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# Influence of Various Trim Conditions on Vessel's Fuel Consumption

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***Abstract:*** ***Shipping companies, operators and mariners underestimate the importance of trim to the factors such as company's budget expenditure, vessel's fuel consumption and environmental pollution. As the result, negative effect on those factors due to inefficiently trimmed ship arises. Therefore, the objective of this thesis is to verify the role of vessel's trim on fuel consumption and determine the optimum trim value for different types of ships at different conditions. The trim of the ship is important both to carry the maximum amount of cargo safely and maximise the fuel efficiency of the ship. Two main factors affect the trim - one is the shape of the underwater form of hull/water plane area at the particular draft and the other is the distribution of weights such as ballast water, cargo and fuel in the vessel. The influence of trim on fuel consumption is hydro-dynamically related to the ship's resistance. Thus, as a vessel adjusts her angle of trim, the total resistance also changes. As the result, for the ships with the same deadweight and speed ratio, the total fuel expenditure can vary considerably. Therefore, depending on resistance a ship experiences, the optimum trim condition can be obtained. This manuscript clearly indicates that each vessel is unique and has an individual approach that should be applied to achieve the most efficient condition of sailing. Thus, for a fishing boat, it is essential to maintain zero trim or little trim to fore, while for unloaded container ship the optimum trim is achieved at 3 meters by the stern. For VLCC and passenger ship, however, the optimum position is reached at the same value of trim, namely 1-meter aft trim. Applying the results of conducted experiments, the optimum trim condition can be obtained and unnecessary losses of shipping company will significantly be reduced. Moreover, efficiently consumed fuel will allow decreasing the amount of gas emissions produced, reducing the negative effect on the environment. Furthermore, to sharpen the understanding of the role of trim of fuel consumption, it is recommended to study the influence of various angles of trim on fuel efficiency while the different types of ships maintain constant draft.***

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## I. INTRODUCTION

In today's eco-focused and high fuel prices, world vessels should aim to operate in the most energy efficient way in order to consume as little fuel as possible (Radwan et al., 2019). The trim configurations should be optimized to reduce the total operating cost but also to lower the amount of exhaust gas emissions, by that improving environmental conditions.

The inefficiency of trim configuration represents a significant financial burden for the shipping industry. On average, improper trim hourly can cost as much as 0.6 tons more fuel than correctly maintained one (Büssow, 2011), resulting in a total of about 15 tons of wasted fuel per day. If shipping company buys a bunker fuel in Rotterdam where the price for 1 ton of heavy fuel oil is close to 280$ by 2017, this represents a loss of $4,200 per day, or roughly $1,200,000 per year (with 285 days at sea).

Unfortunately, the literature review (Clark, 2005; Moustafa et al., 2015; Reichel et al., 2014; Veenstra, 2002) states that there is a gap in the knowledge, namely not every vessel realises that being one of the operational parameters, trim greatly influences the fuel consumption. Not maintaining proper trim leads to unfavourable conditions such as increased expenses for shipping companies and growth in gas emissions. There are various ways to improve ship energy efficiency. By applying these methods, the dual advantage will be achieved and the aforementioned problems will be eliminated. All shipping companies will benefit largely from the strengthening of fuel efficiency. For instance, more than 1 million dollars in estimated annual savings can be re-directed to new sources of incomes, such as expanding company's selection of ships to high-demand markets. In addition, the upcoming environmental regulations on sulphur oxides, nitrogen oxides and greenhouse gases will exert an additional impact on gas emissions permitted to be sent out (Baldi et al., 2015). However, by optimizing vessels' trim the reduction in gas emissions will be imminent.

The research focuses on the verification of the influence of different vessels' trim conditions on fuel consumption and determination of an optimum trim; factors such as speed and draft are also taken into account. The results are relevant to the most of shipping companies and mariners as they will receive a practical instrument that enables to significantly reduce ships' fuel consumption and the amount of gas emissions produced.

They underestimate the importance of trim to the factors such as company's budget expenditure, vessel's fuel consumption and environmental pollution.

The aim of the study is to verify the influence of various trim conditions on vessel's fuel consumption and determine the optimum trim value for different types of ships at different loading conditions.

## II. METHODOLOGY & LIMITATIONS

Four different types of ships were targeted to be researched in order to achieve the set goal of this study, namely to discover the relationship between various trim configurations and fuel consumption and find an optimum trim which leads to less resistance and fuel usage. The relation between the fuel expenditure and ship's speed at various loading conditions was also studied. All the ships were examined at both different trim angles and speeds, by that the resultant fuel consumption was recorded. The data obtained from those experiments was converted to the diagrams representing the relation between trim and fuel consumption. It is likely that for various loading conditions the fuel consumption is different, therefore some of the model ships provide an opportunity for the user to make a selection between either 'loaded' or 'unloaded' conditions.

Among other different designs, the experimental investigations were selected as the most adapted approach for this manuscript. The choice of the other designs is unlikely owing to some reasons. First of all, tank testing is impossible to conduct due to the fact that there is no available laboratories and installations in the area of research execution. Furthermore, computational fluid dynamics method is also not relevant because of the lack of software and facilities available in the dislocation of researcher. Thus, because all the experiments within this research are based on simulator runs, the results directly depend on the accuracy of the hydrodynamic models presented by Kongsberg Company.

### A. Fishing boat – unloaded condition

The first vessel to be examined was the fishing boat with no cargo on board. Each trim condition was tested at 2 different speeds: "half ahead" and "full ahead". The results for this ship are presented in Appendices B and C. From the both graphs it can be observed that the larger the trim to the aft, the higher the fuel consumption. In relation to "full speed", it is worth mentioning that the difference between the highest and lowest trims is 21.1 kg of fuel per hour, meaning 506,4 kg per day. Such a big difference causes a huge amount of losses for a shipping company. This also means that ship produces many emissions, which negatively affect the environment. The most economical trim, as referred to the chart, is 0.1 meters to bow, where the fuel consumption equals to 472.1 kg/hour. However, as a fishing boat trims more to forward, the expenditure of fuel rises dramatically, being 473.7 kg/h and 476.9 kg/h for 0.2 m and 0.4 m trim respectively.

