Input paper for the following Committee(s): check as appropriate

☐ ARM ☐ ENG ☐ PAP

X DTEC ☐ VTS

Purpose of paper:

☐ Input

☑ Information

Agenda item [1] n.n

Technical Domain / Task Number [2] ………………………………

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Large Language Models (LLMs) for Next-Generation Vessel Traffic Services (VTS): Applications and Opportunities

1 SUMMARY

As maritime traffic data becomes increasingly available due to the growing volume of vessel movements, advancements in data harnessing technologies and developments of new digital data sources i.e. low satellite imagery, it presents opportunities for the maritime industry to leverage the potential benefits that Large Language Models (LLMs) technology could offer. Among the rapid developments in various AI technologies, Large Language Models (LLMs) stand out due to their powerful capabilities in understanding natural language, summarizing unstructured information, retrieving knowledge from large datasets, and generating context-sensitive responses.

Three use cases were identified and discussed in this paper including 1) **risk identification from multi-source heterogeneous data** in real-time monitoring; 2) **automated analysis of VHF voice communications and traffic management responses;** 3) **LLM-based post-event analysis** of near-miss collision and other safety-critical cases. Preliminary assessment is that LLMs would potentially ease the workload of VTS operators from the current human-centric data analysis processes which are often tedious, prone to errors and inconsistent. LLMs have the potential to embody the concept of “doing more and better with less.

This information paper introduces LLMs and outlines their opportunities, limitations, and use case applications for VTS. It aims to share ongoing maritime LLMs development in Singapore and to solicit feedback from the committee.

2 POTENTIAL APPLICATION SCENARIOS

This section provides a more detailed feasibility-oriented discussion of how LLMs could support digital technology development and applications for maritime systems such as next-generation VTS. Three potential application scenarios have been identified: (i) risk identification from multi-source heterogeneous data in real-time monitoring; (ii) automated analysis of VHF voice communications and traffic management responses for reducing workload; and (iii) LLM-based post-event analysis of near-miss and other safety-critical cases for improving efficiency and retaining domain experts’ knowledge. The following subsections

1

set out each scenario in greater detail, with emphasis on their purpose, data inputs, LLMs roles, feasibility considerations, technical challenges, expected benefits, and limitations/controls in VTS operations.

2.1 Risk Identification from Multi-Source Heterogeneous Data in Real-Time Monitoring

Operational Context / Purpose: Operators are expected to monitor AIS screens, Radar, VHF voice, CCTV, and multi-source heterogeneous data (e.g. ship's schedule, navigation rules and established traffic organization) simultaneously, while also considering dynamic factors such as tides, currents, and visibility. This heavy reliance on manual interpretation and summary under time pressure can easily lead to fragmented awareness or delayed recognition of developing risks, especially in high-density waterways. An LLM-assisted approach could provide structured and timely support by integrating these inputs into concise, operator-oriented and easy-to-understand explainable insights, helping VTS personnel to detect potential risks before they escalate.

Inputs Data:

- Sensor data: AIS tracks and encounter metrics (CPA/TCPA), VHF voice, radar, CCTV, and satellite imagery.
- Environmental data: nautical chart, tides, currents, and weather conditions.
- Vessel and operational data: vessel particulars, schedules, and VDES transmissions.
- Knowledge sources: heterogeneous expert knowledge bases, including international navigation rules (e.g. COLREGs), local traffic organization measures, and past representative cases.

