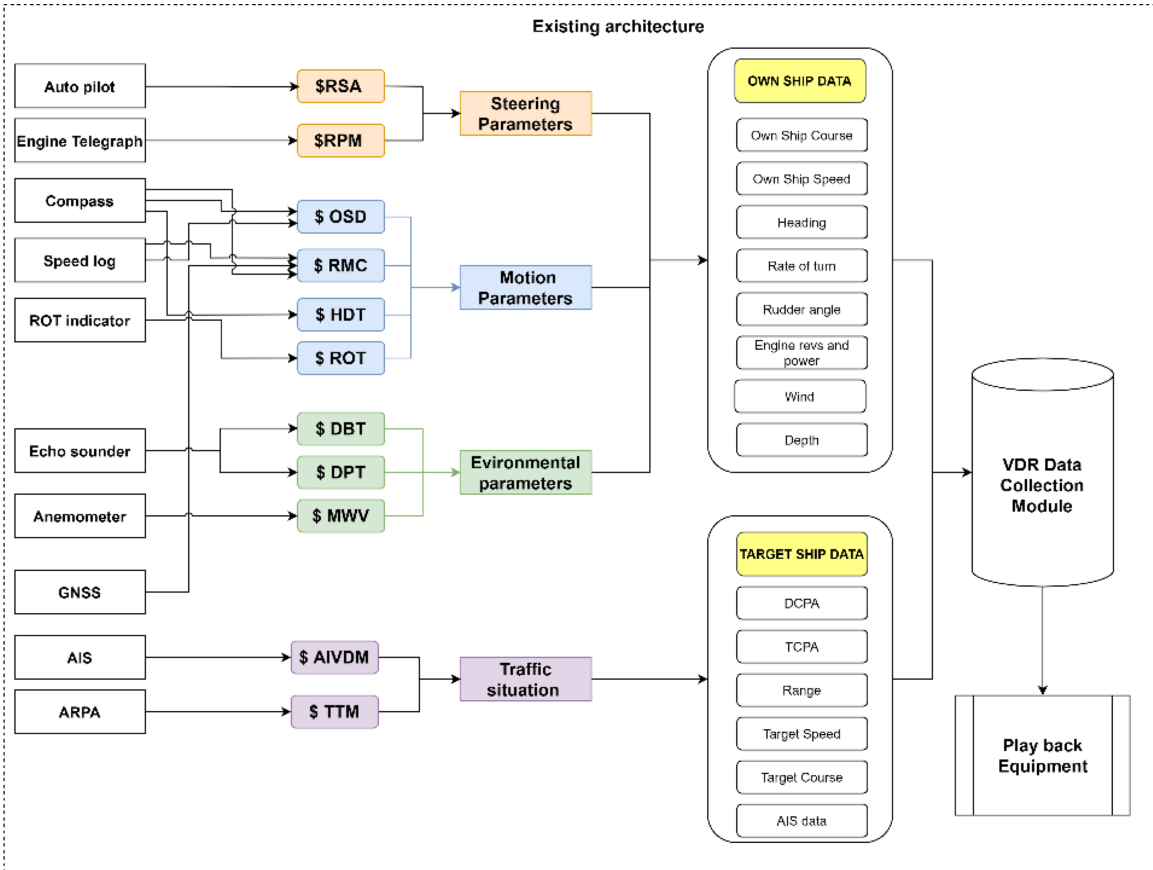

Model data flow and collection from VDR for close-quarter situational analyses and collision avoidance

Master's thesis in the International Master´s Program- MSc Maritime Management

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MASTER’S THESIS 2022

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ABSTRACT

The current leap in digitalization in the maritime industry is propelling the research and development of many new technologies to assist in the decision-making process for the navigator in close-quarter situations (CQS) for effective collision avoidance. The Voyage Data Recorder (VDR) onboard vessels records and stores various information from different sensors available such as position, speed, course, etc., In the case of maritime casualty, the data collected by VDR can be retrieved for investigation purposes. According to the new amendments to the VDR regulations, the recorded data can be played in real-time using playback equipment. The VDR data if available continuously and extracted easily, can enhance the research work to develop collision avoidance technologies in CQS that can be used for autonomous shipping in the future. Many scientific articles have been published about methodologies used for collision avoidance using advanced programming techniques and different variables that are required which could be available in the VDR data.

This master thesis researches different variables, its source sensors, and data interfaces that are available in the VDR. Moreover, it also explores the international regulations and standards used for recording the data and its interfaces. Additionally, this research also explores different methodologies proposed by researchers and identifies the variables that were used in collision avoidance and for CQS analyses. Another outcome of this thesis is the development of a simple conceptual model for data flow parameters relationship showing various variables available in the VDR data and their source sensors which can be extracted and used Collision Alert System (CAS) for CQS.

Keywords: Voyage data recorder, close-quarter situation, navigational sensor, autonomous navigation, collision avoidance, collision risk assessment, data interface, performance standards, playback equipment, automatic radar plotting aids, IMO, NMEA, IEC.

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Rithvik Dandu Basappa

List of Abbreviations

AIS- Automatic Identification System

ARPA- Automatic Radar Plotting Aid

CAS- Collision Alert System

CQS- Close Quarter Situation

CSV- Comma-Separated Values

DBT- Depth below transducer

DCPA- Distance to the Closest Point of Approach

DPT- Depth

DTM- Datum Reference

EPFS- Electronic Position Fixing System

GLL- Geographic Position – Latitude/Longitude

HDT- Heading True

IEC- International Electrotechnical Committee

MMSI- Maritime Mobile Service Identities

NMEA- National Marine Electronics Association

OSD- Own Ship Data

ROT- Rate of Turn

RPM- Revolution Per Minute

RSA- Rudder Sensor Angle

TCPA- Time for the Closest Point of Approach

TTM- Tracked Target Message

VDR- Voyage Data Recorder

XML- Extensible Markup Language

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1 Introduction

This chapter provides the background of the thesis, outlines the purpose and research questions, and defines delimitations. Firstly, the background is presented and the reasons for conducting the research are given. Secondly, the purpose of the report is presented, followed by the research questions necessary to achieve the objectives of the study. Finally, the limitations are considered and presented.

1.1 Background.

The unsolved issue in the digital investigation of marine accidents was one of the primary results of the ship Costa Concordia's disaster, the explanation is a lack of standardization of data formats in Voyage Data Recorder (VDR) systems for forensics analysis (Piccinelli & Gubian, 2013). Under the regulations of the International Convention for Safety of Life at Sea (SOLAS) Chapter -V (Safety of Navigation) Regulation 20 it is mandatory for the ships to carry Voyage Data Recorder (VDR) to assist in the marine casualty investigation (IMO, 2020). The VDR was first installed onboard the vessel in 1993 to investigate a maritime accident caused by human error and prevent it from happening again. VDR stores the information and data from various bridge sensors concerning the position, vessel conditional status, time, command, and control of the vessel over a period, leading up to a casualty in a secure and retrievable format to analyze the causes behind marine casualties (IMO, 1997).

The International Maritime Organisation (IMO) published revised performance standards for VDR's which were adopted under the new resolution (IMO, 2012). The main significant changes in the revised standards were under the data retention regulations where from the data collection point of view, the current VDR should be equipped with a long-term recording medium that can retain the data for at least 30 days (OCIMF, 2020). The performance standards also require that there should be a data output interface based on an internationally recognized format for example like ethernet, USB, Firewire (IMO, 2012). Further new amendments to regulations require manufacturers to provide playback software where VDR should provide an interface for downloading the stored data and playback the information to an external computer (IMO, 2012). Some of the examples are remote navigational assessment and audits, onboard review of data using playback software and VDR data analysis and navigational assurance software (OCIMF, 2020).

However, this is possible only by using the software provided by the same manufacturers in their playback equipment. The proprietary rights are with the manufacturers for secure and safe handling of the data (Austin & Wilson, 2009).

Maritime traffic is becoming very complex with the increase in the number of high speeds, large scale, and heavy load vessels (Wen et al., 2015). The assessment of the situation can become difficult for humans and perform navigation at a satisfactory level, but the decisions made are highly subjective and can lead to errors in effective decision making and subsequently collision between vessels (Statheros et al., 2007).

Benedict et al. (2010) proposes the idea of using VDR based data for enhanced CQS assessment for vessels in traffic situations. Understanding own vessels dynamic data, maneuvering characteristics and environmental conditions is key to the decision-making process and also the vessels behavior under different loading and weather conditions, their response in different CQS can enhance the knowledge by continuous analysis of the extracted data and can contribute to proper collision assessment and risk management.

Mehdi et al. (2017) provide a VDR based maneuvering database framework with the ship centric approach where the article proposes that extensive network of sensors that provides fairly precise and consistent data on the own ship, the maritime environment, and traffic data (targets in the vicinity of the own ship) can be used for collision avoidance. A comprehensive network of sensors provides where the vessel dynamic data can be pro-actively used from the VDR of the vessel and the same can be implemented into the algorithm for the CAS (Mehdi et al., 2017). In this framework, using the dynamic data from VDR is proposed where parameters like vessels motion, its steering and control, status, and environmental conditions are collected and used in a collision-avoidance system (Mehdi et al., 2017).

Many published papers mentions the challenges and barriers involved in extracting the data from VDR. For example, the storage format and the reproduction methods are different from one manufacturer to another making it economically and timely difficult for research and analysis of extracted data (Gug & Jong, 2003). The Marine Accident Investigation Branch, the Marine Casualties Investigative Body, UK (MAIB) report, states that more than 90% of the data sets that have been interrogated till 2016 had issues involving archiving data, downloading data, and format of the data sets (Cantelli-Forti, 2018). Furthermore, the performance standards for VDR and

Simplified Voyage Data Recorder (SVDR) do not impose any specific standards or formats on how data is stored in the system where every manufacturer has therefore implemented their different approach to store the data (Austin & Wilson, 2009). According to Austin and Wilson (2009), it is understood that it is a big challenge for accident investigators and researchers to analyze the data from the VDR systems efficiently as the data that is currently available to the researchers needs a lot of effort to process clean, filter and readjustment for proper analysis and usage.

There are many scientific articles published addressing the use of VDR data in marine casualty investigation analyses such as replay software systems for the real marine accident (Zaghloul, 2009), forensic analysis of Costa Concordia (Piccinelli & Gubian, 2013), and remote maintenance using VDR data (Jung et al., 2015). But there are very few scientific articles considering the use of VDR data on a real-time basis for collision alert systems (CAS) for close-quarter situation (CQS).

Thus, there is a need for further studies and research to extract the VDR data in a format that can reduce the time and cost for data processing and ease the process for accident analyses. Additionally, the extracted data from VDR can be used for collision avoidance (Mehdi et al., 2017). The extraction of data can be shown in a model for data flow parameters relationship from different sensors to the VDR data collection unit. A data-flow diagram is a visual representation of data flowing through a system or a process (usually an information system). The data flow diagram also includes information on each entity's outputs and inputs, and its interface (Bhuvaneswari & Venetia, 2021). There are no control flows, decision rules, or loops in a data-flow diagram. Specific operations based on the data can be represented by a flowchart (Bhuvaneswari & Venetia, 2021).

1.2 Research purpose.

The purpose of this thesis is to explore the data that is recorded and stored by the VDR which will help to understand all the different types of variables available for collision avoidance and CQS analyses. Moreover, it also throws light upon IMO requirements and data interface standards used in the VDR system configurations to understand data flow parameter relationships between various navigational sensors and VDR. In addition, the thesis aims to identify specific data variables used by researchers in their scientific articles for collision avoidance in CQS and investigate its availability in the VDR data.