Concerning the "half speed" graph, one can state that this chart has some similarities as well as differences with the "full speed" graph. Firstly, the trend of decreasing fuel consumption with reducing aft trim is analogous. However, here the distinction between extreme points is less being 9.8 kg an hour. The lowest fuel consumption in this condition is observed when the vessel is trimmed by the bow to 0.1 meters. Again, as with Appendix B, fuel expenditure, thus gas emissions increase with the increase of forward trim. Another important point of attention is that while a fishing boat produces 11.6 knots at half speed, it sails with 14.2 knots with full speed, meaning that less than extra 3 knots of speed require almost twice as much fuel as in the situation when ship proceeds at half speed.

From the tests conducted it was commented on the fact that the total fuel consumption decreases with moderate trim by bow, while in the trimmed by the stern condition it increases. This occurs probably because of the deduction of the wetted surface that results in lower total resistance and better functionality of the bulb due to immersion. Moreover, the form of the vessel in the trimmed by bow condition alters the wave formation at the stern, thus reducing the wave resistance (Guedes Soares & Lopez Pena, 2013). Furthermore, the resistance of the vessel when trimmed by stern increases greatly, due to an increase in the waterline's length, producing bigger waves, thus, increasing the wave resistance. It must be noted that the emergence of the bow section of the ship leads to a higher concentration of the underwater volume in the bow that usually improves the hull's performance.

### B. Fishing boat – loaded condition

As the fishing boat provides an opportunity to choose between loaded and unloaded conditions, it is essential to examine the operational process of the ship loaded with 665 tons of cargo on board. Same as unloaded vessel, the fuel consumption of this boat was tested with 2 various speeds corresponding to 10.5 knots for half speed and 13.0 knots for "full ahead". As it can be observed from Appendices D and E, for the loaded fishing boat it is more efficient to maintain little trim by fore or aft rather than having big draft difference prevailing to bow.

In relation to "full ahead" condition, the difference between optimum and non-optimum trims can reach enormous values, namely 50 tons of fuel per hour that will negatively affect the ship performance, total expenditure of shipping companies and environmental conditions. The most efficient trim is at 0.1 meters by fore where total fuel consumption equals to 609.2 kg/hour. In addition, even 0.7 meters aft trim does not highly differ from optimum trim being 614,4 kg an hour.

Another point of consideration is the fuel consumption of loaded fishing boat proceeding at half speed. Here, even though the total fuel consumption is close to the half of "full speed" condition, the expenditure of bunker oil extremely rises with forward trim. In this situation, the most economic trim value comes to stop at 379.4 kg/hour.

Generally, Appendices D and E have nearly the same tendency suggesting the fishing boat in a loaded condition to maintain no trim or a little trim to fore or aft. It is worth mentioning that comparing loaded and unloaded vessels, the former consumes almost 1.5 times more fuel than the other one. This is because loaded ship experiences much more resistance rather than unloaded one.

According to the results, the resistance in the trimmed by bow condition is lower than in the opposite condition. This occurs probably because of the deduction of the wetted surface area that results in lower frictional resistance. However, due to improper immersion of the propeller when vessel suffers from exceeding forward trim, the fuel consumption rapidly rises.

### C. VLCC – loaded condition

The second vessel to be examined was VLCC with the initial draft of 8.43 meters.

Due to the limitation of the simulator, only loaded condition was available during experimental stage. The big advantage of this ship is that it has "Nav Full" speed indication that allows test executor to make investigations at three different speeds. The results and process of examination are shown in Appendices F, G and H.

Starting from the investigation of the behaviour of VLCC at "Nav Full" speed (Appendix F), generally, it is clearly observed that with an increase in aft trim the fuel consumption also rises. When a ship's trim become close to zero, expenditure of fuel drops and reaches its minimum value. However, as soon as VLCC trims forward its level of oil consumption extremely grows. The most intriguing thing in this research is that when VLCC reaches 1.7 m trim to bow, fuel consumption suddenly falls and it decreases until 3.68 $m^3$ an hour at 3.1 m forward trim. This result could be related to the limitation based on simulator's performance. However, McKinsey and Company who stated that forward trim could save fuel by 3% for tankers (Baik, 2016, p. 17) achieved the analogous result. However, with further increase in draft difference prevailing to bow, vessel's expends rise.

The biggest fuel consumption is caught at two points, namely 1.7 and 3.8 m trim by the head, where it equals to 3.90 $m^3$/hour. The lowest expenditure of oil is when the difference between the aft and forward drafts equals to 0.5 meters. At this condition, VLCC consumes 3.38 $m^3$ of fuel per hour. So, the total variation between highest and lowest points is more than 0.5 cubic metres of fuel hourly, that is the big difference which produces a negative effect on environment and shipping company's budget. Following the graph further, as soon as it reaches the second highest point at 3.8 meters forward trim, the line goes down but does not meet the minimum value of fuel consumption. It is obvious that VLCC will have never maintained 5 meters trim but as per the scope of this research, various trim conditions and situations are taken into account to show the transfiguration of different unexpected solutions.

Concerning the "full ahead" situation, the tendency of this graph has more differences rather than similarities with the chart mentioned above. In total, it can be observed that fuel consumption does not change while ship maintains trim by the stern and significantly vary with the difference in draft prevailing to forward.

As Appendix G shows, the total fuel consumption varies from 2.81 to 2.84 $m^3$ per hour when the ship at 1-meter aft trim and 0.5 meters trim by bow respectively. Further, with an increase of forward trim, expenditure of fuel also rises dramatically. The first extreme point is reached when VLCC is trimmed by 2.5 meters by the head and this situation requires a ship to expend 3.26 $m^3$ of fuel oil hourly. However, with next 20 cm of trim the fuel consumption rapidly decreases until its value stops at 2.97 $m^3$/hour.

As an increase in forward trim continues, the graph goes up as well. Starting from 2.7 meters trim the fuel consumption only rises and even can become equal to 3.5 $m^3$ per hour. It is worth mentioning that VLCC consumes the same amount of fuel at the same trim but with "Nav Full" speed.

Here, an important point of consideration is that a vessel sailing at 14.8 knots ("Full ahead" speed) spends 3.1 cubic metres of fuel per hour on average, while ship sailing with 15.4 knots ("Nav Full" speed) expends 3.65 $m^3$ of the same fuel as a standard. Therefore, to gain 0.6 extra knots VLCC will need to consume 0.55 $m^3$ more fuel, which is as a general rule is not efficient. Another interesting fact about this graph is that the maximum fuel consumption of a vessel maintaining full speed is approximately equivalent to the minimum fuel consumption accessible by a ship proceeding at "Nav Full" speed.

