Indirect Vessel Velocity Control to Reduce the Impact of Underwater Noise at Cetacean Locations

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Abstract— **This paper proposes a novel approach to reducing the environmental impact of marine traffic on cetaceans, focusing on controlling vessel velocity to minimize underwater noise. The approach is based on a simulation system integrating a dynamic vessel model, an autopilot (with Integral Line-Of-Sight guidance law), a noise transmission model, a wind and current model and a decision-making system. The main contribution of the paper is the ability to dynamically adjust vessel velocity according to underwater Sound Pressure Levels heard at cetacean location, and the visualization of different scenarios describing interactions between vessels and cetaceans. The results show that adjusting vessel velocity as a function of distance from cetaceans maintains noise levels below the acceptable threshold, demonstrating the simulator's effectiveness in controlling underwater noise heard at cetacean location.**

Keywords— Decision making; velocity control; cetaceans; Underwater Noise; Simulator

I. Introduction

The need to develop and improve decision-making systems for navigation has become pressing to effectively reduce the environmental impact of maritime transport on cetaceans. Simultaneously, the aim is to maintain an important level of automation in these systems. A safe and stable autonomous driving system not only eliminates the risk of collision but also plays a significant role in steering shipping practices towards greater responsibility and efficiency. However, while progress has been made in the development of decision-making systems, much recent research has focused primarily on path planning. Sèbe et al. [1] proposed a decision-making system for collision avoidance between vehicles and cetaceans, considering economic aspects, such as potential damage to vessels [2]. Meanwhile, Zhang et al. [3] introduced a system to compute the optimal path planning and control of autonomous vessels, integrating various constraints in real maritime environments, but without considering underwater noise. Similarly, Ellouzi et al. [4] developed an optimized autonomous decision-making strategy using visualization and data mining.

Cetacean localization systems often incorporate real-time monitoring using underwater acoustic sensors or cameras to detect and track cetacean vocalizations and movements [5]. In addition, studies on dynamic path optimization [6] have focused on adjusting vessel velocity and routes according to cetacean location and behavior to avoid potential collisions or disturbances. However, despite the recognition of problems such as unwanted noise and the high impact of proximity on cetaceans, the existing scientific literature lacks studies addressing vessel velocity control to reduce noise levels during the localization of cetaceans. To the best of our knowledge, there is currently no control system for estimating noise levels at cetacean locations using propeller revolutions per minute (RPM) control, as opposed to approaches suggesting vessel shutdown, as proposed in [7].

Thus, this study suggests an innovative approach using velocity control algorithms based on propeller RPM adjustment to build a simulator that includes a dynamic vessel model, noise transmission model, and wind and current model for a decision support system. The system was designed to dynamically adjust the vessel velocity by considering underwater noise estimation and environmental constraints. The main contributions of this study are articulated along the two main axes. First, by integrating physical constraints, the proposed simulator enables real-time adjustments of vessel velocity as a function of Sound Pressure Levels heard at cetacean localization. This feature offers a dynamic and adaptable response to changing environmental conditions, helping reduce underwater noise. Second, owing to data aggregation, our simulator can visualize different scenarios describing the interactions between vessels and cetaceans. This visual representation enhances the understanding and awareness of these interactions, providing valuable information for the development of effective decision-support systems for maritime navigation. By providing a graphical perspective of vessel-cetacean interactions, our simulator facilitates situation analysis and decision-making for maritime operators, contributing to more responsible and environmentally friendly navigation.

Section II details the main contribution of the study, covering the development process of the modeling and simulation platform required to create the suggested simulator. In Section III, the results of the simulation experiments conducted to validate the testbed, including three case studies is presented. This section presents the data collected, analyses carried out, and conclusions drawn from these experiments, providing an in-depth assessment of the simulator's performance and efficiency under a variety of conditions.

II. Suggested Simulator

A. Model Overview

The objective of this research is to develop a proof-of-concept for a decision support system implemented using a software simulator. This simulator was designed to assist pilots and operators using optimization algorithms to reduce

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risk constraints, with a dual emphasis on adjusting vessel velocity to minimize the impact of their noise on cetaceans. Fig. 1 illustrates the architectural framework. One design constraint is based on a hard-real-time feedback loop concerning the position, velocity, and environmental constraints of the vessel. By processing these data, the system can recommend a series of optimal paths and propose the corresponding vessel velocity values.