Additionally, the study will focus on the development of a simple data flow diagram showing the availability of identified variables and their source sensors for the extraction from VDR in a structured manner for collision avoidance and risk analysis for the CQS.

1.3 Research Questions

1. What variables are available in the VDR data that is useful for collision avoidance in CQS?
2. What are the relationships between identified variables that can be extracted from the VDR data?

1.4 Delimitations

Due to the highly sensitive nature of the variable available in the VDR data, it was not possible to acquire a sample of any real VDR data from any vessel in service for analysis, despite sincere efforts. As a result, the exploration and identifying of the data from different sensors onboard bridge equipment was carried out using sample data available in equipment manuals and online platforms.

Throughout this research, it was not successful to acquire VDR data from ship owners sighting various confidentiality reasons one of them being voice recording embedded in the dataset. This sets another barrier to gathering data easily for marine traffic analysis even though voice recording of the bridge is not a requisite for traffic analysis but only for marine casualty investigation. Due to the lack of available data from the VDR, it was difficult to identify and look into the details about the variables that are stored in the VDR. As the data storage and format, proprietary rights belong to different VDR manufacturers, and considering the limited timeline of the thesis, it was not possible to approach the manufacturers for the data and carry out the analyses of the data stored in VDR. However, an actual sample data from the VDR to analyse its contents and match the deducted variables would have increased the validity of the research and would have helped to understand the actual data structure available from a practical perspective.

As the research is concentrated mainly upon the VDR equipment, sensors connected to it, vessels that are not required to carry the VDR according to SOLAS regulations or non-SOLAS ships are not taken into consideration. Some of the vessels are installed with an SVDR due to interfacing constraints and its age. SVDR is required to record only the most necessary data for accident investigation. This study mainly focused on the process of acquiring the required data for research purposes and hence all the available data from VDR is taken into consideration but not SVDR as all the data in SVDR is also available in VDR. However, the difference between VDR and SVDR is provided to the reader.

Automatic Identification System (AIS) data also is recorded in VDR with the NMEA sentence formatter $AIVDM. This data is geospatial data and the data from AIS is not considered within the scope of this study due to lack of time and needs separate research addressing marine traffic analysis and CQS analyses.

1.5 Disposition

The remainder of this report is structured as follows:

Chapter 2, Frame of reference – This chapter surveys the literature and documents related to VDR, rules, and regulations concerning VDR, data that is to be recorded according to performance standards. The review considers VDR related published data interfacing standards to understand the interfacing for the design of the data flow diagram. Furthermore, this chapter surveys the available literature relating to close-quarter situational analyses and collision avoidance systems. Researching and identifying the variables that are stored in the VDR like position, speed, navigational data.

Chapter 3: Research methodology- This chapter explains the methodology used to conduct this master thesis. Explains the process of identifying the variables that are available in the VDR data required for CQS and collision avoidance. Moreover, also provides information about designing model for data flow parameters relationship.

Chapter 4: Results and Analysis. This chapter starts by explaining the VDR system architecture, different sensors connected to it, and the data interfaces. Then, provides the findings of different variables used in conventional CAS and past proposed collision avoidance methods. Finally, variables required for CQS and collision avoidance are presented. Based on deducted variables a model for data flow parameters relationship is designed to extract the values for the identified variables.

Chapter 5: Discussion- This chapter includes the summary and conclusions from the results and analysis and provides a discussion about the proactive use of VDR data and the extraction of variables.

Chapter 6: Conclusions – This chapter presents the conclusions of the report and suggests areas of further work.

Chapter 7: References

Appendix- In this chapter NMEA data structure of the approved sentence formatters are presented from where variables are available.

2 Frame of Reference

This chapter presents the relevant rules and regulations concerning VDR and data interface standards being used in the maritime industry. Moreover, it also reviews some of the published articles, theories and concepts, and frameworks used by different authors regarding collision avoidance systems. In this section, all the prerequisite information concerning the VDR system architecture, rules, and regulations, data that is recorded in the data collection unit will be explained.

2.1 Voyage Data Recorder (VDR)

The voyage data recorder is the equipment installed onboard ships to record and store the information relating to the vessels position, its movement, physical status, command, and control of the vessel over a time that can be retrieved in a secured format after an occurrence of a casualty to analyses the reasons behind marine casualties (Gug & Jong, 2003). Moreover, VDR also records the bridge conversation and VHF communication (Katona & Toma, 2014). Ashour (2015) provides an overview of the typical VDR system configuration which consists of Data Acquisition Unit (DAU), Data Processing Unit (DPU), Power supply unit, Alarm unit, Microphone unit, and Playback equipment as shown in *Figure 1*. Additionally, a play-back device with dedicated play-back software along with other units comprises the whole of VDR (Zong & Zhou, 2018). In the VDR, the past 12 hours of the recorded data will be stored, and older data will be overwritten by the latest data (Ashour, 2015).

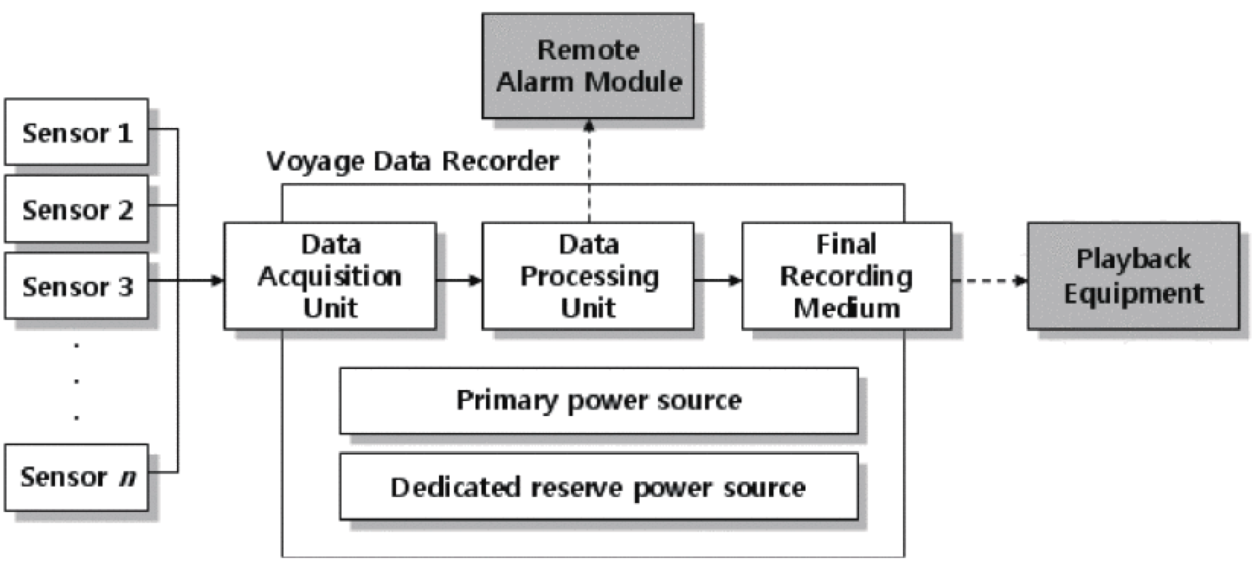

Figure 1: VDR system configuration (Kang et al., 2009, p5510)

Ashour (2013) states “although the primary purpose of the VDR is for accident investigation after the fact, innovative uses of the VDR by the operators both in real-time and post voyage modes have demonstrated VDRs can improve safety of operations”. To facilitate these options the extracted data from the VDR must be available for researchers in a structured and standard format for accurate analysis. However, according to Cantelli-Forti (2018), there is a gap in the stages between “extraction to analysis” of the data and this is not possible in the current scenario. The reason is that the VDR manufacturers use a system with the modified firmware that acts as a software “write block or data block” (Cantelli-Forti, 2018). Since the code is proprietary this block is not verifiable, and the procedure varies differently concerning different VDR manufacturers (Cantelli-Forti, 2018).

2.1.1 Rules and regulations on the use of VDR

VDR is a system including any items required to interface with the sources of input signals, their processing and encoding, the final recording medium, the playback equipment, the power supply, and the dedicated reserve power source (IMO,2004). Under regulation 20 of SOLAS chapter 5 on VDR passenger ships and cargo vessels of 3.000 GT and above constructed on or after July 1, 2002, must carry a VDR to assist in accident investigations, while on cargo ships of 3.000 GT and above which were built before July 1, 2002, an SVDR is accepted to be fitted for the same purpose (IMO, 2021).

Maritime Safety Committee of the International Maritime Organization (IMO) adopted a revised recommendation on performance standards for VDRs later in 2012 July and apply to all full VDR systems installed on or after July 1, 2014 (IMO, 2012). Simplified VDRs can be installed and are not required to record the same amount of information as a full VDR system but all the ship's basic data (IMO, 2004).

2.1.2 Data variables recorded by VDR

IMO performance standards for VDR dictate all the required data that has to be recorded. Based on these performance standards International Association of Classification Society (IACS) has given the recommendations for quality, resolution, and the list of equipment that these data can be gathered.

The following *Table 1* presents the recommended variables to be recorded by a VDR according to the recommendations from IACS (IACS, 2018) along with their descriptions, equipment connected, and regulations involved. The SVDR is a simple form of VDR, that records information that is only necessary and does not record information as extensive as the VDR (IMO, 2012). Understandably, this is a much cheaper option for small ships or older ships having difficulties with interfacing from analog systems (Zaghloul, 2009). The interfaces of Radar and ECDIS may be recorded only if there are standard interfaces available. *Table 1* also presents the comparison of variables that must be recorded by VDR and SVDR to understand the differences between the two.

Table 1: List of data variables to be recorded by VDR and SVDR with their resolution requirement (IACS, 2018)

Data variables	**Description**	**Resolution required**	**Data recorded by**	
			SVDR	**VDR**
Date and time	The ship's date and time, referenced to UTC, should be obtained from a source external to the ship. An internal clock should be synchronized with valid day and time data and be used if the external clock fails	Sufficient resolution and continuity should be available during playback.	✓	✓
Ships Position	An electronic Position-fixing device (EPFS) can be used to determine latitude and longitude, as well as the datum. The recording should still be able to establish the EPFS's identity and the status during playback.	Up to 0.0001 min of arc.	✓	✓
Speed	As specified by SOLAS, speed through the water and speed over the ground, as well as an indicator of which it is, are obtained from the ship's speed and distance measuring equipment.	Up to 0.1 knots.	✓	✓
Heading	Heading as indicated by the ship's heading source.	Time interval ≤ 1 sec Upto to 0.1 deg.	✓	✓
AIS	All AIS data should be recorded.	No resolution	✓	✓
Radar	The recording of the electronic signals of radar displays required by SOLAS should allow for faithful reproduction of the entire radar display that was visible at the time of recording on playback but under the constraints of any bandwidth	Updating period of the radar picture ≤ 15 sec.	✓	✓