From this experiment, it is concluded that the difference between maximum and minimum points of fuel expenditure amounts to 0.7 cubic meters hourly and, as per the data mentioned in a theoretical framework, such a variation causes 15.000 tons of $CO_2$ emissions per year. This huge amount of gases seriously affects the environment. To prevent terrible consequences, it is necessary for VLCC to maintain optimum trim, which is equal to 0.5 meters by the stern.

Looking at the graph of VLCC sailing at half speed, it can be seen that a chart mainly reproduces the tendency of "full ahead" diagram with minor differences. Starting from 1-meter aft trim up to 0.5 meters by head a vessel keeps constant fuel consumption of 1.63 $m^3$ per hour. Looking forward, it is worth mentioning that this value corresponds to the optimum value of trim. The following growth of bow trim will lead to increased expenditure of fuel which will fluctuate until a ship is at 2.5 meters forward trim. From this point, the next 10 cm of trim a vessel consumes 0.2 cubic meters of oil less. However, as with "full ahead" graph the succeeding bow deepening will bring slowly increased fuel consumption.

The ship maintaining "half ahead" does not steadily magnify her fuel rate but erratically. The graph's fluctuation starts as ship sinks by bow deeper than 0.5 meters. Moreover, in accordance with Appendix H, the maximum rate of fuel spending is 1.9 $m^3$ per hour, which is twice as little as the maximum fuel consumption while the ship is at "full ahead" speed.

Another important experimental output is that the lower the speed the fewer changes in fuel consumption vessel suffers from when it is trimmed. The reason for that is while sailing at slow speed, vessel experiences less resistance, thus fewer losses which could affect her performance.

### D. Container vessel – unloaded condition

The next vessel to be experienced is container vessel. The program installed to a simulator allows to choose between loaded and unloaded conditions. The latter condition was studied first.

As with VLCC, container ship provides an opportunity to examine it at three different speeds, namely "Nav Full", "Full Ahead", and "Half Ahead". The results of this experiment are available in Appendices I, J and K.

Starting from the highest approachable speed which equals to 27.4 knots (Appendix I), it can be stated that container ship has a very clear trend showing where vessel experiences minimum or maximum fuel consumption rate. Generally, it is more efficient to maintain aft trim rather than forward because while container ship sails at trim by stern her engine burns less fuel.

Regarding the most efficient trim condition possible for a container ship, according to the outcomes of an investigation, vessel spends the least amount of fuel at 2.5 to 3.0 meters aft trim. Whereas ship maintains this trim, the total fuel consumption equals to 7.34 tons hourly.

A very interesting appearance can be concluded from the results of this experiment, specifically while container vessel sails at even keel condition; it consumes the same amount of fuel as if it is trimmed by stern at 4.6 meters. Moreover, the difference between even keel and optimum trim conditions is 0.24 tons of fuel per hour. Such a huge diversity of fuel consumption causes an extremely negative effect for the environment, namely 5.500 tons of $CO_2$ emissions produced. Furthermore, shipping companies suffer great financial losses due to this fact. As a vessel sinks by bow deeper than optimum trim, fuel expenditure steadily rises. At 1-meter trim by the stern, it equals to 7.52 tons/hour. Further, it increases even more being 7.66 and 7.70 tons per hour for 0.5 and 1 meters forward trim respectively. Consumption of oil reaches 7.8 tons when the vessel is trimmed by 1.5 meters and 7.85 tons at 2 meters trim. Later vessel experiences even more losses.

Moving to "Full ahead" condition illustrated in Appendix J, the tendency of the graph shows nearly the same outcomes as the previous figure (Appendix I). Clear and explicit trend indicates how container vessel should be trimmed to perform at its best.

The lower the speed the less the fuel losses – it is the first outcome that comes from this investigation. Furthermore, as the ship reduces its speed the difference between optimum and non-optimum trims goes down as well.

Starting from the maximum trim by stern, which is equal to 4.6 m, where fuel rate is equivalent to 3.91 tons per hour, and moving to forward, container ship spends less fuel, reaches its optimum value at 2.8 meters trim by the stern, and stays constant up to 1.9 meters. At those points, fuel expenditure throughout the whole test was the least and equals to 3.81 tons/hour.

Subsequently, as a container vessel sinks deeper into the water by bow, the fuel rate rises. Increased resistance and less submerged propeller explain it. From this moment, the fuel consumption line only goes up at a stable rate. Before even obtaining even keel position, at 0.7 meters trim the line passes the same fuel consumption point as it is on maximum aft trim. It is worth mentioning that when the difference in drafts is zero, a ship expends 3.93 tons of oil hourly.

Concerning the further increase in fuel rate, at 1.5 meters forward trim vessel reaches 4 tons of oil consumption and at 2.2 meters it attains 4.08 tons. Thus, in Appendix J, the difference between the maximum and minimum fuel consumptions is 0.27 tons of fuel every hour, which daily gives approximately 6.5 tons and annually 2.3 thousand tons of oil. This fact again demonstrates the statement that by optimization of trim the fuel consumption, thus the money spent on it could be saved.

With respect to container ship sailing at 16.9 knots, the speed which corresponds to "Half ahead" indication on telegraph, this experiment supports the idea that the lower the speed a vessel maintains the less the difference in fuel consumption when the ship is trimmed. Difference between the highest and lowest fuel expenditures, as per this experiment, is 0.13 tons per hour. Moreover, throughout the whole process of investigation consumption of fuel varied very slowly.

Furthermore, the distinction between the quantity of fuel spent at highest aft trim and even keel condition amounts to only 0.03 tons per hour. Particularly, at 4.6 meters, aft trim a vessel hourly spends 1.9 tons of oil and with zero trim, it consumes 1.93 tons. However, before actually reaching even keel condition, a container ship maintains a difference in drafts where her fuel expenditure is minimum, namely starting from 3.6 up to 1.8 meters trim by stern a ship's engine needs to burn 1.87 tons of fuel per hour to sail at "half ahead" speed. In all respects, while a vessel maintains the trim between 3.6 and 1.8 meters, the voyage it executes will proceed optimally.

Subsequently, as a ship submerges deeper by bow, it experiences little more resistance, thus a fuel required to sail at 16.9 knots insignificantly rises. Appendix K proves this showing that at 1.5- and 1.0-meters aft trims the fuel consumed equals to 1.88 and 1.90 tons respectively.

