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# Comparative Analyses of Manoeuvring Patterns in Real and Virtual AtoN Environment

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ABSTRACT: This paper presents a comparative analysis of manoeuvring patterns through the fairway which is marked with physical and virtual Aids to Navigation (AtoN). The impact of V-AtoN environment on decision-making and on consequent manoeuvres has never been studied in such a way. The results published in this paper were obtained using TRANSAS Navi Trainer 5000 and TRANSAS ECDIS 4000 simulators where 12 deck officers with at least 5 years of sea service participated. The results of the study indicate that there is a significant difference in manoeuvring patterns between the two environments. In case of virtual environment, more intense drift angles, ROTs as well as XTDs are observed. The paper demonstrates significant impact of virtual environment on behaviour of OOW.

## 1 INTRODUCTION

The priority of safety at sea has never been out of focus. For decades, maritime regulations have been supplemented and upgraded in order to keep the vessels and crews at the level necessary for safe navigation, protection of the environment, property and, above all, human lives. Regulatory changes have been followed by technological developments. The accelerated development of the IT sector since the beginning of the 2000s has not bypassed the maritime sector. The International Maritime Organization (IMO) launched the concept of e-navigation in 2009, and in 2014 upgraded it using the Strategic Implementation Plan (SIP) with the aim of improving maritime safety and security, relying on the improvement of Maritime Situational Awareness (MSA) and on decision-making [1], [2]. Maritime industry is vulnerable to cyber risk and tends towards further digitalization. One of the key goals of the e-navigation concept is the digital integration of coastal and ship technologies. For vessels equipped with ECDIS, such digitalization is already visible through electronic Aids to Navigation (e-AtoN) implementation. There are many reasons for the transformation of existing physical AtoN into e-AtoN or installation of new e-AtoN. There are three types of e-AtoN [3], [4], [5]:

- real e-AtoN: physical AtoN supplemented by AIS from same physical source;
- synthetic e-AtoN or S-AtoN: physical AtoN supplemented remotely by AIS;
- virtual e-AtoN or V-AtoN: no physical AtoN at the location where solely remotely generated AIS signal exists or AtoN in digital format.

Numerous studies were published on the subject of V-AtoN. V-AtoN are installed in remote and sensitive regions where physical AtoN are hard to place and maintain [3], in congested waters for traffic monitoring [6] or in any other area where it is believed that their installation will improve safety and contribute to reduce risk of collision. Research related to traffic flow changes upon installation of V-AtoN [7] shows that the places where ships collided in the past "are not necessarily the most congested areas". The same source states that despite the installation of V-AtoN may have improved safety, it is still necessary to navigate virtually marked waters more carefully in order to prevent collisions caused by human error. In [8] authors proposed solution for calculation of probability that the vessel will exceed fairway boundaries on any side, dependent on traffic density and availability of manoeuvring scenarios. Despite all efforts and investments done for digitalization of fairways, ship collisions are often caused by navigators' lack of attention to hazardous obstacle facilities [9].

The problem of human error, which is still considered the biggest cause of maritime accidents, is being tried to be reduced by the intensive use of simulators in the educational process of seafarers. Nautical simulators provide a simulated environment that allows trainees to experience a range of scenarios in a safe and controlled settings, which can be difficult or impossible to recreate in real life. An interesting study [10] shows the level of existing variations in the European full mission simulator training institutions based on implementation of IMO Model course 6.10 – Train the simulator trainer and assessor. Apart from the mentioned, there are other IMO model courses that require the use of simulators. Certainly, an extremely important element that significantly affects the effectiveness of education using the simulator is its fidelity [11].

In this paper, Chapter 2 compares real-physical and virtual AtoN. The same chapter describes differences between Automatic Identification System (AIS) and VHF Data Exchange System (VDES). Chapter 3 explores importance of simulator usage for educational purposes as well as situational awareness in virtual environment. In order to explain technical background of research, nautical simulator setup as well as scene setup are explained in Chapter 4. Simulations and their results are presented in Chapter 5. As virtual marine environment is so progressive nowadays, the authors found it necessary to create more detailed elaboration of simulated manoeuvring patterns in both real and virtual environment through Chapter 6, followed by conclusions in Chapter 7.

## 2 PHYSICAL VS VIRTUAL ATON

Physical aids to navigation refer to structures or devices that are physically present in the environment and used to assist within navigation. Examples include lighthouses, buoys, beacons, markers etc. These physical aids are typically visible to human eye and can provide a visual reference point for navigation. They are often placed in areas where visibility is limited or where there are hazards that need to be avoided.

