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FURTHER TECHNICAL AND OPERATIONAL MEASURES FOR ENHANCING THE ENERGY EFFICIENCY OF INTERNATIONAL SHIPPING

Goal-based approach to fuel and CO_2 emissions monitoring - uncertainty considerations

Submitted by the Institute of Marine Engineering, Science and Technology (IMarEST)

SUMMARY

Executive summary:	This information paper focuses specifically on the uncertainty in monitoring systems based on the four fuel and CO_2 monitoring approaches discussed in MEPC 65/INF.3/Rev.1 from two perspectives: .1 Factors which contribute to uncertainty. .2 Case study with an analysis of actual ship data. The main conclusions of the information paper are set out below.
Strategic direction:	7.3
High-level action:	7.3.2
Planned output:	7.3.2.1
Action to be taken:	Paragraph 10
Related documents:	MEPC 63/23 paragraph 5.59; MEPC 65/INF.3/Rev.1

Introduction

1. The Committee may recall that MEPC 63/23 paragraph 5.59 invited further submissions on specific aspects of an IMO performance standard for fuel consumption measurement for ships and that MEPC 65/INF.3/Rev.1 provided information in relation to a goal-based approach to fuel and CO_2 emissions monitoring, including the various principles related to monitoring and reporting based on ISO 14064:2006.

2. The Annex to this document provides information on the uncertainty of fuel and CO_2 emissions monitoring approaches presented in MEPC 65/INF.3/Rev.1, by considering the factors which contribute to uncertainty and a case study with an analysis of actual ship data.

Uncertainty Factors

3. A number of common and specific factors need to be considered in the evaluation of uncertainty and when making comparisons between monitoring approaches. These include identifying where the boundary of control lies, the accuracy and installation of metering equipment, human factors, external influences, physical ship construction and on-board management.

4. A review of the NOx Technical Code, which could be used as the basis of direct emission monitoring of CO_2 emissions, shows that to achieve an acceptable level of accuracy, and hence low uncertainty, the permissible deviations of measurements for various parameters used for the derivation of exhaust gas mass flow, combined with the specified accuracy requirements for the exhaust gas analyser, have to be carefully considered.

Case Study

5. A sample of ship data collected over a 3.5-year period from bunker delivery notes (BDNs), bunker fuel tank measurements and flow meters was analysed to investigate the uncertainty of the two on-board monitoring approaches. The difference between the bunker fuel tank and flow meter measurement approach did not exceed +/-5% and this represents the probable upper bound of uncertainty of these monitoring approaches.

6. This uncertainty cannot be solely attributed to either of these two fuel monitoring approaches, but represents a probable upper bound of uncertainty, as it is unlikely that the approaches cancel each other out over the period examined.

7. The influence of the BDN data on the difference between bunker fuel tank and flow meter monitoring was analysed and it was found to have negligible effect and no bias. Uncertainty is associated with BDN data, but this is outside the boundary of control of the vessel.

8. The study showed the difficulty of accurately monitoring fuel consumption over shorter periods of time. It noted that, for any one voyage, it is possible to regularly observe differences between individual flow meter and tank measurement consumption estimates of 15-20%. This is likely to be indicative of the magnification of uncertainties when the fuel consumed is calculated as a small difference between two large numbers.

9. Further analysis of datasets is required to confirm a suitable uncertainty range for monitoring systems across the international fleet.

Action requested of the Committee

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

Annex

Goal-based approach to fuel and CO_2 emissions monitoring – uncertainty considerations

Alastair Fischbacher; Anne-Marie Warris; Jonathan Holloway; Katharine Palmer; Ken Reid; Niels Björn Mortensen; Per Tunell; Poul Woodall; Richard Vie; Rob Collier; Tristan Smith[1]

1. Introduction

This information paper was developed by a group of individuals acting in their personal capacity to provide further material to the International Maritime Organization (IMO) Marine Environmental Protection Committee (MEPC) in addition to that presented in MEPC 65/INF.3/Rev.1.

MEPC 65/INF.3/Rev.1 identified four approaches to fuel and CO_2 emissions monitoring and linked them to a goal-based framework based on a cumulative combination of through-life cost, complexity and accuracy. The four approaches are:

.1 Bunker Delivery Note (BDN) and periodic stock-take of fuel tanks.
.2 On-board bunker fuel tank monitoring.
.3 Flow meters for applicable combustion processes.
.4 Direct emission measurements.

Recent submissions to MEPC in relation to further technical and operational measures for energy efficiency of existing ships include three phases: data collection, reporting, and verification checks on a periodic basis, commonly known as monitoring, reporting and verification (MRV).

This paper considers the uncertainty in monitoring systems using two perspectives:

.1 Factors which contribute to uncertainty.
.2 Case study with an analysis of actual ship data.

2. Uncertainty in monitoring systems

The terms ‘accuracy’ and ‘uncertainty’ are used in MEPC 65/INF.3/Rev.1 in relation to monitoring systems that collected discrete measurement data in a repeatable manner.

Accuracy of sensors[2] and individual measurements are important components of the overall uncertainty of the final data derived from a monitoring system. Accuracy is just one of three components of uncertainty, which are:

- *Measurement uncertainty* – represents the accuracy of individual sensors; high-accuracy sensors reduce measurement uncertainty. This component of uncertainty can occur from human error associated with the reading or recording of a sensor or due to a lack of knowledge about how the measurement process is to be carried out.

- *Uncertainty due to variability of input parameters* – technically known as aleatory uncertainty. This component of uncertainty is due to any unaccounted variability of input parameters to a calculation. This can occur, for example, due to the use of the wrong reference value for fuel density when this parameter is known to have a range of values.

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[1] The authors are writing in their personal capacity only and the views expressed in this paper do not necessarily represent those of and are not to be attributed to their organizations.
[2] The term ‘sensor’ is used synonymously with a device that measures a quantity at a given point in time (e.g., a fuel flow meter) and with a process for measuring a quantity at a given point in time (e.g., a tank measurement carried out by a crew member).