	compression techniques that are required for the VDR to function.			
ECDIS	VDR can record the electrical signals from the ECDIS monitor that is being used as the primary means of navigation at the moment. The recording process should be such that, upon playback, a faithful reproduction of the whole ECDIS display that was visible at the time of recording may be presented.	Updating period of the ECDIS picture $\leq$ 15 sec.	✓	✓
Echosounder	The depth information should where available, depth under the keel, the depth scale currently being displayed, and other status information should be recorded	Depth up to 0.1 meters, and frequency $\geq$ 1 Hz.		✓
Rudder order and response	This should include the status and settings of the heading or track controller if fitted and indicate the control station, mode, and power unit(s) in use.	Time interval $\leq$ 1 sec Rudder angle up to to 1 deg.		✓
Engine and thruster order and response	The recorded data must include the position of engine telegraph, direct engine or propeller pitch controls, shafts, revolutions per minute or equivalent, ahead and astern indicators and propulsion pitch and thrust direction, feedback indications.	RPM $\geq$ 1 rpm. Pitch angle $\geq$ 1 deg. Interval $\leq$ 1 sec		✓
Wind speed and direction	Where a ship is fitted with a suitable sensor, wind speed and direction should be recorded, including its true or relative status.			✓
Rolling motion	If an electronic inclinometer is mounted, the recording process should allow for the reconstruction of the rolling motion during playback.			✓
Hull openings status	The hull opening mandatory status information required to be displayed on the bridge has to be recorded. This might vary from ship to ship based on their type and construction according to SOLAS ch 2-1.			✓
Watertight and	Watertight and fire door mandatory status information required to be displayed on the bridge has to be			

fire door status	recorded. This might vary from ship to ship based on their type and construction according to SOLAS ch 2-1 and for the fire door status according to SOLAS ch 2-2.	✓
Accelerations and hull stresses	Where a ship is fitted with hull stress and response monitoring equipment, all the data items that have been pre-selected within that equipment should be recorded with an interval not exceeding 1 second.	✓
Electronic logbook	When a ship is equipped with an electronic logbook that follows the Organization's requirements, the information from it should be registered.	✓
Bridge audio	According to MSC/Circ.982, the audio has to be recorded from all workstations. The recording should be made in such a way that when played through, a natural speaking voice provides enough intelligibility when the ship is operating normally. While there is a single audio warning somewhere on the bridge or other disturbance, including noise from defective equipment or mounting, or wind, this performance should be sustained at all workstations. The standards of the audio signal should be compatible and be in IEC61996.	✓
Communications audio	VHF communications relating to ship operations should be recorded on an additional separate channel.	✓

2.2 Standards and protocols used by navigation systems

Under SOLAS chapter V Safety of Navigation, regulation 19, the carriage requirements for shipborne navigational systems and equipment states that all the external interfaces and interconnections must have complied with international standards such as IEC standards (IMO, 2021). Due to advancements in technology and navigational equipment, there are different types of standards and interfaces are being used. The interfacing standards and their characteristics used onboard for navigational equipment are briefly described in this section to understand the differences between them.

2.2.1 Interface standards and standard communication protocols

IEC TC80/WG6 stands for International Electrotechnical Committee, Technical Committee 80 - Maritime navigation and radiocommunication equipment and systems – Work Group 6– Digital interfaces (Rødseth & Tjora, 2014). The standards defined by IEC TC80/WG6 are primarily used in navigational data networks and has established a range of standards that are used onboard ships (Rødseth & Tjora, 2014). The interface standards used are:

- **IEC 61162-1**: Maritime navigation and radiocommunication equipment and systems - Digital interfaces - Part 1: Single talker and multiple listeners. This digital interface emerged from IEC 61162-1 (IEC 2010) which was an IEC version of NMEA 0183 (NMEA 2008). IEC 61162-1 is a serial line standard with a nominal speed of 4800 bits per second (bps). This is harmonized standard of NMEA-0183 (NMEA, 2005).
- **IEC 61162-2**: Maritime navigation and radiocommunication equipment and systems – Digital interfaces – Part 2: Single talker and multiple listeners, high-speed transmission. IEC 61162-2 is a specification that allows higher transmission speeds, up to 38400 bps (38.4 kbps) (Rødseth & Tjora, 2014). This is harmonized standard of NMEA-0183 High Speed (NMEA, 2005).
- **IEC 61162-3**: Maritime navigation and radiocommunication equipment and systems - Digital interfaces - Part 3: Serial data instrument network. IEC 61162-3 is an IEC version of NMEA 2000, a CAN-based bus standard operating on 250 kbps (ISO 2007). This is harmonized standard of NMEA-2000 (NMEA, 2005).
- **IEC 61162-450**: Maritime navigation and radiocommunication equipment and systems - Digital interfaces - Part 450: Multiple talkers and multiple listeners. CAN (Controller Area

Network) is a real-time priority-based bus standard. IEC 61162-4 is a series of standards supporting Ethernet interconnections. It currently consists of IEC 61162-450 (IEC 2011) which is a basic encapsulation mechanism for sending IEC 61162-1 text telegram as multicast messages (Rødseth & Tjora, 2014).

- **NMEA 0183**: The NMEA 0183 Interface Standard defines electrical signal requirements, data transmission protocol and time, and specific sentence formats for a 4800-baud serial data bus. This standard is intended to support one-way serial data transmission from a single talker to one or a few listeners. This data is in printable ASCII form and may include information such as position, speed, depth, frequency allocation (Kalaimagal & Sivaramakrishnan, 2012).
- **NMEA-0183 High Speed**: This standard operates at a 38.4K-baud rate. Specific sentence formats are the same as NMEA 0183. This is the same as the standards mentioned in IEC61162-2 (Rødseth & Tjora, 2014). NMEA 0183 standards are widely used today at the basic level and this protocol has the capacity of delivering approximately ten messages or sentences per second (Luft et al., 2002).
- **NMEA 2000**: This standard contains the requirements of a serial data communications network to interconnect marine electronic equipment on vessels. The standard describes a low-cost moderate capacity bi-directional, multi-transmitter/multi-receiver instrument network to interconnect marine electronic devices. It is based on CAN (Controller Area Network). Although this standard is 50 times faster than NMEA 0183, it is not intended to support high-bandwidth applications such as video (Luft et al., 2002).

Luft et al. (2002) state that it is proved satisfactory when a single unit is broadcasting data for use by other equipment but reaches a limit when systems combine data. However, it is expected to continue in the maritime industry in the future (Luft et al., 2002). The performance standards for VDR states that when non-standard or proprietary data is stored in the VDR, the software can translate the data into open industry-standard formats (IMO, 1997).

2.2.2 VDR recorded data and their interface protocol

According to (IMO, 2012) the equipment connected to the VDR to gather data for analysis is required to comply with the international interfacing standard which is IEC 61162. The NMEA 0183 data set is referred to in the IEC 61162-1 standard, while NMEA 2000 data set is referred to in the IEC 61162-2 standard. Thus, VDR interfaces must comply with the NMEA 0183 and NMEA 2000 or IEC 61162-2 interface specifications (Seong & Kim, 2019). The following *Table 2* provides the overview of the data that is required to be recorded by the VDR and data source equipment and the requirement standard interface protocol used onboard ships.

Table 2: VDR data collection and Interface protocol adopted and modified (Kang et al., 2016)

Recorded Data	**Sources**	**Required Interface protocol**
Date & time	Electronic position fixing system. EPFS	IEC 61162-1
Ship's position	Electronic position fixing system. EPFS	IEC 61162-1
Heading	Gyro compass	IEC 61162-1
Speed (STW/SOG)	Speed log	IEC 61162-1
Wind speed & direction	Anemometer	IEC 61162-1
Depth	Echo sounder	IEC 61162-1
Rudder order & response	Autopilot	IEC 61162-1
Engine order & response	Engine controller	IEC 61162-1
Radar (post-display selection)	Radar	Analog(R/G/B/V/H)
Bow thruster	Bow thruster	IEC 61162-1
Main alarms	Alarm system	IEC 61162-1
Bridge audio	Microphone	Analog
Communication audio	VHF radio	Analog
AIS information	AIS	IEC 61162-2

Yu et al. (2012) explains that the NMEA protocol mainly consists of a header also known as approved sentence formatter starting with symbol "$" and data parts as shown in *Figure 2*. Analyzing the data structure of NMEA data in detail, it is possible to understand which equipment the data is coming from and also measure the variable values (Yu et al., 2012). Explaining further Yu et al. (2012) states that data processing and filtering is required to use the variable data values and the structure might vary from different manufacturers. An example of the data protocol structure of the NMEA is shown in *Figure 2* below.

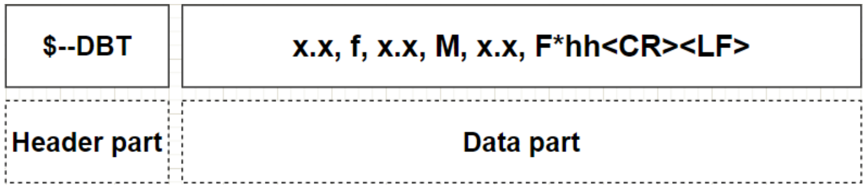

Figure 2: NMEA data protocol structure example, (Yu et al., 2012, p 603)

The data in NMEA0183 format must contain approved sentence formatters to document the items specified by the IMO with the requirement set out in the resolution (Zaghloul, 2009). The following *Table 3* provides the details about all the IMO approved sentence formatters and their respective descriptions.

Table 3: Approved sentence formatters and their descriptions (NMEA, 2000)

Approved sentence formatters	**Description**
$DBT	Depth below transducer
$DPT	Depth
$DTM	Datum Reference
$GGA	Global positioning systems fix data
$GLL	Geographic position- Latitude/ Longitude
$HDT	Heading true
$MWV	Wind direction and angle
$OSD	Own ship data
$RMC	Recommended minimum specific GNSS data
$ROT	Rate of turn
$RPM	Revolution per minute
$RSA	Rudder sensor angle
$TTM	Tracked target message
$VHW	Water speed and heading
$ZDA	Time and Date UTC, day, month, year, and local time zone

The VDR should be equipped with playback equipment and software that provides an interface for downloading and playing back data that is compatible with an external off-the-shelf laptop computer. A globally recognized standard, such as Ethernet, USB, FireWire, or similar, should be supported by the interface. A download of the stored data for a user-defined period should be available (IMO, 2012).

2.3 Close Quarter Situations (CQS) and Collision Avoidance

To identify and determine the variables required for CQS analyses and collision avoidance, it is essential to understand the methodology applied to avoid the danger of collision. Subsequently, it is also required to get the basic knowledge about the different advanced programming techniques and methods applied for collision avoidance systems.

2.3.1 The methodology for collision avoidance

In conventional navigation, the convention on the International Regulations for Preventing Collisions at Sea (COLREGs), 1972 rule 5 states that vessels have to keep a proper lookout "Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions to make a full appraisal of the situation and the risk of collision". Construing this statement from rule 5 (Burnett, 1996) states that the surrounding environment, weather conditions, traffic situation and check on the vessels steering, and control must be very well understood to steer clear of any danger. For any navigation that must be conducted safely, the mentioned variables are very important to all vessels irrespective of their level of an autonomous state.

Automatic Radar Plotting Aid (ARPA) is an approved system used for collision avoidance in CQS as mentioned in COLREGS (IMO, 2002) whose data can be used by the navigators to determine close quarter situations and take effective collision avoidance actions. An example of how ARPA displays the tracked target data is presented in *Figure 3.* In a CQS, the danger of ship-to-ship collision is assessed using two key metrics provided by ARPA which are Distance to the Closest Point of Approach (DCPA) and Time to the Closest Point of Approach (TCPA) (Hilgert & Baldauf, 1997). In CQS, for the current state of navigation, DCPA calculates the closest distance between two passing ships, and TCPA calculates the time remaining to reach that point (Kang et al., 2019). Based on these quantitative indicators as presented in *Figure 3*, navigators make collision avoidance strategies effectively for ships involved in CQS and the potential collision situations (Kang et al., 2019).

Target Number		1	
Bearing	→	BRG	154
Range	→	RNG	9.565
Course over ground	→	T COG	045.0 T
Speed over grounf	→	T SOG	10.63 kn
Closest Point of Approach	→	CPA	3.636 NM
Time for Closest point of Approach	→	TCPA	10:25
Bow Crossing Range	→	BCR	2.341 NM
Bow Crossing Time	→	BCT	15:25

Figure 3: Tracked target ARPA display adopted and modified, (Bole et al., 2005, p 239)

Perera et al. (2010) present the five-step methodology used for collision avoidance in CQS in ocean navigation to make a full appraisal of the situation and take effective action to avoid a close quarter situation.