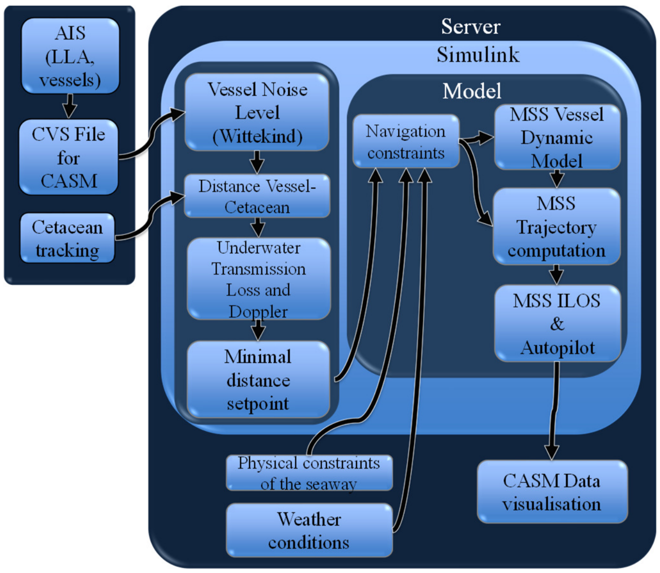

Figure. 1. Decision support system architecture for the simulator design

B. Model Design

The proposed simulator can be divided into four distinct blocks, each comprising of detailed steps that provide a comprehensive explanation of the methodology.

1) Noise Modelling

The input data of the system are the noise levels generated by vessels and perceived by cetaceans at their locations, expressed in units of pressure. To implement this approach effectively, this study relied on a comprehensive noise dataset. The noise model is designed to provide accurate estimates of underwater noise levels associated with several types of vessels. It also considers specific vessel characteristics, such as size, velocity, engine specifications, and noise emission patterns. A maritime ambient noise mapping library [8] based on equations presented in [9] is used to estimate the noise level. This library maps maritime ambient noise using the Wittekind model to estimate the source noise level (N_L), as shown in (1), where *SL1* represents low-frequency cavitation noise, *SL2* represents high-frequency cavitation noise, and *SL3* represents diesel engine noise:

$$N_L = 10 log_{10}(10^{SL1} + 10^{SL2} + 10^{SL3}). \quad (1)$$

This model used the default value for the speed of sound propagation. To adapt to the characteristics of the environment, a study of sound propagation in water is required to approximate the noise level perceived by marine mammals.

2) Underwater noise transmission modelling

Several models have been developed to characterize the speed of sound in deep water and determine the best formulation. The study opted for the simplest and most effective model according to [10], namely the François and Garison model. Transmission loss (T_L) is incorporated to ensure an accurate representation of underwater sound conditions, considering both attenuation and sound propagation. To choose which T_L model to use, we rely on the work in [11], which states that the basic model, which includes the absorption coefficient, is the most appropriate. This model offers a better overall fit to the measured data, with relatively minor contributions from attenuation and a more pronounced contribution from propagation. To determine the T_L, the shipping ambient noise mapping library is used [8]. This modification allows for the estimation of the T_L value as follows, using hybrid of spherical and cylindrical spreading:

$$T_L = 1.5 \times 10 log_{10}(r) + rA \times 10^{-3}, \quad (2)$$

where *A* is the absorption coefficient and *r* is the covered distance in meter. The library does not consider the Doppler effect in the computation of the transmission loss. Subsequently, a Doppler effect coefficient [12] is introduced into the frequency within the absorption coefficient. The absorption coefficient *A* (Thorp's formula, in dB/km), is defined in Equation (3) in the case of a mobile transmitter and a stationary receiver:

$$A = \begin{cases} 0.11 \frac{(f\delta f)^2}{1+(f\delta f)^2} + 44 \frac{(f\delta f)^2}{4100+(f\delta f)^2}, \text{ with} \\ +0.000275(f\delta f)^2 + 0.003, \end{cases} \quad (3)$$

$$\delta f = \frac{c}{c - v\cos\alpha}, \quad (4)$$

where δf is the Doppler effect coefficient, which depends on the velocity of sound propagation in water *c*, the velocity of the vessel *v*, the angle between the direction of the vessel, and the localization of the cetacean α and *f* (kHz) the frequency [12]. In (4), to vary the coefficient δf, which depends on the speed of sound in water *c*, the water temperature *T* is used in Simulink, as described in (5):