- *Uncertainty due to unknown errors in input parameters* – technically known as epistemic uncertainty. This component of uncertainty is due to any unknown elements of the calculation. This can occur due to an incorrectly installed sensor, if there is uncertainty in the calculation of the volume of a tank, due to, for example, an approximation in the model/calculation used to convert input parameters to an output parameter, in the calibration condition of a sensor, or in the linearity or stability of a measurement procedure over time.

The process of recording discrete measurements can also introduce uncertainty to the total. When outputs of multiple measurements are used in the quantification of a parameter, the total uncertainty associated with the calculation of the total value for fuel or CO_2 emissions is the total of the measurement uncertainty of every individual sensor, and the uncertainties due to variability in input parameters and to unknown errors in input parameters.

Further information on accuracy and uncertainty is contained in Appendix 1.

3 Factors which contribute to uncertainty

This section considers the various contributory factors that influence the uncertainty of a monitoring system.

In any of the proposed regulatory MRV approaches, the emphasis is on the uncertainty of longer-term fuel consumption and CO_2 emissions. For regulatory purposes, important are: 1) the quantification of uncertainty of a monitoring system which measures fuel and CO_2 emissions and delivers data that are neither systematically nor knowingly under- or overstated and 2) identification and reduction of possible sources which could contribute to the under- or overstatement.

This differs from the reason why a ship typically monitors its fuel consumption on a periodic basis, normally at least daily, for management purposes. In this case emphasis is placed on the correctness of daily monitoring, which in turn enables meaningful analysis of technical and commercial performance trends.

Some changes to the factors that contribute to the uncertainty of a monitoring system when using fuels such as LNG, methanol and bio-fuels are likely; however, these are not discussed in this paper.

3.1 Boundaries

In determining uncertainty of a monitoring system it is common to identify factors which a ship can and cannot control.

3.1.1 Factors outside the boundary of control

In determining the boundary between control and not control, MARPOL Annex VI Regulations 14 and 18 have been considered; these define the requirements related to quantity, density and sulphur content of bunkers delivered and state that the accuracy of these parameters is not the responsibility of the ship or of the ship owner.

Therefore, it is assumed that, for the purpose of a future regulated MRV approach, the uncertainty associated with data in the BDNs would not be included in the analysis of the overall uncertainty of a monitoring system under the control of a ship, even though the data in BDNs will have a level of uncertainty.

Factors over which the ship has no control should be excluded from an analysis of the overall uncertainty of a monitoring system.

3.1.2 Factors within the boundary of control

Several factors are within the control of the ship; some may be common to one or more monitoring approaches, whilst others are specific to only one.

3.1.2.1 Factors common to all monitoring approaches

Metering equipment – manufacturers' accuracy and installation

In acquiring or using installed metering equipment, the following should be considered:

- The defined accuracy value of the meter.
- The range of standard operating conditions for the equipment.

The specific metering accuracy can only be assured if the metering equipment is installed, operated, calibrated and maintained to the manufacturer's specification[3].

User-centred design and data sources

In determining what equipment to use and where to install it, the human interface should be considered, including:

- Ease of access to sensors for reading, calibration and maintenance.
- Design and availability of data / correction tables or other similar sources.
- Manipulation of data, either manually or using IT-based software.

3.1.2.2 Factors related to on-board bunker fuel tank monitoring

Temperature of fuel

The density of the fuel is required to enable the conversion from volume to mass and is supplied on the BDN. However, the density of the fuel varies with the temperature of the fuel; therefore measurement of the temperature of the fuel is required to determine the actual density of the fuel in the bunker tank.

Weather and sea-state

Readings taken at sea and to a lesser extent in port are affected by weather conditions.

The effect this may have needs to be considered, including the paramount requirement of safety when taking readings at sea.

Heel and trim

Cargo, bunker, ballast and other operations may change the trim and heel of a vessel. The effect this may have needs to be considered, including:

- Determination of heel and trim.
- Sounding tables used to correct measurement data.

Number of measurement points

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[3] Currently no IMO requirement exists for any fuel flow or tank measurement equipment to be designed or certified to any defined level of accuracy, other than that required by class or Flag for the purposes of quantifying capacity and calculating trim and stability.

If no systemic bias exists in the measurement uncertainty of a given tank, then the number of tanks does not influence the overall uncertainty.

Fuel tank shape

Fuel tanks are often not regular in shape or uniform in size and there are internal structures inside tanks associated with hull strength requirements. The effect this may have needs to be considered, including:

- Determination of tank volume.
- Sounding tables used to determine volume.

On-board fuel management

The quantity of fuel taken on board as determined by bunker fuel tank measurements is not always equivalent to the quantity of fuel combusted. The fraction of the fuel which could contain water, sludge and other non-combustible elements needs to be considered[4].

3.1.2.3 Factors related to flow meters

Two principal types of flow meter can be used: mass flow meters (sometimes referred to as Coriolis type) and volumetric flow meters. Besides the accuracy of the flow meters themselves, additional issues (temperature and the location of the flow meter in the fuel system) need to be considered, depending on the type of flow meter used.

Temperature of fuel

The density of the fuel is required to enable the conversion from volume to mass and is supplied on the BDN. However, the density of the fuel varies with the temperature of the fuel; therefore, measurement of the temperature of the fuel is required to determine the actual density of the fuel when using volumetric flow meters.

Fuel use in boilers, incinerators and other combustion processes, e.g., inert gas generators.

It is necessary to determine which combustion processes are included or excluded.

The significance of the fuel consumption of boilers, incinerators and other combustion processes needs to be considered.

3.1.2.4 Factors for direct emissions measurement

For a monitoring system based on direct emissions measurement of the mass of CO_2 emissions, the concentration of CO_2 in the exhaust gas and the exhaust gas mass flow need to be considered.

A review of the NOx Technical Code suggests that this could be used as the basis of direct emissions monitoring.

In the NOx Technical Code two of the three methods of determining the exhaust mass flow[5] are based on the direct measurement of fuel flow and other parameters, both measured and derived, and then on the use of formulae to calculate the exhaust mass flow value.

