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Fuel usage data analysis for efficient shipping operations

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ABSTRACT

There are incentives from maritime regulatory bodies to operate ships more efficiently, driven by the need to reduce CO_2 budget.

In order to establish more efficient ship operations, fuel consumption across the full operational profile of a vessel is needed. This could be accomplished through a complete characterisation through extensive sea-trials, or interpretation of data from monitoring systems. Results from repeated testing under controlled sea-trial conditions provides high-fidelity data, however, this approach is prohibitively expensive and requires repeating as the condition of the vessel changes with time. Conversely, data monitoring devices are relatively inexpensive, however, the process of analysing data can be complex, particularly when a ship's activities are diverse.

This paper describes a methodology for associating ship activity with corresponding segments of a data-stream from a commercially available monitoring system. Further analysis is then performed to determine the fuel efficient performance of the ship. The case-study used is a harbour tug, although the approach used is applicable to other ship types, its success on this basis indicates the methodology is robust. To validate the methodology, results from the data analysis are compared to fuel consumption data measured under sea-trial conditions, and are found to be in close agreement.

1. Introduction

There is a requirement not only for economic reasons, but also for environmental reasons, to reduce the fuel consumption of ships.

Regulations on exhaust gas emissions from ships are becoming increasingly stringent, as laid out in Annex VI "Regulation for the Prevention of air pollution from ships" of the International Convention for the Prevention of Pollution from Ships (MARPOL), which came into force on 19th May 2005 (MARPOL, 1997).

These regulations, for example, cover a requirement to reduce the sulphur content of fuel when being burned in Emission Control Areas. A revision to Annex VI coming into force on 10th October 2008, introduced a new Regulation 4 "Equivalents", stating that: "An Administration of a Party may allow any fitting, material, appliance or apparatus to be fitted in a ship or other procedures, alternative fuel oils, or compliance methods used as an alternative to that required by this Annex if such a fitting, material, appliance or apparatus or other procedures, alternative fuel oils, or compliance methods are at least as effective in terms of emissions reductions as that required by this Annex…"

The results of the methodology presented in this paper allow ship operators to demonstrate their fuel consumption usage and exhaust gas emissions, related to the day-to-day operation of their vessel, aiding operators when showing compliance with Annex VI.

The 2nd IMO GHG Study (Buhaug et al, 2009) highlight six "Principal options for improving energy efficiency", split into two categories: "Design" and "Operation". Data analysis from monitoring devices, as described in this paper, can address concerns in both categories, including "voyage optimisation" from the "Operation" side, where, for example, an optimally fuel-efficient speed may be chosen, in typical day-to-day running conditions, rather than an artificial, theoretical running point, such as trial conditions. This aspect can cross over into the "Design" category, allowing designers to optimise the propulsion system with the hullform for expected service conditions, obtaining more efficient designs for in-service conditions. This is an iterative procedure however, which is financially impractical, and emphasises the importance of using realistic simulators when designing for in-service conditions (Trodden, 2014).

As Hideyuki (2011) points out, Performance Monitoring and its analysis can be used to not only assess the base-performance of a ship, but also the effect of changes in draft and trim, hull condition, weather and operating procedures. Furthermore, the approach taken in this paper can be adapted and used for condition monitoring (Simon and Litt, 2010), an important component in predictive maintenance.

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Nomenclature

SFOC specific fuel oil consumption [g/kW h]
FCM measured fuel consumption [l/h]
SoG speed over the ground [knots]
SSFRC steady-state free-running condition
NSSFRC non-steady-state free-running condition
SSNFRC steady-state non-free-running condition
tol tolerance used when identifying SSFRC periods
n number of data points to be within tolerance. Used for identification of SSFRC periods

The methodology described in this paper uses equipment already commonly found on most ship types. Algorithms are described which separate the data-stream, as output from monitoring devices, into periods associated with steady-state, free-running condition, and non-steady-state free-running condition. This allows performance analysis of not only base-line, steady-state performance, associated with factors such as hull fouling, but also transient performance, associated with factors such as the way the vessel is being operated.

This paper applies the described data analysis methodology to isolate the steady-state free-running condition of a harbour tug, and shows that the tug is being operated in a fuel efficient manner, making the most of a retrofitted economy engine speed selector.

2. Particulars of the basis ship

The basis ship used in this study is a harbour tug, whose main duties are assisting ships on and off their moorings, and assisting their manoeuvring in and out of port. A harbour tug exhibits widely varying operation in typical everyday scenarios, are often operated, on the whole, by their masters independently of control or orders from shore. These factors lead to potential ambiguity and fluctuations in data which vary from one voyage, or job, to the next. This makes the analysis of such a data-stream challenging when determining ship activity type. It is for these reasons that a harbour tug has been chosen as the basis ship type for this analysis, the argument being that if analysis can successfully be conducted on a tug boat, it can certainly be done for ship types with less variance in their data-streams for a specific activity.

The main specifications of the basis ship are found in Table 1.

2.1. Propulsion system

The speed of the engines are controlled digitally by selecting one of four pre-sets, labelled in the wheelhouse as “13%”, “50%”, “70%” and “100%”, nominally corresponding to engine rotational speeds of approximately 380, 570, 620 and 740 rpm. The “%” designation will be used throughout this paper.

Table 1
Particulars of the basis ship.

Main particulars	
Length overall	30.58 m
Draught	2.66 m
Gross tonnage	296
Performance	
Maximum speed	12 knots
Bollard pull	40 tonnes
Main Engines	
Number of engines	2
Continuous rating	1700 BHP
Propulsion	
Type of propulsion	Voith Schneider
Number of propulsors	2

The pitch of the Voith Schneider propulsors are controlled by analogue levers, ahead and astern, graduated from 0 to 10 corresponding to zero and maximum pitch. When the tug is free-running, that is, not assisting another vessel, steering is achieved by setting the pitch levers to the same value, and using a wheel which vectors the net thrust of the two Voith Schneider units in the intended direction of travel.