$$c = \begin{cases} 1449.2 + 4.59T - 0.055T^2 + 0.00029T^3 \\ +(1.39 - 0.012T)(S - 35) + 0.017Z \end{cases}, \quad (5)$$

where Z and S are the depth in water and salinity in parts per thousand (for the Fjord, S=35% and Z=35 m, respectively, in the simulation [13]), as defined by Mackenzie, 1981 [14]. Other models can be used, such as those presented in [15] or more recently in [16]. Finally, the noise heard by marine mammals in their location S_{PL}, is the result of the subtraction of the T_L from the N_L as described in (6):

$$S_{PL} = N_L - T_L. \quad (6)$$

3) Risk Assessment

Risk assessment is carried out according to a systematic methodology involving the simulation of various critical scenarios, including those where the distance between cetaceans and vessels is minimal and where the noise perceived by cetaceans is maximized at their specific locations. These scenarios are carefully defined to represent adverse conditions, enabling a comprehensive analysis of high-risk situations. To gather a complete dataset for this study, several sources of information are used, each with a specific purpose. The collection of data from satellite images generously provided by the CASM platform provides valuable information on vessel positions, paths, and velocities. This satellite-derived data is crucial for enriching the understanding of maritime traffic patterns. In addition, to ensure accurate monitoring of beluga locations, data from *Observatoire Global du Saint Laurent* (OGSL) [17], an organization specializing in cetacean observation, are used. The OGSL provides essential data on the location of belugas at specific times. However, simulations presented are a proof of concept, and the accurate location at a specific time of cetacean is not known. The results of these assessments are presented in Table 1, where potential risk scenarios are identified as a function of vessel velocity and proximity to belugas. Fig. 2 illustrates three of these scenarios, each accompanied by its respective noise level, providing a clear visualization of potential risk situations. Wind patterns are also considered, as they directly influence vessel stability and path. Reliance on the Marine Simulator System (MSS) [18] is crucial for setting these parameters, ensuring strict compliance with the recommended velocity values, with a sound pressure level between 120 and 130 dB re 1µPa. This threshold is based on the extensive studies presented in [19], which analyzed the impact of noise depending on source type and levels on cetacean behaviors (based on human observation). By adopting this value, a strategic approach is designed to maintain the noise level perceived by cetaceans within the limits of the behavioral influence zone, thus effectively avoiding danger zones.

TABLE I. POSSIBLE RISK SITUATIONS FROM OGSL AND AIS

Date	Number of Belugas	Number of vessels	Distance (Km)	Hull Velocity (Knots)
03-08-2022	15	1	2.36	12.8-13
15-08-2022	60	2	3.73-4.54	8-12.05
22-08-2022	32	1	3.34	9.7
07-09-2022	4	1	10	5.6
25-10-2022	1	1	5	7.9
30-07-2023	1	1	1.39	12.05

4) *Vessel Velocity Control*

Vessel velocity control is based on a simple but effective algorithm that considers various parameters of vessel dynamics. The velocity is not directly controlled, but the RPM of the propeller, which is the main noise source. Using the dynamics of the vessel, its velocity is adapted based on the trust force and heading autopilot control. Operating with a maximum preset Sound Pressure Level (S_{PL}) threshold value (γ=130 dB) estimated at the cetacean location, the algorithm ensures a vigilant response to the acoustic conditions of the underwater environment. When the measured S_{PL} exceeds this threshold, signaling a potentially high impact on the environment, the algorithm triggers a dynamic adjustment in the velocity of the vessel. This adjustment process is mathematically defined by (7), where $C_{RPM}[n]$ represents the current shaft rotation per minute setpoint of the propeller at sampling n, $C_{RPM}[n-1]$ is the previous velocity setpoint at sampling $n-1$, S_{PL} is the measured sound pressure level, γ is the predefined maximum noise threshold heard at the cetacean location, and k (rad/(s•dB)) is a constant factor function of the sampling frequency.

$$C_{RPM}[n] = C_{RPM}[n-1] + k(S_{PL} - \gamma). \quad (7)$$

However, when the measured S_{PL} is below 130 dB, indicating an acceptable condition for the environment, the algorithm maintains the C_{RPM} at its current setpoint value. This two-level approach, described in Algorithm 1, allows dynamic adjustments only when necessary. It provides a real-time control mechanism that not only mitigates potential noise impacts on the underwater environment during high S_{PL} conditions but also preserves the optimum velocity during quieter periods. This dynamic adaptation guarantees a balanced response to various acoustic scenarios, making the system versatile and environmentally friendly.