When the difference in drafts prevails to bow, the total expenditure of fuel increases even further. To be precise as soon as a container ship is trimmed by 0.5 meters forward, it spends 1.94 tons of fuel. In addition, at 1.0 and 1.5 meters bow trim experimental ship hourly consumes 1.95 and 1.97 tons of fuel oil accordingly. The maximum amount of fuel that is burnt by container ship's engine is at 2.2 meters trim by bow. At that point, the hourly consumption is equal to 2 tons of fuel.

From the results of the experiment conducted with model container vessel, it is worth mentioning that these outcomes are completely different compared with the others. Up till now container vessel is the only ship which optimally sails having 2 to 3 meters trim by the stern. This again confirms the fact that each ship is unique and individual approach should be discovered for any of it.

### E. Container vessel – loaded condition

As the potential of Kongsberg simulators permits, loaded container ship is also considered within the scope of this research. Experiments at three various speeds were conducted to examine the influence of trim on fuel consumption at this particular condition. Looking ahead, it is worth mentioning that the results of experiments conducted with loaded container vessel differ from its unloaded prototype.

The maximum aft trim available for this particular ship is 1,4 meters. Regarding the ship sailing at "Nav Full" speed, the fuel consumption at this point is 9.3 tons per hour. As Appendix L shows with reduction of aft trim, the fuel spent by container ship decreases as well. The first 30 cm of trim the line goes down drastically, later it experiences much smoother decline. When the vessel reaches even keel condition, it consumes 9.06 tons of oil hourly, which is much more efficient comparatively to maximum aft trim. However, this value is not even the optimum fuel consumption of container ship.

The optimum expenditure of fuel oil is reached when the ship is trimmed by bow, namely at 0.2 - 0.4 meters. At those trim conditions, the ship spends the least amount of fuel, equaling to 9.03 tons per hour. As the ship sinks deeper by bow, it experiences more resistance, thus it consumes more fuel. Analyzing Appendix L, line rises slowly but steadily. At 2.9 meters trim by head fuel consumption line reaches the peak where it equates to 9.22 tons per hour. An interesting fact is that at 1,4 meters stern trim (maximum aft trim) a container vessel consumes more fuel that at 2,9 meters by bow (maximum forward trim).

Moving down the telegraph to "Full Ahead" position and adhering the same procedures as described above, the outcomes presented in Appendix M can be retrieved. First, as a container ship is fixed at the maximum trim by the stern, it consumes 4.65 tons of fuel hourly. Later, correspondingly to "Nav Full" chart, as a vessel sinks deeper by bow, initially fuel consumption reduces rapidly but subsequently flows very calmly. Actually, at some points, a container vessel maintains the same fuel consumption continuously.

The optimum trim condition is reached when the ship is at even keel. From zero trim to 0.4 meters, it spends 4.54 tons of fuel hourly. However, further immersion by bow causes increased expenditure of fuel. Thus, at 0.7 meters forward trim, a vessel consumes 4.55 tons of oil. Further growth of trim prevailing to bow induces higher consumption of fuel. The maximum fuel consumption is reached at maximum trim by the head, namely vessel sailing at 2.9 meters trim spends 4.64 tons of fuel oil hourly. At this situation, the fuel consumed at the maximum trim aft and maximum trim forward nearly equal to each other. Comprehensive description is available in Appendix M.

As it was mentioned before, the slower the speed the less the variation in fuel consumption when a ship is trimmed. As the evidence, the graph illustrating the behavior of a container vessel sailing at "Half Full" speed can be presented. Here, the difference between the maximum and minimum rates of fuel consumption is only 0.05 tons hourly (Appendix N).

At 1.4-meter trim by stern an expenditure of fuel equals to 2.25 tons. From this point till 0.8 meters aft trim a fuel consumption line steadily goes down. From 0.8 meters trim by stern up to 1.5 meters trim by bow a container vessel sails at minimum fuel rate, namely at 2.2 tons per hour. Consequently, it can be deduced that for a slow steaming vessel change in trim does not have a big influence. Regarding the change in fuel consumption with following increase in forward trim, at 1.7 meters trim by the head, a ship spends 2.21 tons of fuel hourly. The same amount of oil is consumed until a vessel reaches 2.7 meters trim where the fuel rate becomes 2.22 tons per hour. Appendix N shows the thorough investigation process of this experiment.

When a container ship sails optimally at 16.1 knots that correspond to "Half Ahead" indication on telegraph, it consumes 2.2 tons of fuel every hour, while at 21.2 knots ("Full Ahead") vessel spends 4.54 tons of fuel. It means that the differential 5 knots require 2.3 tons of fuel oil extra. However, when a container vessel maintains 26 knots, thus sails at "Nav Full" speed, it consumes 9.03 tons of fuel. In comparison with the previous example, here to compensate extra 5 knots a vessel needs to expend 4.5 tons of fuel additionally, which is a huge difference. Furthermore, these extra knots will cost a huge amount of money for shipping companies and degrade the environment. This again proves the statement that the last 2-3 knots a vessel can reach cause the biggest losses and has the worst consequences for the environment. Moreover, another interesting fact is that for the unloaded ship it is much more optimally to maintain trim by the stern, whereas for loaded vessel it is more efficient to be trimmed by the bow.

### F. Passenger Ship

The influence of trim on fuel consumption was investigated with passenger ship as well. Here, the value of fuel consumption is measured in liters per minute. As with other vessels, the experiments were conducted at two different speeds, namely "Full Ahead" and "Half Ahead". Comparing with previously mentioned ships, passenger vessel's graphs presented in figures 22 and 23 and Appendices O and P quite differ from it. It is explained by special hull form and parameters of this type of ship. At full speed, a vessel sails at 20.9 knots and maximally consumes 69.68 liters of fuel per hour. Little less oil is expended while the ship is at the maximum trim aft, namely 69.65 liters at 1.1 meters trim. As a passenger ship changes her trim to the head, the rate of fuel consumption dramatically reduces at the beginning. At 1.0-meter trim by stern already a vessel's engine burns the minimum amount of fuel equaling to 69.2 liters every minute. However, as a ship submerges deeper by bow it experiences large deviation in fuel expenditure. As the result, at 0.9- and 0.8-meters aft trim, it consumes 69.3 and 69.4 liters of fuel per minute respectively.