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[4] IMO 3rd GHG Study (MEPC 67/INF3) in figure 28 provides an indication of percentage of fuel combusted in main engine, auxiliary engines and boilers for various types of ships.

[5] NOx Technical Code Chapter 5, 5.5.2 & 5.5.3.

If the exhaust flow is measured directly by instrumentation in the exhaust gas system, the NOx Technical Code requires this to be to a recognised international standard and highlights the need to take precautions: "*Precautions shall be taken to avoid measurement errors which will result in emission value errors.*"[6]

Consideration needs to be given to the actual values of accuracy for the instruments used and the method adopted in the NOx Technical Code when determining the uncertainty of a monitoring system based on direct emissions measurement, given that the range of accuracy allowed for individual measurements within the Code could lead to a high level of uncertainty.

Appendix 2 sets out the relevant uncertainty equations for the monitoring approaches discussed above.

4 Case study with an analysis of actual ship data

This section presents an analysis of data collected using BDNs, on-board bunker fuel tank monitoring and flow meters for applicable combustion processes for a fleet of ships over a 3.5-year period in order to investigate the uncertainty of the two on-board monitoring approaches. The data used are from 28 ships operated by one company, which in total equates to approximately 80 ship years of operation. Whilst the sample is long in duration, it is narrow in scope and further analysis of datasets is required to verify that this sample is broadly representative of the industry and to confirm suitable uncertainty values for fuel consumption and emission monitoring approaches across the international fleet.

The analysis calculated the difference between fuel consumption from tank measurements, which included deducting or including the BDN quantity depending on the voyage, and flow meters fitted to each ship.

The results show that for an individual ship, over the period examined, the difference in the measurements from a monitoring system based on bunker fuel tank measurement and one based on flow meters did not exceed +/- 5%. This range cannot be solely attributed to either of these fuel monitoring approaches, but represents a probable upper bound of uncertainty, as it is unlikely that the approaches cancel each other out over the period examined.

The influence of the BDN on the difference between bunker fuel tank and flow meter measurements was analysed and it was found to have negligible effect and no bias. Furthermore, the difference between bunker fuel tank measurements and flow meter measurements tended towards zero and no consistent bias was observable. This implies that neither the bunker fuel tank nor the flow meter measurements under- or overestimate fuel consumption.

On a voyage-by-voyage and a ship-by-ship basis the analysis shows that a degree of randomness and moderate imprecision is attributable to the 1) BDN, 2) bunker fuel tank soundings or 3) flow meter measurements, or to some combination of the three.

The results illustrate that improving the accuracy of a single measurement is not the only determinant of the uncertainty associated with a monitoring system based on the same sensor over a period of time.

For any one individual voyage, it is possible to regularly observe differences between the flow meter and tank measurement consumption estimates of 15-20%. This variability in the difference is also observed with consistently high standard deviations across the ships studied. This shows the difficulty of accurately monitoring fuel consumption over shorter periods of time and is likely to be

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[6] NOx Technical Code Chapter 5, 5.5.2.1.

indicative of the magnification of uncertainties when the fuel consumed is calculated as a small difference between two large numbers.

Appendix 3 provides details of the case study analysis.

5 Other considerations

It may not be appropriate or necessary to use the same monitoring approach for all combustion processes, provided that the measurement of vessel fuel consumption and emissions is correctly assessed and reported.

Consideration needs to be given to the loss of data and how this is managed and the requirements associated with any back-up approach used to ensure adequate data are available in the event of any system failure.

6 Conclusion

When considering the uncertainty related to monitoring approaches:

- It is important to review the boundaries of control when making comparisons between monitoring systems, as any change in a boundary will affect uncertainty.
- Several common and specific factors need to be considered in any evaluation of uncertainty.
- Consideration needs to be given to the actual values of accuracy for the sensors used and the method adopted (based on the NOx Technical Code) when determining the uncertainty of a monitoring system based on direct emissions measurement.
- Different fuel and CO_2 emissions monitoring approaches are not mutually exclusive and a combination would achieve the desired outcome.

Furthermore, the analysis of data for the sample of ships indicates that:

- The difference between the bunker fuel tank and flow meter measurements did not exceed +/-5% and this represents the probable upper bound of uncertainty of these monitoring approaches.
- There is no evidence that BDNs induce bias (under- or overstatement).
- Improving the accuracy of a single measurement does not necessarily reduce the uncertainty of the monitoring system.
- On a voyage-by-voyage basis a greater degree of randomness exists, which demonstrates the difficulty of accurately monitoring fuel consumption over shorter periods of time.
- Further analysis of datasets is required to confirm a suitable uncertainty value for monitoring systems across the international fleet.

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Appendix 1 – Further detail on accuracy and uncertainty

The terms ‘accuracy’ and ‘uncertainty’ are used in MEPC 65/INF.3/Rev.1.

Monitoring of fuel quantities or CO_2 emissions involves the deployment of a number of discrete measurements of fuel consumption, together with an emissions factor or by direct emissions measurement to monitor CO_2 emissions, as well as exhaust gas flow if necessary, and reporting the CO_2 emissions over a defined longer period of time (e.g., annually).

Accuracy is commonly defined as: the closeness of the agreement between the result of a measurement and a true value of the measurand. Determining the accuracy of a measurement usually requires calibration of the analytical method with a known standard.

Uncertainty is associated with the result of a measurement, and it characterises the dispersion of values that could reasonably be attributed to the measurand. It is typically expressed as a range of values in which the value is estimated to lie, within a given statistical confidence, but it does not attempt to define or rely on a unique *true* value.

1. Accuracy

A sensor can record a series of measurements over time as depicted by the red dots in Figure 1 below. The sensor can be described as having an accuracy, a term which in ISO 5725-1:1994 consists of the precision and trueness of the measurement.

