

would overshoot if the pilot altered the course after WOP. As a result, if the pilot fails to act prior to WOP, the bridge team, specifically the master, may override the pilot's authority [14].

On January 27th 2016, a passenger ship, Azamara Quest, was on its way to Picton in New Zealand, carrying a total of 1046 passengers and the ship's crew. The pilot on board the ship made insufficient steering by making small rudder angle changes. When the pilot noticed the rudder was insufficient, the rudder angle was gradually increased. However, the ship still ends up damaging its bottom. According to the investigation, even though the pilot did not realise the turn was delayed, there was still sufficient sea room for manoeuvre. Nonetheless, the bridge team did not take the necessary action to override pilot authority due to a lack of knowledge in determining WOP [6], [15].

With references to the example given on the grounding of Azamara Quest or a similar incident, the ATT's benefit is that it is calculated using the hard rudder angle, implying that the WOP produced is the last point of action. If the WOP using hard rudder angle had been correctly marked in the paper chart or electronic chart display information system (ECDIS), the Azmara Quest's master could have taken over control from the pilot when the ship was nearing the WOP and instructed the helmsman to steer the rudder hard over since he knows that the ship will overshoot after that point.

2 LITERATURE REVIEW

2.1 Route monitoring through Advance Transfer Technique (ATT)

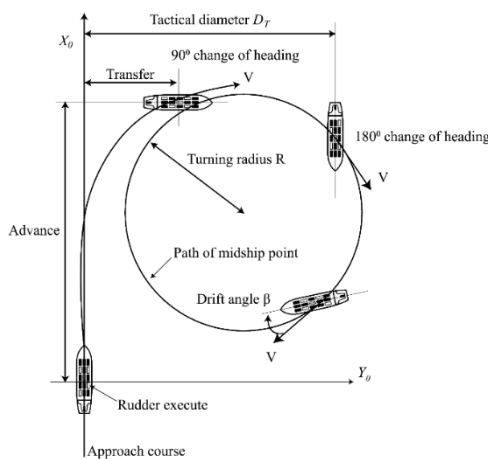


Figure 1. Example of ship's manoeuvring characteristic [16]

ATT is one of many methods that can be used to determine WOP [17]. As opposed to other technique, ATT use maximum angle while executing course alteration [1]. The name Advance Transfer Technique is used because this technique requires advance and transfer information from a ship manoeuvring characteristic, as seen in Figure 1. It is frequently used for navigating harbours and confined water (HCW) while under pilotage [18]. The WOP is calculated through ATT, explained as follows.

With reference to Figures 2, 3, and 4, the following symbols and abbreviations are used to describe the formula:

d_{adv} = Advance as per ship turning circle
 d_{trs} = Transfer as per ship turning circle
 d_{CG-WPT} = Distance measured from CG to WPT
 θ = The alteration angle

ATT is constructed with references to the model, as seen in Figure 2. The formula to calculate the position of WOP was able to be created. According to Anwar (2015), WOP is measured from the WPT to the ship's CG. Hence, for this study, it is termed as d_{CG-WPT} . To acquire d_{CG-WPT} , d_a is subtracted from the advance distance, d_{adv} , for this reason:

$$d_{CG-WPT} = d_{adv} - d_a \quad (1)$$

d_a can be obtained as follows by applying the tangent rule:

$$\tan \theta = \frac{d_{trs}}{d_a}$$

$$d_a = \frac{d_{trs}}{\tan \theta}$$

Therefore, the formula of ATT [1] is acquired as below:

$$d_{CG-WPT} = d_{adv} - \frac{d_{trs}}{\tan \theta} \quad (2)$$

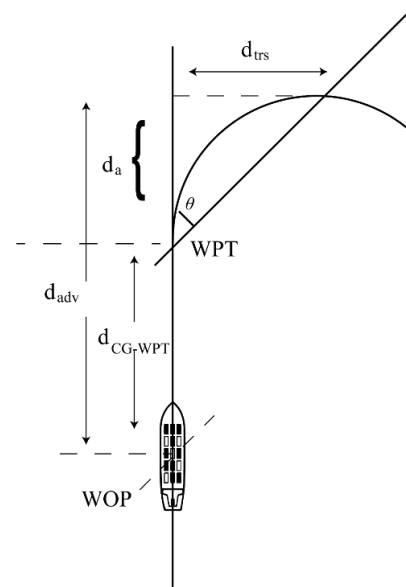


Figure 2. Marking WOP [1]

2.2 The problems that lead to the need to improve ATT

Mariners are using ATT to identify the WOP. However, few problems are associated with the technique [2], [19]. The following are the primary concerns that were discovered:

2.2.1 Negative WOP value for 20° change of course or less

As shown in equation (2), the formula for ATT has a disadvantage for course alteration that is less than 20°. The following is a sample of WOP calculated for 20° and 50° alteration angles (The ship's advance distance is 0.455nm, and the transfer distance is 0.231nm).