Starting from 0.6 meters trim by stern where vessel's engine burns 69.55 liters of oil, the fuel consumption line rises slowly and oscillating. When the vessel reaches even keel condition, it spends 69.61 liters of oil per minute. Later fuel consumption slightly increases and at 0.4 meters trim drops again. The next 20 cm immersion by bow enlarges the fuel rate by 0.05 liters and then decreases once more. At maximum forward trim a passenger ship expends 69.66 liters of fuel every minute.

The chart of "Full Ahead" passenger vessel 'behaves' spontaneously but clearly indicates that the most optimum condition is reached at 1.0-meter aft trim (Appendix O).

Looking at the results of the next experiment conducted with a passenger ship sailing at "Half Ahead" speed (Appendix P), it can be observed that in general the graph illustrating this investigation is similar to the outcomes of "Full Ahead" chart. Even though 2 graphs are corresponding to each other, there are some distinctions which can easily be seen.

First, the graph of "Half Ahead" ship is much smoother and the difference between the maximum and minimum values of fuel consumption amounts for 0.35 liters every minute. Secondly, as a ship reaches 0.6 meters aft trim, the rate of fuel burnt by her engine does not fluctuate as spontaneous as on the "Full Ahead" chart. As it was mentioned above, the similarities between these two charts also present. At maximum trim by stern, a passenger ship consumes 43.45 liters of fuel per minute, whilst at exactly 1.0-meter aft trim a vessel spends 43.19 liters of oil. However, as soon as the bow submerges deeper to the water, fuel rate subsequently increases. Initially, it rises very rapidly and slows down once a ship reaches 0.6 meters trim by the stern.

It is worth mentioning that the difference in fuel consumption between the vessel sailing at 0.6 meters aft trim and 0.9 meters forward trim is 0.1 liters.

The maximum amount of fuel is spent when the forward draft prevails over the aft draft by 0.7 meters. At this point, a passenger ship consumes 43.55 liters of fuel oil every minute. Appendix P clearly indicates how different trim angles affect the fuel consumption of passenger ship sailing at "Half Ahead" speed.

## III. EXPERIMENTS WITH CONSTANT DRAFT

The above-mentioned vessels were investigated giving due regard to trim value at different loading conditions and speeds without taking into consideration the draft of the vessel. This is due to the fact that in real life situation it is very complicated to maintain constant mean draft while loading and discharging ballast. However, in order to widen the scope of the investigation and compare the findings of these experiments with the results of the previous experiments, a fishing boat was taken into consideration to verify the influence of trim on fuel consumption at various speeds while the vessel is at a constant mean draft.

### A. Fishing Boat – unloaded condition (Draft=3.3 m)

Based on the experiments conducted above, an unloaded fishing boat was tested with similar procedures but at a constant draft. It is worth mentioning that the minimum draft for this vessel is 3.13 meters and the maximum is 3.90 meters. Hence, this range restricted the selection of drafts. Therefore, for this experiment, the following mean drafts were taken into account: 3.30, 3.50 and 3.70 meters. A fishing boat was tested at two different speeds, namely "Full Ahead" and "Half Ahead".

Starting from a fishing boat at 3.30 meters mean draft, it should be noted that the difference in fuel consumption between the experiments conducted with vessels at permanent and non-permanent drafts is apparent. Appendices Q and R illustrate the influence of trim on fuel consumption for this situation. The most evident observation from these charts is that the larger the aft trim the bigger the fuel consumption. The similar finding was obtained with the previous experiment. However, in this case, at both speeds the total fuel rate was 2% lower compared with a vessel sailing not at the constant mean draft. Moreover, while vessel maintains 3.30 meters draft, she obtains optimum trim at 0.2 meters by stern despite her speed. Sailing at this trim condition a vessel at full and half speeds consumes 466.7 and 282.5 kg of fuel per hour respectively. However, early investigations showed that unloaded fishing boat obtains optimum trim at 0.1 meters forward trim. Further comparing both experiments, the fuel consumption line of a ship sailing at the constant draft after reaching optimum trim value calmly moves up, while the other line grows very rapidly.

### B. Fishing Boat – unloaded condition (Draft=3.5 m)

Considering an unloaded fishing boat at constant 3.50 meters mean draft and comparing the findings of this experiment with results of a vessel sailing at 3.30 meters draft, it is obvious that due to an increase in the wetted surface area the total resistance, thus the amount of fuel burnt by fishing boat's engine will increase reasonably. Accordingly, vessel at 3.50 meters draft spends 20 kg of fuel more at each trim condition.

The trend of the fuel consumption line is almost the same in both experiments, however, starting from maximum trim by the stern, the vessel at 3.50 meters mean draft will reach her optimum condition 10 cm earlier than a fishing boat with a smaller draft, namely at 0.3 meters trim by the stern. Appendices S and T graphically shows how trim affects fuel consumption while an unloaded fishing boat maintains 3.50 meters mean draft.

### C. Fishing Boat – unloaded condition (Draft=3.7 m)

The maximum mean draft of the fishing boat at which ballast can be transferred from aft to fore tanks or vice versa is 3.70 meters. When a fishing boat sinks deeper, it experiences more frictional resistance due to an increase of wetted surface area. This leads to higher consumption of fuel and consequently larger gas emission. At 3.70 meters mean draft a ship spends every hour 40 kg of fuel oil more than at 3.30 meters draft. Statistically, it means that every 1 cm increase in mean draft causes enlargement in fuel consumption by 1 kg hourly.

Comparing this experiment with the investigation of an unloaded fishing boat sailing not at the constant draft, it can be stated that the latter consumes much less fuel. To be more precisely, a vessel with constant draft while sailing at an optimum trim condition expends more fuel oil than another boat maintaining her largest aft trim. To visualize the above-mentioned experiment Appendices U and V can be helpful.

### D. Fishing Boat – loaded condition (Draft=4.8 m)

Moving to the loaded fishing boat, this vessel similarly was examined at three different mean drafts and two various speeds. The mean draft range, in this case, varies between 4.67 and 5.41 meters. The following drafts were taken under consideration: 4.80, 5.00 and 5.20 meters. To be more precisely, the distinction in fuel consumption between two experiments reaches more than 4 kg of fuel every hour.

Even though this difference is only equivalent to 1%, permanent sailing at this condition can cause considerable losses to the shipping company.