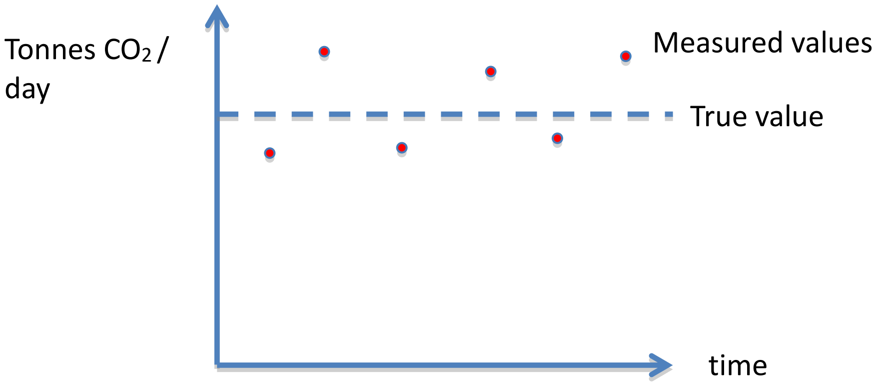

Figure 1: measured values obtained from a sensor, relative to a hypothetical ‘true value’

Precision is important when considering an individual measured value. Provided that the sensor’s accuracy is stable (does not vary over time) and linear (does not vary with magnitude), then when summing measurements over a period of time (as in the case of totalling fuel consumption or CO_2 emissions), the precision of the measurement improves as the variability observed in the measurements settles to a mean value. The mean value represents the trueness of the sensor. This can be seen in Figure 2, which includes a distribution of measurement results normally distributed about a mean value which has an offset from the reference value equal to the measurement’s trueness.

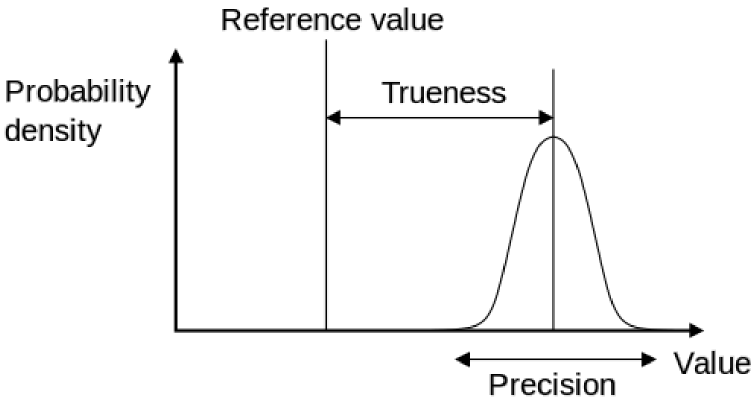

Figure 2: accuracy as defined in ISO 5725-1:1994, composed of trueness and precision

2. Uncertainty

Accuracy of sensors and individual measurements is an important component of the overall uncertainty. However, this is just one of the three components of uncertainty:

- *Measurement uncertainty* – represents the accuracy of individual sensors; high-accuracy sensors reduce measurement uncertainty.
- *Uncertainty due to variability of input parameters* – technically known as aleatory uncertainty – represents any unaccounted-for variability of input parameters to a calculation.
- *Uncertainty due to unknown errors in input parameters* – technically known as epistemic uncertainty – represents unknown components of the calculation.

The process of recording discrete measurements can also introduce uncertainty to the total.

Measurement uncertainty could occur from human error associated with the reading or recording of a sensor or due to lack of knowledge about how the measurement process was carried out.

Uncertainty due to variability of input parameters could occur, for example, due to the use of the wrong reference value for fuel density when this parameter is known to have a range of values.

Uncertainty due to unknown errors in input parameters could occur due to incorrectly installed sensors, or if there is uncertainty in the calculation of the volume of a tank, or in an approximation in the model/calculation used to convert input parameters to an output parameter, in the calibration condition of a sensor, or in the linearity or stability of a measurement procedure over time.

When outputs of multiple measurements are used in the quantification of a parameter, then the total uncertainty associated with the calculation of the total value for fuel consumption or CO_2 emissions is the total of the measurement uncertainty of every individual sensor and the uncertainties due to variability in input parameters and to unknown errors in input parameters.

Appendix 2 – Summary equations and sources of uncertainty for the four monitoring approaches

Approach	**Annual report of CO2**	**Sources of uncertainty**	**Analysis**
BDN and periodic stock take	$(ST_2 \times \rho_2 \times Cf - ST_1 \times \rho_1 \times Cf) + \sum BDN \times Cf$ *Stock take at end of year – stock take at beginning of year + sum of BDN's over year*	Measurement: volume of fuel in *ST1* and *ST2,* temperature of fuel Aleatory: density of fuel, emission factor Epistemic: *BDN* including density of fuel	ST2 – ST1 is typically small relative to sum of BDN; therefore, even if uncertainty in the stock take quantification is high, the uncertainty in periodic total is dominated by the uncertainty in the BDN
Bunker fuel tank monitoring	$\sum TS \times \rho \times Cf$ *Sum of tank readings*	Measurement: volume of fuel at each tank measurement, temperature of fuel Aleatory: density of fuel, emission factor Epistemic: density of fuel from *BDN*	As the method aggregates multiple tank measurements, even if the precision of each tank measurement is low, as long as the measurement accuracy is linear and stable, then the periodic total's uncertainty will be dominated by the trueness of the measurement in combination with the uncertainty in the fuel density and emission factor
Flow meter (volume)	$\sum FM \times \rho \times Cf$ *Sum of flow meter measurements*	Measurement: instantaneous volume of fuel flow, temperature of fuel Aleatory: density of fuel, emission factor Epistemic: density of fuel from *BDN*	As for bunker fuel tank monitoring. The uncertainty in a periodic total obtained from a flow meter will only be superior to that of a measurement obtained using tank readings if the trueness of the flow meter is superior to the trueness in tank reading measurement. An often-stated benefit of flow meters – their ability to be used to obtain high-precision and high-frequency measurements of fuel consumption – is of little importance when they are used to calculate periodic total emissions
Direct emissions measurement (method 1)	$\sum \mathrm{C\ co2w} \times \mathrm{qmew}$ *Direct measurement of emissions by multiple of exhaust gas constituent concentrations and exhaust gas mass flow rate*	Measurement: instantaneous exhaust gas constituent concentrations and exhaust gas mass flow rate	The potential of the uncertainty of a periodic total obtained from this direct emissions measurement to be lower than other methods relies on the method's measurement uncertainty (dominated by the accuracy, particularly trueness, of the sensors) being lower than the uncertainty associated with the use of standard/reference emission factor values

