DEVELOPMENT OF AUTOMATIC MODE DETECTION SYSTEM BY IMPLEMENTING THE STATISTICAL ANALYSIS OF SHIP DATA TO MONITOR THE PERFORMANCE

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SUMMARY

The shipping industry depends on a global regulatory framework to operate efficiently. The industry is currently facing various technical and regulatory challenges. Performance monitoring, vessel optimisation, reduction of emissions and maintenance have become high priorities for ship operators. The marine industry is also moving towards autonomous operation to reduce human error. The rate of sensor technology implementation has increased and also raised new technological challenges. The analysis of sensor data creates new challenges to achieve operational excellence. This paper presents the implementation of statistical analysis on ship data and develops a system to automatically detect the vessel operational modes based on sensor data.

NOMENCLATURE

IMO	International Maritime Organization
MARPOL	Marine Pollution
CO_2	Carbon dioxide
SO_X	Sulphur Oxides
NO_X	Nitrogen Oxides.
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
SEEMP	Ship Energy Efficiency Management Plan
EU	European Union
MRV	Monitoring Reporting and Verification
GT	Gross Tonnage
RV	Research Vessel
OSV	Offshore Supply Vessel
KPI	Key Performance Indicator
GPS	Global Positioning System
kn	Knots
NM	Nautical mile
hp	Horsepower
kW	Kilowatt
Lat	Latitude
Lon	Longitude
SPC	Statistical Process Control
I-MR	Individual-Moving Range
UCL	Upper Control Limit
LCL	Lower Control Limit
DP	Dynamic Positioning
t	Tonne
Con.	Consumption
GUI	Graphic user interface
AMD	Auto-Mode Detection

1. INTRODUCTION

The shipping industry currently operates under a complex set of national and international regulations. The industry will be required to adopt new technologies over the next decade to face upcoming regulations and market challenges. Key environmental regulations are coming into force to control the emissions of greenhouse gases, carbon dioxide (CO_2), sulphur oxides (SO_X) and nitrogen oxides (NO_X). According to the IMO MARPOL Annex VI, the industry must adhere to a sulphur limit of 0.1% of oil for ECA (Emission Controlled Areas) from 2015 and 0.5% globally from 2020. (DNV GL, 2012) NO_X emissions are regulated according to the MEPC 58 established in 2008 (revised MARPOL Annex VI) (DNV GL, 2012).

In parallel, the European Commission have introduced the MRV (Monitoring, Reporting and Verification) regulation to reduce CO_2 emissions from ships with GT more than 5000 moving in European waterways (European Commission, 2013). According to this regulation the ship operators will be required to monitor and report the verified annual amount of CO_2 emitted from their ships (European Commission, 2013).

One of the ways to reduce emissions of noxious and greenhouse gases is to improve energy efficiency in the shipping operation. Voyage optimisation and energy management are two principal options for increasing the energy efficiency (Buhaug *et al*, 2009). It is possible to reduce energy consumption on board a ship by working towards optimal operation for a given mission. However, this may require monitoring and hence benchmarking the performance of a ship in a specific activity. In light of this, performance monitoring is a key tool to increase a ship's operational efficiency and reduce harmful emissions.

Modern ships have various sensing and measuring devices providing values for parameters ranging from propulsion to navigational systems. Recording and analysis of data from these systems enables operators to monitor the energy consumed to perform an activity (Lloyd's Register, QinetiQ & University of Southampton, 2015). Robust and accurate knowledge of energy consumption of a ship for a given mission, without the need for the crew's input, will lead to optimal operational management. One of the key elements to achieve this goal is to distinguish different ship activities such as sailing, standby or cargo loading from each other, in other words, automatically detecting the mode of operation.

Automatic mode detection will first and foremost require a thorough understanding of the ship's activities coupled with the input of relevant data, which enables predictions to be made based on analysis and trends of the operational behaviour. These predictions, in turn, lead to the formulation of mode detection to identify the engine uses and fuel consumption based on the operational activities. This paper describes how the vessel operational modes are automatically detected and the impact of the mode detection on performance monitoring.

2. BIG DATA IN SHIPPING

'Big data' has become a buzzword in the shipping industry and has already changed the competitive landscape of many industries (Lloyd's Register, QinetiQ & University of Southampton, 2015). Big data refers to large amounts of data that are complex to analyse. Big data analytics defines the process of data analysis to uncover hidden patterns to identify correlations, ambiguities, trends and other useful information (DNV GL, 2014). The analysis and management of big data will become increasingly essential and is expected to have a great impact in the marine industry (Buhaug *et al*, 2009). Big data has four main dimensions: volume, velocity, variety and veracity (Lloyd's Register, QinetiQ & University of Southampton, 2015; DNV GL, 2014). The volume, which reflects the size of the data becomes larger day by day. There are technical challenges to sort and analyse high volumes of data. The data transmission rate (velocity) is getting faster, meaning more data is collected in a shorter time. In addition, the large volumes of data at high rates of transmission come from different types of sensors feeding the data into the system. The variation in big data is high. The industry will be faced with significant challenges in encountering and dealing with big, complex and fast data (DNV GL, 2014). However, by using statistical analysis to turn the data into value, there is great potential to improve ship operations.