Table 1. Calculated WOP using ATT formula

Scenario	Change of course (θ)	d_{adv} (nm)	d_{trs} (nm)	WOP
1	20°	0.455	0.231	-0.180
2	50°	0.455	0.231	0.261

As seen in Table 1, the computed WOP is negative in scenario one but becomes positive in scenario 2. The value indicates that in scenario 1, the ship's course must be altered 0.18nm after WPT, implying that the vessel had deviated from the charted course before the course alteration was initiated. However, the course alteration for 50° will occur 0.261nm prior to WPT.

2.2.2 Charted course and final heading not aligned

The method operates on the concept depicted in Figure 3, where the final heading and the charted course are not aligned. The primary reason for this problem is that advance and transfer provided in ship manoeuvring characteristics are measured referring to 90° course change [20]. As a result, the identical advance and transfer values are utilised in the calculation, even though the change of course is less than 90°.

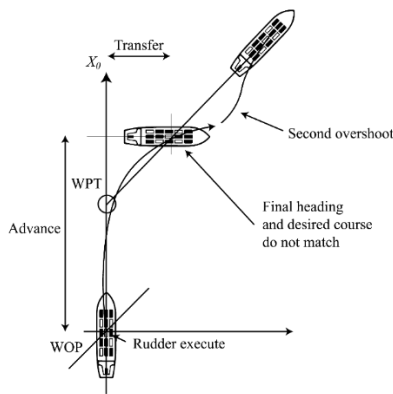


Figure 3. Advance transfer technique principle [19]

2.3 Development of an Improved Mathematical Model

The turning circle is utilised to ensure the final heading and charted course are aligned, as seen in Figure 4. Thus, the new concept has moved WOP to WOP' as shown in Figure 4. For this reason, another term will be added and used as follows:

d_{WOP} = Distance of WOP' from WPT

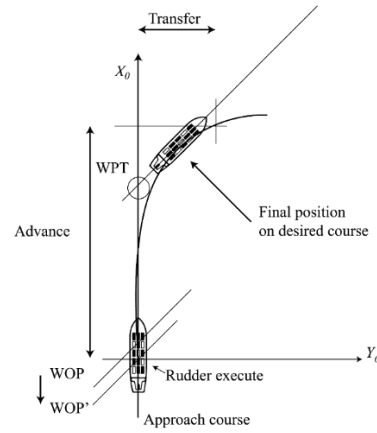


Figure 4. ATMM development concept [2]

A mathematical model can be created using the related previous analysis equation as a starting point [21]. For this reason, the ATT equation was used as the foundation of the advance transfer mathematical model (ATMM). Figure 5 was constructed by following the generic turning circle to interpret the ATMM's development.

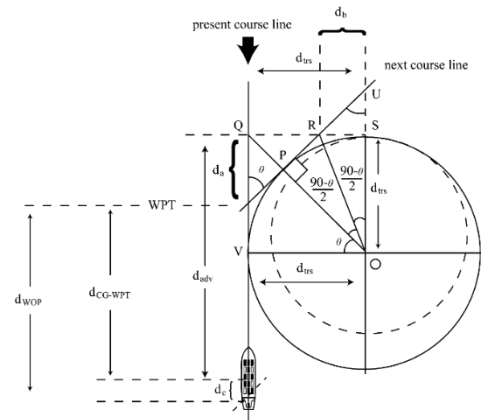


Figure 5. Distribution details [2]

As seen in Figure 5, the distance from the bridge's global navigation satellite system (GNSS) antenna to the CG will be included in the ATMM design. As a result, in equation (1), the distance between WOP' and WPT, otherwise abbreviated as, d_{WOP} , is added, made up of 1) d_{CG-WPT} and 2) d_c . Hence:

$$d_{WOP} = d_{CG-WPT} + d_c$$

Based on the existing ATT formula in (1), $d_{CG-WPT} = d_{adv} - d_a$, the above equation can be rewritten as:

$$d_{WOP} = d_{adv} - d_a + d_c \quad (3)$$

The following step is finding the value of d_a and d_c . The following trigonometric function can be used to determine d_a :

$$\tan \theta = \frac{QR}{d_a} \quad (4)$$

$$d_a = \frac{QR}{\tan \theta}$$

From QS, subtract RS to obtain QR. $QS = d_{trs}$. As seen in Figure 5, RS is represented as d_b . Hence, $QR = d_{trs} - d_b$. Subsequently, (4) can be re-written as follows:

$$d_a = \frac{d_{trs} - d_b}{\tan \theta} \quad (5)$$

Because $\triangle ROS$ is a right-angled triangle, d_b can be acquired by using the trigonometry tangent rules:

$$\tan \angle ROS = \frac{d_b}{d_{trs}} \quad (6)$$

$$d_b = d_{trs} \cdot \tan \angle ROS$$

To determine $\angle ROS$, first, due to $TU \perp OP$, in other words, $\perp UPO = 90^\circ$. With regards to triangle rules, the total interior angle is 180° . Thus, $\triangle PUO = 180^\circ$, which is the sum value of $\angle UOP$, $\perp UPO$, and $\angle PUO$. Therefore:

$$\angle UOP = 90^\circ - \theta$$

Consistent with the rule for a line tangent to a circle, RS and RP have the same value, $|RP| = |RS|$, which makes $\angle ROS = \angle POR$. For this reason, $\angle ROS$ is half of $\angle POS$. Hence, $\angle ROS$ can be expressed as:

$$\angle ROS = \frac{\angle POS}{2} \quad (7)$$

$$\angle ROS = \frac{90^\circ - \theta}{2}$$

The following is derived with reference to (6) and the input from (7):

$$d_b = d_{trs} \cdot \tan \angle ROS \quad (8)$$

$$d_b = d_{trs} \cdot \tan \left(\frac{90^\circ - \theta}{2} \right)$$

Inserting (8) into (5), d_a can be obtained as:

$$d_a = \frac{d_{trs} - d_{trs} \cdot \tan \left(\frac{90^\circ - \theta}{2} \right)}{\tan \theta} \quad (9)$$

The location of the ship is monitored via the GNSS receiver during navigation is typically located at the bridge. Due to the reason that the turning circle is drawn referring to the ship's CG, the specific WOP shall contain the distance between CG and the bridge, hence $d_{CG} = d_c$, and this is applied as follows.

To identify the location of d_{CG} , firstly, the position of CG needs to be confirmed. In an actual ship, L_{CG} can be accessed directly from the ship's loadicator [22]. On the other hand, when a ship floats, the ship's longitudinal centre of buoyancy (L_{CB}) will be vertically

aligned with L_{CG} . For this reason, L_{CG} can also be equated to the L_{CB} [23]. The small differences between L_{CB} and L_{CG} is not significant, therefore it can be neglected [23].

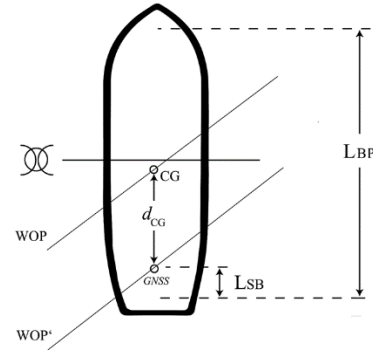


Figure 6. d_{CG} is measured from the vessel's longitudinal CG (L_{CG}) and the ship's bridge (L_{SB}) [2]

With reference to Figure 6, the d_{CG} can be located as follows:

$$d_c = d_{CG} = \frac{LBP}{2} + L_{CG} - L_{SB} \quad (10)$$

In conclusion, with reference to (3), d_{WOP} can be simplified as follows [2]:

$$d_{WOP} = d_{adv} - d_a + d_c \quad (11)$$

$$d_{WOP} = d_{adv} - \left(\frac{d_{trs} - d_{trs} \cdot \tan \left(\frac{90^\circ - \theta}{2} \right)}{\tan \theta} \right) + \left(\frac{LBP}{2} + L_{CG} - L_{SB} \right)$$

2.4 Problem statement and the research AIMS

For a long time, ATT has been used in maritime navigation to determine the most favourable WOP, particularly during navigation in HCW. A recent study was able to improve the ATT into a mathematical model, namely ATMM. Two research was conducted using tanker ship [17] and LNG ship [2] to prove the effectiveness of the ATMM.

Therefore, this study aims to assess the effectiveness of ATMM using a bulk carrier ship while in ballast condition and fully loaded condition. This study has considered the International Maritime Organisation (IMO) requirements towards ensuring the developed mathematical model is accepted to be used onboard a merchant's vessel. According to IMO ISM (2018) [24], when developing a new safety system, the following should be considered:

1. A new system should comply with the regulations.
2. A new system should enhance the safety management system (SMS).

For this reason, the following are the objective of the study:

- Objective 1 : To verify that ATMM complies with XTL as required by IMO
- Objective 2 : To verify that ATMM can enhance the safety of navigation as outlined in SMS

3 METHODOLOGY

The research begins with an explanation of how the ATMM was developed, taking into account the shortcomings of the previous ATT model through a literature review. Then, both methods were used to calculate WOP where a bulk carrier was manoeuvred using a ship simulator to obtain the XTD data. Following that, a comparison study on the XTD data was carried out to corroborate the ATMM's improvement over the ATT [25]. The comparison study between ATT and ATMM was verified in three stages to accomplish the research's objectives.

The first objective is to verify that ATMM conforms to all the applicable rules and regulations. For this reason, the XTD results shall comply with the cross-track limit (XTL) as required by the IMO [26]. An XTL is defined as a limit where a ship is allowed to diverge from the planned track [27].