Approach	Annual report of CO2	Sources of uncertainty	Analysis
Direct emissions measurement (method 2, air and fuel measurement method)	$\sum C_{co2w} \times (q_{maw} + (FM \times \rho))$ *Exhaust mass flow calculated by sum of air mass flow into combustion process and fuel mass flow.* *Direct measurement of emissions by multiple of exhaust gas constituent concentrations and exhaust gas mass flow rate*	Measurement: instantaneous exhaust gas constituent concentrations, air flow mass flow rate, volume of fuel flow, temperature of fuel Aleatory: density of fuel Epistemic: density of fuel from BDN	The potential of the uncertainty of a periodic total obtained from this direct emissions measurement to be lower than other methods relies on the method’s measurement uncertainty (dominated by the accuracy, particularly trueness, of the sensors combined with the use of some standard/reference values) being lower than the uncertainty associated with the use of standard/reference emission factor values
Direct emissions measurement (method 3, fuel flow and emission balance method)	$\sum C_{co2w} \times FM \times \rho \times W \times C_{xw}$ *Exhaust mass flow calculated from fuel mass flow, fuel composition and raw exhaust gas concentrations.* *Direct measurement of emissions by multiple of exhaust gas constituent concentrations and exhaust gas mass flow rate*	Measurement: instantaneous exhaust gas constituent concentrations, volume of fuel flow, temperature of fuel Aleatory: density of fuel, fuel composition Epistemic: density of fuel from BDN	The potential of the uncertainty of a periodic total obtained from this direct emissions measurement to be lower than other methods relies on the method’s measurement uncertainty (dominated by the accuracy, particularly trueness, of the sensors combined with the use of some standard/reference values) being lower than the uncertainty associated with the use of standard/reference emission factor values

Key:

Symbol	Term
ST_x	Stock take of quantity of all fuels on-board at time x
ρ_x	Density of all fuels (at time x) corrected for temperature
BDN	Bunker delivery note
Cf	Emission factor of all fuels
TS	Measurement of fuel volume consumed by taking the difference of temporally adjacent tank measurements
FM	Cumulative volume flow meter reading
C_{xw}	Exhaust gas constituent concentrations
C_{co2w}	Concentration of CO_2 in the exhaust
q_{mew}	Exhaust mass flow rate
q_{maw}	Air mass flow rate
W	Fuel oil composition of all fuels to calculate gas mass flow

Appendix 3 – Case Study Analysis

1. Introduction

Data analysis was undertaken using a set of measurements of fuel consumption based on a fleet of 28 ships.

Ideally, a control dataset that defines a benchmark approximating ‘the truth’ (as discussed in Figure 1) would have been used to assess, one by one, the uncertainty of each of the four monitoring approaches. However, in the absence of such a dataset, the analysis was undertaken based on a fleet of ships for which three different monitoring approaches were used to gather data:

- BDN.
- On-board bunker fuel tank monitoring.
- Flow meters for applicable combustion sources.

The dataset also provides insight into the uncertainty implicit in BDN. No data were available to consider the uncertainty of the direct emissions measurements.

The specifics of the approach used to produce the data in this analysis are described below.

Data were obtained for 34 vessels, all of similar type. Six ships were discarded because of shortage of data or a perception of irregularities, leaving a set of 28 vessels on which the calculations were performed. The data covered a total period of between 2 and 3.5 years, depending on the ship.

The bunker fuel tank measurements are undertaken periodically and only when the ship is in port. Some measurements are taken coincident with the receipt of bunker fuel. The bunker fuel received is defined from the measurement before and after the bunkering operation, but because only the measurement after bunkering is reported, the pre-bunkering measurement is estimated by subtracting the record of bunkers received (recorded on the BDN) from the measurement post-bunkering. Both flow meter and tank measurements are of tonnes.

2. Analysis approach

The study compared the values obtained from the two approaches by calculating a % difference, *d* , for each period between adjacent tank measurements.

$$d = \frac{(TS_1 - TS_2) - \sum_1^n FM}{0.5 \times \left((TS_1 - TS_2) + \sum_1^n FM\right)} \times 100$$

Where TS_1 is the measurement at the beginning of the period and TS_2 is the measurement at the end of the period. The flow meter readings are taken daily, and to calculate a fuel consumption equivalent to that found from the difference between adjacent tank measurements, summed over the period of *n* days.

A filter was also applied discarding calculations of *d* greater than 20% or less than -20%, as these were deemed likely to be spurious and the result of data reporting errors (e.g., the recording of data in the spreadsheet used to collate the measurements, most likely associated with a mistype of the amount or of the date the measurement was taken). These errors were identified from when the record of the BDN did not match with the tank measurement that it coincided with, and with such a high magnitude that they are assumed to be due to data management issues rather than incorrect information in the BDN.