3. SHIP OPERATIONAL MODES

The operational mode could be defined as the activity of a ship for a certain time to accomplish a mission, including waiting time at anchorage. The operational modes can be specific to the ship's type, or common. Specific operational modes vary from ship to ship. For instance, "Dynamic positioning" is a specific operational mode for an Offshore Supply Vessel (OSV) or "Towing" for a tug or "Loading" for a commercial vessel like a container ship. Examples of common modes are "Stand by" or "Sailing". The operational modes are influenced by weather conditions and vessel activities and affect the speed and fuel consumption.

Defining the modes helps the ship operators to know how economically a vessel was operated in performing activities during any specific time period. The operational modes also help the crew to track the fuel consumption and emissions and to determine performance of the ship for the given activity.

Royston Ltd has a fuel monitoring product focused on the marine industry called "engine*i*". It provides real time fuel consumption, speed over ground, estimated time of arrival and distance data. It also represents the data visually on the bridge and sends the data on-shore at regular intervals. "engine*i*" has an option for the manual logging of the operational mode by the crew. Manual entry of the operational mode has the following limitations:

- Manual mode operation is controlled by the crew. So there is an element of human error.
- The crew select vessel operational modes based on their experience, so entry could be subjective.
- The crew need to change the operational modes and this may conflict with their main duty at certain times.
- Unreliable data would be generated by selecting wrong modes or forgetting to change the mode.

Royston Ltd is aware of the limitations of manual mode logging and is therefore keen to develop an automatic mode detection method to improve performance monitoring.

4. AUTOMATIC MODE DETECTION METHOD

In this study, the Research Vessel (RV), "The Princess Royal", which belongs to Newcastle University was used as the basis ship. It has two Cummins QSM11 (600 hp) engines with fixed pitched propellers. The cruising speed is 15 knots and maximum speed is around 20 knots (Newcastle University, 2015). The Princess Royal was built and is used for scientific research and hence does not have any specific modes of operation. "engine*i*" had already been installed on the research vessel, so the data from The Princess Royal could be used to develop automatic mode detection. After developing the auto-mode detection system on the Princess Royal, it was applied to an OSV for further investigation as the OSV has different modes.

4.1 INITIAL DEVELOPMENT OF TOOLS

Auto-mode detection means that the vessel's operational modes would be automatically detected based on the operational activities. Ships function in different modes in various operational conditions. Using the auto-mode detection system, the crew would not be required to switch the mode every time the ship mode changed. It works based on statistical analysis of the vessel sensor data. The mode will be changed on a minute by minute basis according to the operational behaviour. A profile for an individual vessel will be made for the fuel consumption, distance travelled and speed over the ground. The limits will be added based on the statistical analysis of these parameters for each minute. The mode will not be changed as long as the values are within limits.

The mode profiles would be different for different types of vessels and may vary even for vessels of the same type. For example, the same types of vessel with different engines would require different limits for fuel consumption and speed. The operational behaviour and activities need to be analysed to determine the mode limits in different conditions.

4.2 SYSTEM OVERVIEW

The auto-mode detection system will function without human intervention. The system has been developed based on a data-driven model with the sensor data (fuel flow meter and GPS) as input. Figure 1 shows the overall system diagram and demonstrates how the sensor data is used for developing the auto-mode detection.

Flow meters typically give the fuel consumption in litres and GPS sensors provide the position (latitude and longitude). This data forms the input to the "engine*i*" system on a minute-by-minute basis. The distance travelled is calculated from the latitude and longitude by using the haversine formula (Veness, 2007):

Distance (nautical mile) = acos[sin(Lat1) sin(Lat2)+ cos(Lat1) cos (Lat2) cos(Lon2 – Lon1)] 3440.065

The figure of 3440.065 is used to calculate the distance in nautical miles. The GPS sensor gives the latitude and longitude in degrees and this need to be converted to radians to calculate the distance. So the values need to be multiplied by $\pi/180$. Speed over ground in knots can be calculated by dividing the distance in nautical miles by the time in hours (Miller, 2013).

The "engine*i*" system outputs the values for fuel consumption, speed, distance and position to the data base and the parameters are statistically analysed for profiling and thresholds are created according to those profiles. Finally, the individual mode profile will be defined from the threshold limits.

A two-step process is used to generate the predicted mode based on the sensor data. Historical data needs to be statistically analysed to determine the operational behaviour of the vessel; this is done in Step-1 and the mode profile is created in Step-2 from the results from Step-1. Step-1 will be conducted only once in the auto-mode process. After creating the mode profile, all data will directly go through that profile from Step-2.

4.3 DATA ANALYSIS METHOD

Different data analysis methods, for example moving average or mean and standard deviation could be applied to data from on board monitoring as in this study. Simon and Litt (2012) used mean and standard deviation to determine the steady state in an aircraft's engine. Their study, however, showed that using standard deviation for a large scatter data could provide ambiguous results. Trodden *et al*. (2015) developed their own methods to sequentially filter data streamed from a tug boat to determine steady state operation. Other studies explore the use of multiple linear regression to develop prediction and control models for the ship fuel consumption (Bocchetti *et al*, 2015, Erto *et al*, 2015). In this study, statistical process control (SPC) and correlation analysis were used to identify the limits for the different operational activities. SPC is a group of tools and techniques used to achieve process stability and improve capability (Leavengood & Reeb, 1999, Khan, 2013). SPC involves defining the distribution of the process and continuously monitoring and comparing process performance (Leavengood & Reeb, 1999).