The second objective is to verify that ATMM can enhance SMS. The intended improvement in this research was obtained by maintaining the ship on the targeted course while reducing XTD. The reduction was justified by adopting the methodology for calculating percentage variation [28]. The magnitude of XTD reduction and its trend can be observed numerically through percentage change. However, the significant reduction can only be verified through a statistical test. Therefore, in the third analysis, to establish the statistical dominance of one of two random variables over the other, the Wilcoxon Mann Whitney U test was used [29], [30]. The test is well-known in clinical studies, where it is often used to assess the efficacy by comparing two treatments [31]. As a result, this research will contribute to the deciding factor of whether ATMM is preferable compared to ATT in assessing the WOP.

3.1 Data collection through ship simulator test

The information about the bulk carrier selected for this study is shown in Table 2 and Figure 7 below.

Table 2. Ship general characteristic

Description	Ballast	Fully Loaded
Vessel Type	Bulk carrier	
Displacement	23565 tonnes	33089 tonnes
Speed	15 kts	14 kts
Engine Type	Slow speed diesel (1 x 8827 kW)	
Propeller Type	FPP	
Bow Thruster	None	
Length	182.9 m	
Breadth	22.6 m	
Bow draft	7.5 m	10.1 m
Stern draft	7.6 m	10.7 m
Height of eye	22 m	

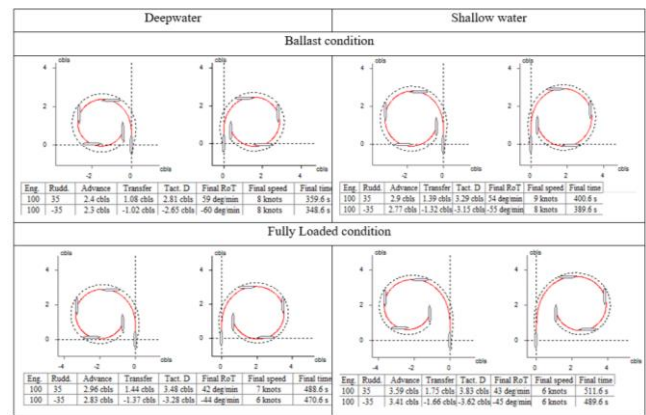


Figure 7. Turning circle extracted from the simulator

The data regarding the chosen ship were obtained from the simulator. The data from Figure 7, specifically the advance and transfer, were used to calculate WOP for nine courses for every 10° and drawn in the simulator. A helmsman was assigned to follow the courses and carry out the course alteration at calculated WOP by the application of hard rudder angle. Then, the XTD of the vessel was monitored and recorded.

It is worth emphasising once more that the purpose of this study was to assess which WOP mathematical model capable of providing a more accurate track-keeping function by lowering XTD. As a result, manoeuvring simulations were conducted using both ATT and ATMM, and the XTDs for both approaches were compared to see if ATMM achieved a significant improvement. Three steps of analysis were performed on the data collected from the manoeuvring simulation. For the first study, the results were compared to the International Maritime Organization's XTL standards for XTD deriving from ATT and ATMM [32]–[34] following guidelines published by Kristić et al. (2020) [27], as shown in Table 3 below.

Table 3. XTL value

HCW	
Zone of confidence	6.5
Half Ship's breadth	11.3
Position accuracy	15
Safety Allowance	50
$\frac{LOA \times \sin 20}{2}$	31
XTL (m)	113.8

Table 4. Analysis of deep-water manoeuvring under ballast conditions

Location	Side	θ	d_{adv} (nm)	d_{trs} (nm)	d_{CG} (nm)	d_{WOP}		XTD < XTL(113.8m) ?				XTD graph
						ATT	ATMM	ATT(m)	ATMM(m)	ATT	ATMM	
Kemaman Malaysia	Starboard	10°	0.24	0.108	0.0329	-0.372	0.174	58	YES	20	YES	
		20°	0.24	0.108	0.0329	-0.057	0.184	115	NO	25	YES	
		30°	0.24	0.108	0.0329	0.053	0.194	119	NO	8	YES	
ENC number: 3JS P9200	Starboard	40°	0.24	0.108	0.0329	0.111	0.204	125	NO	30	YES	
		50°	0.24	0.108	0.0329	0.149	0.215	105	YES	2	YES	
		60°	0.24	0.108	0.0329	0.178	0.227	83	YES	12	YES	
		70°	0.24	0.108	0.0329	0.201	0.241	50	YES	2	YES	
04°10.78' N 103°35.4'E	Starboard	80°	0.24	0.108	0.0329	0.221	0.256	48	YES	19	YES	
		90°	0.24	0.108	0.0329	0.240	0.273	45	YES	22	YES	
23.8- 29.3m (deep water)	Port	10°	0.23	0.102	0.0329	-0.348	0.17	84	YES	6	YES	
		20°	0.23	0.102	0.0329	-0.050	0.179	127	NO	16	YES	
		30°	0.23	0.102	0.0329	0.053	0.188	131	NO	5	YES	
		40°	0.23	0.102	0.0329	0.108	0.198	156	NO	17	YES	
		50°	0.23	0.102	0.0329	0.144	0.208	102	YES	10	YES	
		60°	0.23	0.102	0.0329	0.171	0.22	91	YES	17	YES	
		70°	0.23	0.102	0.0329	0.193	0.232	74	YES	3	YES	
		80°	0.23	0.102	0.0329	0.212	0.246	65	YES	21	YES	
90°	0.23	0.102	0.0329	0.230	0.263	55	YES	39	YES			