As stated in Chapter 1, virtual AtoN is the subtype of e-AtoN. V-AtoN is electronic device or system that provide navigational assistance through digital means. These aids use digital signals to provide accurate and up-to-date information on the location of vessels, hazards or other important navigational data.

There are several key points which distinguish physical and virtual AtoN [4], [12]:

1. Reliability - Physical aids to navigation are generally more reliable than virtual ones because of their electronic or technical vulnerabilities. Physical aids are typically built to withstand extreme weather conditions and can last for many years without requiring significant maintenance. Virtual aids, on the other hand, are reliant on electronic devices, which can malfunction or break down over time.
2. Accuracy – Virtual AtoN are generally more accurate than physical AtoN because of digital signal usage which enables creation of precise location and navigational data. GNSS is the most common source of positioning with accuracy of just few meters. Physical aids may not be as precise, particularly in areas where visibility is reduced. There are many vulnerabilities of V-AtoN as they mainly rely on GNSS and AIS technology [4], [13]. However, VHF Data Exchange System (VDES) is seen as an alternative and successor to AIS [14], [15].
3. Visibility – Physical AtoN are more visible due to their physical structure. On the other hand, virtual ones are mainly displayed in electronic form on ECDIS. This fact is a limiting safety factor for non-SOLAS ships.
4. Cost – Physical AtoN can be expensive to build and maintain, particularly in remote or hazardous locations. Virtual ones can be more cost-effective because they do not require physical structures or ongoing maintenance.

In summary, physical and virtual AtoN each have their own advantages and disadvantages. While physical aids may be more reliable and visible, virtual aids can be more accurate and cost-effective.

The following Subchapter deals with the risk and limitations of AIS – which still maintains its primacy in e-navigation as backbone of V-AtoN implementation.

### 2.1 *AIS vs VDES – where is the future?*

The development of AIS began in the late 1990s as a joint initiative between the IMO and the International Electrotechnical Commission (IEC). The primary goal was to improve the safety and efficiency of maritime navigation by providing vessels with real-time information about nearby ships and other maritime traffic. It was first mandated by the IMO in 2000 for vessels over 300 gross tons engaged in international voyages, and the mandate was later expanded to include smaller vessels and vessels engaged in domestic voyages.

The AIS system uses VHF radio signals to transmit and receive data between vessels and shore-based stations. The system works by continuously broadcasting a vessel's position, speed, course, and other information, which can be received and displayed by other vessels and shore-based stations equipped with AIS receivers. Since its inception, AIS has become an essential tool for maritime navigation and has contributed significantly to improving the safety and efficiency of maritime traffic. In recent years, the system has also been used for a variety of other applications, such as marine research, environmental monitoring, and search and rescue operations [13].

Despite the positive aspects and advantages of using AIS, there are still many vulnerabilities present in the system, as evidenced by the doubling of the number of peer-reviewed articles related to AIS between 2015 and 2020 [16]. AIS has fallen behind recent technological advances in the past few years. Problem of AIS signal propagation is far from solely geometrical since it relies on VHF and GNSS transmission. At present, AIS message transmission utilizes the A and B channels, which often leads to saturation of VHF data channels. The situation is expected to worsen with the expansion of AIS and increase in traffic. In response to this issue, The International Telecommunication Union (ITU) has introduced two additional AIS ASM channels as part of the VDES [16], [17]. VDES is designed to be backward-compatible with AIS, which means that vessels equipped with AIS can still receive VDES messages.

Here are the main advantages of VDES over AIS [17], [18]:

1. Data transmission rate: AIS has a fixed data transmission rate of 2.5 to 9.6 kbps, while VDES has a variable data transmission rate of up to 308 kbps.
2. Coverage: Unlike AIS, VDES provides ships with possibility to exchange information over satellites providing global coverage.
3. Security: VDES has enhanced security features, such as encrypted messaging, which makes it more secure than AIS.

Despite all its shortcomings, AIS is still the primary tool used to create V-AtoN environment. With the further development of the of e-navigation concept, the decline of such a trend and the promotion of VDES technology are expected, especially when it comes to security of V-AtoN.