B. *Modeling in Simulink*

The designed Simulink simulator is based on the implementation of the Wittekind model [20] function and the MSS model, specifically adapted to capture the dynamic behavior of vessels. The Wittekind function, integrated into MATLAB, is used to estimate the noise of the vessel. Simulator integration uses a comprehensive set of inputs, including the water temperature, cetacean locations, vessel position, and velocity. These variables collectively contribute to the estimation of sound pressure level (S_{PL}). The S_{PL} is then used to compute the C_{RPM} and adjust the vessel velocity according to its dynamics. This process, inherent in the simulator architecture, dynamically adjusts the velocity of the vessel by manipulating the propeller RPM described in Algorithm 1, where k=1.

Algorithm 1: Vessel C_{RPM} Adjustment

```
Data: α, β, T_s, n
Input: v, S_PL, C_RPM[n-1]
Output: C_RPM[n]
n ← 0;                                   /* Start simulation with first sample */
T_s ← 0.05;                              /* Sampling simulation time */
γ ← 130;                                 /* Maximum noise in dB */
β ← 160;                                 /* Maximum propeller shaft RPM */
v_min ← 5;                               /* Minimum vessel velocity */
LPF ← butter(1, 2π/5.5, T_s);  /* O(1) LP filter, 5.5 time constant */
while Waypoint not reached, ILOS control law do
    Call Compute S_PL
    δ=C_RPM[n-1] - T_s(S_PL − γ)
    if v ≥ v_min and δ ≤ β then
        C_RPM[n] ← LPF(δ)
    end
    Set 0 ≤ C_RPM[n] ≤ β;                /* Saturate between min and max */
    Call Vessel dynamic with Setpoint C_RPM[n]
    Call Autopilot
    n ← n + 1;                           /* Next sampling time */
end
```

Using six inputs, namely S_{PL} value, minimum tolerated propeller C_{RPM}, current C_{RPM}, S_{PL} threshold (γ= 130 dB), and maximum C_{RPM} (β=160 RPM) value with coefficient k (proportional to T_s), which are submitted to a dynamic vessel model described in the MSS library subject to marine current and wind. The simulation tracks a set of waypoints using the Integral Line-of-Sight (ILOS) guidance law [21] to define the heading setpoint and a PID (Proportional-Integral-Derivative) with a reference feedforward controller governing the autopilot system. The ILOS guidance law and autopilot are defined in the MSS library. Crucially, both the ILOS and PID autopilot controller parameters remain adaptable, enabling dynamic adjustments and providing flexibility in simulating a variety of vessels. Similarly, the adjustment of vessel dynamics ensures the accurate emulation of different marine vehicles, enhancing the realism of the simulator and enabling the distinct characteristics of various marine vehicles to be reproduced. This adaptability is crucial for optimizing the acoustic footprint of underwater environments.

III. EXPERIMENTAL VALIDATION

A. *Experimental Data*

By combining these datasets, this study builds a holistic picture of vessel activities and cetacean behaviors (as discussed in the risk scenarios earlier), enabling the identification of potential risks in the presence of both shipping and cetaceans. It is also important to note that vessel characteristics, such as size and engine specifications, play a crucial role in the simulator behavior. Variations in these vessel attributes have a significant impact on the resulting S_{PL} values, and hence, on velocity variations. The vessels used for this simulation are observations from AIS data and defined three cases N1, N2, and N3, as detailed in Table 2, using the paths presented in Fig. 2. In Table 2, V_{cis} represents the vessel's cavitation starting velocity, Disp the vessel's displacement in meters, C_b the block coefficient, M the engine weight in tons, N the number of engines operating simultaneously, and mount the mounting mode (0 indicates elastic engine mounting, and 15 indicates rigid engine mounting). These data are used to estimate low-frequency cavitation noise, high-frequency cavitation noise, and diesel engine noise. The latitude and longitude positions of the vessels and cetaceans are detailed in Table 5.