Compliance to XTL by % 83% 100%

Table 5. Analysis of shallow water manoeuvring under ballast conditions

Location	Side	θ	d_{adv} (nm)	d_{trs} (nm)	d_{CG} (nm)	d_{WOP}		XTD < XTL(113.8m) ?				XTD graph
						ATT	ATMM	ATT(m)	ATMM(m)	ATT	ATMM	
Balti- more, USA	Starboard	10°	0.29	0.139	0.0329	-0.498	0.196	71	YES	12	YES	
		20°	0.29	0.139	0.0329	-0.092	0.208	112	YES	4	YES	
		30°	0.29	0.139	0.0329	0.049	0.221	185	NO	3	YES	
ENC number: 4414n12 0	Starboard	40°	0.29	0.139	0.0329	0.124	0.234	146	NO	4	YES	
		50°	0.29	0.139	0.0329	0.173	0.249	98	YES	6	YES	
		60°	0.29	0.139	0.0329	0.210	0.264	88	YES	19	YES	
		70°	0.29	0.139	0.0329	0.239	0.281	90	YES	24	YES	
38°55.21' N 076°24.7 8'W	Starboard	80°	0.29	0.139	0.0329	0.265	0.301	104	YES	40	YES	
		90°	0.29	0.139	0.0329	0.290	0.323	126	NO	59	YES	
10.7- 14m (shallow water)	Port	10°	0.28	0.132	0.0329	-0.472	0.189	64	YES	5	YES	
		20°	0.28	0.132	0.0329	-0.092	0.201	127	NO	2	YES	
		30°	0.28	0.132	0.0329	0.048	0.213	203	NO	1	YES	
		40°	0.28	0.132	0.0329	0.120	0.226	178	NO	3	YES	
		50°	0.28	0.132	0.0329	0.166	0.239	137	NO	9	YES	
		60°	0.28	0.132	0.0329	0.201	0.254	103	YES	15	YES	
		70°	0.28	0.132	0.0329	0.229	0.27	120	NO	27	YES	
		80°	0.28	0.132	0.0329	0.254	0.289	143	NO	40	YES	
90°	0.28	0.132	0.0329	0.277	0.31	158	NO	52	YES			

Compliance to XTL by % 50% 100%

Table 6. Analysis of deep-water manoeuvring under fully loaded conditions

Location	Side	θ	d_{adv} (nm)	d_{trs} (nm)	d_{CG} (nm)	d_{WOP}		XTD < XTL(113.8m) ?				XTD graph
						ATT	ATMM	ATT(m)	ATMM(m)	ATT	ATMM	
Auck- land,Ne w Zea- land	Starboard	10°	0.296	0.144	0.0329	-0.521	0.197	63	YES	9	YES	
		20°	0.296	0.144	0.0329	-0.100	0.210	112	YES	6	YES	
		30°	0.296	0.144	0.0329	0.047	0.223	181	NO	16	YES	
ENC number: 4vjqr11	Starboard	40°	0.296	0.144	0.0329	0.124	0.237	121	NO	19	YES	
		50°	0.296	0.144	0.0329	0.175	0.252	110	YES	4	YES	
		60°	0.296	0.144	0.0329	0.213	0.268	94	YES	12	YES	
		70°	0.296	0.144	0.0329	0.244	0.286	102	YES	1	YES	
36°37.55' S 175°05.6 4'E	Starboard	80°	0.296	0.144	0.0329	0.271	0.306	118	NO	11	YES	
		90°	0.296	0.144	0.0329	0.296	0.329	119	NO	22	YES	
42-43m (deep water)	Port	10°	0.283	0.137	0.0329	-0.494	0.191	69	YES	4	YES	
		20°	0.283	0.137	0.0329	-0.093	0.203	120	NO	11	YES	
		30°	0.283	0.137	0.0329	0.046	0.216	170	NO	12	YES	
		40°	0.283	0.137	0.0329	0.120	0.229	112	YES	12	YES	
		50°	0.283	0.137	0.0329	0.168	0.243	93	YES	0	YES	
		60°	0.283	0.137	0.0329	0.204	0.258	71	YES	14	YES	
		70°	0.283	0.137	0.0329	0.233	0.275	65	YES	1	YES	
		80°	0.283	0.137	0.0329	0.259	0.294	91	YES	10	YES	
90°	0.283	0.137	0.0329	0.283	0.316	99	YES	28	YES			