1. **Identification of Obstacles**: Several instruments and devices, such as the eye/camera, radar/Automatic Radar Plotting Aid (ARPA), an Automatic Identification System (AIS), can identify fixed and moving obstacles in ocean navigation. ARPA provides precise range and bearing information for surrounding obstacles, while AIS can provide all structural details, location, direction, and the speed information for vessels (Perera et al., 2010).
2. **Collection of Navigational Information:** Other vessels' navigational data can be divided into three categories: static, dynamic, and voyage-related data (Tetreault, 2005). Static data includes the Maritime Mobile Service Identity (MMSI), Call Sign and Name, IMO number, class of ship, dimensions and location, and position of a communication antenna (Tetreault, 2005).

   The dynamic data includes vessel direction, position time stamp, course over ground, speed over ground, heading, navigational status, and rate of the turn. The details about the voyage can be extended to include vessel draft, freight type, destination, and route plan. All this data is readily available and obtained from the Automatic Identification System (AIS) (Tetreault, 2005).
3. **Analysis of Navigational Information:** When the vessel is involved in a close-quarter situation, it is necessary to gather the data about the other vessel's navigational information and hazards involved. To avoid the danger of collision, continuous

monitoring and careful observation of the target vessel must be carried out at regular intervals (Perera et al., 2010).

4. **Assessments of the Collision Risk:** The analysis of the close-quarter situation and navigational information can aid in determining the likelihood of the collision. To ensure the safety of own vessel, the collision avoidance alert system can determine the danger of collision continuously and in real-time Perera et al., 2010).
5. **Decisions on Navigation:** Collision avoidance decisions in ocean navigation are based on each vessel's speed and direction, the distance between two vessels, the distance to the Closest Point of Approach (DCPA), the time to the DCPA, and other environmental factors (Perera et al., 2010).

This methodology is also applicable and the same for autonomous ships to avoid the collision. The different variables used in these five steps that are available to the navigator for an effective decision-making process in CQS are presented in *Table 4.*

Table 4: Variables used in five-step methodology in CQS in conventional ocean navigation

Steps	Variables used	Author
Identification of Obstacles	○ Range of the target ○ The bearing of the target ○ Structural details ○ Location ○ Direction ○ Speed information of the vessel	Perera et al. (2010)
Collection of Navigational Information	○ Details of the target vessel (MMSi No, Call sign, Name, IMO number, Class, Dimensions, Location, and position of communication antenna). ○ Vessel direction ○ Course overground ○ Speed overground ○ Heading ○ Navigational status ○ Rate of the turn. ○ Vessel draft ○ Freight type ○ Destination and route plan.	Tetreault (2005)

Analysis of Navigational Information	------	Perera et al. (2010)
Assessments of the Collision Risk	------	Perera et al. (2010)
Decisions on Navigation	○ Vessel's speed ○ Direction, ○ Distance to the Closest Point of Approach (DCPA) ○ Time to the DCPA ○ Environmental factors	Perera et al. (2010)

2.3.2 Past proposed research areas for autonomous navigation

Following advances in autonomous navigation, scholarly papers have been carried out outlining various approaches and methods for ship collision alert systems (Goerlandt et al., 2015). Presently, many research and development projects are going on to develop collision avoidance methods for autonomous navigation that is expected to revolutionize future maritime transportation (Geng et al., 2019). According to Geng et al. (2019), different methods are being applied by various authors in their research articles using advanced programming techniques such as machine learning, sophisticated sensing, and artificial intelligence (AI).

Statheros et al. (2007) provide details about the areas where most researchers have worked for collision avoidance systems for autonomous navigation which are categorized into three groups.

1. **Mathematical models and algorithms:**

   The mathematical models refer to a detailed mathematical representation of a ship's dynamics and its surroundings. They are algorithms that can be described as measuring algorithms to solve the collision avoidance problem in autonomous ship navigation.

2. **Soft computing – Evolutionary algorithms, neural networks, and fuzzy logic.**

   In this method, the author describes part of AI and machine learning techniques are involved. Advanced programming techniques such as neural networks, fuzzy logic, are used. These methods like neural networks and fuzzy logic have very good learning capabilities and simplify complex mathematical computations.

3. **Hybrid autonomous navigation systems.**

Hybrid autonomous navigation systems are an optimal combination of all or a subset of the above strategies for collision-free ship navigation.

Goerlandt et al. (2015) present a list of selected articles proposing different CAS methods developed based on the areas of research work, which belong to the above-mentioned groups. The following *Table 5* provides information about different authors and the method used by them.

Table 5: Different methods used for CAS and their area of research. Modified and adopted from (Goerlandt et al.,2015)

Methods	**Methods for collision alert system**	**Authors**	**Category**
1	Criteria to categorize collision risk	Hilgert and Baldauf (1997)	Mathematical Model
2	Fuzzy systems	Lee and Rhee (2001)	Soft Computing
3	Fuzzy ship domains	Kao et al. (2007)	Soft Computing
4	CAS based on ordered probit regression modeling	Chin and Debnath (2009)	Mathematical Model
5	Application of dynamic adjustment factors to a baseline quantitative risk assessment.	Mou et al. (2010)	Mathematical Model
6	Fuzzy ship domains	Wang (2010)	Soft Computing
7	Fuzzy systems	Ren et al. (2011)	Soft Computing
8	Fast time simulation techniques	Baldauf et al. (2011)	Soft Computing
9	Fuzzy systems	Bukhari et al. (2013)	Soft Computing

2.3.3 Variables accounted for CAS in the past proposed research.

Most of the collision alert systems (CAS) proposed in the literature are based on the safe area around the ship to ensure not to collide with other ships. This method includes variations of two sets of ideas: The ship safety domain, and potential points and areas of collision (Szlapczynski & Krata, 2018). A simple understanding of the ship safety domain is the area or distance around the own ship that should be clear of any danger and obstacles or other ships (Baran et al., 2018). Potential points and areas of collision as the name of the term suggests are areas where contact or collision between another vessel or a target may occur. Many research articles have presented areas around the ship and the target ship which are in different shapes such as circles, ellipses, irregular shapes, polygons, and smooth curves that should be avoided (Wang & Chin, 2015). Formulation of these safe areas uses variables like location, orientation, size, and speed of the own and target ships at any given point in time (Wang & Chin, 2015).

The proposed CAS methods are based on the application of different observable system states. The system states represent the variables with observable and measurable quantities (Goerlandt et al., 2015). The variables are categorized into three system states which are dynamic system state, Quasi, and Static and /or Static system state. Where dynamic system state includes the variables which can be continuously measured and transformed, static system states are the variables like vessel dimensions and quasi-static states can be prevailing environmental conditions (Goerlandt et al., 2015). *Table 6* gives an overview of variables considered in collision alert systems methods published in scholarly scientific articles.

Table 6: Variables accounted for collision alert assessment by different methods (Goerlandt et al., 2015)

Variables	**Use of Variables by different authors in their CAS methods**									
	A1	*A2*	*A3*	*A4*	*A5*	*A6*	*A7*	*A8*	*A9*	*ARPA*
Dynamic SS										
DCPA	X	X		X	X		X	X	X	X
TCPA	X	X		X	X		X	X	X	X
Relative bearing						X				
Relative heading					X		X			
Range	X					X		X		
Variation of bearing									X	
Ship speed	X	X	X			X		X		
COLREG status	X							X		
Static SS										
Ship Length	X	X	X		X	X		X		
Ship Gross tonnage				X						
Quasi-Static SS										
Wave conditions			X					X		
Visibility	X							X		
Day/Night condition				X						
Operating Area	X		X		X	X		X		

3 Research Methodology

In the following section, the reader is provided with an introduction to the research design followed by methods applied for data collection and analysis. In compliance with the stated purpose and research questions, two main objectives were strategized. Literature and documentation surveys were used to understand the state of the art of VDR and CAS for CQS, and subsequently, for determining the requirements for the model for data flow parameters relationship.

The presented research was carried out according to descriptive and deductive research. Descriptive research is defined as to systematically and accurately describing the facts and characteristics of an area of interest (Dulock, 1993). Literature and documentation surveys are an integral part of descriptive and deductive research.

According to Dulock (1993) descriptive study is carried out to discover relationships between or among variables. Grant and Booth (2009) states a literature review entails some method of locating resources for possible inclusion—whether or not a formal literature search is required—selecting items for inclusion, synthesizing them in textual, tabular, or graphical form, and evaluating their contribution or values. In this research a literature review was conducted to understand the concept, its architecture, the data collected and stored by the VDR. Moreover, a detailed study of the variables from the VDR data that can be used for CQS, and collision avoidance was implemented. A study was carried out to find out the methodology used for collision avoidance in conventional navigation and proposed methods by various authors for CAS. Furthermore, understanding the source of the data and their interface standards currently being used onboard vessels was necessary to investigate the VDR architecture. To explore this detailed study was conducted into interface standards for example NMEA and the contents of sensors output sentences with the help of approved sentence formatter were analyzed *see appendix*.

A deductive approach was used throughout this study for identifying the variables required for CAS for CQS *Figure 4* along with descriptive research for a clear understanding of the background VDR infrastructure and data interfaces required and being used. According to Newman (2000), the hypothesized factors are used to start the analysis, which then gathers data, analyzes it, and draws conclusions on the match between the observed and postulated components. The idea of using variables from VDR data for CQS and collision avoidance is proposed herein was conducted in two steps. Firstly, identify the variables required for CAS in CQS . Secondly, once the variables are identified that is required final set of variables required to be stored in the VDR was determined.

In this process, the NMEA data structure of various sensor outputs that are connected to the VDR was analysed to extract the values of the deducted variables and a model for data flow parameters relationship was designed.

Figure 4: Deductive approach model (Balckstone, 2018, pg-20)

3.1 Literature review

In this study literature review of scholarly papers, standards/ regulations, and documents from the manufacturer was conducted. Peer-reviewed published articles were used to conduct a literature review related to variables used in collision avoidance systems. According to Mahmood et al (2014) grey literature includes magazine articles, trade press articles, academic dissertations, institutional reports, consultant reports, book chapters, and conference proceedings. The inclusion of grey literature in addition to peer-reviewed literature expands the number of sources that contributed to the evidence levels (Mahmood et al, 2014). The primary source of data and information in this study is a review of VDR standards and regulations, as well as documents and reports from VDR manufacturers.

Bryman and bell (2015) recommend conducting the literature review using scholarly papers. Hart, (2018) states one of the contributing reasons for conducting a literature review is to discover the important variables related to a certain topic. From the literature review, articles related to collision avoidance systems were reviewed to identify the variables used in these articles for CQS analyses. The identified variables were then investigated for their availability in the VDR data that is fed from different sensors by analysing their NMEA data structures and approved sentence formatters (see appendix 1), and the final set of variables was determined that is necessary for CQS analyses and collision avoidance. Moreover, Allen (2017) states that researchers employ archival analysis to look at what other researchers have found out about specific topics. Databases including Google Scholar, Web of Science, Elsevier, Science Direct, Chalmers Lib were used to identify and use a scientific journal, books and regulations, and standards. Bryman and Bell (2015) explain using key specific words significant to the area of study facilitates the process of identifying specific related information. As a result, this technique was employed, with various variations of chosen keywords voyage data recorder, close-quarter situation, navigational sensor, autonomous navigation, collision avoidance, collision risk assessment, data interface, performance standards, playback equipment, automatic radar plotting aids, IMO, NMEA, IEC with the combination of "and" and "or" were used to restrict the scope and limit the search results.