B. *Simulation Results without Velocity Adjustment*

To illustrate the effectiveness of our proposed simulator, the following simulations (Fig. 2) present the sound pressure levels (S_{PL}) estimated for different combinations of velocity and distance. The fixed parameters for these simulations are detailed in Table 3, and the vessel and beluga positions are modified for each potential risk scenario, as detailed in Table 5. This systematic testing approach ensured a comprehensive assessment of the robustness and applicability of the suggested solution across a range of three realistic scenarios (N1, N2, and N3). The simulation results for the three scenarios without velocity adjustment are shown in Fig. 3. In this figure, the noise heard at the cetacean location is higher than the threshold.

TABLE II. CARACTERISTICS OF VESSELS FOR THE SIMULATIONS

Case	**V_{cis} (knots)**	**Disp (m)**	**C_b**	**M (ton)**	**N**	**Mount**
N1	9	102088	0.88	185.8	1	0
N2	9	105235	0.88	189.6	2	15
N3	9	47352	0.88	111.3	1	0

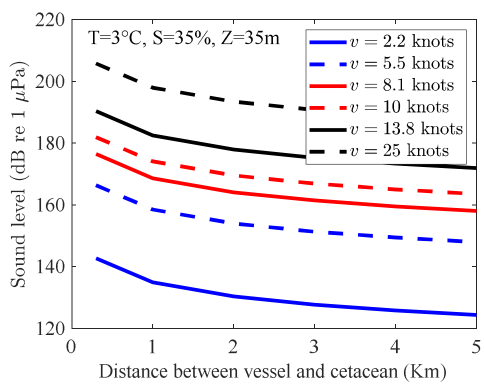

Figure. 2. Sound Pressure level as a function of velocity and distance

TABLE III. ENVIRONMENTAL PARAMETERS FOR THE SIMULATION

Parameter	**Value**
Water temperature	3°C
Current direction	5 degrees
Current speed	2 Knots
NORSOK Wind direction	150 degrees
NORSOK Wind speed	15 m/s
NORSOK Time constant	10 sec.
NORSOK Wind spectrum	20 meters
Length of the vessel	175m

1) *Estimated Vessel Noise Level (S_{PL})*

If vessel characteristics, particularly velocity, are decisive in the estimation of sound pressure levels (S_{PL}), it is essential to explore the impact of different vessel velocities on S_{PL} values. As illustrated in Table 4, the correlation between the vessel velocity and S_{PL} values is evident, with a significant increase in S_{PL} as the vessel velocity increased. Crucially, although the 10-knot velocity limit is established in marine navigation, the simulations reveal high S_{PL} values for this velocity, representing a risk to belugas and confirming our hypotheses regarding the existence of a potential risk to these marine mammals. This underlines the importance of adjusting velocity using the proposed solution.

2) *Simulation Results with Velocity Adjustment*

In the three cases studied, the ships approach the cetaceans and overtake them. As the distance between the vessels and listener location decreased, the level of underwater noise heard increased. Consequently, it is possible to minimize the underwater noise generated by vessels by reducing its velocity. Specifically, for each increase in S_{PL} accompanied by a decrease in distance, indicating a potential risk scenario, the velocity of the vessel is reduced, as illustrated in Fig. 5. However, the vessel dynamic implies some time to reduce C_{RPM}, meaning that the S_{PL} threshold value is not always respected. This figure 5 shows the results of the simulations of the estimated noise level, considering different values of velocity and distance, and the corresponding adjustments made to the vessel's velocity in real time. This analysis highlights the significant influence of both distance and vessel velocity on the noise levels encountered at cetacean locations, as indicated by S_{PL}. When the distance between the velocity and the observation point exceeds approximately 1 to 3 km, the S_{PL} reaches its minimum level and gradually decreases as the vessel moves further away and then increases in velocity.