Compliance to XTL by % 78% 100%

Table 7. Analysis of shallow water manoeuvring under fully loaded conditions

Location	Side	θ	d_{adv} (nm)	d_{trs} (nm)	d_{CG} (nm)	d_{WOP}		XTD < XTL(113.8m) ?		XTD graph		
						ATT	ATMM	ATT(m)	ATMM(m)			
Great Belt, Denmark	Starboard	10°	0.359	0.175	0.0329	-0.633	0.232	68	YES	4	YES	
		20°	0.359	0.175	0.0329	-0.122	0.248	138	NO	2	YES	
		30°	0.359	0.175	0.0329	0.056	0.264	203	NO	13	YES	
		40°	0.359	0.175	0.0329	0.150	0.281	155	NO	27	YES	
		50°	0.359	0.175	0.0329	0.212	0.299	166	NO	43	YES	
		60°	0.359	0.175	0.0329	0.258	0.318	142	NO	61	YES	
		70°	0.359	0.175	0.0329	0.295	0.339	124	NO	76	YES	
		80°	0.359	0.175	0.0329	0.328	0.364	148	NO	94	YES	
		90°	0.359	0.175	0.0329	0.359	0.392	181	NO	101	YES	
55°15.52' N 010°52.08' E 13.6-15.3m (shallow water)	Port	10°	0.341	0.166	0.0329	-0.600	0.222	63	YES	4	YES	
		20°	0.341	0.166	0.0329	-0.115	0.237	131	NO	6	YES	
		30°	0.341	0.166	0.0329	0.053	0.252	185	NO	5	YES	
		40°	0.341	0.166	0.0329	0.143	0.268	138	NO	7	YES	
		50°	0.341	0.166	0.0329	0.202	0.285	148	NO	22	YES	
		60°	0.341	0.166	0.0329	0.245	0.304	115	NO	29	YES	
		70°	0.341	0.166	0.0329	0.281	0.324	128	NO	44	YES	
		80°	0.341	0.166	0.0329	0.312	0.347	114	NO	66	YES	
		90°	0.341	0.166	0.0329	0.341	0.374	147	NO	70	YES	
Compliance to XTL by %						22%	100%					

4 RESULT AND DISCUSSION

Tables 4 and 5 summarise the analysis of deep-water and shallow-water manoeuvring under ballast conditions, respectively, whilst Tables 6 and 7 summarise the analysis of deep-water and shallow-water manoeuvring under fully loaded situations. The tables show whether or not the XTD complies with XTL as indicated by a simple 'YES' or 'NO'.

4.1 XTL compliance analysis

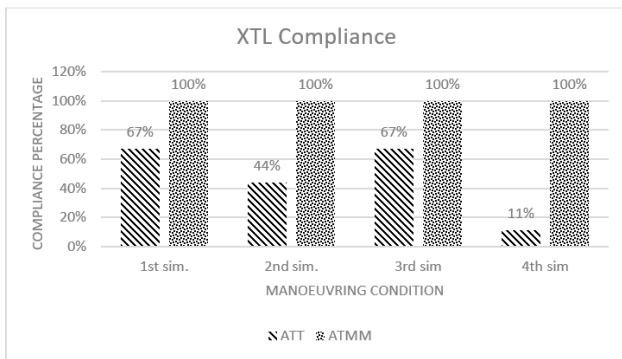


Figure 8. Compliance to XTL according to simulation

From Figure 8, it can be seen that, for the first simulation study, a bulk carrier at ballast condition was used in the deep-water area. Only 67% of the turns conformed to XTL when ATT was used and 100% when ATMM was used.

The subsequent analysis used the identical bulk carrier in ballast condition but with a shallow water area. Only 44% of the turns conformed to XTL when ATT was used and 100% when ATMM was used.

During the third simulation study, the bulk carrier was changed to a fully loaded condition, and the manoeuvring was conducted in deep water. Using ATT, the compliance was only 67%. This contrasted to the manoeuvring using the ATMM, where compliance to XTL continued at 100%.

During the final simulation study in shallow water using a fully loaded bulk carrier, the ATT model only achieved 11% XTL compliance, whereas when manoeuvring using ATMM, 100% compliance was recorded. It can be concluded that ATMM provides better XTD in terms of its compliance with XTL. ATT has slight disadvantages, particularly when the simulation is carried out in shallow water.