In this study, grey literature publications matched the content and quality requirements, as well as provided significant, contextual information that helped this study to conduct a systematic review. Grey literature such as published documentation surveys rules and regulations by the International Maritime Organisation (IMO), recommendations by Recognized Organisations, the International Association of Classification Societies (IACS) were also referred. Moreover, Standards provided by the National Marine electronic association (NMEA), International Electrotechnical standards (IEC), and International Standard Organisation (ISO) was looked upon for a better understanding of the navigational equipment data standards. Along with this, VDR manufacturers like FURUNO and JRC manuals which are available online, Data interface service manuals were also referred to to understand data interfacing and system architecture. Some of the examples of selected keywords are VDR, NMEA data, VDR playback software, ARPA, AIS, bridge equipment, collision avoidance, risk management in collisions, VDR regulations and framework.

According to Rowley and Slack (2004) identifying the main themes of the literature review and beginning to organize topics and records in conjunction with the key themes is the aim of structuring the literature review. Based on this the identified scholarly articles and grey literature were classified into different categories related to the voyage data recorder; Rules, regulations, and recommendations for VDR by competent authorities like IMO, IACS. Data interface and management; for example, NMEA, IEC 61162, and published scholarly papers related to CQS, vessel collision avoidance.

The literature review method diagram is shown in *Figure 5*, followed by *Table 7* that explains the initial and final selection of journal articles and grey literature chosen for the literature review, and finally, *Table 8* presents the category of literature review and authors of the final selected articles. *Table 9* presents the details of non-academic and grey literature used for this research.

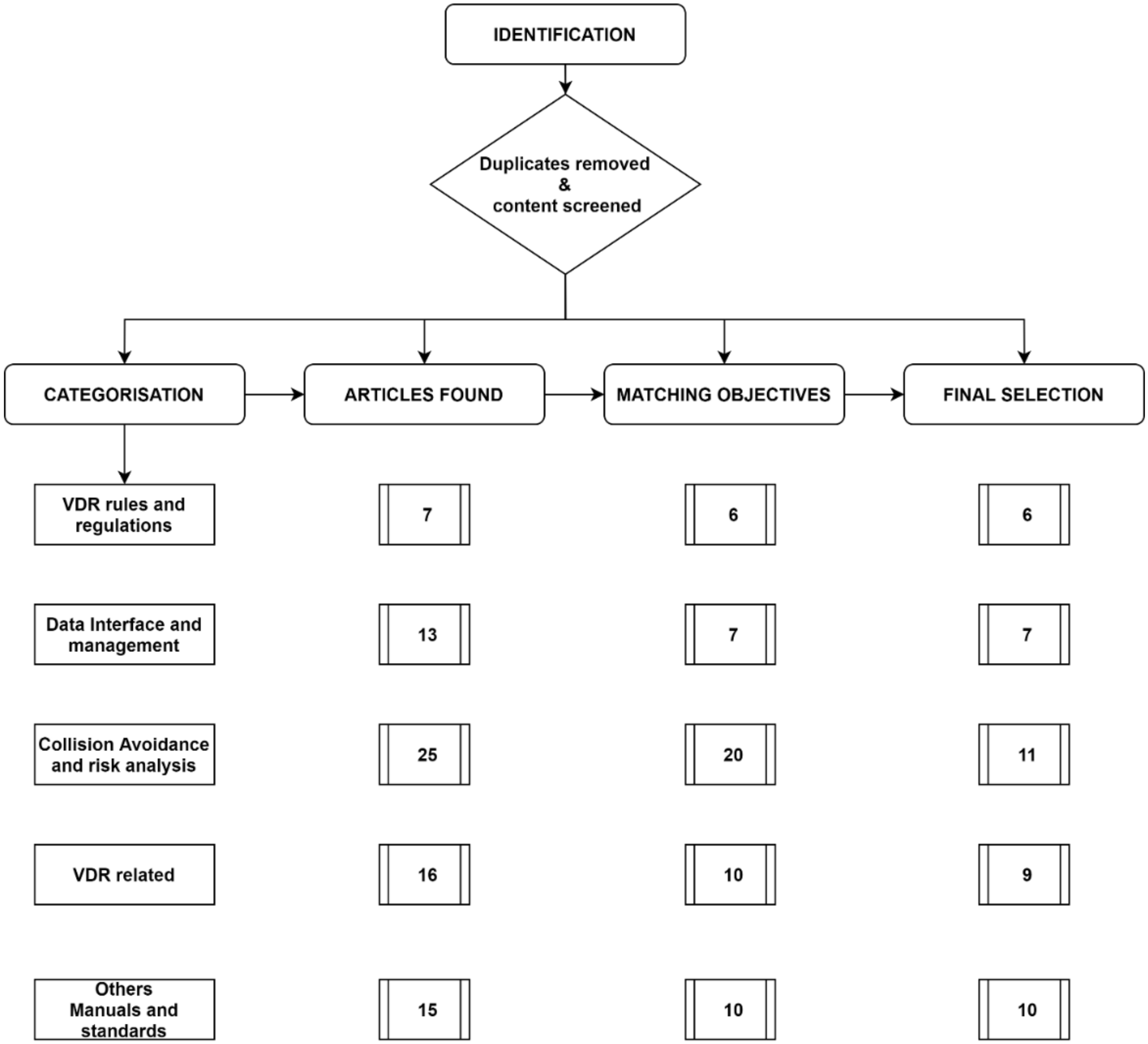

Figure 5: Literature review process diagram

Table 7: Overview of selected articles and journals in the literature review

Literature category	Articles and Journals and grey literature	Number of papers Initial	Final
VDR rules and regulations	IMO resolutions and performance standards	6	5
	IACS recommendations	1	1
Data Interface and Management	Data standards -: AIS, NMEA and IEC	5	4
	Articles related to shipboard interface	7	3
Collision avoidance and risk analysis	Autonomous navigation, vessel collision risk assessment	15	9
	Ship course prediction tools and various algorithms	10	2
VDR related	Proactive uses of VDR on board ships	13	7
	VDR technical data access and handling	3	2
Other articles, Manuals	VDR Manuals	3	1
	Other related articles	12	9

Table 8: Overview of authors and selected articles

Article Category	Articles and Journals	Authors
Data Interface	Scientific articles related to shipboard interface	1. Luft & Cassidy, 2000 2. Kang et al, 2016 3. Yu et al., 2012
Collision avoidance and risk analysis related scientific articles	Autonomous navigation, vessel collision risk assessment	1. Szlapczynski & Krata, 2018 2. Wang & Chin, 2016 3. Baran et al., 2018 4. Benedict et al., 2010 5. Mehdi et al., 2017 6. Perera et al., 2010 7. Statheros et al., 2008 8. Hilgert & Baldauf, 1997 9. Wen et al., 2015 10. Burnett, 1996
	Ship course prediction tools and various algorithms	1. Geng et al., 2019 2. Goerlandt et al., 2015 3. Debnath & Chin, 2009
VDR related scientific articles	Proactive uses of VDR onboard ships	1. Jung et al., 2015 2. Zaghloul, 2009 3. Seong & Kim, 2019 4. Cantelli-Forti, 2018 5. Gug & Jong, 2003 6. Katona & Toma, 2014

		7. Piccinelli & Gubian, 2013 8. Ashour, 2013

Table 9: Overview of selected non-academic literature

Category	Sources	Authors
VDR rules and regulations	IMO resolutions and performance standards*	1. IMO resolution MSC 163 (78), 2004 2. IMO, 2012 3. International Convention for Safety of Life at Sea (SOLAS), 1974 4. IMO, 1997 5. IACS, 2018
	IACS recommendations*	1. OCIMF, 2020.
Data Interface and Management	Data standards like AIS, NMEA, and IEC*	1. NMEA, 2002 2. NMEA, 2005 3. IEC 61162-1 4. IEC 61162-2
	VDR technical data access and handling*	1. Austin and Wilson, 2009
Manuals	VDR Manuals*	1. Furuno
Others		1. Rødseth & Tjora, 2014*

IMO regulations, recommendations from IACS, related articles to VDR, and manufacturers manuals were used to understand the VDR system architecture, different sensors connected, their interface standards, and the data that is required by the VDR to store.

Based on this theory many scientific articles related to collision avoidance systems were reviewed to understand the different methods used for collision avoidance systems.

3.2 Analysis of interface standards and contents of sensor output.

Literature review of documentation surveys and published standards such as SOLAS, IMO performance standards, IACS recommendations for VDR was carried out to comprehend the data interfaces and international standards that have to be complied with for onboard vessels. Initially, statutory carriage requirements for shipborne navigational systems and equipment were referred to, to understand the standard and interfaces required. A review of international interface standards was conducted to identify the different types of interfaces used by the industry. Consequently, the interfacing standards used for VDR, and other sensors were determined as IEC 61162 and NMEA standards.

Detailed analysis of the NMEA data structure was carried out using the sentence headers to identify the values for the deducted variables that can be extracted for CAS in CQS. Data management is required to interpret the data and involves steps as represented in *Figure 6.*

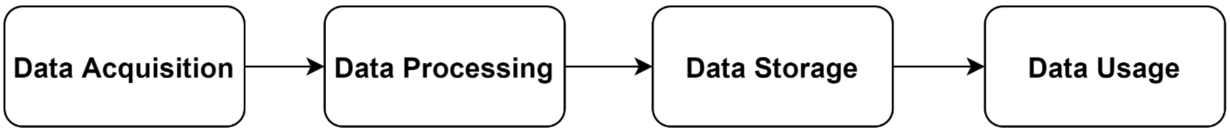

Figure 6: Data Management Steps (Lind et al., 2020, p 310)

Finally, to facilitate the proactive use of VDR data, it is necessary to understand the data flow parameters relationship between the various navigational sensors connected to VDR. The data flow parameters relationship is designed and presented based on identifying the sensors and their output data flow and required variables that must be stored in VDR.

3.3 Research quality

To provide a result that is considered good in terms of validity and reliability, the data selected for the study is the primary data source. According to Rahi (2017) the publications, notes, theses, conference reports, recognized organization reports, and some government publications are all examples of primary evidence and primary data is the most influential methodology for any quantitative approach.

In this study, along with scientific articles, non-academic literature such as document surveys, recommendations, and standards published by various internationally recognized organisations such as the International Maritime Organisation (IMO), International Association of Classification societies (IACS), International electrotechnical committee (IEC), National Marine Electronics Association (NMEA) was referred. Additionally, user manuals from VDR manufacturers to understand the VDR architecture and interfaces being used by the industry were used.

Globally accepted, IMO performance standards which are the mandatory regulations to be complied with all the VDR installed onboard the vessel was used as the starting point, which is reliable and valid, and fulfilled the prerequisite of the study. Scientific articles related to collision avoidance were cited to identify the variables the authors used for collision avoidance and CQS analyses. The most important variables used for collision avoidance and CQS analysis were deducted. To find the deducted variables, recognized standards such as IEC 61162 and NMEA standard interface protocols in consolidated publications were referred to. As the standards published are reviewed and accepted by the industry the data found was considered reliable and valid. Further, for the design of a simple model for data flow parameters relationship for extraction of variables, standard NMEA protocols according to the manuals and documents published by recognized organisations were analysed to focus on the availability of the deducted variables that can be extracted from VDR data.