## 3 USE OF SIMULATORS FOR EDUCATIONAL PURPOSES

The usage of nautical simulators is an essential tool in the education and training of seafarers. They can help seafarers to learn and practice a range of skills, such as navigation, ship handling, communication, etc. By using simulators, seafarers can learn to respond to a variety of situations, including adverse weather conditions, equipment failure, and other emergencies, without putting themselves or others at risk [11], [19].

IMO has developed and established a set of Model courses that include usage of nautical training simulators. Some of them are:

– Model Course 1.07 - Radar Navigation at Operational Level;
– Model Course 1.08 - Radar Navigation at Management Level;
– Model Course 1.22 - Bridge Resource Management;
– Model Course 1.27 - Operational Use of Electronic Chart Display and Information Systems.

It's worth noting that while the IMO provides guidance and recommendations for training and education in the maritime industry, individual countries may have their own specific training requirements for seafarers. International Convention on Standards of Training, Certification and Watchkeeping (STCW) approves the use of simulator that are in compliance with Section A - I/12 as a substitution for onboard training. Full affirmation of such a rule is recognized by the Netherlands, where so-called "equivalence" of work on the simulator and sea service is approved [19].

Human error is a major factor in accidents and incidents in the maritime industry, and it is often caused by a lack of experience or inadequate training [11], [20]. By providing realistic simulations of different scenarios, nautical simulators can help seafarers to gain experience and practice their skills in a safe and controlled environment. In that way, likelihood of mistakes being made in the real world is reduced since the seafarers will be better prepared to handle a range of situations.

Social fidelity is very important for simulator-based training. In [20] authors conclude that adequate collaborative learning activities in simulator-based training improve marine engineers' training and enhances the reliability of marine engines. The question arises whether the existing way of nautical simulator usage improves the skills and abilities of OOW in a virtual environment.

Since the goal of V-AtoN implementation is to increase safety at sea, it is necessary to discuss in more detail how such an environment affects perception and behaviour of OOW.

### 3.1 *Situational awareness in virtual environment*

From perspective of OOW, situational awareness means being aware of the current position, passage plan, environment, as well as whether any other ship or factor triggers augmentation of safety or security risk level [21], [22]. In order to be able to base command decisions, OOW must be aware and rely on all available resources including own ship's sensors, as well as on sight and hearing [23].

V-AtoN is considered as a digital presentation of physical AtoN. Virtual buoys can provide additional information that may not be available through traditional navigational aids. For example, they can provide real-time data on weather conditions, water depth, and other environmental factors that may impact navigation. Taking into account the similarities and differences of these two, as described in the Chapter 2, the question arises to what extent V-AtoN affects the situational awareness of seafarers.

Actually, they can influence and enhance their situational awareness of seafarers by providing additional information about the surrounding environment and at the same time boost safety at sea [4]. However, it is important to note that they should not be relied upon exclusively and should always be used in conjunction with other navigational aids and in accordance to best practices [23]. Jaram et al. [24] state that comparing influence of technology on situational awareness results in conclusion that benefits of technology outweigh the disadvantages of the same. These and other similar statements prompted the authors of this paper to conduct a simulation and evaluate whether the virtual environment has a negative effect on seafarers' decisions or not. Results are obtained by simulating ship transit through marked fairway. The following chapter describes the simulation setup in details.

## 4 SIMULATION SETUP

### 4.1 *Nautical simulator*

As stated in [25], "the first test of the formulation of the human element is the ability to execute manoeuvres and achieve the desired result". For the purpose of this research TRANSAS Navi Trainer 5000 and TRANSAS ECDIS 4000 simulators were used. Prior running the exercise for totally 48 times by 12 deck officers with at least 5 years of sea service in officer rank, there were several setups completed.

Area of simulation was chosen randomly, and the fairway was created 3 NM south of Mamula Island at the entrance to Boka Bay. Planned route was created with minor course alterations which are large enough to ensure that all data relevant for this research will be evaluated. Each leg of the route was 0.3 NM long and total distance is 1.2 NM. Largest course alteration as per planned route is 010° (Figure 1).

Route RT 2 Ship None Export...

| WP | Name | Latitude | Longitude | Course, ° | Distance, nm | Total distance, nm |
|---|---|---|---|---|---|---|
| 0 | | 42°21.619N | 018°32.809E | XXXX | XXXX | XXXX |
| 1 | | 42°21.914N | 018°32.879E | 009.9 | 0.300 | 0.300 |
| 2 | | 42°22.214N | 018°32.879E | 000.0 | 0.300 | 0.600 |
| 3 | | 42°22.509N | 018°32.809E | 350.0 | 0.300 | 0.900 |
| 4 | | 42°22.804N | 018°32.879E | 009.9 | 0.300 | 1.200 |

Figure 1. Route planned for the purpose of simulation.