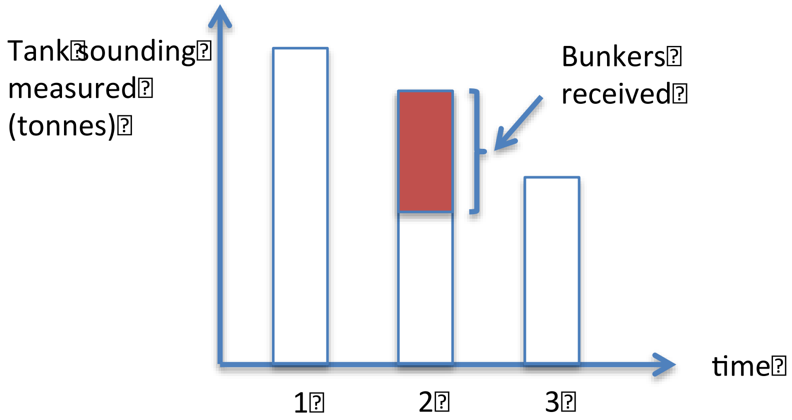

Figure 3 - Diagram to show the integration of the quantity of bunkers received with a tank measurement

Due to the integration of the bunker quantity in the total tank content's quantity measurement, there is an additional element in the uncertainty when these tank measurements are used for estimation of fuel consumed in the voyage before and after the bunkering operation. This is shown diagrammatically in Figure 3. The quantity of bunkers received is deducted from the total tank measurement according to the amount listed on the BDN. If the BDN is of lower accuracy than the standard measurements performed by the crew, or introduces a systemic bias, then this would influence the calculation of *d*. For example, referring to Figure 3, a bias towards an over-reporting of bunkers received on the BDN would increase a measurement-based estimate of fuel consumed between time 2 and time 1 and decrease the same estimate performed between time 3 and time 2.

3. Analysis result

Figure 4 displays an example set of results for one of the 28 ships examined. Calculations were obtained for 35 periods (representing 36 discrete measurements). The upper graph displays the difference, *d*, calculated for each period/measurement in time sequence (e.g., earliest data corresponding to measurement reference 1 and most recent data corresponding to measurement reference 35). The same data are displayed as a histogram in the lower graph. This specific ship had a mean value of *d* of 0.13%, a median value of *d* of 0.63% and a standard deviation of *d* of 8%. The difference d for any one measurement comparison was observed to be as large as ~15% (which is reflected in the high value for the standard deviation).

However, both the shape of the distribution and the low (absolute) mean and median show that when multiple measurements are combined, the % difference is significantly smaller and there is no clear indication of any significant bias that might be representative of drift in the flow meter or poorly calibrated tank measurement data.

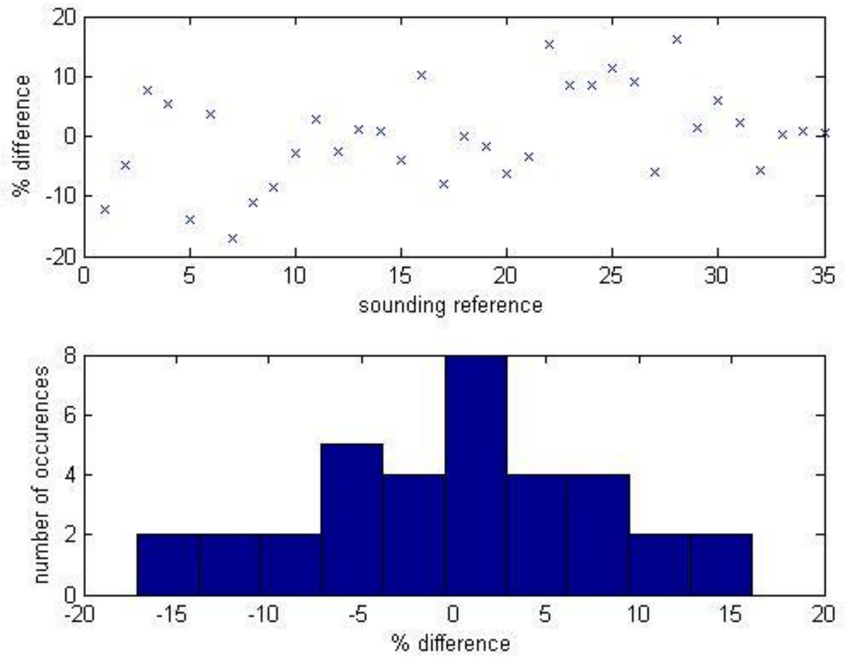

Figure 4 - *d* calculations for vessel 1

Figure 5 displays further analysis of the calculated values of *d*, plotting *d* against the estimated quantity consumed between measurements (upper plot), and also the absolute level in the tank (lower plot). The data show that as the quantity consumed between measurements increases, the absolute value of *d* appears to decrease. This could be indicative of the dominance of the uncertainty in calculations of fuel consumption using tank measurements (absolute uncertainties can be exacerbated for a value calculated as the difference between two uncertain values of similar magnitude, but this absolute uncertainty reduces as the difference between the two values increases). However, when looked at for other specific ships, this particular trend (reducing % difference with increased duration), was not always visible, and further work on the data would be needed in order to determine whether the implied relationship was statistically significant).

There does not appear to be any clear trend identifiable in the relationship between the % difference and the total tank contents. It was thought that it might show an increase at lower values of total tank contents, where a small absolute difference (in tonnes) becomes a large % difference. However, this is not visible for this vessel or with any consistency across the 28 vessels analysed.

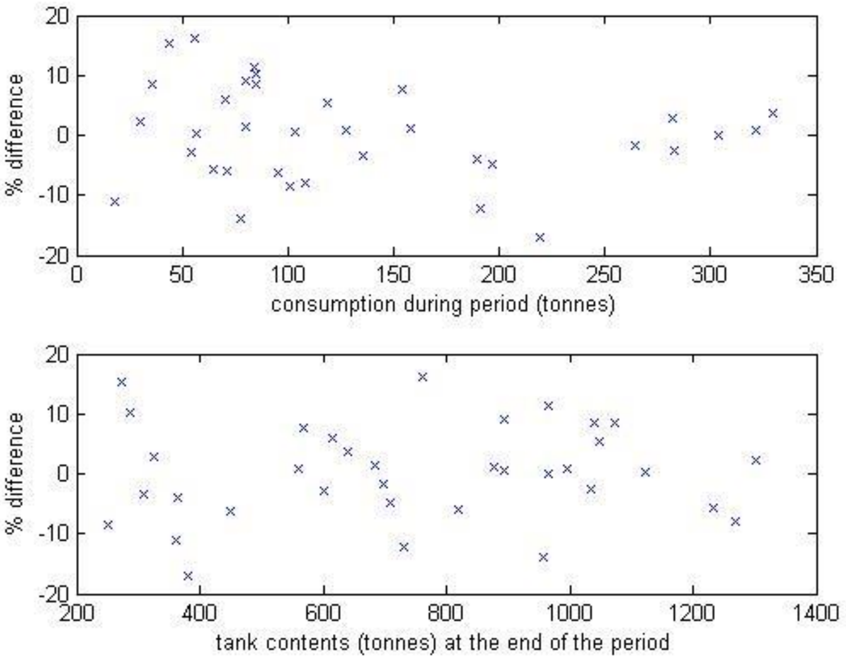

Figure 5 - further *d* calculations for vessel 1

Figures 6, 7 and 8 display the results for all 28 ships: the mean, median and standard deviation percentage difference, *d*, respectively, for the full period (2 to 3.5 years in duration and between 10 and 70 tank measurement references per ship over that period).