As a result of the analysis carried out by Murphy et al. (2012), a new “eco-button” has been installed, which corresponds to an additional engine rotational speed setting of approximately 33%. Murphy et al. (2012) claim that a reduction of approximately 20% in fuel consumption could be made at a speed of 67% of the maximum recorded value. The following analysis will determine if this claim has any foundation, and whether or not the eco-button is being utilised.

2.2. On-board monitoring devices

On-board data monitoring devices installed on board this study's basis ship, comprise two main units; a Global Positioning System (GPS) receiver and main engine fuel consumption meters. The equipment used to measure fuel consumption consist of differential flow meters placed on both the inlet and outlet fuel lines of the engines with the difference between the fuel entering and leaving the engine resulting in fuel consumption. The System accuracy for the flow meters have a repeatability rating of $\pm 0.5\%$ for the positive displacement flow meters (Enginei, 2015).

The basis ship is not equipped with a conventional speed log to measure speed-through-water, however the speed-over-ground, location and heading is recorded from the GPS receiver.

There are numerous factors such as atmospheric conditions, sky blockage and receiver quality which make it challenging to determine the accuracy of a GPS receiver at any one time. Typically, for a basic receiver conforming to the GPS Standard Positioning Service (SPS) Performance Standard (Department of Defence, 2008), real world data from the Federal Aviation Administration (2014) show that modern high-quality GPS SPS receivers provide an horizontal accuracy of at least 3.5 m.

Any fluctuations in the accuracy of the measurement systems will cause unsteady oscillations in the data-stream.

If these oscillations are relatively large and densely populate the data-stream, the filtering algorithms will recognise them as unsteady periods and discard them from steady-state analysis. If the oscillations are relatively small or sparse, then they will not affect the identification of SSFRC due to the “look forward, look back” nature of the filtering algorithms, as described in Section 4.

In practise, any inaccuracies arising the measurement systems do not present any issues as a sufficiently high number of SSFRC are identified to perform further analysis on.

The on board data monitoring systems are recording constantly, regardless of the ship's activities. A data-point from each of the monitored parameters is logged every sixty seconds.

3. Characteristics of tug boat operations in the application of data processing

It is necessary to have a basic understanding of how a harbour tug operates, in order to analyse her performance. A tug's remit is to assist vessels in manoeuvring in and out of port. Whilst a tug is in the physical act of assisting another ship, the tug is directed by a Pilot on board the assisted ship. The tug's operators are therefore unable to impose on the tug's master any directives on how to offer assistance in the most fuel efficient manner. The time period when a tug is travelling to or from a particular assignment is under the control of the tug's operators, and therefore operating procedure can be dictated to the tug's master, ensuring fuel efficient operation. This period of travel, outside of assisting another ship, is termed, in this study, the free-running period.

In order to analyse the data collected from a tug's monitoring devices, there is a requirement to understand the nature of services a tug fulfils whilst assisting a vessel. The two main areas of tug assistance required are (Hensen, 2003):

1. Assistance during mooring and un-mooring activities.
2. Assistance in manoeuvring to and from a ship's berth.

The first of these two activities is generally characterised by low speed, high fuel consumption, whilst the second activity can be challenging to define due to multiple possibilities. The following can define the second scenario:

- During initial assistance procedures, the tug's speed will generally be low with high fuel consumption.
- Once the assisted ship and the tug are under-way, the tug may continue to have relatively high fuel consumption, signifying that she is moving the assisted ship.
- Once the assisted ship and the tug are under-way, the tug may have very low fuel consumption, signifying that the assisted ship is moving the tug. These events usually last for very short durations, and generally are not captured in the recorded data-streams due to the relatively low sampling rate.
- Once the assisted ship and the tug are under-way, the tug may appear to be free-running, signifying that she is not doing much work at that particular time. These events usually last for very short durations, and generally are not captured in the recorded data-streams due to the relatively low sampling rate.

3.1. Steady-state conditions

Given the above discussion, there may be two distinct types of steady-state condition, one which occurs when the tug is free-running, referred to as the steady-state free-running condition (SSFRC), and one which occurs when the tug is assisting another vessel, referred to as the steady-state non-free-running condition (SSNFRC). It is the SSFRC which is isolated and further analysed in the investigation of this paper.

3.2. Commentary of a typical harbour tug-boat assignment

Fig. 1 illustrates an example of how the speed-over-ground and fuel consumption of the basis-ship varies with time over an assignment. The tug starts her engines at point A, and after a while proceeds to move off her berth at point B, and travel towards the ship which requires assistance. The period between points E and F is associated with the tug assisting the other ship. At point F the tug begins her voyage back to her berth, and at point I the tug has been tied up, and the engines switched off.

It can be seen from Fig. 1 that, for this particular basis-ship, a typical assignment has two free-running periods, one outward part, points C–D, and one return part, points G–H. The steady-state period highlighted in Fig. 1 has been identified by the algorithms described in Section 4.1, using specific values for SSFRC selection criteria. These specific values have managed to capture the outward steady-state period, C–D, but has failed to capture the shorter, less steady return period, G–H. This demonstrates the need to be specific in the definition of what constitutes a SSFRC. It also illustrates the requirement to account for both SSFRC and Non-Steady-State Free Running Condition (NSSFRC) when assessing the overall performance of a vessel. To elucidate further: assessing the SSFRC data is useful when investigating changes in performance over time, from factors such as hull fouling. Assessing both SSFRC and NSSFRC is useful when investigating changes in performance over time, from factors such as operating procedure.