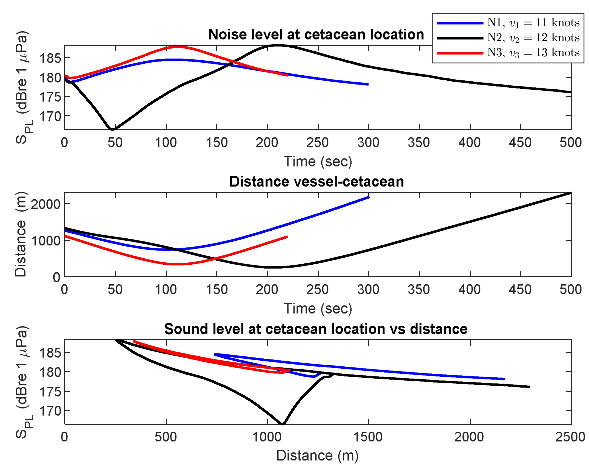

Figure. 3 Current estimated noise level without velocity adjustment

TABLE IV. NOISE LEVEL ESTIMATION FOR VESSEL VELOCITIES

Vessel velocity (knots)	**S_{PL} (dB 1re µPa)**		
	N1	**N2**	**N3**
0	90.25	125.36	101.68
2	117.25	125.52	112.62
3	**127.8**	**127.08**	**120.05**
5	141.11	134.82	132.18
8	153.36	144.95	142.49
10	159.18	149.47	147.01
12	163.93	152.58	150.13

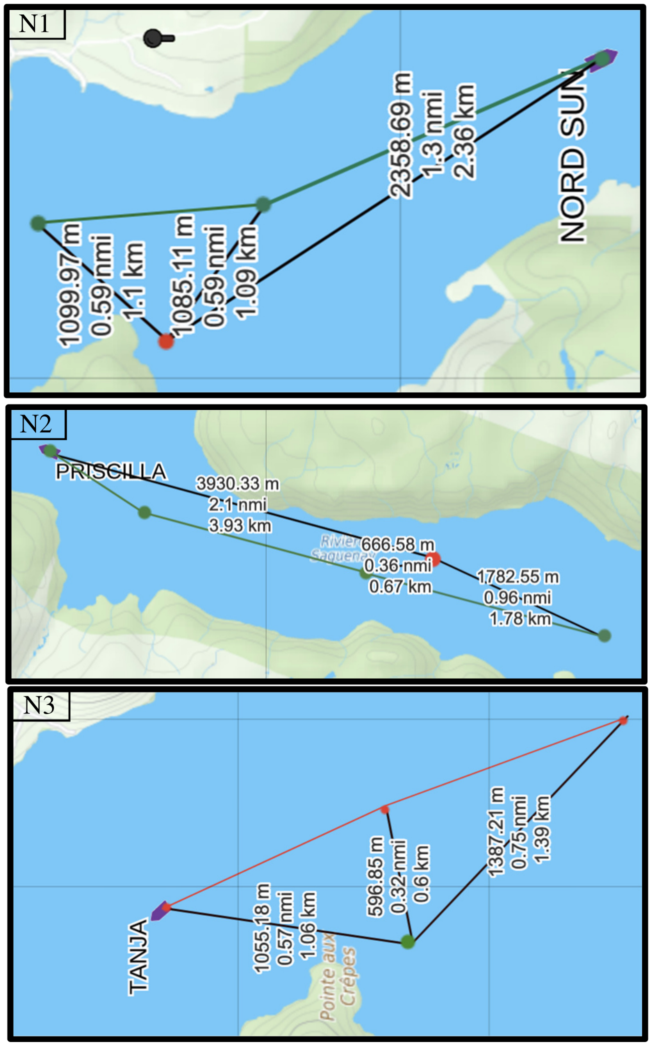

Figure. 4 Localization of vessels and cetaceans for three study cases in the Fjord of Saguenay, Quebec, Canada (location of cetacean could be different since OGSL database provide approximative information on date, hour and location of the observation)

IV. Conclusion

This study presents an innovative approach to the development of a decision support system for marine navigation, with a particular focus on reducing the impact of vessel noise on cetaceans, particularly belugas. By integrating sophisticated noise and sound propagation models as well as optimization algorithms for adjusting the velocity of a vessel and generating optimal waypoints, the proposed simulator offers a comprehensive and effective solution for minimizing environmental risks while improving operational efficiency. The results of the simulation experiments have demonstrated the robustness and efficiency of the system, providing real-time adjustments of vessel velocities according to sound pressure levels and enabling clear visualization of interactions between vessels and cetaceans.