4.2 XTD percentage change

Table 8. Percentage change by course change

Course change	Condition	Water depth	Direction	XTD (m)		% Change of XTD	
				ATT	ATMM	Individual turn	Average
10°	Ballast	Deep	Starboard	58	20	-65.5%	-87.7%
			Port	84	6	-92.9%	
	Fully Loaded	Shallow	Starboard	71	12	-83.1%	
			Port	64	5	-92.2%	
		Deep	Starboard	63	9	-85.7%	
			Port	69	4	-94.2%	
20°	Ballast	Deep	Starboard	68	4	-94.1%	
			Port	63	4	-93.7%	
	Fully Loaded	Shallow	Starboard	115	25	-78.3%	-92.5%
			Port	127	16	-87.4%	
		Deep	Starboard	112	4	-96.4%	
			Port	127	2	-98.4%	
Fully Loaded	Deep	Starboard	112	6	-94.6%		
		Port	120	11	-90.8%		

30°	Ballast	Shallow	Starboard	138	2	-98.6%	-95.3%	
			Port	131	6	-95.4%		
	Deep	Starboard	119	8	-93.3%			
		Port	131	5	-96.2%			
	Shallow	Starboard	185	3	-98.4%			
		Port	203	1	-99.5%			
40°	Fully Loaded	Deep	Starboard	181	16	-91.2%	-89.0%	
			Port	170	12	-92.9%		
	Shallow	Starboard	203	13	-93.6%			
		Port	185	5	-97.3%			
	Ballast	Deep	Starboard	125	30	-76.0%		
			Port	156	17	-89.1%		
Shallow	Starboard	146	4	-97.3%				
	Port	178	3	-98.3%				
50°	Fully Loaded	Deep	Starboard	121	19	-84.3%	-91.4%	
			Port	112	12	-89.3%		
	Shallow	Starboard	155	27	-82.6%			
		Port	138	7	-94.9%			
	Ballast	Deep	Starboard	105	2	-98.1%		
			Port	102	10	-90.2%		
Shallow	Starboard	98	6	-93.9%				
	Port	137	9	-93.4%				
60°	Fully Loaded	Deep	Starboard	110	4	-96.4%	-78.8%	
			Port	93	0	-100.0%		
	Shallow	Starboard	166	43	-74.1%			
		Port	148	22	-85.1%			
	Ballast	Deep	Starboard	83	12	-85.5%		
			Port	91	17	-81.3%		
Shallow	Starboard	88	19	-78.4%				
	Port	103	15	-85.4%				
70°	Fully Loaded	Deep	Starboard	94	12	-87.2%	-80.6%	
			Port	71	14	-80.3%		
	Shallow	Starboard	142	61	-57.0%			
		Port	115	29	-74.8%			
	Ballast	Deep	Starboard	50	2	-96.0%		
			Port	74	3	-95.9%		
Shallow	Starboard	90	24	-73.3%				
	Port	120	27	-77.5%				
80°	Fully Loaded	Deep	Starboard	102	1	-99.0%	-65.0%	
			Port	65	1	-98.5%		
	Shallow	Starboard	124	76	-38.7%			
		Port	128	44	-65.6%			
	Ballast	Deep	Starboard	48	19	-60.4%		
			Port	65	21	-67.7%		
Shallow	Starboard	104	40	-61.5%				
	Port	143	40	-72.0%				
90°	Fully Loaded	Deep	Starboard	118	11	-90.7%	-56.3%	
			Port	91	10	-89.0%		
	Shallow	Starboard	148	94	-36.5%			
		Port	114	66	-42.1%			
	Ballast	Deep	Starboard	45	22	-51.1%		
			Port	55	39	-29.1%		
Shallow	Starboard	126	59	-53.2%				
	Port	158	52	-67.1%				
Fully Loaded	Deep	Starboard	119	22	-81.5%			
		Port	99	28	-71.7%			
Shallow	Starboard	181	101	-44.2%				
	Port	147	70	-52.4%				

As seen in Table 8, the negative value of the percentage change implies a reduction of XTD. As a result, a considerable reduction in XTD was observed during the manoeuvring analysis. It can be seen that during ballast conditions while manoeuvring in deep water, the XTD was reduced by 51.1%–98.1% for the manoeuvring analysis with starboard alteration, while for manoeuvring analysis with port alteration, the XTD was successfully reduced by 29.1%–95.9%. Meanwhile, in shallow water, the XTD for starboard manoeuvring analysis was reduced by 53.2% to 98.4%, and by 67.1% to 99.5% for port manoeuvring analysis. For manoeuvring analysis with a fully loaded condition, the bulk carrier recorded 81.5%–99.0% of

XTD reduction during the manoeuvring analysis to starboard and 71.7%–100% of XTD reduction for port alteration. In shallow water, the fully loaded bulk carrier reduced the XTD by 36.5%–98.6% for starboard alteration and 42.1%–97.3% for port alteration.

The succession of reductions for every ten degrees of course deviation suggested that the bulk carrier was approaching the intended course. Even though it is apparent that the ATMM was able to reduce the XTD, it is necessary to determine whether the two independent datasets originated from the same distribution using the Mann-Whitney U test. To accomplish this, IBM SPSS was used to analyse the data.