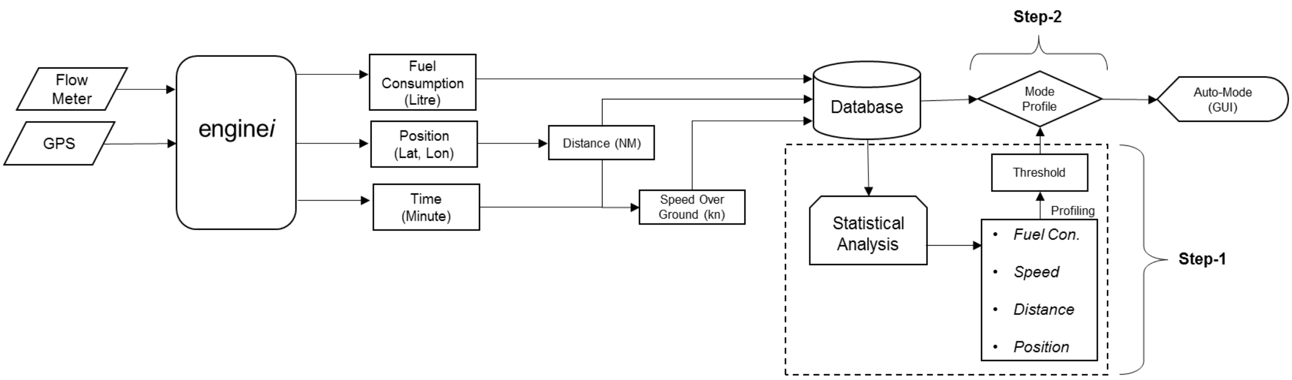

Figure 1: The overview of automatic mode detection.

Correlation analysis is a method of identifying the strength of linear relationships between multiple variables (Leavengood & Reeb, 1999). Correlation analysis is used to check the relationships between the parameters within each mode. Control charts are an effective tool for SPC. In control charts, samples are taken from the process and averages as well as ranges are calculated (Khan, 2013). These are plotted on a chart and interpreted with respect to the process limit or control limits. Control limits are the limits within which the process should be running under normal conditions (Leavengood & Reeb, 1999). I-MR chart is a method for displaying the process performance and was used as a control chart for auto-mode detection. It consists of two charts called Individual (I) and Moving Ranges (MR) charts. I-MR chart is used to detect changes in time ordered data to examine individual values and the control limits are calculated using the average moving range. This chart is used for comparing the performance of the process at different stages (Khan, 2013).

Figure 2 shows the I-MR chart for the distance travelled by The Princess Royal each minute for an hour. The changes of distance travelled and the moving ranges have been monitored. In Figure 2, the X-Axis is the minute of observation and Y-Axis is distance (NM). Similarly, separate I-MR charts have been created for fuel consumption and speed over the ground for each hour by considering 60-minute samples. Different upper (UCL) and lower (LCL) control limits have been obtained for individual hourly fuel consumption, distance travelled and speed. These can be used to identify the changes in the operational behaviour of the vessel.

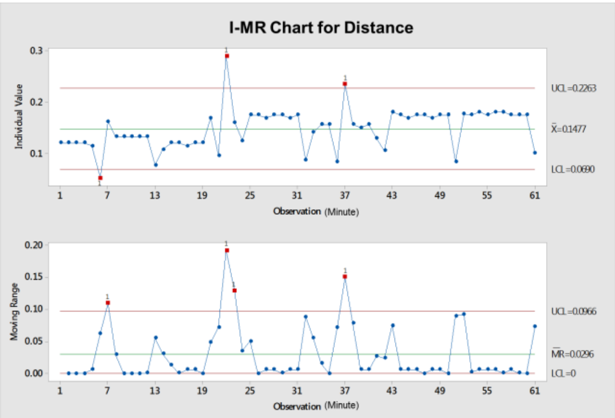

Figure 2: I-MR chart for distance (NM).

The thresholds were identified after analysing the limits and performing the correlation analysis. The mode profiles have been created based on the thresholds of fuel consumption, speed and distance travelled for the individual modes. The SPC method is given below.

UCL and LCL were calculated in Statistical Process Control (SPC) charts for the individual modes.

$$UCL = Mean + 3\ \hat{sd}$$

$$LCL = Mean - 3\ \hat{sd}$$

$$\hat{sd} = \frac{Average\ Moving\ Range}{d_2}, where\ d_2 = 1.128$$

(Bocchetti, *et al*, 2015)

d_2 is a coefficient based on the assumption that the values are normally distributed (Stephenson, 2015).

The mode profile will vary from vessel to vessel. After creating the mode profile, Step-1 will not run again and all data will go directly through the mode profile by following Step-2. "engine*i*" sends data recorded for each minute to the automatic mode detection system and will identify the corresponding mode. The vessel mode and information will be displayed on the bridge. All information would be accessible through a website for on-shore decision-making for optimum operations and, by applying trend analysis, decisions on maintenance scheduling can be taken.

5. TEST RESULT ANALYSIS

The auto-mode detection system has been experimentally implemented on the "The Princess Royal" (RV). The Princess Royal was run in three modes: *Mode-1* (Port), *Mode-2* (Sailing) and *Mode-3* (Stand By). The test results compare the crew pressed mode and the automatically predicted mode during a journey.

In this experiment, an additional mode has been used which is called *Mode-0*. Sometimes a vessel's operational activities are affected by various external factors like wind, wave, tide etc. So *Mode-0* will appear if the data does not match with any of the mode profiles.