Wind and waves are among the main environmental factors affecting ship's behaviour. However, in order to eliminate external factors, sea state was set to calm with no wind at all. Water current was eliminated as well. Depth in and around fairway remain unchanged reading more than 100 m. Cross track distance (XTD) for each leg was set to 0.02 NM. Lateral buoys were employed at WP0 and consecutively every 0.15 NM apart on each side of the fairway, at the XTD distance from its middle. Buoys were physical and virtual depending on simulation sequence – each participant passed twice through physically marked channel and then twice through virtual one.

Thorough examination was made in order to isolate important parameters which have to be monitored. The following parameters were observed:

- Distance made good;
- Heading;
- Drift angle;
- Rudder angle;
- Rate of turn (ROT).

### 4.2 *Subject ship model as the test case*

The subject vessel used as a test case in this simulation is bulk carrier. Her principal dimensions are shown in Table 1.

Table 1. Principal dimension of bulk carrier used for simulation purposes

| | |
|---|---|
| Ship type | Bulk carrier |
| Loading condition | Ballast |
| Displacement | 23565 m |
| M/E | Slow Speed Diesel x 1 |
| Power of M/E | 8827 kW |
| Maximum speed | 15.0 kt |
| LOA | 182.9 m |
| Breadth | 22.6 m |
| Draft forward | 7.5 m |
| Draft aft | 7.6 m |
| Type and no. of propeller | FPP x 1 |
| No. of rudders | 1 |

Exercise was run in manual steering mode with M/E set at Dead Slow Ahead. Participants were not allowed to change any settings during the simulation.

## 5 SIMULATION RESULTS

Figure 2. represents typical graphical presentation upon simulating passage through marked fairway. The most important data required for proper interpretation and understanding of different manoeuvres is presented. In order to make the Figure 2 clearer, a short explanation follows.

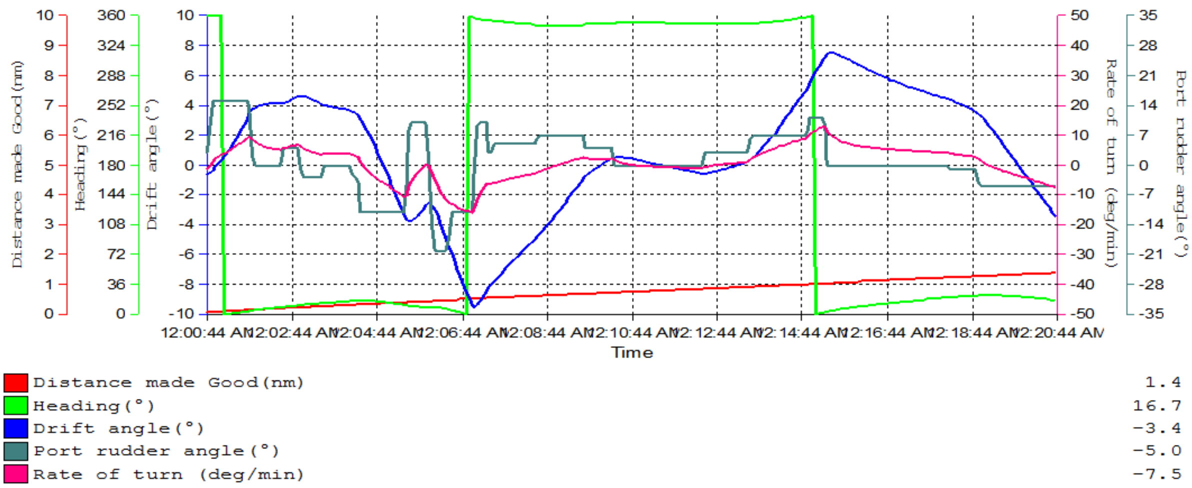


Figure 2. Typical graphical presentation of simulated passage though fairway (Export from TRANSAS Navi Trainer 5000)

X-axis is time-stamped and their vertical gridlines are two minutes apart. Y-axis contains several labels presenting measured parameters. If horizontal gridlines are extended outwards to labelled scales, it is possible to read a value of the specific parameter at a given time.