4 Results and Analysis

In this chapter, the results are presented from the data collected from the literature review of published articles, international standards and regulations, and documents from manufacturers. This section provides a brief description of the Voyage data recorder, its system architecture with related data interface standards. Furthermore, details about the collision avoidance systems and different variables required for CAS in CQS are outlined. Subsequently, based on the identified variables and their sources a model for data flow parameters relationship is designed for extraction.

4.1 Voyage data recorder

Results from the review of the literature show that the performance standards for VDR and S-VDR do not impose any specific standards or formats on how data is stored in the system where every manufacturer has therefore implemented their different approach to store the data. It is also understood that it is a major challenge for accident investigators and researchers to analyse the data from these systems efficiently as the data that is currently available to the researchers needs a lot of effort to process clean, filter, and readjustment for proper analysis and usage.

4.1.1 VDR System architecture

The details of different parts of the VDR are described below:

Data Collection Unit (DCU) mainly fitted in the bridge which gathers all the data from bridge integrated sources. Data from various sensors, which comprises voices, navigational parameters, ship's location. are fed to a unit called the Data collection unit (DCU). The data is digitalized, compressed, and is stored in a specified format in a protective storage unit, called "Data Recording unit" which is mounted in a safe place. The Data Processing Unit, interface components, and spare batteries are all located in the DCU. It gathers data from sensors per IMO and IEC regulations. The data from the DCU is stored in the DRU's flash memory. The data can be accessed by using playback software for investigation purposes as well as for proactive uses.

Data Recording Unit (DRU): The final recording module, also sometimes called VDR CAPSULE, comprises a tamper-proof electronic storage medium(s) encased in a protecting casing. A VDR Capsule is capable of withstanding heavy weather, collisions, fires, and pressure conditions even when a ship is at a depth of several meters in water. This tamper-proof storage unit can be a retrievable fixed type with an underwater locator or floating unit with an in-built EPIRB for early location in the event of an accident. The DRU components are embodied in the protective capsule. The capsule ensures the survival and recovery of the recorded data after an incident. According to NMEA the data that is collected or pulled in from all the integrated sources is, as mentioned above, kept in the storage capsule and holds information for the 12 hours (or 48 hours) preceding it and continuously refreshed as the voyage progresses.

Audio Module: Microphones to record bridge audio: It consists of an audio mixer for recording audio from microphones placed in the wheelhouse, bridge wings, ECR, and various other locations. VHF audio signals are also interfaced with this unit.

Alarm system Module: In this panel connected to the Data Collection Unit will sound an audio-visual alarm if there is any error or fault developed in the equipment or if the sensor inputs are missing.

Power Source module: The VDR should be capable of operating from the ship's main and emergency source of electric power. If the ship's source of electrical power supply fails, the VDR should continue to record Bridge Audio from the dedicated reserve power source for 2 hours. At the end of these 2 hours, all recordings should cease automatically.

Replay Station: The VDR should provide an interface for downloading the stored data and playback the information to an external computer. The interface should be compatible with an internationally recognized format, such as Ethernet, USB, FireWire, or equivalent. A playback software should be provided with VDR with the capability to download the stored data and playback the information. The software should be compatible with an operating system available with commercial off-the-shelf laptop computers and where non-standard or proprietary formats are used for storing the data in the VDR, the software should convert the stored data into open industry-standard formats.

From the results of the literature review a generic VDR architecture is created to show as an example in *Figure 7*. The different sensors such as GPS, speed log, heading, echo sounder, autopilot, engine telegraph, steering gear, M/E remote system, anemometers, bow thrusters, are feeding the input to the VDR data collection unit. The figure also provides details about serial, analog, and digital interfaces used to connect the sensors. The data collection unit also provides provision for a playback unit.

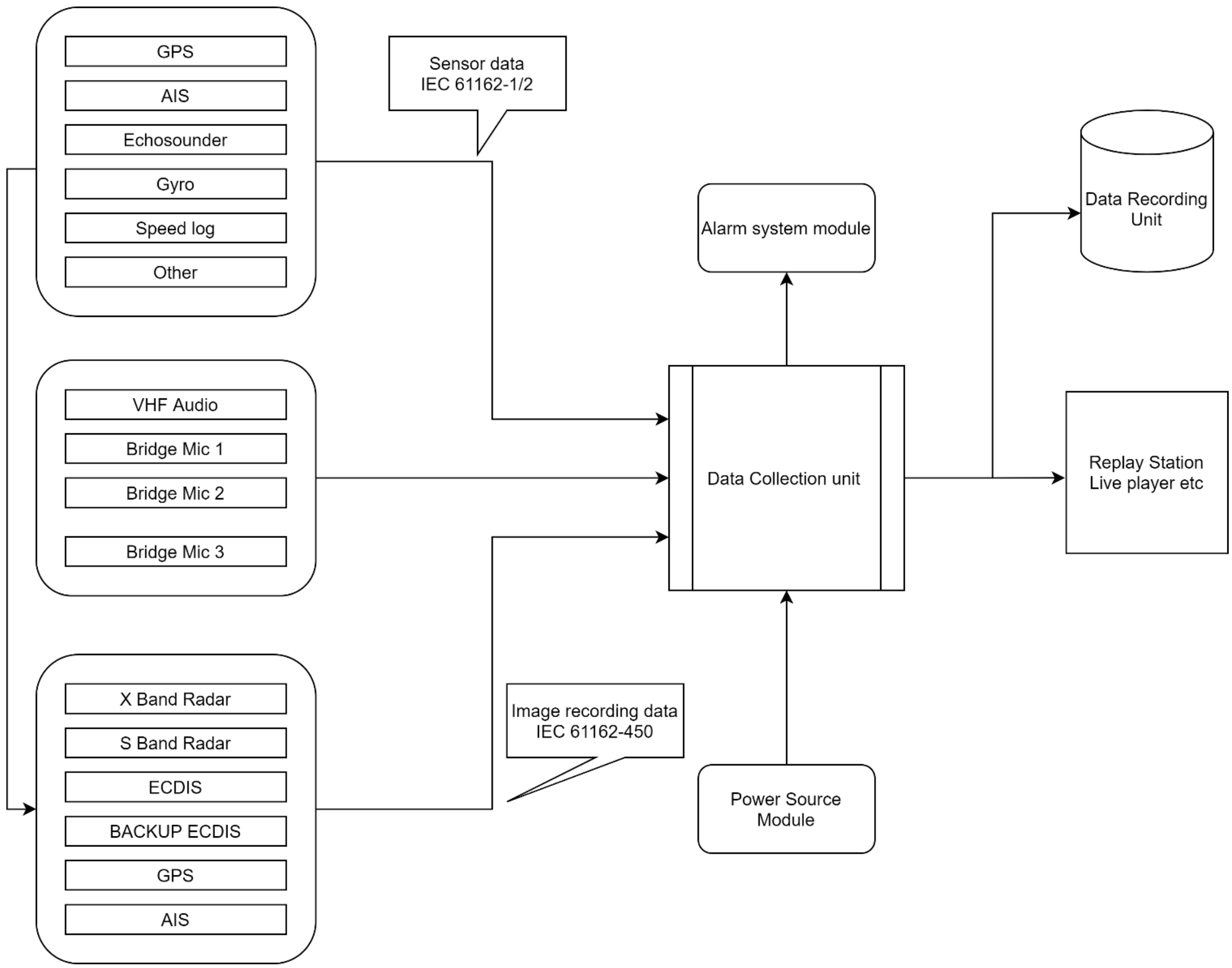

Figure 7: Typical Architecture of VDR

4.2 Data Interface

The non-academic literature review showed that the interfaces for the saved data in the VDR must comply with IEC 61162 of the International Electrotechnical Commission. It is also found that all the source sensors that are connected to VDR such as GPS, compass, transfer the data using IEC 61162 interface protocol which is also the NMEA data interface.

4.2.1 NMEA sentence format and protocol

From the literature review, the NMEA-0183 standard defines the electrical signal requirement, data transmission protocol, data transmission timing, and specific message formats for a 4800 baud serial data interface. NMEA-0183 devices employ an asynchronous serial interface with the following parameters.

- Baud rate: 4800bps
- Data bits: 8 (d7=0)
- Parity: None
- Stop bits: One

Devices are designated as either talkers or listeners with some devices being both. A talker is any device that sends data to other NMEA-0183 devices. A listener is any device that receives data from other NMEA-0183 devices. Instruments that are both talker and listener will have a separate connection for each function. All data either transmitted or received is interpreted as 8-bit ASCII. As found in the academic literature review every VDR and their interface protocols are the NMEA sentences that contain the header or approved sentence formatters representing the data of a particular sensor or source is mentioned.

4.2.2 Sensors connected to VDR

The literature review of the scholarly articles and also from a grey literature review about the recorded data, sources, and required and recommended interface protocols, this section explains and gives details about the sensors that are connected to the VDR, and all the data transmitted that are identified using standard sentence formatters. For use with IMO maritime electronic equipment, the NMEA protocol has been designated in standard form which contains approved sentence formatters for specific data description. These identified sentence formatters from different sensors can facilitate during data analysis to identify the datasets and values for required variables used in close-quarter analyses and collision avoidance systems.

The source of the data that must be recorded as required by the performance standards of the VDR was identified and the required interface protocol was researched. For example, the feed for the recorded data "Heading" is from the sensor gyrocompass. Once the data description from different sensors was noted, IEC standards and NMEA standards were referred cited to pinpoint the approved sentence formatters or headers for the sensors connected to VDR from their output data flow. For example, the output data from ARPA consist of different NMEA sentences like $TTM, $OSD, etc. Analysing the NMEA data structure (see Appendix 1) of the $TTM variables such as target speed, course, target distance, is available and can be extracted for CAS for CQS. Similarly, as a result of the detailed analysis of all the NMEA data structures, the different available variables that can be extracted and its source is shortlisted and presented in *Table 10*.

Table 10: Variables available in NMEA sentence formatters, modified accordingly (NMEA, 2002)

Approved sentence formatters	**Variables available**	**Source or Sensor**
GGA, GLL, RMC, SNU	Position (Lat. & Lon.)	EPFS- Electronic position fixing system. GNSS- Global Navigational Satellite system
RMC, VTG	COG & SOG	
GGA	Satellite information	
DTM	Datum	
ZDA, GGA, GLL	UTC time	
TTM	Targets speed, course, distance	ARPA
RSD	VRM's, EBL's, Cursor	
OSD, VHW	Heading	
OSD, VHW	Speed through the water	
DBT, DPT	Depth under the sounder vibrator	Echo Sounder
HDT, OSD, VHW	Heading	Compass
OSD, VHW, VBW	Speed through the water	Speed log (doppler log)
MWV, MWD, VWT	Wind direction speed	Anemometer
RSA	Rudder Order/ Response	Auto Pilot
RPM	Main Engine Order and Response	Engine telegraph

AIVDM	AIS information	AIS

4.3 Close Quarter Situations and Collision Avoidance

The collision alert systems used in conventional ocean navigation and variables used to avoid the close-quarter situation. The variables used in different collision avoidance systems proposed by various scholarly authors in their scientific papers are identified in this section. From the academic literature review, it is noted that most of the scholarly papers commonly use the terminology of own ship which is the ship to be navigated and target ship is the ship to be avoided.

4.3.1 Close-quarter situational analyses and variables used

To carry out effective navigation and steer clear of any CQS good situational awareness of the surrounding environment and prevailing conditions is necessary. In conventional ocean navigation, several sensors and devices are used by the navigators to facilitate better situational awareness and to make a good appraisal of the current circumstances and situations.

Once the close-quarter situation is encountered correct action and action to avoid collision must be taken at an appropriate time with consideration of COLREGS, current existing traffic situations, and own vessel's maneuvering characteristics. In the process, the navigator has to predict the behavior of the target vessel and this prediction is based on precision situational awareness gathered from the skills of the navigator. Knowledge about the own vessels maneuvering characteristics like turning circle, response time, stopping distance is very essential to take the right action to avoid a collision.