The Princess Royal was operated over a two hour trial journey. During the trial, some false entries of the mode were intentionally made. After analysis of the auto-mode data and crew-pressed data, it was found that on two occasions, the auto-mode detection system correctly identified the modes, which were intentionally pressed wrongly by the crew. Firstly, the crew used the standby mode from the 12th minute until the 18th minute but during that period, the vessel speed over ground was 10 to 20 knots so the vessel was really in Sailing Mode. The auto-mode detection system identified the correct mode during that period.

After 91 minutes, the crew again pressed the standby mode but by using the GPS data, the auto-mode system identified that the vessel was in port. *Mode-0* (Undefined) was used in only 3 samples from the total of 120. Around 2.5% of modes were *Mode-0*. That amount did not match with any mode profile. The auto-mode system detected that 62% of the modes matched with the crew pressed mode- whilst 35.5% of the modes were corrected by the auto-mode system. Those modes were entered intentionally incorrectly by the crew.

6. AUTOMATIC MODE DETECTION SYSTEM

Fuel consumption, speed over ground, distance and port position are the main input parameters for the Auto-Mode Detection system. Speed and Distance are highly correlated but not identical because speed is measured instantaneously and distance travelled is cumulative over time. Figure 3 shows the correlation between the speed over ground and the distance.

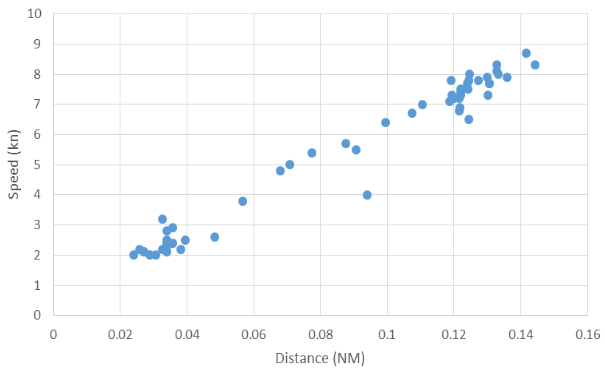

Figure 3: Speed and Distance correlation for Sailing data.

Fuel consumption is the key input parameter required for the Auto Mode Detection system. In addition, either distance or speed can be used to develop a robust system. There is a possibility of a conflict in the mode detection due to the narrow tolerance of the dataset especially during transition from one mode to another. Therefore, all sensor data was considered for the mode profile to reduce the areas of uncertainty.

The auto-mode detection system has also been developed for an OSV. The OSV has four modes: Port, Sailing, Stand By and DP (Dynamic Positioning). The auto-mode detection is a data-oriented system. To identify the mode profile, it is necessary to analyse several days' worth of data from the vessel using basic statistics, correlation analysis and statistical process control. The mode profile will be created for an individual mode by using the thresholds. The sensor data will go through the mode profile to compare with the threshold points. It will identify the vessel's mode when it gets a match with the thresholds. The threshold calculation process is discussed in Section 7. Five days' worth of data was analysed to monitor the OSV activities, speed and fuel consumption in different modes. The sampling rate was one sample per minute and therefore 1440 per day. However, the vessel does not necessarily operate in all modes on any given day. To overcome this, five random days were selected, following consultation with the operator to ensure the vessel had operated in all modes. Figure 4 shows how the OSV data was analysed to get the mode profile.

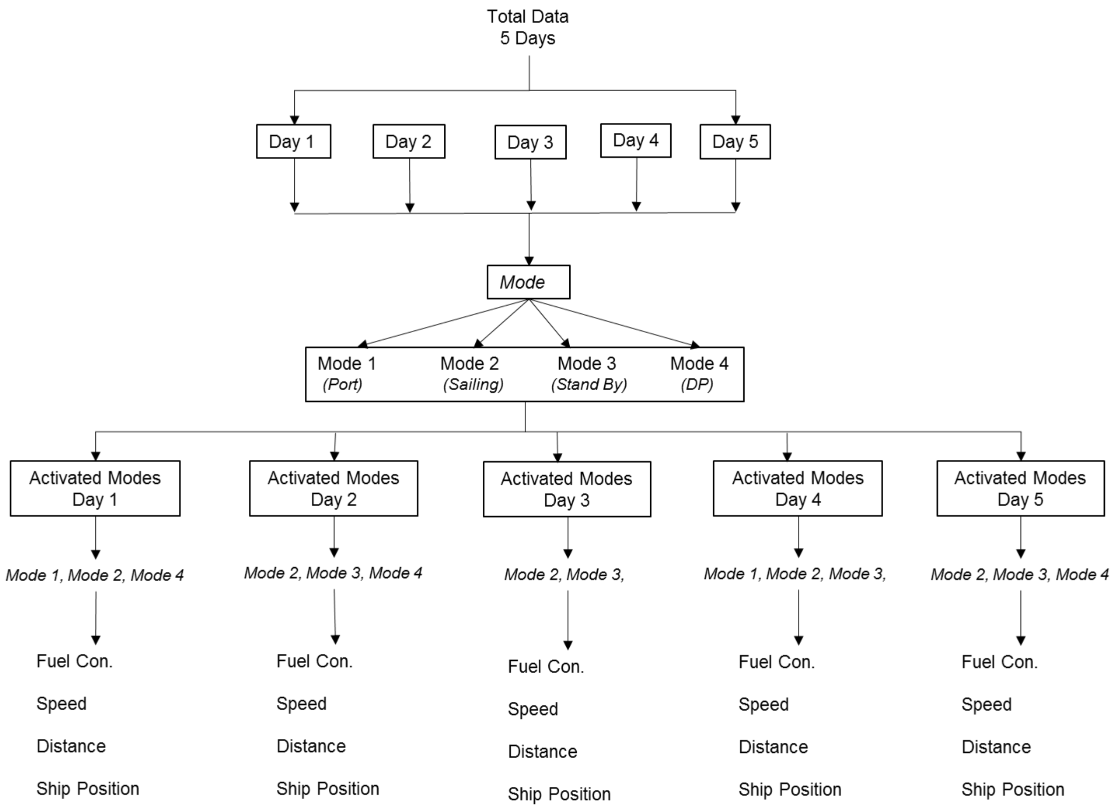

Figure 4: The OSV data structure for analysis to create the mode profile.