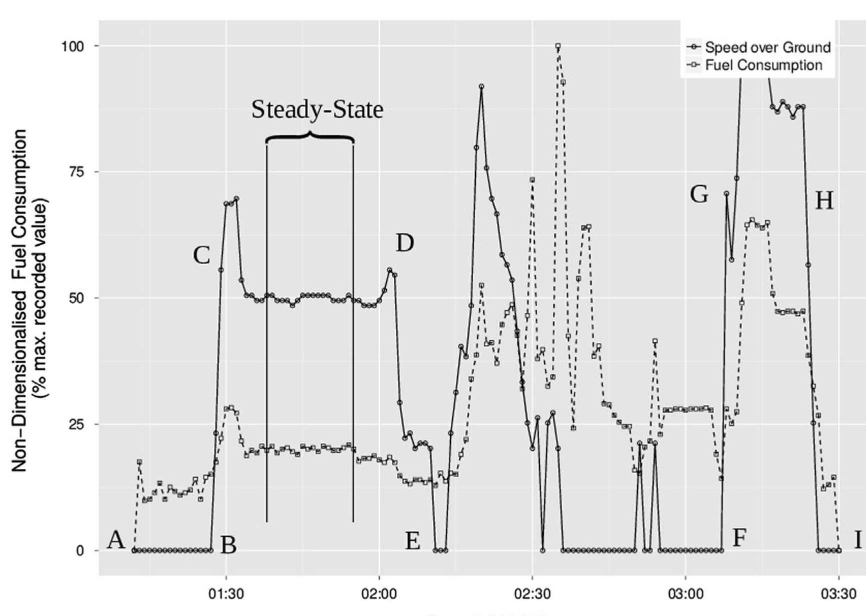

Fig. 1. An example of the time history of non-dimensionalised speed-over-ground and fuel consumption, with a steady-state period highlighted from the analysis described in this paper.

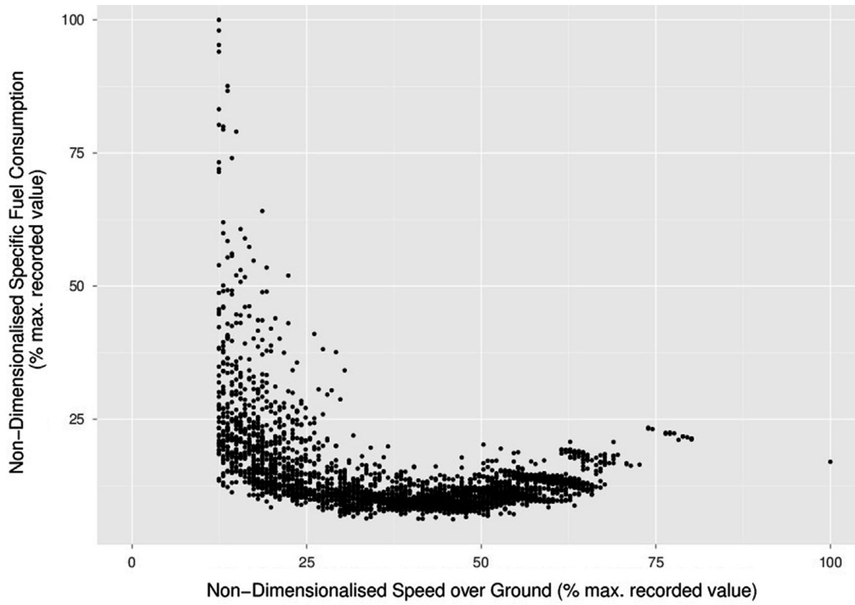

Fig. 2. Unfiltered data of fuel consumption rate as a function of speed, superimposed on sea-trials results analysis of Murphy et al. (2012).

4. Data analysis methodology

The analysis of this paper utilises one month's worth of data, constituting 43,143 data-points. Fig. 2 shows the raw, "unfiltered data". Unfiltered data in this context meaning that the data has not been through any processing after being recorded. It will be observed from this figure, that there are no data points which correspond to a non-dimensionalised speed-over-ground of approximately 12.5% or less. This is due to the data-monitoring hardware not logging these points because of technical issues. This does not affect in any way the methodology described in this paper, as will become apparent, SSFRC periods take place over a range of approximately 50–100% relative SoG.

Fig. 2 illustrates a significant amount of scatter in the data, demonstrating that it is necessary to associate data points with a particular ship activity, so that performance assessment can be appropriately made depending on the type of vessel activity, whether it be free-running in the steady-state, or accelerating to cruising speed.

To determine the base-line performance of the basis vessel, only the SSFRC is isolated from the rest of the ship's activities. This is achieved by passing the data-streams through various filtering and sorting algorithms, as described in Section 4.1.

4.1. Determining the steady-state free-running condition

When a system has reached a steady-state, it has numerous properties which are unchanging with time. In practise, there is always a degree of fluctuation in these properties, and it is the extent of these fluctuations which determine the state of the system.

There is little in the way of literature pertaining to the use of filtering techniques to data from on-board monitoring devices which are in the public domain (Hansen, 2011). Simon and Litt (2010) describes a method of using the mean and standard deviation of a selection of parameters to determine the steady state in an aircraft's engine flight data. In this study, it was found that with using the Standard Deviation as a measure for tolerance can be ambiguous, as a data-set with a large amount of scatter would result in an algorithm which may assign a steady-state period to one of slow acceleration, for example.

Many data analysis methods, for example moving average or trend analysis, require a curve/line to be applied to the data, and the subsequent analysis performed on this curve. The difficulty with this is that a certain degree of "smoothing" takes place on the data, and thus, for example, a relatively short period of steady-state activity could be discarded if on either side of it the recorded values are quite different to the steady-state. Using limits on the slope of the time-series data may occasionally yield periods of true steady-state conditions, however, the success of this technique depends upon the magnitude of the change in oscillations. These types of analysis may work well for a ship whose operating profile does not vary significantly, or rather, the variables in the data-stream do not vary significantly. However, for workboats such as tugs there are many periods of high fluctuation with large scatter in the data, this, it has been found, do not render the analysis amenable to the aforementioned techniques. Consequently, the following methodology has been developed in order to initiate the process of Fuel Usage Data Analysis for Efficient Shipping operations. To enhance this area further, the use of Kalman filters (Kobayashi and Simon, 2003) could be developed, as at present optimum values of n and tol are manually selected for the particular ship in question, as described below.