Automatic Radar Plotting Aid (ARPA) is the most widely used collision alert system onboard vessels to tackle any close quarter situation where proximity indicator variables like distance to the closest point of Approach (DCPA) and time for the closest point of approach (TCPA) of the target vessel is used. The values of DCPA and TCPA are set by the navigator and the system gives the alarm when the threshold limit is crossed. This data is readily available to the navigator in the displayed screen of ARPA after the target is obtained from the tracked target using ARPA *Figure 3*. The specified limitations are not only rigid, but they also apply to all situations, ship statuses, and current environmental conditions, rendering them unsuitable for collision avoidance use. As mentioned in the literature review humans can find it difficult to evaluate situations and conduct navigation at a satisfactory standard especially in multiple close quarters situations and in restricted waters.

4.3.2 Data variables used for CQS and collision avoidance.

In the academic literature review, in the past proposed collision avoidance research, the variables are categorized into three different types of system states. 1) Dynamic system state which includes variables like DCPA, TCPA, Relative bearing, Relative heading, Range, Variation of bearing, Ship's speed, and COLREG status. 2) Static system state includes variables like Ship's length and Ships gross tonnage. 3) Quasi-static system state includes variables like Visibility, Wave conditions, Day and Night conditions, and Operating area.

Analyzing the variables accounted for CAS for CQS in scientific papers, all the required variables are identified and listed in *Table 11*.

Table 11: Variables used in CAS and CQS

System State	Variables used
Dynamic	DCPA TCPA Ship Speed Range Relative Heading Relative Bearing Variation of bearing COLREG Status Operating Area (AIS)
Quasi-Static	Wave Conditions Visibility Day or night condition.
Static	Ship Length Ships Gross tonnage

The final variables required for a collision-avoidance and CQS can be identified and deducted in various parameters in the VDR data which are available in NMEA format and can be extracted. These parameters and variables are presented below in *Table 12*.

Table 12: Parameters and variables available in the VDR data.

Parameters	Variables
Steering	Rudder angle Engine Revolution and power Bow and Aft thrusters
The actual motion of the vessel	Own ships course and speed. ROT Heading Draft
Environmental conditions	Targets The priority of the targets using COLREGS Target Course and speed DCPA and TCPA Wind- Direction of the wind and its force in that situation. Depth of the water - only for congested waters. AIS data.
Ship status and conditional data	Maximum and available rudder angle The time required for rudder command Max available engine revolution and power Time for crash astern. Loading parameters Draft Lateral areas Maximum control settings limit like rudder angle, turning rate, engine power, astern time.

Based on the variables and parameters presented in *Table 12* a detailed data analyses carried out of the contents in NMEA data sentences *see Appendix I* from various sensors using their IMO approved sentence formatters as mentioned in *Table* 10, the variables required for CQS analyses and collision avoidance are deducted and can be categorized into the following.

1. Target ship data
2. Own ship data
3. Environmental conditions

Based on *Table 11* and *Table 12*, the deducted variables that can be potentially extracted from which the NMEA data sentence is presented in *Table 13*.

Table 13: Deducted variables and their source in NMEA data sentence

Variables	Source
Target ship data	
DCPA	$ TTM
TCPA	$ TTM
Range	$ TTM
Target speed	$ TTM
Target course	$ TTM
AIS data	$ AIVDM
Own ship data	
Own ships course	$ OSD, $ RMC
Own ships speed	$ OSD, $ RMC
Heading	$ HDT, $ OSD
Rate of turn	$ ROT
Rudder angle	$ RSA
Engine Revolution and power	$ RPM
Environmental Conditions	
Wind	$ MWV
Depth	$ DBT, $ DPT

There are also other variables considered by various authors which are not available from the sensor data and these variables must be observed, evaluated, and manually fed by the operator or navigator for CQS analyses. Some of the examples of variables are mainly wave conditions, visibility.

4.4 Design of model data flow parameters relationship

In the past proposed framework by researchers for vessel collision avoidance using VDR based maneuvering database, it is understood that the VDR acts as a data collector for various important parameters such as steering, motion, and environmental conditions, etc. From the VDR system architecture *Figure 7*, it is understood that various sensors such as GPS, speed log, compass, etc are connected to the VDR data collection unit. Based on the obtained results and analysis of the NMEA data output and its contents from different sensors, a model data flow parameters relationship is designed for the extraction of variables that are available for the researchers to carry out the CQS analyses.

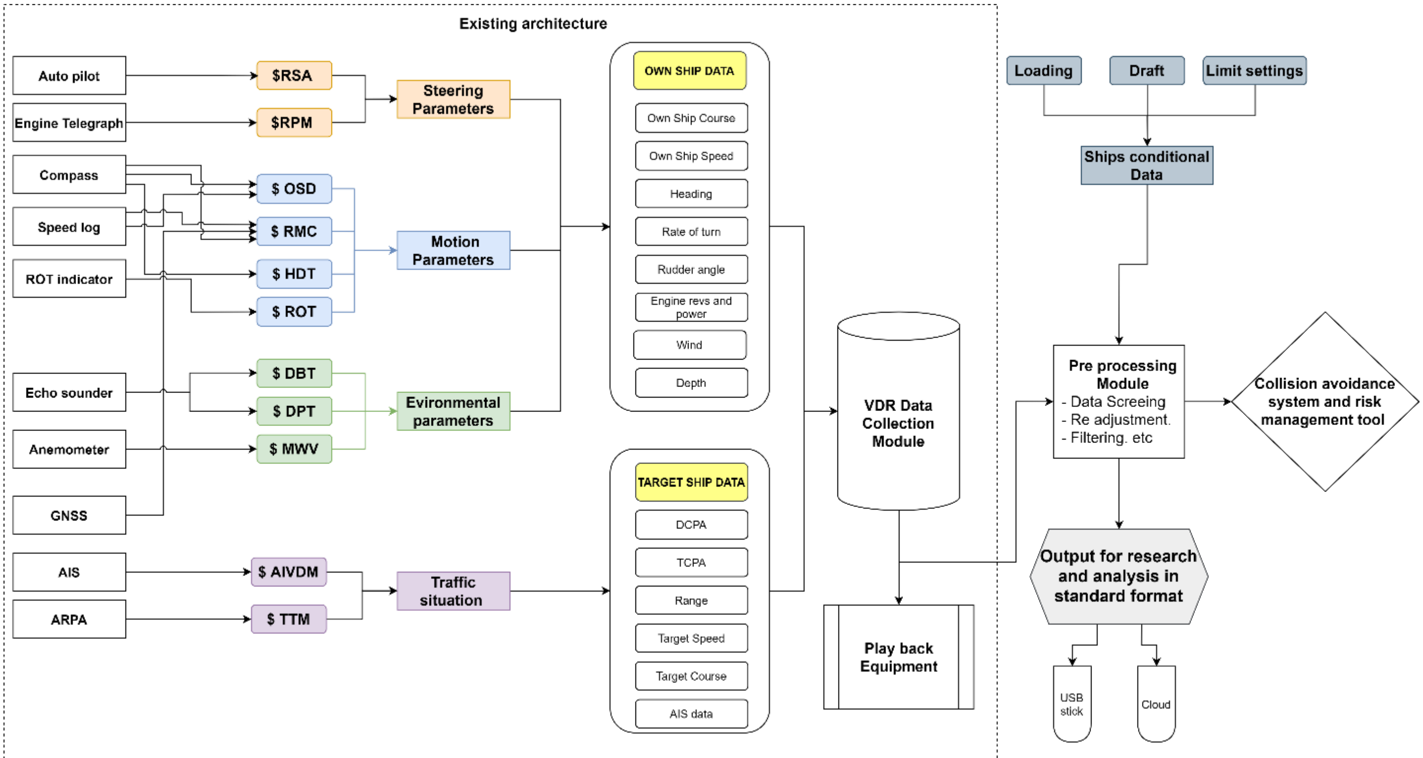

Figure 8: Sensor data flow for proactive use

In *Figure 8*, the sensors act as a source of data for all the variables required. The values for own ship data variables can be extracted from sensors such as autopilot, engine telegraph which belong to steering parameters. Rudder angle and response and engine and thruster order and response can be extracted from the NMEA data feed of $RSA and $RPM. For variables like heading, own ships course and speed, rate of turn can be extracted from sentences like $OSD, $RMC, $HDT, $ROT, where the source is the gyro, speed log, ROT indicator. Environmental parameters like depth and wind can be extracted from the sentences like $DBT, $DPT, $MWV which come from sensors like echo sounder and anemometer.

The most important for a collision-avoidance system is Target ship data which consists of variables like TCPA, DCPA, Target speed and course, operating area, or AIS data which comes from AIS and ARPA in the form of $AIVDM and $TTM sentences.

The existing infrastructure as marked in the diagram, all the data goes into the VDR data collection unit and the interface required for the playback equipment from the VDR data collection unit is IEC 61162-450 commonly known as ethernet. This interface is capable of transmitting the images from ARPA and ECDIS display and is effective in transferring a large amount of data. Various manufacturers have provided a system and software to monitor this data in real-time via playback equipment and have provisions for transferring the data ashore. This provision can be used for extracting the variables required for close-quarter situational analyses and collision avoidance systems continuously in such a format that is easily processed and analysed. For example. CSV format.

However, the ship conditional data which includes loading, draft input, limit settings feed is not required as per the existing requirement to record by the VDR, but this data will help to understand what the loading condition was at the time of a certain event and the loading conditions is directly related to the vessels maneuvering characteristics. The available data from all the sensors are in a raw format that is NMEA or IEC 61162 with proprietary coding by different VDR manufacturers. The data output from the VDR can be in such a format that it can be transferred through a USB stick or direct upload to the cloud platform for real-time analysis and available for close-quarter situation analyses and collision avoidance systems.

5 Discussion

The theoretical framework of the thesis has established that the current architecture of VDR has the provisions for extracting variables necessary for close-quarter situation analyses and collision avoidance systems. The result shows that the interfaces used for different sensors connected to the VDR data collection unit can facilitate the VDR data for proactive uses. However, as identified in this study the regulatory framework which provides the proprietary rights to the VDR manufacturers acts as one of the barriers for easy CQS analyses and use of VDR data for collision avoidance systems. Furthermore, the recorded voice from the bridge audio embedded in the VDR data makes ship owners reluctant to share the data for third-party research and analyses. This section provides a discussion about why the VDR data is so important for marine traffic and CQS analysis and also discusses the barriers to use VDR data.

The results suggest the data recorded from different sensors as required by IMO performance standards are stored in the VDR data collection unit in the form of raw NMEA data. The recent amendments to the VDR mandate playback equipment and an interface for downloading and playing back recorded data to an external computer. This provision implies that data is available for proactive use provided there is the proper infrastructure to extract the variables required.