Port Mode is detected by using the latitude and longitude of the home port and the vessel's current position. The system will detect Port Mode automatically as soon as the vessel comes within one nautical mile of the port location. The auto-mode detection system could be used for multiple port operations as well. All other modes will not be activated in Port Mode, even if the vessel remains in stand-by or has significant speed in the Port area. Figure 5 illustrates this Port mode concept.

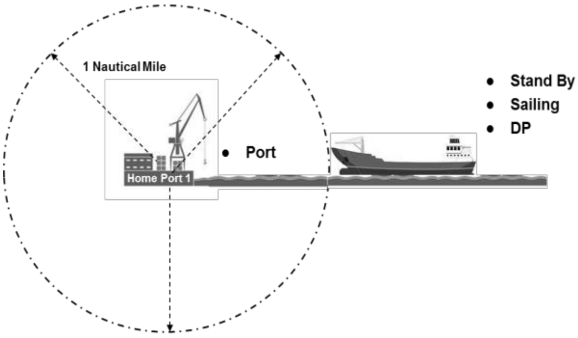

Figure 5: The OSV operations mode detection.

The relationship between the modes of the OSV has been analysed based on the ship's data. Table 1 shows the interrelationship of the fuel consumption, speed over ground and distance for all modes.

Table 1: Characteristics of different modes of the OSV

	Speed Over Ground (kn)			
Mode	**Port**	**Sailing**	**Stand By**	**DP**
Port	-	L	L	L
Sailing	H	-	H	H
Stand By	H	L	-	H
DP	H	L	H	-
	Distance (NM)			
Port	-	L	L	L
Sailing	H	-	H	H
Stand By	H	L	-	H
DP	H	L	L	-
	Fuel Consumption (Litre)			
Port	-	L	L	L
Sailing	H	-	H	H
Stand By	H	L	-	L
DP	H	L	H	-

Note:
L= Characteristic for the mode in far left column lower than for mode in each column.
H= Characteristic for the mode in far left column higher than for mode in each column.

DP would have higher fuel consumption than Stand By. Sailing Mode is expected to have higher fuel consumption than all others modes. In the case of distance, the Sailing Mode covers comperatively higher distances than other modes. The mode selection sequence for the auto-mode detection system is shown in Figure 6.

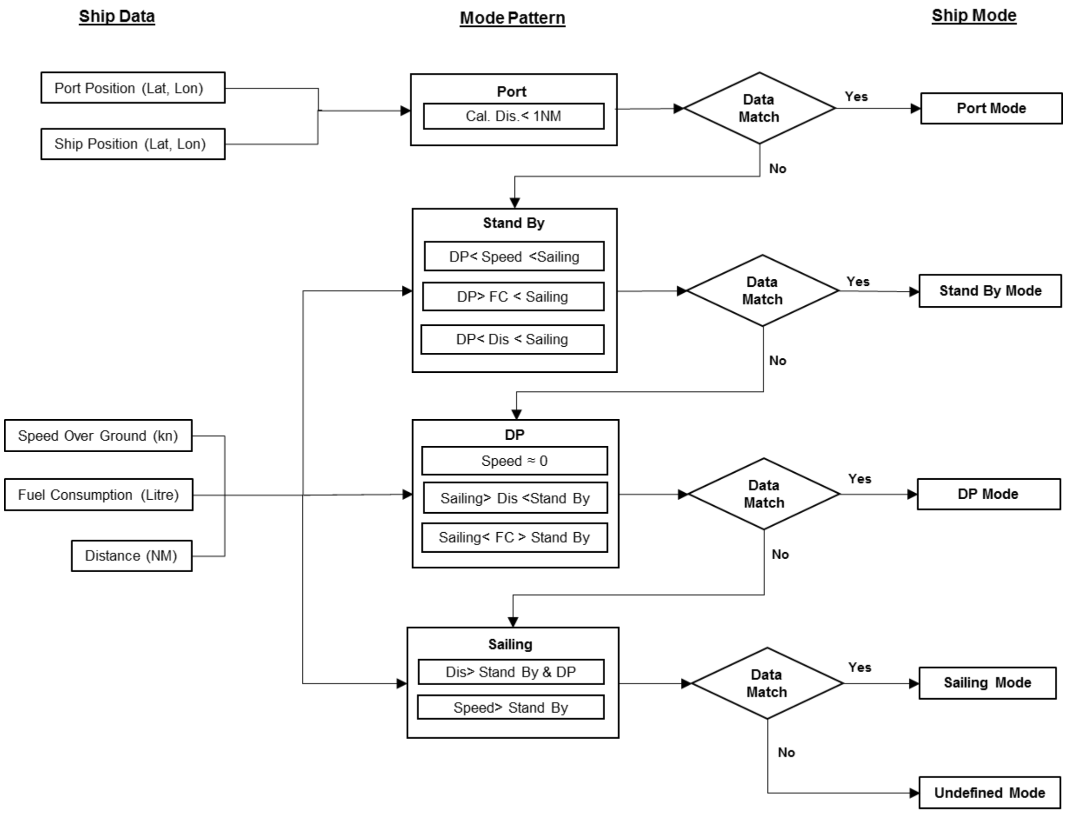

Figure 6: Mode identification process.