In order to isolate the SSFRC from other conditions, filters are sequentially applied to the data-stream. The first filter ensures that the remaining data corresponds to the vessel being under-way. This is achieved by discarding points from the data-stream which have a speed-over-ground and fuel consumption values of zero. The remaining data that is left refers to either NSSFRC, SSFRC or SSNFRC. To remove the SSNFRC, a location filter is applied which removes all data other than when the tug is travelling from her berth, to the ship's dock. There will be times when there are SSFRC periods outside the area applied by the location filter which are thus excluded from further analysis. For the reasons described in Section 3, it can sometimes be challenging to distinguish between the SSFRC and the SSNFRC. Other filters could be applied, such as geo-spatial queries from AIS data (Cushing, 2014), which would capture these periods, however, for the steady-state performance analysis purpose of this research it is not necessary, as enough SSFRC data can be obtained over the aforementioned location. The location filter applied in this study assumes that the tug leaves her berth from rest, and does not start to immediately assist another vessel upon departure. Only the outward leg of the voyage is considered, as often the tug returns back down this stretch of river whilst assisting another vessel. A check on heading direction ensures that the tug is travelling to the ship's dock, and not vice versa.

This location filter removes data-points from the remaining data-stream associated with when the tug is assisting other vessels, leaving only data-points associated with SSFRC and NSSFRC remaining. The data-points that remain after the location filter is applied are mostly SSFRC, with a relatively small number of transient points as the tug accelerates to cruising speed after departing her berth.

When determining SSFRC points from within the remaining data-stream, two variables are examined, namely the number of points to simultaneously analyse (or time steps), n, and the tolerance, *tol* of the point which is currently being categorised with respect to the other n points.

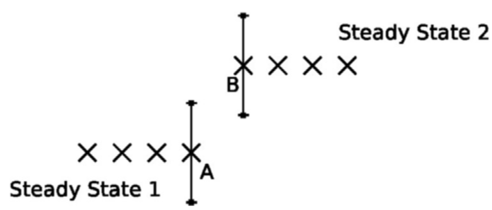

Fig. 3. Illustration of the requirement to assess points before *and* after the point in question. If only regarding previous points, then point “B” would be rejected from “Steady State 2”, similarly, if only regarding proceeding points, point “A” would be rejected from “Steady State 1”.

4.1.1. Number of points to simultaneously analyse when determining the steady-state free-running condition

The purpose of choosing the number of data-points to determine a SSFRC, n, is to ensure that periods where there is a gradual acceleration are not categorised as a SSFRC.

When examining the data-stream for steady-state conditions, there is a necessity to look n steps behind, as well as n steps in-front of the current data point. The reason for this is that if only the preceding n steps are considered, then the current point may be discarded (if the other n are out of tolerance), even though it is a relevant point to the *beginning* of a SSFRC period. Similarly, if only the proceeding n steps are considered, then a relevant point may potentially be lost from the *end* of a SSFRC period. This is illustrated in Fig. 3.

A total of $2 \times n$ points are necessary to determine if a steady-state exists, however, only n consecutive points, within the $2 \times n$ block, must be within tolerance to certify if the current point is part of a steady-state period.

4.1.2. Tolerance of data-points when determining the steady-state free-running condition

The tolerance which the n data-points must be within, in order to define a SSFRC period, is defined as a certain proportion of the corresponding parameter's mean value.

Two parameters are investigated in the determination of the SSFRC periods; the fuel consumption, and the speed-over-ground. Both parameters are examined separately, and in conjunction with one another to determine the impact of each parameter on the outcome of identifying SSFRC periods. This analysis is carried out in Section 5.