The inconsistency between the mean and the median is indicative of the distributions of *d* not being perfectly Gaussian or symmetrical, although in most instances the inconsistency is comparatively small.

For this fleet, we see that the range in both mean and median is encompassed within +/- 5%, and that there does not appear to be a consistent bias across ships, with the mean of the 28 mean differences being -0.1%. That is to say that some randomness and moderate imprecision are attributable to either the BDN, the flow meter or the tank measurement, or some combination of the three measurements, but when viewed as an aggregate across a fleet of ships, the average difference is very close to zero.

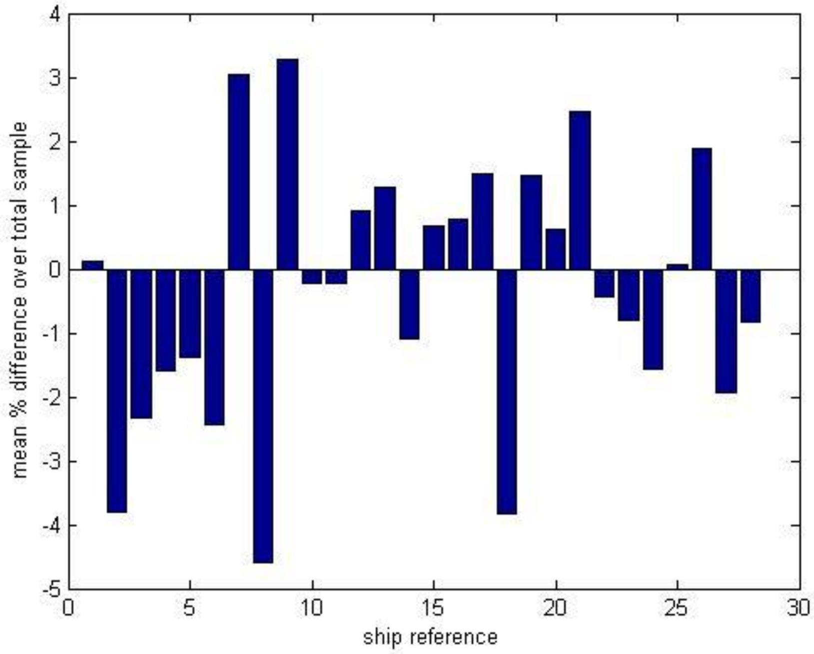

Figure 6 - Mean *d* for each of the 28 vessels studied

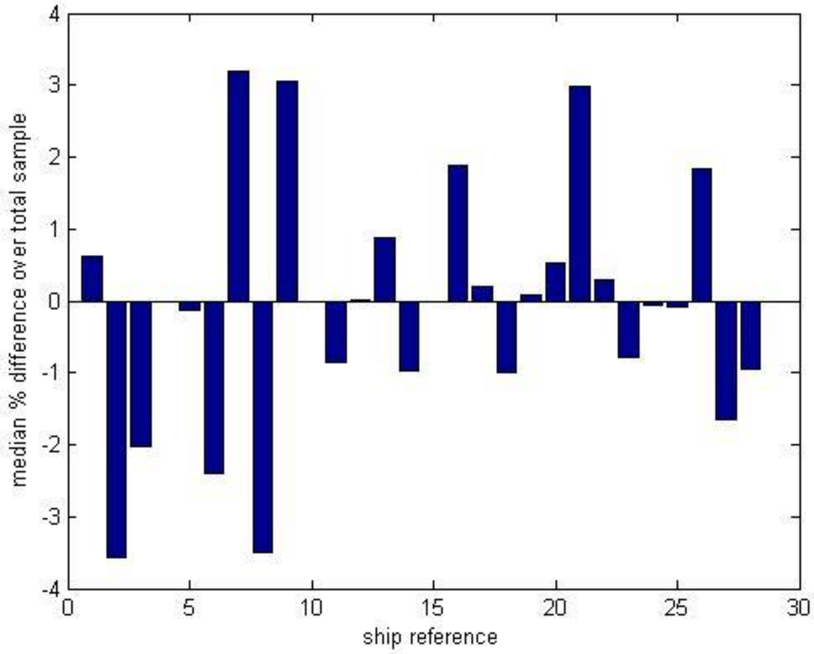

Figure 7 - Median *d* for each of the 28 vessels studied

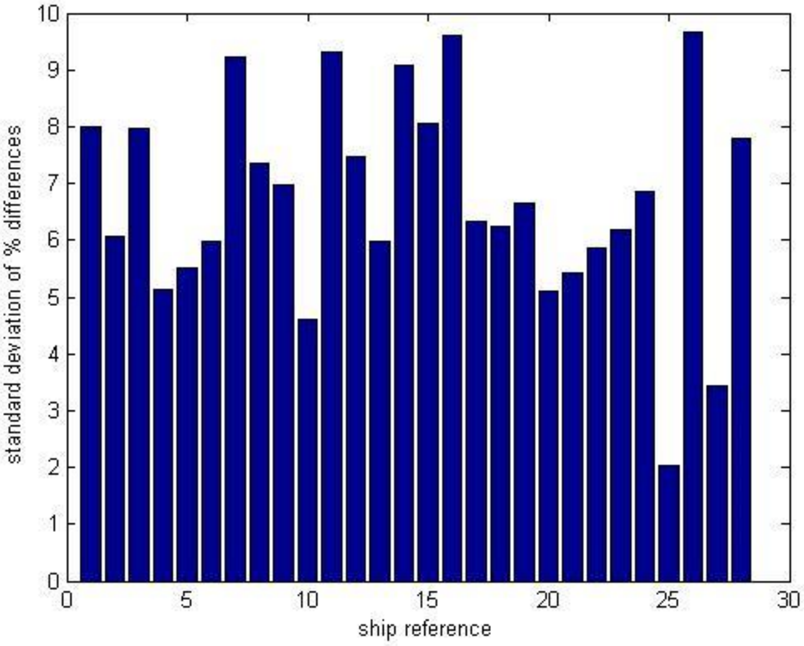

Figure 8 - Standard deviation of *d* for each of the 28 vessels studied

In an attempt to understand whether the BDN has a significant influence on the uncertainty of the fuel consumed (when tank measurements are used to calculate fuel consumed), the values of d associated with three different categories of tank measurement were collated from all 28 ships analysed above. The three categories of voyage relate to the diagram in Figure 9 and are:

- Bunkering operation after the voyage, BDN fuel quantity removed from the end of voyage/bunkering tank measurement.