Table 9. Test by manoeuvring conditions

Test No	Manoeuvring conditions	Models	N	Mean rank	Sum of Rank	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig (2-Tailed) P-Value
1	Ballast condition, Deep water.	ATT	18	27.5	495	.000	171	-5.127	.000
		ATMM	18	9.5	171				
2	Ballast condition, Shallow water	ATT	18	27.5	495	.000	171	-5.126	.000
		ATMM	18	9.5	171				
3	Fully Loaded Condition, Deep water	ATT	18	27.5	495	.000	171	-5.128	.000
		ATMM	18	9.5	171				
4	Fully Loaded Condition Shallow water	ATT	18	27	486	9.000	180	-4.842	.000
		ATMM	18	10	180				

Table 10. Test by the course change

Course change	Models	N	Mean rank	Sum of Rank	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig (2-Tailed) P-Value
10°	ATT	8	12.5	100	.000	36	-3.373	.001
	ATMM	8	4.5	36				
20°	ATT	8	12.5	100	.000	36	-3.371	.001
	ATMM	8	4.5	36				
30°	ATT	8	12.5	100	.000	36	-3.368	.001
	ATMM	8	4.5	36				
40°	ATT	8	12.5	100	.000	36	-3.361	.001
	ATMM	8	4.5	36				
50°	ATT	8	12.5	100	.000	36	-3.361	.001
	ATMM	8	4.5	36				
60°	ATT	8	12.5	100	.000	36	-3.361	.001
	ATMM	8	4.5	36				
70°	ATT	8	12.13	97	3.000	39	-3.048	.002
	ATMM	8	4.88	39				
80°	ATT	8	11.88	95	5.000	41	-2.838	.005
	ATMM	8	5.13	41				
90°	ATT	8	11.5	92	8.000	44	-2.522	.012
	ATMM	8	5.5	44				

4.3 Mann-Whitney U Test

The following are the null and two-sided research hypotheses for the nonparametric test in this study:

- H0: The two models' mean XTD ranks are identical.
- H1: The two models' mean XTD ranks are not identical.

The null hypothesis H0 will be rejected if the P-Value < 0.05.

The first test was carried out according to the manoeuvring area, as shown in Table 9, in which the difference was statistically significant with $p = 0.000 < 0.05$ for all tests. Therefore, H0 was rejected. The Wilcoxon W value represented the sum of rank for all tests that pointed to ATMM, implying that ATMM had a lower rank XTD value, consistent with the study's objectives.

The next test was carried out for nine-course changes, as shown in Table 10. Evidently, there was a statistically significant difference for all nine alterations, where U varied from .000 to 8.000, z varied between -2.522 to -3.373 and P-Value varied from .001 to .012, which was less than 0.05. Therefore, H0 was rejected for all nine-course changes. The Wilcoxon W value represented the sum of rank for all tests that pointed to ATMM, implying that ATMM had a lower rank XTD value, consistent with the study's objectives.

5 CONCLUSION

Ships sail from one destination to another by navigating along the course line prepared by the navigation officer. Navigating on the planned track is vital for the ship's safety and can reduce fuel consumption. Nevertheless, more importantly, it will keep the vessel safe as many accidents happen due to ignorance of the XTD. XTD can be reduced by various methods; one of them is through the correct application of WOP through ATT.

It is essential to highlight that ATT has been used in marine navigation for a long period of time to calculate the most optimal WOP. Recently, a study was able to convert the ATT into a mathematical model termed ATMM. A small number of studies were undertaken utilising tanker ships and LNG tankers to demonstrate the ATMM's usefulness. As such, this study aims to evaluate the efficiency of ATMM by utilising a bulk carrier ship.

It may be concluded that this study accomplished its objectives because the ATMM significantly lowered the XTD and is suitable for use onboard bulk carrier ships as one of the ways to determine WOP, particularly during channel turns and pilotage. The ATMM algorithm can be utilised in the ECDIS. An ECDIS equipped with pre-installed vessel manoeuvring data may automatically calculate the WOP for each course change made during trip planning, considering the vessel's ballast and fully loaded states. As a result of this research, a mathematical model embedded in the ECDIS might be able to detect when the navigator makes an incorrect WOP calculation. For instance, if the

navigator's value is less than the predicted WOP, the ECDIS will display a warning to inform the user that the input is incorrect. The present study found that during the simulation analysis, when the course lines were formed, the ECDIS simulator suggested the WOP line; however, the WOP line suggested was significantly less than the WOP estimated using the mathematical model used in this study. This indicates that the ECDIS simulator does not include a WOP limit. As a result, this issue can be resolved using the developed ATMM.

According to this research, efficient route monitoring will reduce the distance covered and assist in minimising fuel usage. Although the mathematical model used in this study improves course keeping abilities when changing courses, additional research can be conducted on the effect of fuel consumption when applying a large rudder angle while turning. Perhaps further research can be conducted to determine the effect of reducing XTD on energy efficiency.

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