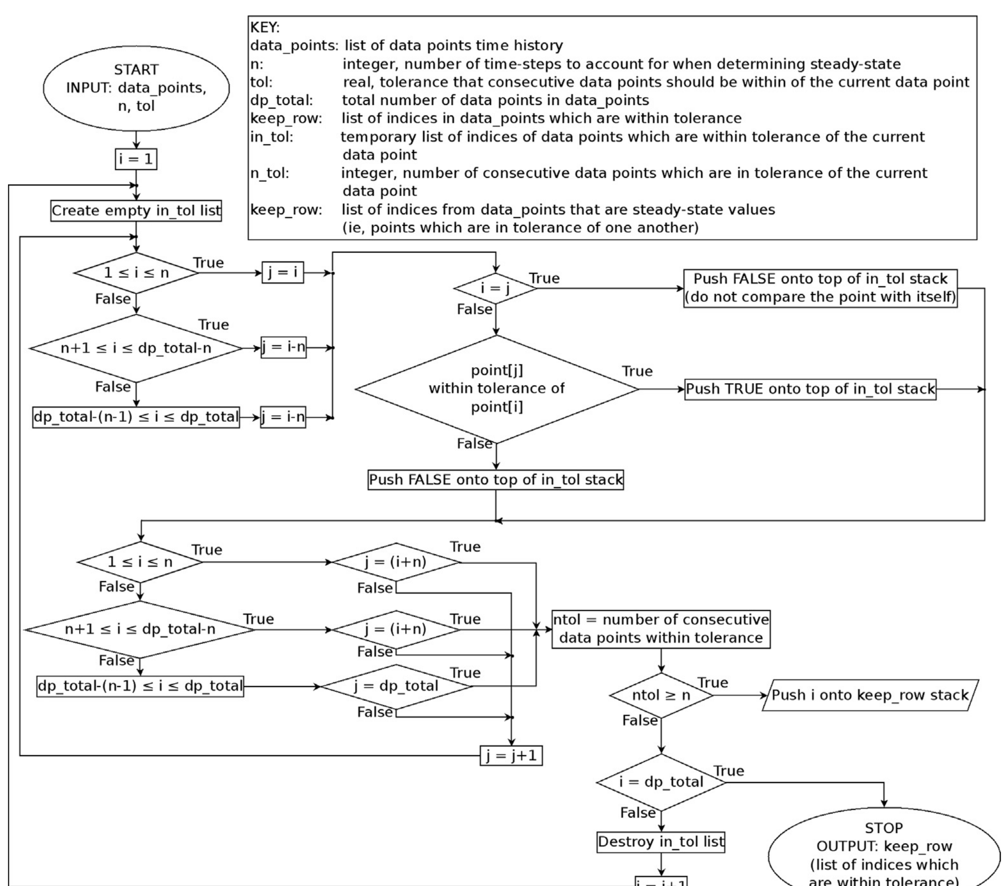

Fig. 4. Algorithm to determine indices of data which are considered to be steady-state.

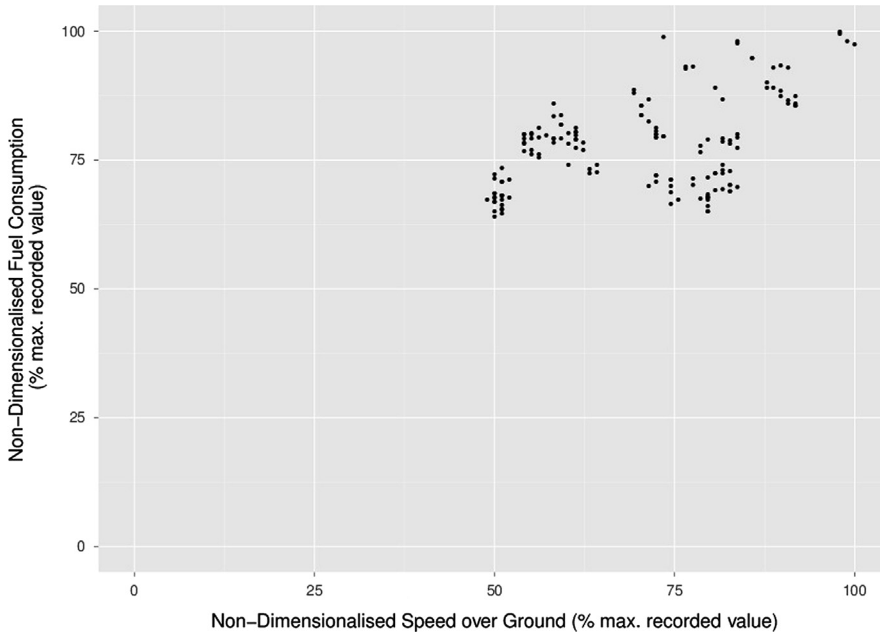

Fig. 5. Performance map of all data-points considered to be SSFRC, as analysed from combined speed-over-ground and fuel consumption criteria. The SSFRC identification criteria, chosen as an example for illustrative purposes, is a tolerance of 5% of the mean values over five consecutive data-points.

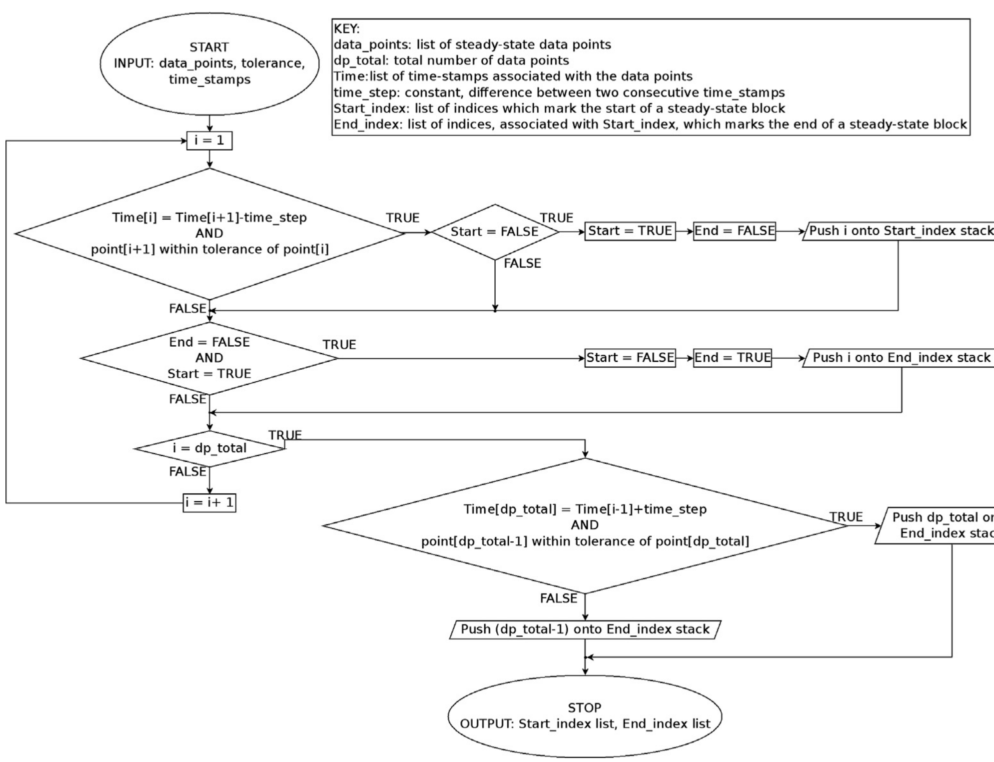

Fig. 6. Algorithm used to determine consecutive periods of steady-state free-running conditions The output from the algorithm of Fig. 6 can be seen in Fig. 7, using the same SSFRC selection criteria of as that of Fig. 5. The size of the data-points in Fig. 7 represents the number of points that make up the SSFRC period.