LLM Role: The role of LLMs in this scenario is to integrate multi-modal and heterogeneous knowledge/inputs into coherent, operator-oriented insights on top of other relevant models and AI tools. Instead of leaving operators to interpret raw CPA/TCPA values, vessel data, rules instead of leaving operators to confront raw CPA/TCPA values, vessel data, navigational rules, and other relevant information simultaneously, while still having to interpret each of them in relative isolation, the LLM-based model can:

- Fuse multi-source data (sensor, environmental, operational, and knowledge bases) and outputs from other models into a unified traffic picture.
- Frame emerging risks by generating concise risk narratives (e.g. "Two bulk carriers converging: DCPA 0.3 NM, TCPA 6 min; one constrained by draft within the traffic separation scheme; Schedule driven detection of congestion at port entry and exit points.").
- Retrieve and apply rules and knowledge by linking real-time situations with relevant COLREGs provisions, local traffic measures, and past representative cases to quickly identify high risk cases in the development stage.
- Highlight key signals in explainable manners through LLM outputs timely that might otherwise be overlooked under time pressure, supporting earlier recognition of developing risks to assist human operators and help ensure sufficient time to mitigate in proactive ways.

Challenges / Technical Pathways:

- Data quality, reliability: Challenge in AIS loss, latency, conflicting signals, or unstructured formats (e.g. free-text reports) can undermine outputs. This requires preprocessing, validation checks, digitization, and schema-based standardization to ensure inputs are reliable and interpretable by machines.
- Heterogeneous data fusion: Challenge in aligning sensor feeds, operational databases, and expert knowledge in near real time is non-trivial. This Needs standardized schemas, secured data quality and robust data pipelines.
- Timeliness: Challenges in real-time VTS operations demand responses within seconds. This stringent requirement demands LLM-based models to be capable of managing low-latency interference for efficient data exchange.
- Explainability and trust: Operators must quickly understand why a situation is flagged. This requires explainable and reliable outputs that include meta information to raw data, rules, or experience from past cases for validation.

Potential Benefits:

- Faster recognition of emerging risks.
- Reduced operator workload in handling multiple data streams.
- More consistent and standardized framing of traffic situations.

Safeguards/Limitations

- Outputs should follow structured formats (e.g. risk cards, event summaries) with clear data references.
- Operator supervision is required; LLMs support but do not replace human judgement.
- Dependent on input data quality and availability to ensure reliable responses.
- Legal and regulatory responsibilities remain with human operators.

2.2 Automated analysis of VHF Voice Communications and Traffic Management Responses

Operational Context / Purpose: Many VHF exchanges in VTS concern routine tasks such as position reporting at reporting lines, acknowledgements, and log-keeping, as well as simple information requests on port operation or nearby vessels. Today, these routine and repeated tasks still require intensive manual processing, transcription, and database checks by operators. With their language understanding and retrieval ability, LLM based tools could automate these regular duties by interpreting reports, recording them, and providing standardized responses from backend data, allowing operators to focus on higher-priority traffic management.

Inputs Data:

- VHF voice inputs: routine reports (e.g. position at reporting lines) and simple queries.
- Backend databases: for example, vessel particulars in traffic, schedules, berth, and port information/ guideline.

LLM Role: LLMs can transcribe and understand routine VHF reports, capture basic information inquiries (e.g. port information/guideline or vessel status), log them automatically, and generate standardized responses or database-backed replies from backend systems and through retrieving reference domain knowledge accurately and adaptively.

Challenges / Technical Pathways:

- Speech recognition: noisy channels, accents, and code-switching reduce accuracy.
- Information extraction: mapping callsigns, vessel names, and positions consistently.
- Standardization: aligning outputs with SMCP (Standard Marine Communication Phrases) phrases and local procedures.

Potential Benefits:

- Automates routine reporting and log-keeping.
- Provides fast, standardized replies to basic information requests.
- Reduces operator workload and frees attention for complex traffic management.

Safeguards/Limitations

- Operator confirmation required before any outbound messages.
- Outputs are limited to standard phrases and verified data sources
- Accuracy is affected by the quality of speech recognition and background noise.
- Current systems untested in live VTS operations; regulatory responsibility remains with operators.