Red line presents vessel's progress [NM] reaching 1.2 NM at the end of the simulation. It can be used as a reference point for exploration of other parameters. Green line presents ship's heading [°] where gyro compass is used as a data source. Large amplitudes are consequence of N-orientated fairway. When heading is being altered from first quarter (course range 0-90°) to fourth quarter (heading range 270-359°), there is a huge amplitude as can be seen after running total distance of 0.5 NM and 1.0 NM, respectively. Due to frequent course alterations, difference between heading and course over ground are evident through drift angle [°] shown in blue. In this example, drift angle reaches value of almost 10°. Rudder angle [°] is teal-colored while rate of turn [°/min] is pink. They are corresponding to each other, where former goes up to 21° while latter goes up to 15°/min.

In order to simplify obtained results, data from each executed simulation was exported in .csv format. Afterwards, data from .csv tables are sorted out and processed.

The authors believe that the most important parameters to be analysed are drift angle, rate of turn and XTD. Average values of drift angle in different environments are shown in Figure 3. Similarly, Figure 4. presents average ROT.

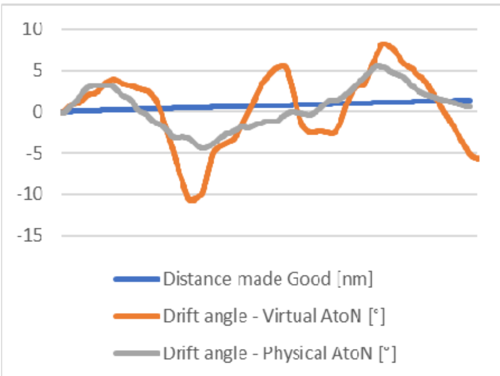


Figure 3. Comparison of average drift angle in real and V-AtoN environment

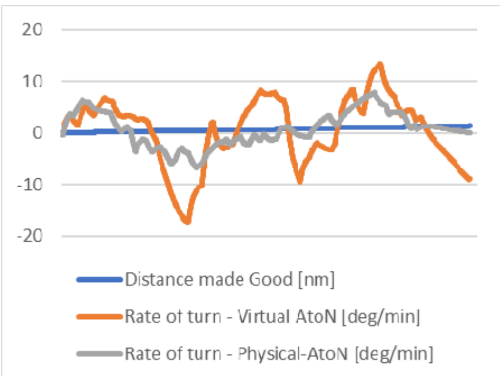


Figure 4. Comparison of average ROT in real and V-AtoN environment

Better picture of the movement of ships during the simulation can be achieved by analysing XTD values. Since the fairway is marked with totally 18 AtoN – 9 on each side, it was necessary to record XTD value abeam of each one. Obtained average values for non-virtual and V-AtoN environment are presented in table 2. Positive sign indicates that the vessel is on the starboard side, while negative sign indicates that the vessel is on the port side of the fairway.

Table 2. Average XTD values in two AtoN scenarios [m]

| Abeam of AtoN | WP no. | XTD Real AtoN | XTD V-AtoN |
|---|---|---|---|
| 1 & 2 | 0 | +1 | 0 |
| 3 & 4 | | -9 | -11 |
| 5 & 6 | 1 | -4 | +4 |
| 7 & 8 | | +10 | +11 |
| 9 & 10 | 2 | -8 | -20 |
| 11 & 12 | | 0 | +15 |
| 13 & 14 | 3 | +10 | -20 |
| 15 & 16 | | -10 | -10 |
| 17 & 18 | 4 | -15 | +28 |

Further discussion on obtain results is presented in Chapter 6.

## 6 DISCUSSION

By analysing graphical presentation (Figure 3), it is evident that in virtual AtoN environment, average drift angle increases, in some instances by more than twice. Such ship's behaviour is consequence of intense rudder orders. The same caused higher ROT intensity (Figure 4). Comparing those two graphs, it is evident that curve peaks of diagrams are at similar positions.

The XTD values help in better inferring the difference of the simulated manoeuvres. During the numerous simulations, many participants occasionally disregarded V-AtoN setup and run over them (Figure 5, blue squares), passing the boundaries of the fairway.