7. MODE PROFILE THRESHOLDS FOR THE OSV

Sailing Mode defines that the vessel is in running condition and covers a substantial distance from the previous point. The minimum speed at which the vessel would travel what would be considered to be a significant distance has been defined as the Sailing threshold.

Normally the OSV operates at a speed in the range of 8-10 knots in Sailing Mode. When the vessel is approaching a destination (rig or port) the speed reduces significantly. UCL and LCL contain 99.7% of measurements and data falling within the control limits indicates the expected mode of operation. However, to allow for the speed reduction, the average minimum speed and distance covered have been used for the thresholds of the Sailing Mode profile, rather than the average LCL, as detailed in Table 2.

Stand By and DP Modes are complex to distinguish in many cases. The Stand By Mode activates when the vessel stops outside of the port area. The vessel would be in this mode for different reasons like changing mode or if it has no operational activities while outside of the port area. In DP Mode, the vessel holds a fixed position and automatically compensates natural forces such as the wind, wave and current (Bjorneseth, Dunlop & Stand, 2008). Different types of thrusters are used in the DP Mode (Singh, 2016). The vessel speed is close to zero in both modes but the fuel consumption is expected to be higher in DP Mode. The expected distance travelled per minute will be very low for both modes although sometimes the OSV has non-zero but very low speed in the DP Mode due to the impact of weather conditions. For this project, the OSV was in calm weather conditions. Distance and fuel consumption data for the Stand By and the DP Mode is shown in Table 3 and Table 4.

The average UCL has been considered as the maximum limit for the fuel consumption. If both fuel consumption and speed go above the Stand By threshold limit, then the OSV is considered to be in Sailing Mode. If the fuel consumption is higher than the limit for the Stand By Mode but no speed has been gained, then the OSV would be in DP Mode.

8. MODE TRANSITION PERIOD AND ANALYSIS

Mode-0 will appear if the ship data does not match with any of the mode profiles. Further investigation has been made on *Mode-0* and any points where the auto-mode output did not match with the crew pressed mode.

Around 3.2% of the mode data was in *Mode-0* for Day-1 using the auto-mode system. Discrepancy analysis has been carried out on *Mode-0* for Day-1 considering 14 cases. Discrepancy analysis demonstrates disparity; a large difference between measurable parameters. Table 5 shows the discrepancy results for the day. Column-2 in Table 5 shows the number of times when the crew pressed mode and the auto-mode were not in agreement. Around 8.2% of the auto-mode data did not match with crew pressed mode. The auto-mode system runs on real-time data but it is not possible for the crew to change the mode every minute. In this case, the OSV has high conflict rates between the auto-mode and crew pressed mode because the crew left the system in Sailing Mode incorrectly when the OSV was in the port area on Day-1.

Column-3 in Table 5 represents *Mode-0* for other cases. The *Mode-0* rate is highest in DP Mode for the OSV. In DP Mode, the vessel is expected to consume higher fuel than Stand By Mode and also cover less distance than the Sailing Mode.

For the OSV, the fuel consumption matched with the DP Mode profile but the distance was over the limit many times. That is the main reason for the *Mode-0* in DP Mode. If the distance threshold is increased for the DP profile, the undefined mode (*Mode-0)* rate may be reduced by more than 50%.

It has been found that the unmatched mode with the crew operation mostly happened when the vessel changed from one mode to another (see the last 3 causes in Table 5). This Transition Period was defined to be associated with the next mode that the vessel operated in.

9. VERIFICATION AND VALIDATION

After working on the discrepancy analysis of the auto-mode detection system for the OSV, the mode profile was updated and implemented for the verification stage. Five other random days were selected and relevant operational data from the OSV collected to verify the developed Auto-Mode Detection system. The verification data was independent from data used for the development and testing of the system. The analysis of the results is shown below.

10 April 2016: Stand-By and DP
Matched with crew pressed mode- 1318 min (91.5%)
Not matched with crew pressed mode- 80 min (5.7%)
Transition Period- 40 min (2.7%)

14 April 2016: Stand-By and DP
Matched with crew pressed mode- 1216 min (84.4%)
Not matched with crew pressed mode- 208 min (14.4%)
Transition Period- 16 min (1.1%)

1 May 2016: Sailing and Stand-By
Matched with crew pressed mode- 1416 min (98.3%)
Not matched with crew pressed mode- 23 min (5.7%)
Transition Period- 1 min (0.07%)

3 May 2016: Stand-By and DP
Matched with crew pressed mode- 1282 min (89.02%)

Not matched with crew pressed mode- 117 min (8.12%)
Transition Period- 41 min (2.85%)

The results demonstrate that the use of the transition period is high when the vessel switches mode from DP to Stand By or vice versa. This increase may be due to a number of reasons such as the OSV getting closer to a rig or gaining some speed for a short excursion before mode changing which would not be considered as Sailing. So the transitional period is also essentially part of the operational activities.