Another interesting difference in both graphs is that a vessel maintaining a constant mean draft reaches her optimum trim condition at 0.3 meters aft trim, while a ship not sailing at a permanent draft obtains the least fuel consumption condition at 0.1 meters forward trim. It is worth mentioning that a "Full Ahead" chart illustrates the smooth growth of fuel consumption line, while a "Half Ahead" graph shows that when a fishing boat submerges deeper by bow, her fuel rate will unstably rise. The more precise information about an experiment conducted with a fishing boat at 4.80 meters draft is shown below (Appendices W and X).

### E. Fishing Boat – loaded condition (Draft=5.0 m)

The next experiment was conducted with a fishing boat at 5.0 meters mean draft.

This is obvious that a vessel at 5.0 meters draft consumes significantly more fuel, namely the difference between those two conditions reaches 15 kg of fuel every hour (Appendices X and Z). To operate a fishing boat at this condition a shipping company annually needs to pay extra 100,000$ comparing with a fishing boat sailing at 20 cm less draft. During the experiment with a fishing boat, the following finding was observed: a vessel at constant 5.0 meters mean draft optimally spends her fuel at maximum aft trim, whereas a ship at 4.8 meters draft by maintaining this trim condition consumes 1 kg more fuel than at 0.3 meters trim by stern (her optimal condition).

### F. Fishing Boat – loaded condition (Draft=5.2 m)

For the loaded fishing boat at constant 5.2 meters mean draft two investigations at two various speeds were conducted. Due to an increase in wetted surface area, the total resistance a ship suffers from consequently rises. As the result, the fuel rate significantly goes up. In this situation, each trim condition leads to a growth of about 35 kg of oil burnt by vessel's engine in comparison with an engine of a fishing boat at 4.8 meters mean draft.

At 5.2 meters draft, a fishing boat is optimally trimmed at maximum trim by stern that equals to 0.4 meters. The minimum fuel consumption value is 635 kg of oil hourly. Comparing Appendices Z1 and Z2, one observes that while a graph presenting "Full Ahead" situation runs quite smooth with little deflections, "Half Ahead" chart illustrates very erratic behavior of a fuel consumption line.

It is an interesting fact that for a fishing boat sailing at the permanent mean draft, the optimum trim condition with minimum fuel consumption is reached at maximum aft trim, whereas for the same vessel but not maintaining a constant draft an optimum condition is at 0.1 meters forward trim. This can be explained by less wetted surface area, thus resistance experienced by a ship sailing not at the constant mean draft.

## IV. FINANCIAL ANALYSIS

The biggest concern for any corporation is its budget and the way money is distributed for various facilities. Therefore, to show the financial importance of trim optimization for a shipping company, the following analyses were conducted.

Financial analysis is described for medium-sized vessel because for this research model ships with different particulars had been experimented. The main details of the ship under this investigation include:

- LOA = 238 meters;
- Breadth = 32.2 meters;
- Gross Tonnage = 66172 tons.

Assuming that the ship sails continuously, on the same path, in a circular manner, the voyage duration remains constant and that the vessel travels 335 days a year (the remaining 30 days are spent in ports or for repairs), the calculations for financial analysis which are presented in Appendix A can be figured out. Due to this Appendix, shipping companies expend a huge amount of money for supplying a vessel with bunker, even though greater fuel consumption leads to bigger pollution for environment. Therefore, by optimizing vessel's trim, beneficial impact on company's budget can be achieved. Moreover, the amount of unnecessary losses will be decreased. In addition, as it was mentioned above, the reduction of fuel consumption will not only benefit the individual shipping company but contribute to better environmental conditions. These are the root reasons why the improvement of operating procedures is highly valuable for international maritime communities.

Moreover, in the cruise industry, for example, trimming is known to have solid benefits in enabling more efficient management of propulsion-based energy (typical savings potential having been found to be around 2 to 5 percent). In the commercial sector, including VLCCs, however, the impact of optimized trimming has been more of a gray area (Mathews, M. 2012). That is why this thesis is focusing on verifying the influence of various trim conditions on vessel's fuel consumption and determine the optimum trim value for different types of ships at different loading conditions.

## V. CONCLUSION

As per the results of conducted investigations, the most effective condition for the fishing boat is zero trim or little trim to fore. However, it is crucial for the unloaded fishing boat not to maintain aft trim, whereas for loaded ship trim by stern has an insignificant impact on fuel consumption. Experiments conducted with container ship demonstrate the dependence of optimum trim position on loading condition even more clearly, as for unloaded vessel the optimum trim is reached at 2.5 – 3.0 meters aft trim, while loaded ship performs at its best with small trim by the bow. It means that to be able to operate a vessel at the most efficient condition after loading operation, a container ship needs to change her trim by at least 2.5 meters. Another important experimental output is that the lower the speed the fewer changes in fuel consumption is experienced by vessel adjusting her trim. Thus, the difference in fuel expenditure for VLCC sailing at

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"Nav Full" speed can reach more than 0.5 cubic meters of oil every hour, while for tanker maintaining "Half Ahead" speed this difference does not exceed 0.3 $m^3$. Big variation between maximum and optimum fuel rates negatively affects both shipping company's budget and environment. It is worth mentioning that depending on vessel's speed, for loaded VLCC 0.5 – 1 meters trim by stern is believed to be the best choice. Overall, as the vessel sinks deeper in the bow, fuel consumption increases. Thus, the optimum trim for passenger ship is obtained at 1.0-meter trim by the stern and subsequent immersion by bow leads to the growth of fuel expenditure.

Giving due regard to the fishing boat maintaining constant draft while adjusting her trim, two main derivations can be achieved. First, with every 1 cm increase of draft, fuel consumption rises by 1 kg per hour. Secondly, depending on ship's draft, fuel consumption can be either larger or smaller in comparison with a fishing boat sailing not at the constant draft. The main result is that trim optimization has an essential influence on the factors such as vessel's expenditure of fuel, company's budget and environmental pollution.