2.3 LLM-based Post-Event Analysis of Near-Miss Collision/Safety-Critical Cases

Operational Context / Purpose: Post-event analysis of near-miss and other safety-critical cases is a vital part of safety management in VTS. Such investigations help identify contributing factors, strengthen reporting practices, and provide valuable lessons for future risk reduction and accident prevention. Today, this process is largely manual: analysts review AIS plots, listen to VHF recordings, check logs and notes, and then compile narrative reports. These tasks are time-consuming, vary in quality depending on individual expertise and interpretation, and often delay the sharing of insights. As a result, important operational knowledge may not be captured systematically. An LLM-assisted approach can help automate and streamline this process by integrating AIS and VHF records, producing draft case summaries, and aligning outputs with existing templates such as those recommended in IALA Guideline G1118.

Inputs Data:

- AIS trajectories and encounter metrics
- VHF transcripts and call logs
- Operational notes, weather, and tidal data

LLM Role: LLMs can combine AIS and VHF records into structured event timelines, automatically extract key moments, and align them with standard case templates to support consistent reporting. Beyond summarization, they can provide analysis like that of human VTS experts: proposing likely contributing factors, highlighting operational or procedural gaps, and suggesting areas for improvement. By drawing on past representative cases and navigation rules, the model can quickly help generate deeper insights to assist human investigators. On the other hand, the LLM-based tool could also embed domain experts' knowledge to iterate the analysis, which helps retain domain experts' knowledge to improve the analysis process about why an incident developed and how similar risks could be mitigated in the future.

Challenges / Technical Pathways:

- Data completeness: AIS gaps and partial VHF recordings limit accuracy.
- Multi-modal alignment: synchronizing AIS tracks, voice logs, and notes.
- Interpretation risk: avoiding over-speculation when evidence is uncertain.
- Integration: ensuring output fit existing reporting systems and guidelines (e.g. G1118).

Potential Benefits:

- Greatly improves efficiency in analyzing typical representative dangerous cases in VTS waters.
- Provides more consistent and standardized documentation across investigations.
- Enhances understanding and systematic learning of past incidents, supporting preventive measures.

Safeguards/Limitations

- Human experts must validate interpretations and causal reasoning.
- Accurancy is dependent on the completeness and quality of AIS/VHF records.

3 Legal accountability remains with the authorities.

4 DISCUSSION

While LLMs possess tremendous potentials in VTS, the path towards effective adoption will require more than proof-of-concept demonstrations. It requires an "whole-of-maritime ecosystem" approach to ensure readiness in data quality and standardization, integration with established procedures, clear human-in-the-loop safeguards, and investment in skills and capacity building for the realisation LLMs potential in a safe, reliable and sustainable manner.

- **Data readiness:** improving the quality, standardization, and machine-readability of AIS, VHF, and related data sources. Particular attention is needed to address variability, inconsistency, and errors in multi-source inputs, as these directly affect the reliability of AI/LLM-based tools in high-stake situations.
- **Operational integration:** ensuring that LLM outputs are compatible with existing VTS procedures, traffic organization measures, and reporting frameworks such as IALA Guideline G1118. The transition will also require system upgrades and robust assessments during development, and implementation and acceptance.
- **Human-in-the-loop safeguards:** Operators remain in control, with LLMs providing structured support rather than independent decision-making.
- **Capacity building:** training and upskilling VTS personnel to work effectively with AI-enabled systems, while fostering trust through transparency and explainability.
- **Collaborative validation:** conducting pilot projects, sharing lessons across VTS centres, and developing common evaluation criteria under IALA guidance.
- **Knowledge capture and feedback:** encouraging practitioners to contribute operational feedback and produce descriptive materials (e.g. narrative analyses of near-miss cases). Such resources provide valuable training data for LLMs, enabling models to learn more thoroughly and helping technical teams design more accurate and fit-for-purpose applications that fully unlock LLM capabilities.

5 REFERENCES

[1] G1178 "AN INTRODUCTION TO ARTIFICIAL INTELLIGENCE (AI) FROM AN IALA PERSPECTIVE"

[2] G1118 "Marine casualty – incident reporting and recording including near-miss situations as it relates to VTS"

6 ACTION REQUESTED OF THE COMMITTEE

The Committee is invited to note the information provided in this paper and take actions as appropriate.