10. DISCUSSION

The operational modes depend on the vessel's activities. Different types of mode could be used for the same types of vessel. If an additional mode needs to be added to the Auto-Mode Detection system, then the fuel consumption, speed and other related data during that mode would need to be analysed to allow the mode profile to be created. The new mode might conflict with the existing modes, so the threshold limits will need to be considered carefully to avoid mode conflict. The operational mode can be influenced by different external parameters like waves, wind or current. Therefore, the accuracy rate has been considered to be up to 5%. The fuel consumption in each mode can now be monitored and used to assess the ship's performance. It may be possible to calculate expected fuel consumption in each mode (Bocchetti *et al*, 2015; Erto *et al*, 2015) and this would provide a comparison that would monitor performance further.

The Auto-Mode Detection system is applicable for all types of vessel. Operational modes are different for different types of vessel and a particular vessel would need to run in all modes for a period of time to collect data. For example, "Towing" and "Manoeuvring" could be used as additional modes specifically for a tug.

The inherent added value of the Auto Mode Detection system is to include CO_2 emissions per unit time per ship's activity. The new European Union (EU) regulation on the monitoring, reporting and verification (MRV) of CO_2 emissions has already entered into force. This regulation covers on board CO_2 emissions and also includes a requirement for monitoring data on transportation work and cargo carried (Lloyd's Register Marine, 2015). It also requires annual reporting of the vessel's CO_2 emissions and the need to record each voyage data set in line with an approved monitoring plan (Lloyd's Register Marine, 2015; European Council, 2015). The CO_2 emissions monitoring will cover all emission sources on board such as the main engines, boiler, gas turbine and auxiliaries. The CO_2 emissions will be calculated based on fuel consumption using appropriate emission factors for the fuel type (IMO, 2009) or alternatively by using direct emission measurement (European Council, 2015).

The fuel consumption data per activity is one of the key uses of the auto-mode detection system. The auto-mode report will cover the different operational mode durations, mode fuel consumption, mode distance travelled and engine usage. Therefore, CO_2 emissions can be calculated for each mode of operation by using the carbon emission factor (IMO, 2009). The auto-mode detection system will support the ship operators in compliance with the EU regulation (MRV) by capturing the required data including data on CO_2 emissions, fuel consumption, distance travelled and time spent at sea and at berth.

11. CONCLUSION

A vessel's fuel consumption and profitability heavily depend on engine operating conditions. Monitoring a set of parameters relating to the condition of a system allows the operators to identify any significant changes leading to the development of faults.

This paper addresses how the statistical analysis of sensor data removes human intervention from the vessel operation and helps with decision support for engine maintenance. The auto-mode summary report will help to develop maintenance plans based on the use of the engines in different modes. The onboard and on-shore members of staff would be able to measure the vessel operational performance and emissions. This paper also demonstrates that the vessel operations contain human error and how those errors have been corrected by implementing statistical analysis of the vessel operation. It also addresses the mode transition period and validates the process by implementing it on data from different days.

12. ACKNOWLEDGEMENTS

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13. REFERENCES

1. DNV GL, *'Shipping 2020'*, DNV GL Final Report, 2012.
2. European Commission, '*Proposal for a regulation of the monitoring, reporting and verification of carbon dioxide emissions from maritime transport and amending Regulation (EU) No 525/2013*', European Commission Transportation, 2013.
3. BUHAUG Ø, CORBETT JJ, ENDRESEN Ø, EYRING V, FABER J, HANAYAMA S, et al. '*Second IMO GHG Study 2009*', International Maritime Organization (IMO), pp 240, 2009.
4. Lloyd's Register, QinetiQ and University of Southampton, '*Global Marine Technology Trends 2030*', LR Marine Project, 2015.
5. DNV GL, '*Big Data- the new data reality and industry impact*', Strategic Research & Innovation Position Paper-4, 2014.

6. Newcastle University, '*Blyth Marine Station and RV Princess Royal*', MAST Marine Station-RV Brochure, 2015.
7. VENESS, C., '*Calculating distance, bearing and more between two latitude/longitude points*', Institute of Geophysics Texas, 2007.
8. MILLER, S., '*Speed, Time & Distance*', School of sailing, 2013.
9. SIMON, D.L., LITT., J.S., '*A Data Filter for Identifying Steady-state Operating Points in Engine Flight Data for Condition Monitoring Applications*', National Aeronautics and Space Administration (Technical Report NASA /TM2010- 216359), 2010.
10. TRODDEN, D.G., MURPHY, A.J, PAZOUKI. K. and SARGEANT. J., '*Fuel usage data analysis for efficient shipping operations*', Ocean Engineering 110, pp 75–84, 2015.
11. BOCCHETTI, D., LEPORE, A., PALUMBO, B., and VITIELLO, L., '*A statistical approach to ship fuel consumption monitoring*', Journal of Ship Research, Volume 59, Number 3, pp 162-171(10), 2015.
12. ERTO, P., LEPORE, A,. PALUMBO, B., and VITIELLO, L., '*A Procedure for Predicting and Controlling the Ship Fuel Consumption: Its Implementation and Test*', Quality and Reliability Engineering International, Volume 31, Number 7, pp 1177-1184(8), 2015.
13. LEAVENGOOD, S. and REEB, J., '*Statistical Process Control: How and Why SPC Work*', Oregon State University (Extension forest product manufacturing catalogue), 1999.
14. KHAN, R., '*Statistical Process Control*', Problem Solving and Data Analysis using Minitab-ISBN 978-1-118-30757-1, 2013.
15. STEPHENSON, W.R. '*Control Chart Construction*', Iowa State University (Department of Statistics), 2015.
16. Lloyds's Register Marine, '*European Union Regulation on Monitoring, Reporting and Verification of Carbon Dioxide from Ships*', EU MRV Guidance (Version 4), 2015.
17. European Council, '*Regulation (Eu) 2015/757 of the European Parliament and of the Council on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC*', EUR-Lex: Access European Union Law, 2015.
18. IMO, '*Guidelines for voluntary use of the ship energy efficiency operational indicator (EEOI)*', MEPC.1/Circ.684, 2009.
19. BJORNESETH, F., DUNLOP, M.D., and STAND, J.P., '*Dynamic Positioning System-Usability and Interaction Styles*', NordiCHI, 2008.
20. SINGH, B., '*An Introduction to Dynamic Positioning System*', Marine Insight, 2016.