4.1.3. *Steady-state free-running condition point sorting algorithm*

An algorithm, presented in the flow chart of Fig. 4, shows the method used to determine points associated with the SSFRC, within the data-stream, after it has been passed through the "under-way" and "location" filters.

The output from the algorithm of Fig. 4, is a list of indices of the data-stream which are only SSFRC points. An example output of this is shown in Fig. 5.

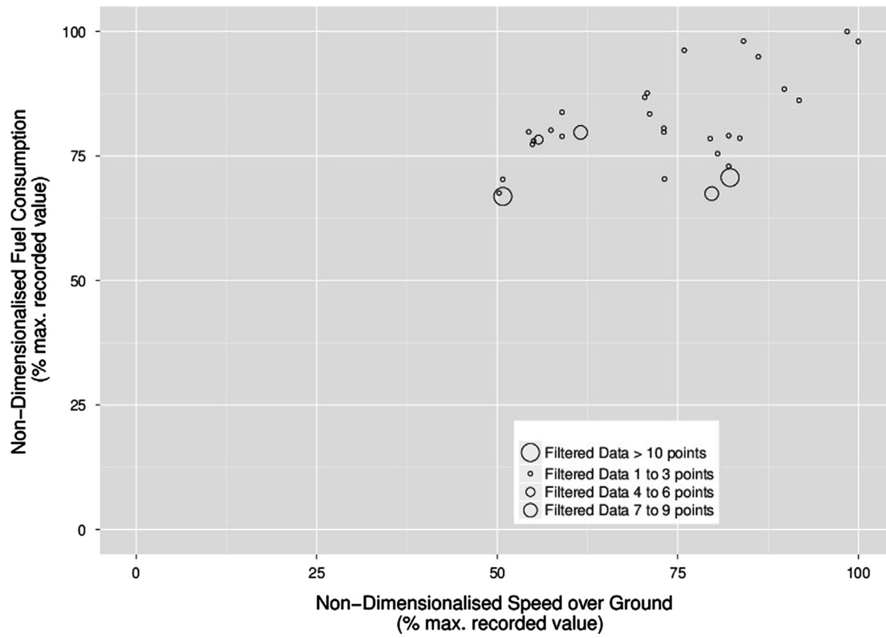

Fig. 7. Performance map of steady-state data segregated into periods, as analysed from combined speed-over-ground and fuel consumption criteria. The SSFRC identification criteria, chosen as an example for illustrative purposes, is a tolerance of 5% of the mean values over five consecutive data-points.

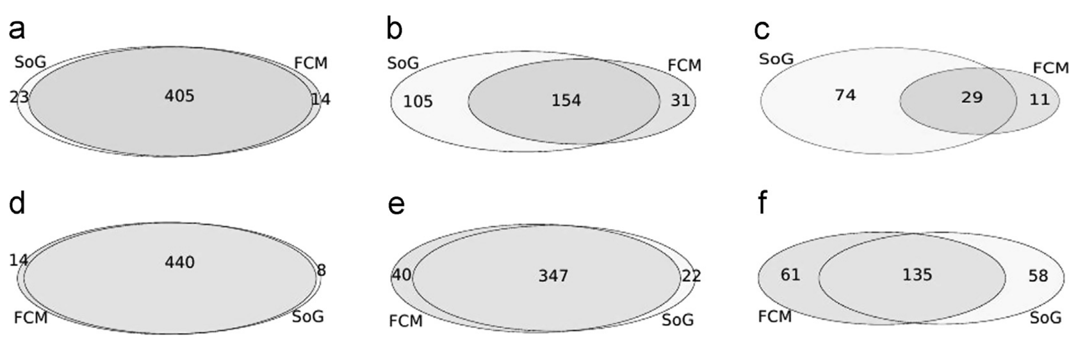

Fig. 8. Venn diagrams indicating the number of points identified as SSFRC from different selection criteria. The total number of data-points was 472 after the under-way and location filters, described in Section 4.1.

4.1.4. Steady-state free-running condition periods sorting algorithm

At this stage, there is no way of determining if one data-point belongs to the same SSFRC period as another. The algorithm of Fig. 4 outputs a list of points associated with only the SSFRC, within a specified tolerance. It is necessary to segregate these points into associated periods, so that further statistical analysis, such as mean values, variance and standard deviations can be meaningfully extracted for each period.

The algorithm used to associate SSFRC data-points with consecutive periods is shown in Figs. 6 and 7.

5. Evaluation of SSFRC selection criteria

Application of the algorithms detailed in Section 4 result in the Venn Diagrams of Fig. 8, illustrating the number of data-points isolated as being SSFRC from using SoG and FCM as selection criteria, both separately and in conjunction with one another.

The purpose of Fig. 8 is to illustrate the sensitivity of the number of data-points selected as SSFRC to the values of the filtering variables, and, in conjunction with Fig. 9, provide guidance on how values for *tol* and *n* are eventually selected.

Fig. 9 shows plots of fuel consumption versus speed of SSFRC periods which have been obtained from using both SoG and FCM as selection criteria, as alluded to in Fig. 8. Larger sizes of the data-point signify a larger number of data-points that make up that period, essentially meaning a longer SSFRC period.

6. Discussion of SSFRC selection criteria

The Venn Diagrams of Fig. 8 show that when the number of consecutive points used as SSFRC selection criteria, *n* is relatively low, the number of points identified as SSFRC from using SoG as a criteria, are roughly equal to the number of points selected from using FCM as a criteria. When *n* is increased, the number of points identified as SSFRC from using both SoG and FCM decrease, indicating that each selection parameter identifies different parts of the data-stream as SSFRC. There does not appear to be any correlation between number of data-points selected from either selection parameter with change in tolerance used as SSFRC identification criteria.