This study stresses two reasons for using VDR as the data source, not from the individual sensors. Firstly, the extraction of data from individual sensors and processing for data usage is difficult and expensive. The playback equipment from most of the manufacturers such as Furuno as mentioned before provides all the necessary variables required for marine traffic and close-quarter situational analyses. The VDR data collection unit should be provided with a data output interface based on an internationally recognized format like ethernet and USB. This provides a gateway to extract the necessary variables and use the data for proactive use. Secondly, the vessel's response in different collision circumstances can enhance the knowledge about the ship's behavior by continuous analysis of the extracted VDR data. The prevailing conditions such as weather conditions, steering, and control conditions, and loading conditions of the vessel have a direct relation to the vessel's behavior and response and can be recorded and analysed using VDR data. The historically recorded data consisting of numerous vessel responses according to maneuvering parameters of actual existing conditions and vessel’s behavior in a particular navigation situation can be put to further use by implementing them into Big data, machine learning, and artificial intelligence (AI) which is currently under research for autonomous navigation. For example, TTM – Tracked Target Message from Radar will give us information about the target vessel's speed, DCPA, and TCPA. This data can be co-related to the vessel's behavior under existing weather and loading conditions through other sensors feeding information about "Rudder order and response" and "Engine and thruster order and response." Analysis of the NMEA output data structure from various sensors, it can be understood that the variables that are categorized with a high and medium level of importance in the results can be extracted from VDR recorded data.

There is no requirement for recording the data for the ship's conditional status like loading conditions, draft, etc. as it is seen in model for data flow parameters relationship. However, there is a provision made by some manufacturers to connect the lodicator (loading computer) to the VDR. This will immensely help to understand the vessels maneuvering characteristics and their response in different weather conditions and close-quarter situations.

The regulations involved with VDR do not impose any specific standards or formats on how data is stored in the system. The proprietary rights for data handling lie with the VDR manufacturers where every manufacturer has therefore implemented their different approach in the management of the data. IMO performance standards state that if non-standard data is stored there must be software to convert the data into open industry-standard formats. However, to carry out the analyses the data must be first extracted, processed, and used which will result in becoming expensive and time-consuming. Data output formats like CSV, XML, Tab must be considered to facilitate easy and quick analyses of the output data. However, this is not as straightforward in the real world as the data formats of the NMEA contain some proprietary coding used by different manufacturers causing another barrier for data analysis.

The NMEA standard is a closed standard. For systematic analysis of the data, one needs to buy the standards and this is very expensive and delays the research purposes. There are also certain limitations to using the NMEA 0813 data interface standard which is widely used can reach its maximum capacity when systems combine data. The study suggests that using NMEA 2000 which works based on Controller Network Area (CAN) is fast and better than NMEA 0183. However, both the standards are closed standards. With the advancement of technology and the use of maritime data is continuously increasing and open industry standards can facilitate the use of the Internet of things (IoT), Big data and can be used in a plethora of proactive uses.

Another major barrier experienced while conducting this study, ship owner's reluctance to share the VDR data with the researchers. As mentioned in the system architecture of VDR microphones are connected and the VDR data contains the recording from the navigation bridge. This is considered highly sensitive data and used only for marine casualty investigations. The voice data is embedded with the data from other sensors and there have to be provisions to extract the variables required for marine traffic and CQS analyses independent of voice data.

6 Conclusion

The use of DCPA and TCPA in CQS to avoid collision in conventional ocean navigation is considered ineffective and has been clearly stated in scholarly articles. The variables required for CAS were identified using scholarly articles. The data recorded according to IMO requirements suggests that the identified variables are available in the VDR data. Based on the investigation of the identified variables data interfaces and model for data flow parameters relationship shows that the VDR data can be proactively used for collision avoidance in CQS provided proper infrastructure is made available for extraction of variables. The data feed on the data collection unit to playback equipment can be used to extract deducted variables.

The main purpose of this study is twofold. Firstly, to identify the variables required for CAS for CQS that are available in the VDR data. Secondly, to design a model for data flow parameters relationship to show that the identified variables can be extracted from the VDR data to facilitate proactive use.

The study concludes that most of the variables necessary for the CAS for CQS are available in the VDR data. The variables which are required for CQS analysis belong to three main categories. They are as follows:

1) Target ship data which includes TCPA, DCPA, Range, target speed, and course.
2) Own ship data consists of variables like own vessel’s steering and motion parameters which include own ship's course and speed, heading, rudder angle, engine and thruster revolutions, and rate of turn.
3) Environmental parameters like wind, depth, and operating area (AIS).

All the sensors that provide the above data are connected to VDR as required by the IMO performance standards. Data that is transmitted from all the sensors must comply with recognized international interface standards which is IEC or NMEA. The NMEA0183 output format must contain approved sentence formatters to document the items specified by the IMO. The target ship data can be obtained from the NMEA sentence $TTM from the ARPA sensor. The own ship data variables are available in NMEA sentence $OSD, $RMC, $HDT where the sources are Gyro compass, Auto Pilot, ARPA. Finally, the environmental parameters can be obtained from sensors such as echo sounder, anemometer, and AIS in the sentences $MWV, $DPT, and $AIVDM.

For the extraction of values for the identified variables required for marine traffic and CQS analysis the designed model for data flow parameters relationship shows the source sensor and its data connection to the VDR data collection unit. The design shows that the identified variables for marine traffic and close-quarter situational analyses are available in raw format and can be extracted from the VDR. The raw data is in NMEA format, and the proprietary rights of data handling, storage and export lie with VDR manufacturers. The playback equipment allows the playback of the recorded data using only the manufacturer's software and the format of the data extracted from the hard drive differs according to the manufacturer.

The historical VDR data collected can be used proactively for collision avoidance systems understanding the vessel's past responses under certain prevailing conditions such as different loading and ballast conditions. By implementing this data into big data and other advanced programming techniques like machine learning and AI can enhance decision-making capabilities.

6.1 Theoretical Contributions

The research conducted herein shows that there is a lack of scholarly papers about VDR as most of the frame of reference used in this research is based on grey literature. This thesis contributes to filling the gap in scientifically published studies and is the only study that focuses on the variables that can be extracted in VDR data required for CAS for CQS. As a result, the study is deemed to not have exhausted the topic area, but rather to have provided a starting point for further research studies.

In addition, to the author's knowledge, the study is the first research to explore the variables required for CAS for CQS analyses and their availability in the VDR data. Furthermore, this study has investigated using playback equipment to extract the data values for identified variables. Previously published scholarly papers have focused on developing collision avoidance systems but there are no publications related to the extract the values for the identified variables. Thus, further studies have required that focus on the subject. During this study, the researcher found numerous areas that should be investigated further, both to build on the findings of the study and to expand on current knowledge and understanding proactive uses of voyage data recorder.

Firstly, a recommendation is made to establish standards in consultation with the VDR manufacturers for specific formats of data sets that will facilitate the feasible and easy process for marine traffic and CQS analysis. Secondly, further research is necessary to explore the best way possible to extract the variables required for marine traffic analysis independent of voice data from VDR. The possibility of extracting the data from playback equipment has to be studied further. This approach can prove to be more feasible and practical to extract the data from playback equipment instead of each sensor, as the infrastructure is already available for playback equipment with class approvals and currently in use.

6.2 Managerial Implications

Due to the lack of standardization of output data formats stored in the VDR system where every different VDR manufacturer has the proprietary rights for the data storage and transfer to an external device has implemented their different approach to handle the data. This can consume a large amount of time and resources to process, analyse, and properly the usage of the data hindering the investigation or research purposes. If proper and secure infrastructure is provided with open system architecture, internationally agreed set data formats of variables stored in the VDR can facilitate faster research and development.

The connection to the playback equipment which is required by the newly amended performance standards of the VDR can act as a gateway for easy extraction of variables required for marine traffic and close-quarter situational analysis. As the infrastructure is already available for playback equipment with class approvals, extracting the data will be more feasible and practical to extract the data from playback equipment instead of each sensor.

The NMEA standards currently in use are closed standards and can limit the usage of data for research purposes. The output format for the identified variable values from the VDR should be extracted from the database in XML, CSV, or TAB files. The variables should be available at a frequency of standard intervals like one second. This can facilitate smooth and quick data processing. Already established recognized data transfer standards such as Ethernet, USB, Firewire, can be used for transferring data from the VDR continuously for proactive uses.

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Appendix I

This chapter includes the data structure of the NMEA data output from various navigation equipment that was studied to identify the variables required for marine traffic and close-quarter situational analyses.

Target Ship Data

TTM Tracked Target Message

```
                                        11      13
        1   2    3    4 5    6    7 8    9    10|      12| 14
        |   |    |    | |    |    | |    |    | |      | | |
$--TTM,xx,x.x,x.x,a,x.x,x.x,a,x.x,x.x,a,c--c,a,a*hh

 1) Target Number
 2) Target Distance
 3) Bearing from own ship
 4) Bearing Units
 5) Target speed
 6) Target Course
 7) Course Units
 8) Distance of closest-point-of-approach
 9) Time until closest-point-of-approach "-" means increasing
10) "-" means increasing
11) Target name
12) Target Status
13) Reference Target
14) Checksum
```

Own Ship Data

OSD Own Ship Data

```
       1    2 3    4 5    6 7    8    9 10
       |    | |    | |    | |    |    | |
$--OSD,x.x,A,x.x,a,x.x,a,x.x,x.x,a*hh

 1) Heading, degrees true
 2) Status, A = Data Valid
 3) Vessel Course, degrees True
 4) Course Reference
 5) Vessel Speed
 6) Speed Reference
 7) Vessel Set, degrees True
 8) Vessel drift (speed)
 9) Speed Units
10) Checksum
```

HDT Heading – True

```
       1   2 3
       |   | |
$--HDT,x.x,T*hh

1) Heading Degrees, true
2) T = True
3) Checksum
```

RMC Recommended Minimum Navigation Information

```
                                                            12
       1         2 3       4 5         6 7    8   9     10  11|
       |         | |       | |         | |    |   |     |   | |
$--RMC,hhmmss.ss,A,llll.ll,a,yyyyy.yy,a,x.x,x.x,xxxx,x.x,a*hh

 1) Time (UTC)
 2) Status, V = Navigation receiver warning
 3) Latitude
 4) N or S
 5) Longitude
 6) E or W
 7) Speed over ground, knots
 8) Track made good, degrees true
 9) Date, ddmmyy
10) Magnetic Variation, degrees
11) E or W
12) Checksum
```

ROT Rate Of Turn

```
       1   2 3
       |   | |
$--ROT,x.x,A*hh

1) Rate Of Turn, degrees per minute, "-" means bow turns to port
2) Status, A means data is valid
3) Checksum
```

RPM Revolutions

```
      1 2 3   4   5 6
      | | |   |   | |
$--RPM,a,x,x.x,x.x,A*hh

1) Source; S = Shaft, E = Engine
2) Engine or shaft number
3) Speed, Revolutions per minute
4) Propeller pitch, % of maximum, "-" means astern
5) Status, A means data is valid
6) Checksum
```

RSA Rudder Sensor Angle

```
      1   2 3   4 5
      |   | |   | |
$--RSA,x.x,A,x.x,A*hh

1) Starboard (or single) rudder sensor, "-" means Turn To Port
2) Status, A means data is valid
3) Port rudder sensor
4) Status, A means data is valid
5) Checksum
```

Environmental parameters

MWV Wind Speed and Angle

```
      1   2 3   4 5
      |   | |   | |
$--MWV,x.x,a,x.x,a*hh

1) Wind Angle, 0 to 360 degrees
2) Reference, R = Relative, T = True
3) Wind Speed
4) Wind Speed Units, K/M/N
5) Status, A = Data Valid
6) Checksum
```

DBT Depth Below Transducer

```
       1   2 3   4 5   6 7
       |   | |   | |   | |
$--DBT,x.x,f,x.x,M,x.x,F*hh

1) Depth, feet
2) f = feet
3) Depth, meters
4) M = meters
5) Depth, Fathoms
6) F = Fathoms
7) Checksum
```

DPT Heading – Deviation & Variation

```
       1   2   3
       |   |   |
$--DPT,x.x,x.x*hh

1) Depth, meters
2) Offset from transducer;
   positive means distance from transducer to water line,
   negative means distance from transducer to keel
3) Checksum
```