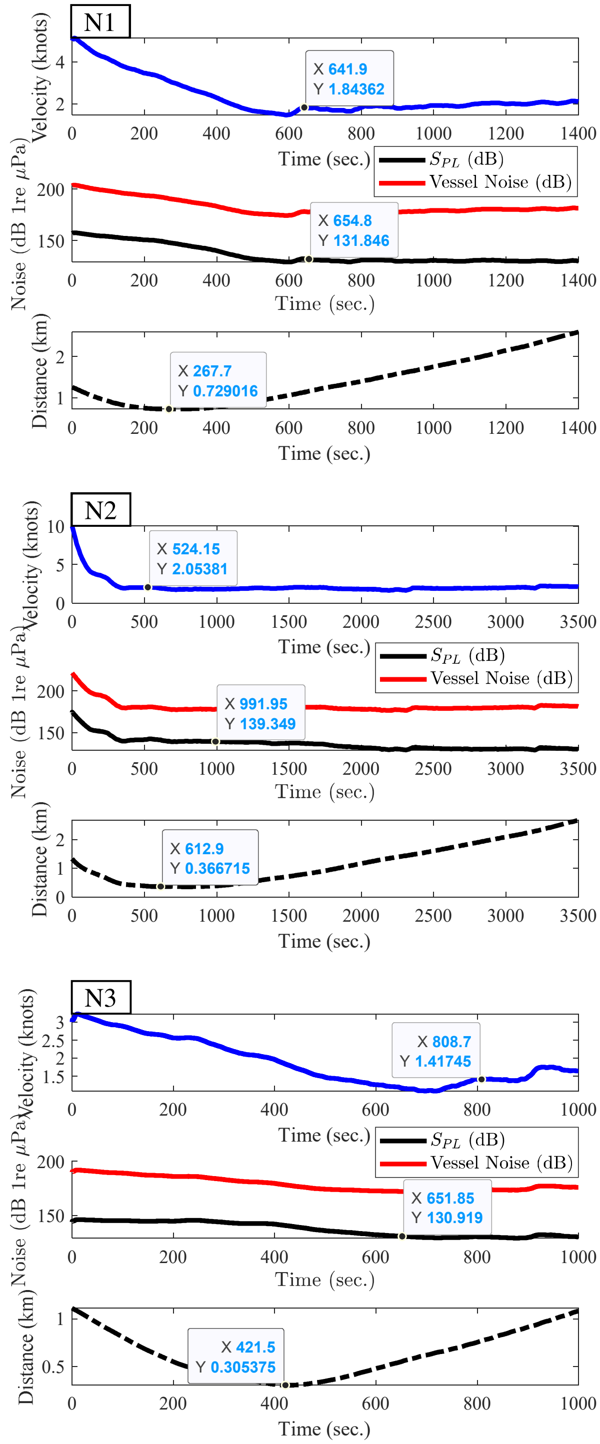

Figure. 5 Real-time velocity adjustment on the S_{PL}

TABLE V. Localisation of vessels and cetaceans

Case	Start waypoint location			Stop waypoint location		Cetacean location	
	Date	**Lat.**	**Long.**	**Lat.**	**Long.**	**Lat.**	**Long.**
N1	03-08-2022	48.220784	-69.886436	48.190810	-69.872017	48.210604	-69.897337
N2	15-08-2022	48.227623	-69.905471	48.244082	-69.995871	48.235250	-69.926004
N3	30-07-2023	48.204312	-69.879742	48.222843	-69.891071	48.212892	-69.892960

These results pave the way for practical applications in marine navigation, particularly in the St. Lawrence area, by providing operators with valuable tools for making informed decisions while preserving the marine environment.

Prospects for future work include several important axes. First, it is crucial to generate optimal paths for vessels by considering the sound pressure level (S_{PL}) and all relevant environmental constraints. This approach refines our decision support system and optimizes marine navigation while minimizing its impact on sensitive marine ecosystems. Second, adding sensors as an input to the simulator to detect the presence of cetaceans in real time is necessary. The integration of real-time detection data will improve the responsiveness and adaptability of the system, thereby enhancing its ability to effectively protect marine mammals. Third, it is essential to implement a decision-support system under real conditions and in real time. This stage of testing in real-life situations validates the system's performance and practical usefulness, paving the way for its operational deployment in maritime navigation. These advances should significantly contribute to the field of automated navigation systems, offering innovative solutions for safer, more efficient, and more environmentally friendly maritime navigation.

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