As can be seen from Fig. 9, when the number of consecutive points used as a selection criteria are increased (moving from left to right in the diagrams), the number of SSFRC periods with long time durations decrease. This is intuitively correct, as it takes more data-points to create one SSFRC period. The diagrams also illustrate, naturally, that increasing the tolerance (that is, changing it from, say, 10–5%) results in tighter restrictions on what constitutes a SSFRC period, and thus there are fewer of them.

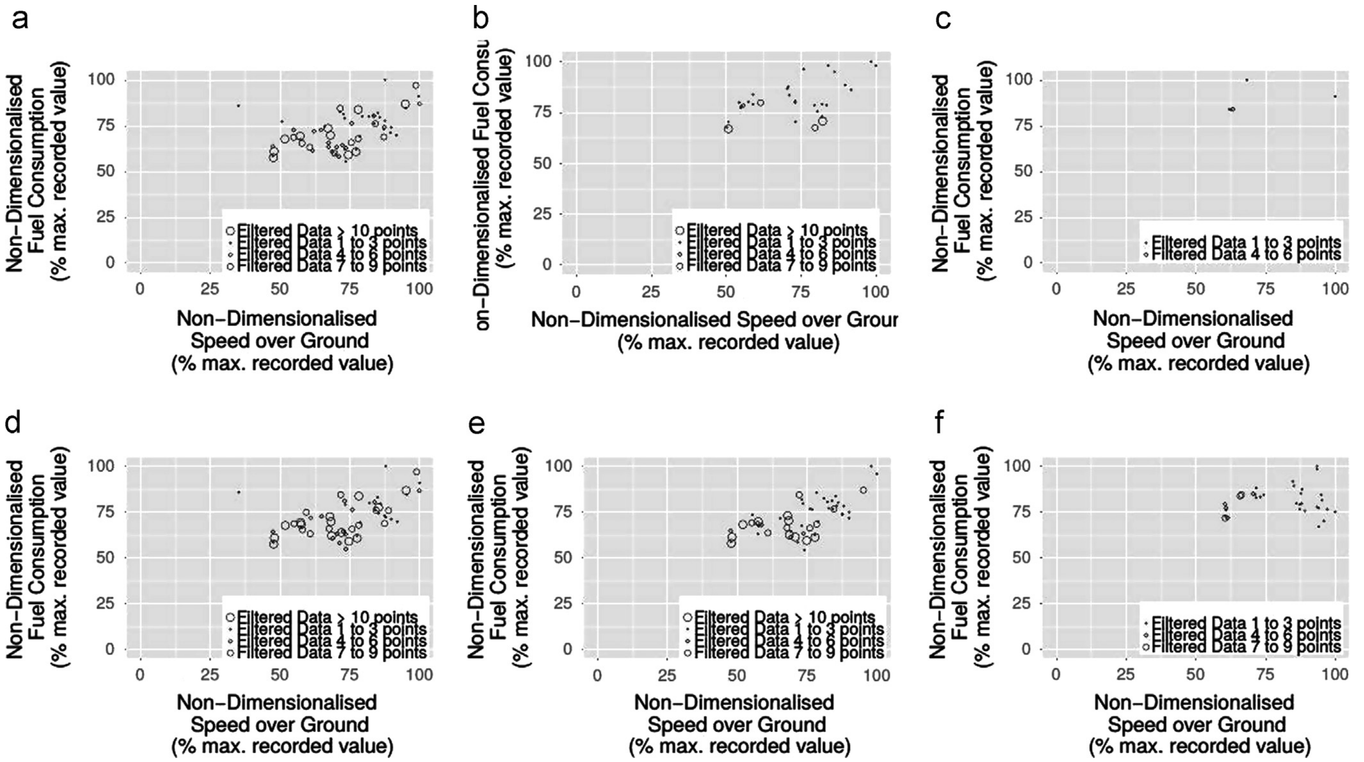

Fig. 9. Performance maps of SSFRC segregated into periods, corresponding to data-points of Fig. 8.

The difference in the number of points identified as SSFRC from using SoG or FCM as a parameter are different, as can be seen in Fig. 8. This phenomena is attributed to one variable being more sensitive, compared to the other, depending on the conditions. For example if the load on the propulsors changes due to a gradual variations in load, for instance from waves, then the engine's governor would tend to cause a proportionally larger fluctuation in FCM to maintain constant speed.

Choosing values for *n* and *tol* which are too restrictive on SSFRC selection will exclude a correspondingly higher number of potential steady-state periods from analysis. It is therefore important that a steady-state condition is well defined, and that appropriate values of *n* and *tol* are selected which identify this pre-defined condition.

6.1. Determining specific values for tolerance and number of data-points to analyse when determining the steady-state free-running condition

There are a multitude of factors which affect the process of SSFRC identification, many of them are ship specific. An example would be a controller which keeps the ship's speed at a certain set-point. In the case of a helmsman, one person may operate the fuel rack at a different rate to another, whereas in the case of an automatic pilot, the systems are very often tuned for each individual ship, with different output magnitude and response times. This implies that different values for *n* and *tol* will be required for each individual ship under investigation.

A mechanism to determine appropriate values for *n* and *tol* is to tune them against a known steady-state condition. A steady-state period is open to conjecture, due to the fact that it is never really steady-state and will always have a certain amount of fluctuations in the data. It is therefore necessary to pre-determine what constitutes a steady-state in terms of fluctuation of data-points (filtered by tolerance, *tol*) and minimum period (filtered by number of consecutive data-points that are within tolerance, *n*).

The objective is to match the pre-determined SSFRC period, with the one determined from the analysis. A tug boat does not spend a long time in a steady-state, and so in order to avoid precluding any relevant SSFRC data-points from analysis, it is necessary to have a relatively low value of *n*, however, as can be determined from the diagrams in Fig. 8, this requires a relatively high value of *tol*.