- Bunkering operation before the voyage, tank measurement which could have been used in the validation of the BDN used as the start of voyage tank measurement.
- No bunkering operations adjacent to the voyage.

Figure 9 and Table 1 display the histograms of the three categories, and tabular data describing each dataset. Small differences are observable in the distributions and the tabular data; however, taken in the context of the sample sizes, these differences are not strongly significant.

This analysis therefore implies that the BDN appears to have no substantial influence on the uncertainty of the tank measurement in either direction – it neither increases nor decreases the uncertainty (standard deviations are constant for all three categories), nor does it apply any bias to the tank measurement (mean and median are approximately constant for all three categories) which would be expected if it was thought to be a significant under- or over-representation of the quantity of fuel consumed.

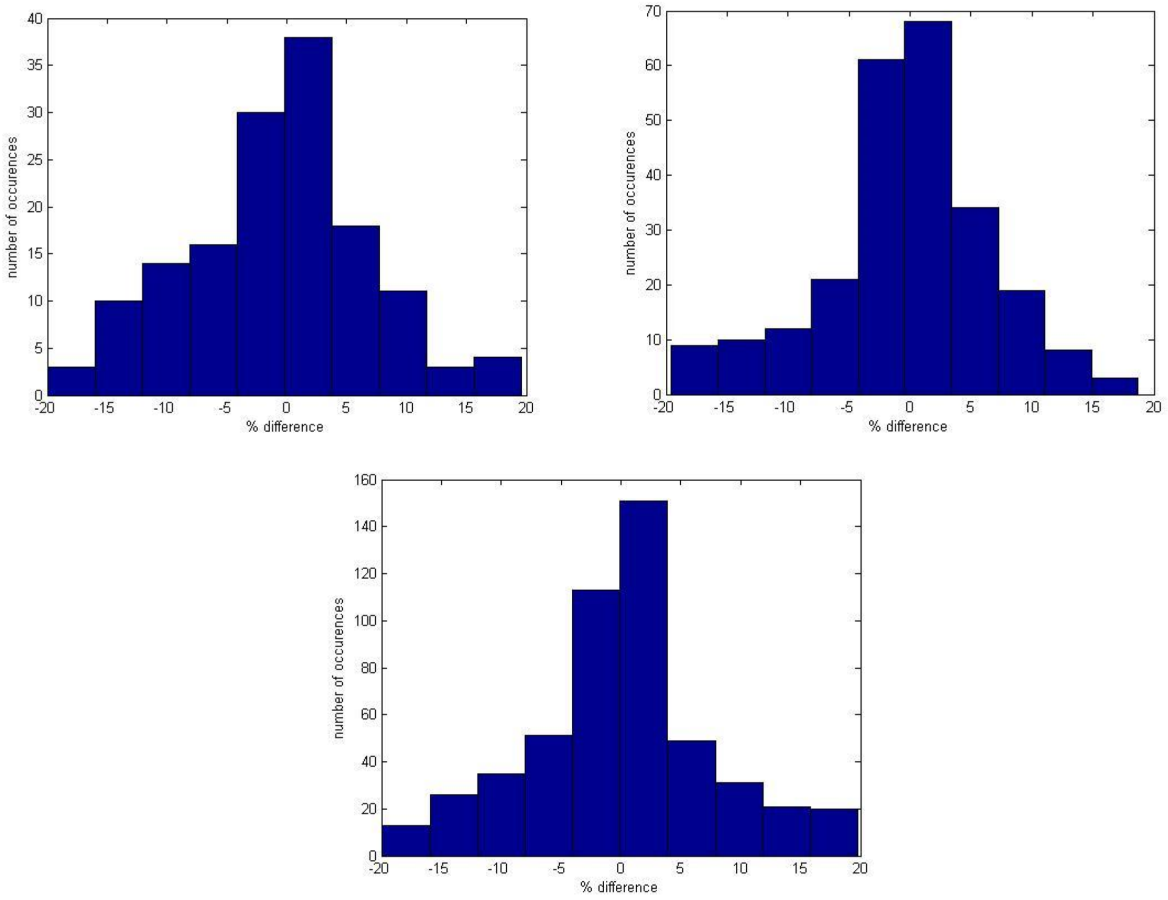

Figure 9 - Distributions of the parameter *d* for the three voyage categories: bunkering after the voyage (top left), bunkering before the voyage (top right), no bunkering adjacent to the voyage (bottom)

Table 1 - tabular mean, median, standard deviation and sample size

	Mean *d*, %	Median *d*, %	Standard deviation of *d*, %	Sample size
Bunkering after voyage	-0.9	-0.1	7.7	147
Bunkering before voyage	-0.4	0	7	245
No bunkering	-0.1	0	7.7	510