## APPENDIX

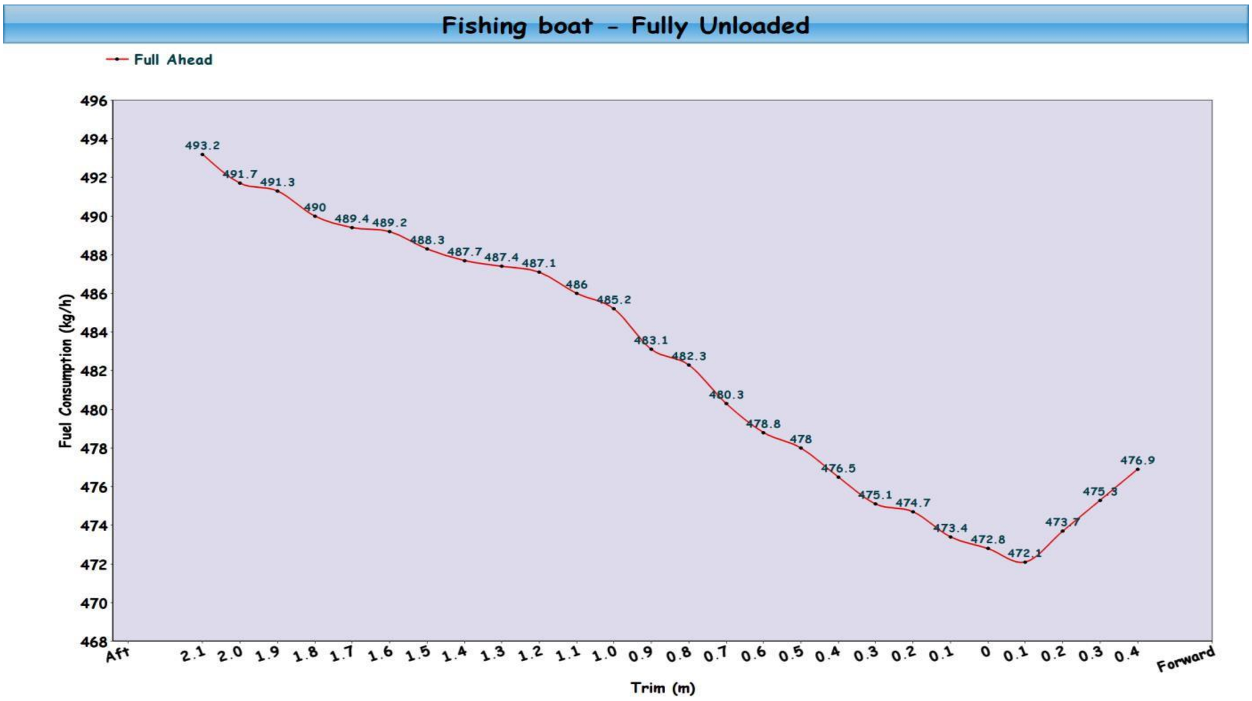
- Calculations:

1) The cost of consumables in Rotterdam is: ("World bunker prices", 2017)
   a. Fuel Oil: $C_{F.O.}$ = 280 \$/t;
   b. Diesel Oil: $C_{D.O.}$ = 400 \$/t;
   c. Marine Gas Oil: $C_{M.G.O.}$ = 500 \$/t;

2) As per the average consumption of medium-sized ship mentioned in paragraph 1.9, the oil spent for voyage from point A to point B and back equals: (Alpeche, J. 2014)
   a. $W_{F.O.}$ ≈ 7.500 tons;
   b. $W_{D.O.}$ ≈ 1.000 tons;
   c. $W_{M.G.O.}$ ≈ 400 tons;

3) Performing 5 circular voyages a year the total cost shipping company spends is: a. $C_{F.O.}$ = 7.500 x 280 x 5 = 10.500.000 \$;
   b. $C_{D.O.}$ = 1.000 x 400 x 5 = 2.000.000 \$;
   c. $C_{M.G.O.}$ = 400 x 500 x 5 = 1.000.000 \$;

**Appendix A**

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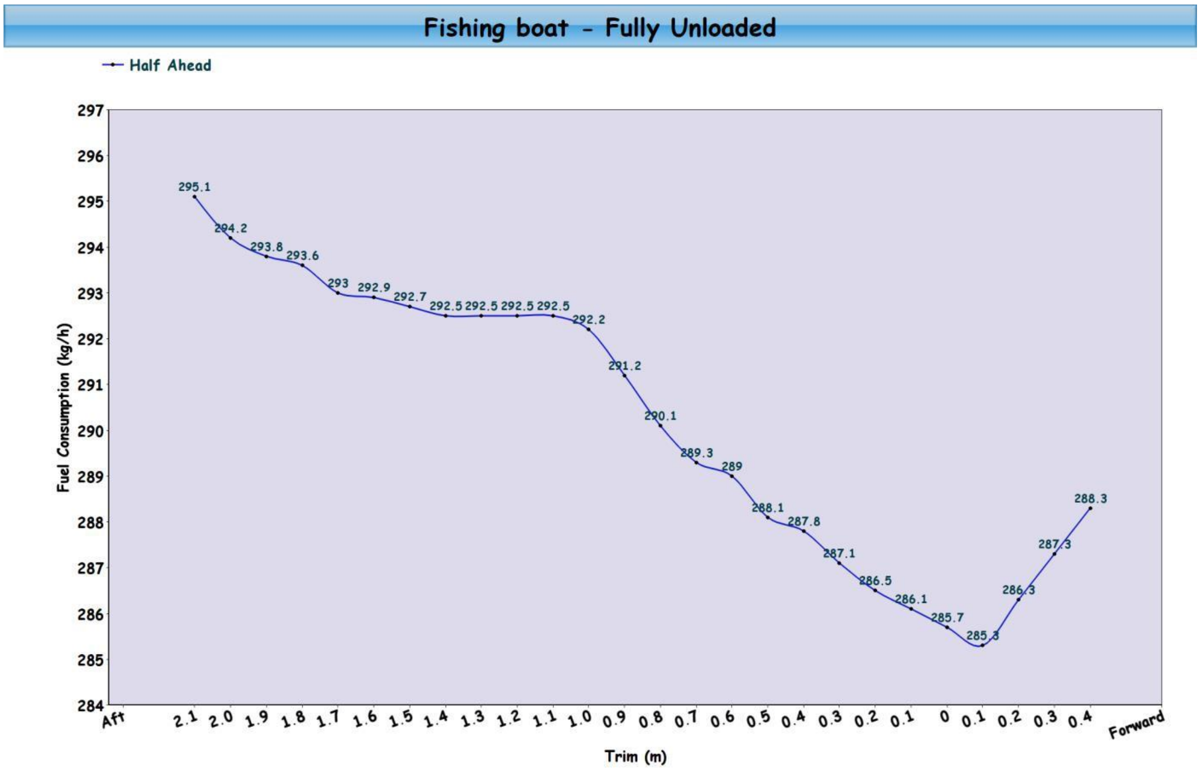