Choosing a value of *n* corresponding to the time of the pre-determined SSFRC period would have the effect of excluding any periods where there is even only one point out of tolerance, thus potentially removing long SSFRC periods which contributes to determining the performance of the vessel. It is possible that by selecting a relatively high value for *tol*, the pre-determined steady-state period will be divided up into several shorter periods of steady-states by the analysis, with some points being removed as they are deemed to be out of tolerance.

There is thus a compromise between *n* and *tol*, the goal being to have the lowest *n* with the highest *tol* which results in the analysed SSFRC period equalling the pre-determined SSFRC period. The selection of values for *n* and *tol* can be obtained from goal-seeking techniques, resulting in a strict set of criteria. Data-points which lie outside of the resulting criteria are considered to be associated with transient operation.

Effects from ship inertia and environment manifest as fluctuations in data-points, therefore their effects are discarded, so long as the magnitude and duration of the fluctuations are greater than the set tolerances.

7. Steady-state free-running condition performance analysis

To determine the performance of a vessel, it is necessary to compare her with the performance in comparable conditions, when the vessel was known to be performing optimally. For the case of the harbour tug operating in the SSFRC, as analysed in this study, comparable conditions would be sea-trials. Fig. 10 shows

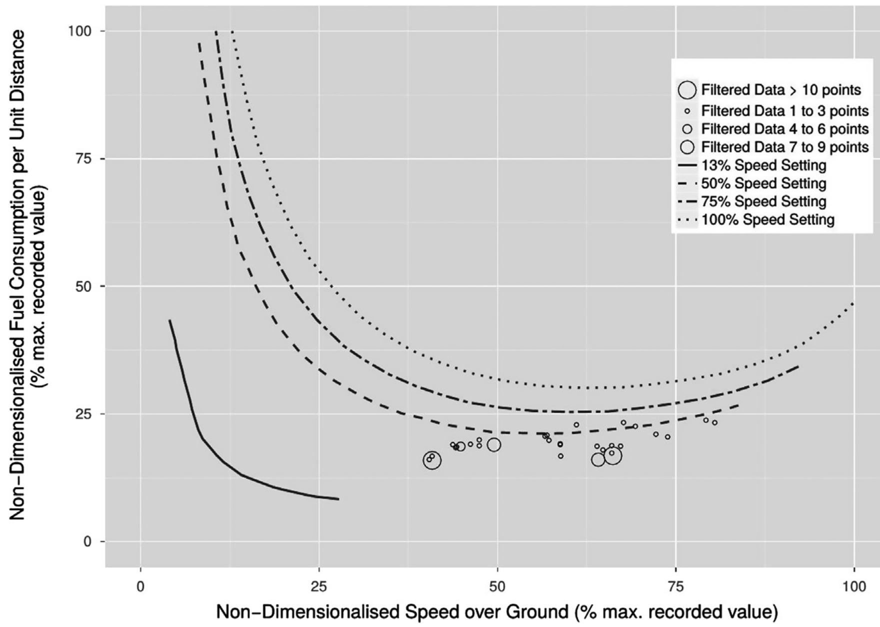

Fig. 10. Performance map of blocks of steady-state data, as analysed from combined speed-over-ground and fuel consumption criteria, with a tolerance of 5% of the mean values over five consecutive data-points, superimposed on results from sea-trials, as obtained from Murphy et al. (2012).

non-dimensionalised fuel consumption vs non-dimensionalised speed-over-ground, as obtained from results from this analysis, superimposed on results from sea-trials. The lines of constant engine speed settings are from the sea-trials, with the ship speed being varied with pitch of the Voith Schneider units. The SSFRC periods were obtained from the analysis described in this paper, using SSFRC selection criteria of 5% for point tolerance, *tol*, over 5 consecutive points, *n*, using both SoG and FCM parameters, representing a balanced value, as noted from Section 5. It must be emphasised that the values used for SSFRC identification only separate the SSFRC from the NSSFRC. As long as there are valid SSFRC periods to be analysed, it does not matter how many there are, they still represent the base-line performance of the vessel at the associated speed. The SSFRC periods as shown in Fig. 10 have a speed range which is consistent with that associated with the basis-ship travelling from her berth to the ship's dock.

The comparison between this analysis and the carefully controlled sea-trial experiments is made in order to determine if the analysis' results are reliable. Fig. 10 indicates that the tug is consistently being operated in the SSFRC in such a manner which outperforms sea-trials. In the time between which the sea-trials were undertaken, and the time the data for analysis was recorded, a new "eco-button" engine speed selector has been installed on the basis vessel. The "eco-button" is based upon the work of Murphy et al. (2012), who suggest a reduction in fuel consumption of approximately 20% at 67% speed-over-ground would result from the installation of this new engine speed setting. The results of this analysis suggests that the tug boat skippers are actively using the eco-button, and that the eco-button is indeed providing reduced fuel consumption. From Fig. 10, it can be seen that the reduction in fuel consumption from using the eco-button at 67% of the maximum recorded value of Speed over Ground is approximately 22%.

8. Conclusions

This paper describes a methodology for isolating from a continuous data-stream periods associated with steady-state free-running condition, and transient free-running conditions.

Analysis of the steady-state free-running condition can be used to assess degradation in performance over time, whereas analysing both can be used to asses performance degradation due to the way in which the vessel is being operated. The steady-state free-running condition is the one in which tug boat operators have most control over, in terms of dictating fuel efficient operating procedures and assessing base-line performance, whereas they have little control over transient manoeuvring or non-free-running conditions.

Results of analysing steady-state free-running periods from on-board monitoring devices show that the basis tug is being operated in an optimally fuel efficient manner, successfully utilising a newly installed economy engine speed selector.

The results of the analysis further show that the reduction in fuel consumption due to the installation of the economy engine speed selector match the claims of the original eco-button authors Murphy et al. (2012).

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