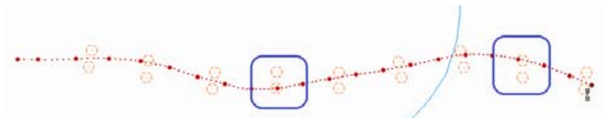

Figure 5. Vessel running over fairway boundaries marked with V-AtoN buoys

Such behaviour forced the authors to conduct an informal interview with the participants. Their general attitude is that use of nautical simulator cannot lead to the elimination of human error in real situations. However, the participants believe that more intensive simulator workout in a virtual environment setup could lead to their better performance at sea.

Variability of simulated transits can be weighted further on with range, variance and standard deviation. As can be seen from the Table 2, range of XTD in case of real AtoN is 25m while in case of V-AtoN is 48m.

Further calculation is dependent on population mean ($\mu$) which is calculated by equation (1), where

$\Sigma X$ presents the sum of all the observations ($x$) in the population of 48 which size is marked by $N$:

$$\mu = \frac{\sum X}{N} \quad (1)$$

Population variance ($\sigma^2$) is calculated by equation (2):

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2 \quad (2)$$

Using equations (1) and (2), real AtoN population mean is $\mu_1$= - 2,7778 while V-AtoN population mean is $\mu_2$= - 0,3333. Population variance in case of real AtoN is $\sigma^2_1$=68.61728 and in case of V-AtoN is $\sigma^2_2$=240.66667.

Square root of population variance ($\sigma^2$), brings the standard deviation ($\sigma$) in case of real AtoN $\sigma_1$=8.28355, and in case of V-Aton $\sigma_2$=15.51343. Values of XTD with standard deviation ($\sigma$) bars are shown on figure 5.

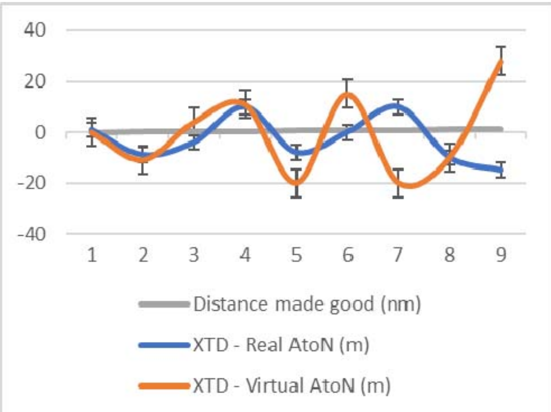


Figure 5. Comparison of average XTD [m] in real and V-AtoN environment

As shown in Figure 5, there are some overlapping of standard error bars, marked on X-axis as 1, 2, 4 and 8. Intense overlapping in these areas means that deviation from the middle of the fairway was not much different in real and virtual environment. Also, there is a slight overlapping in area 3. In other areas, there is no overlapping at all. Deviations from the middle of the fairway are intensified in area 7, where vessels are trying to get back on track, experiencing high drift angles and ROTs, which culminates in area 9 at the end of the marked fairway.

## 7 CONCLUSIONS

The objective of this study was to evaluate manoeuvring patterns of vessel transiting through deep water fairway marked with real and virtual AtoN. Simulations using TRANSAS Navi Trainer 5000 and TRANSAS ECDIS 4000 simulators are executed assuming that the ordinary seamanship practice is applied all the time. The results of this study indicate that there is a difference in manoeuvring trajectory of vessel sailing through the fairway marked with real or virtual AtoN, respectively. Analysing ship trajectories upon running totally 48 simulations, it is concluded that movement patterns in case of virtually marked fairway are significantly different. Several important parameters such as drift angle and ROT found with huge discrepancies. Also, XTD undoubtfully shows that off route deviations are larger in case of V-AtoN environment. Such results indicate that OOW feels more relaxed in virtual AtoN environment thus reducing overall level of safety at sea. Contrary, in case when the fairway is marked with real AtoN, passage is smoother, with smaller drift angles, ROT and XTD. Despite all the efforts made in recent years by the IMO and other stakeholders for the sake of the virtual maritime environment in order to improve digitalization, connectivity, and reduce costs, it is necessary to make additional efforts, primarily in terms of increasing awareness of the risks coming from the V-AtoN environment. Undoubtedly, one way to achieve that is through implementation of additional-specific ECDIS training which will enable OOW to become better acquainted with virtual environment. Such specific training should focus on peculiarities of virtual environment and its differences in relation to physical one. Through different scenarios OOW should be able to become more competent, skilled and aware. Future research should focus on finding ways to make usage of V-AtoN more useful and safer.

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