APPENDICIES

Table 2: Sailing mode data of the OSV.

Mode-2	Sailing					
Distance		Avg (NM)	Max (NM)	Min (NM)	UCL (NM)	LCL (NM)
	Day-1	0.19	0.54	0	0.203	0.175
	Day-2	0.191	0.391	0.042	0.203	0.177
	Day-3	0.144	2.62	0.024	0.156	0.126
	Day-4	0.139	0.202	0.03	0.16	0.12
	Day-5	0.148	0.182	0.038	0.161	0.135
	Avg.	0.1624	0.787	***0.0268***	0.1766	0.1466
	Max	0.191	2.62	0.042	0.203	0.177
	Min	0.139	0.182	0	0.156	0.12
Speed						
		Avg (kn)	Max (kn)	Min (kn)	UCL (kn)	LCL(kn)
	Day-1	11.36	12.7	2	11.63	11.09
	Day-2	11.44	12.8	2	11.72	11.13
	Day-3	8.49	11.5	2	9.38	7.59
	Day-4	8.34	12	2.1	9.39	7.33
	Day-5	8.88	10.8	2.2	9.71	8.04
	Avg.	9.702	11.96	***2.06***	10.366	9.036
	Max	11.44	12.8	2.2	11.72	11.13
	Min	8.34	10.8	2	9.38	7.33

Table 3: Stand By Mode data of the OSV.

Mode-3	Stand By					
Distance		Avg (NM)	Max (NM)	Min (NM)	UCL (NM)	LCL (NM)
	Day-1	0.01	0.66	0	0.0305	0
	Day-2	0.005	0.025	0	0.011	0
	Day-3	0.006	0.034	0	0.013	0
	Day-4	0.01	0.03	0.003	0.03	0.003
	Day-5	0.003	0.029	0	0.01	0
	Avg.	0.0068	0.1556	0.0006	0.0189	0.0006
	Max	0.01	0.66	0.003	***0.0305***	0.003
	Min	0.003	0.025	0	0.01	0
Fuel Con.						
		Avg (ltr)	Max (ltr)	Min (ltr)	UCL (ltr)	LCL(ltr)
	Day-1	2.41	5.41	1.61	2.64	2.18
	Day-2	2.71	5.02	2.07	3.3	2.12
	Day-3	3.83	6.09	2.6	4.88	2.78
	Day-4	3.91	7.07	3.07	5.2	2.63
	Day-5	3.05	5.35	2.4	3.59	2.5
	Avg.	3.182	5.788	2.35	***3.922***	2.442
	Max	3.91	7.07	3.07	5.2	2.78
	Min	2.41	5.02	1.61	2.64	2.12

Table 4: DP Mode data of the OSV.

Mode-4	DP					
Distance		Avg (NM)	Max (NM)	Min (NM)	UCL (NM)	LCL (NM)
	Day-1	0.003	0.066	0	0.01	0
	Day-2	0.004	0.033	0	0.012	0
	Day-3	-	-	-	-	-
	Day-4	-	-	-	-	-
	Day-5	0.002	0.048	0	0.006	0
	Avg.	0.003	0.049	0	0.009	0
	Max	0.004	0.066	0	0.012	0
	Min	0.002	0.033	0	0.006	0
Fuel Con.						
		Avg (ltr)	Max (ltr)	Min (ltr)	UCL (ltr)	LCL(ltr)
	Day-1	4.45	6.2	3.73	4.91	3.99
	Day-2	2.71	5.02	2.07	3.3	2.12
	Day-3	-	-	-	-	-
	Day-4	-	-	-	-	-
	Day-5	5	8.23	3.87	5.57	4.47
	Avg.	4.053	6.483	3.223	4.593	3.527
	Max	5	8.23	3.87	5.57	4.47
	Min	2.71	5.02	2.07	3.3	2.12

Table 5: Discrepancy analysis for Day-1.

Cause	Number of occurrences Diff AMD/Crew	Mode-0	Total
FC>4.1, Matched with DP Profile	17		
Dis>0.006, Speed=0, FC>4.1		42	
Dis<0.03*, dis low, speed>2		1	
Dis >0.03, FC>4.0, High FC and Dis for Stand By			
Dis>0.03, FC<4.0, Low FC for DP and High Distance for Stand By		3	
FC>4.0, Dis in range but high FC for Stand by			
FC>4.0 and FC<4.1, Speed=0, Dis=0		1	
FC<4.0, Matched with Stand by Profile	1		
FC<4.1, Stand by	1		
Vessel speed>2	2		
Port	30		
Stand by, Wrong mode continued	18		
DP, Wrong mode continued			
Sailing, Wrong mode continued	49		
Total	118	47	165
%	8.19	3.26	11.46