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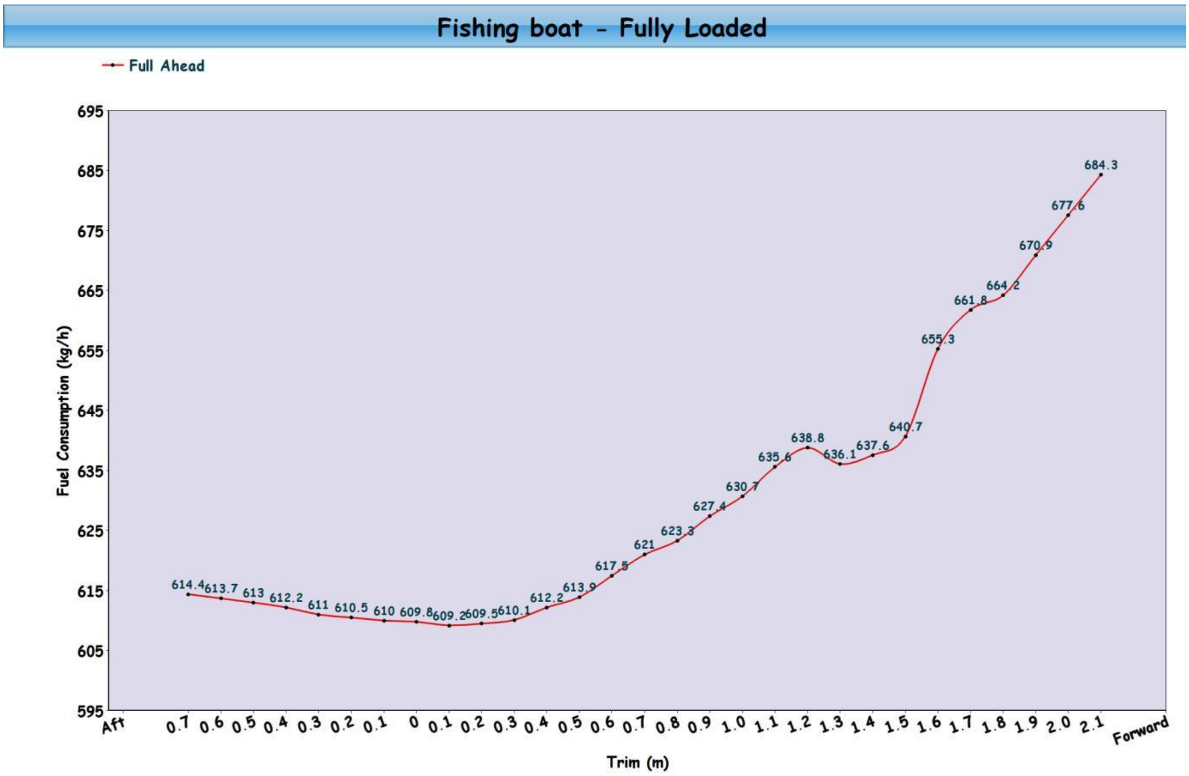


**Appendix D**

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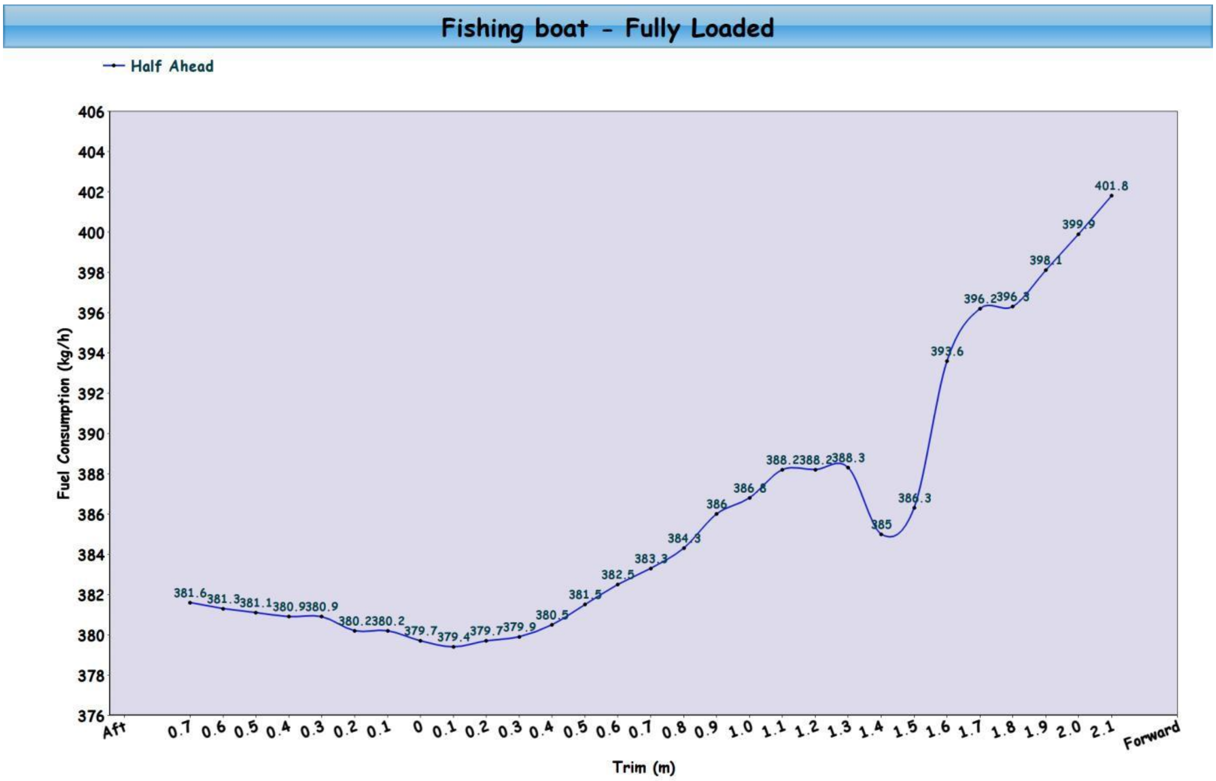


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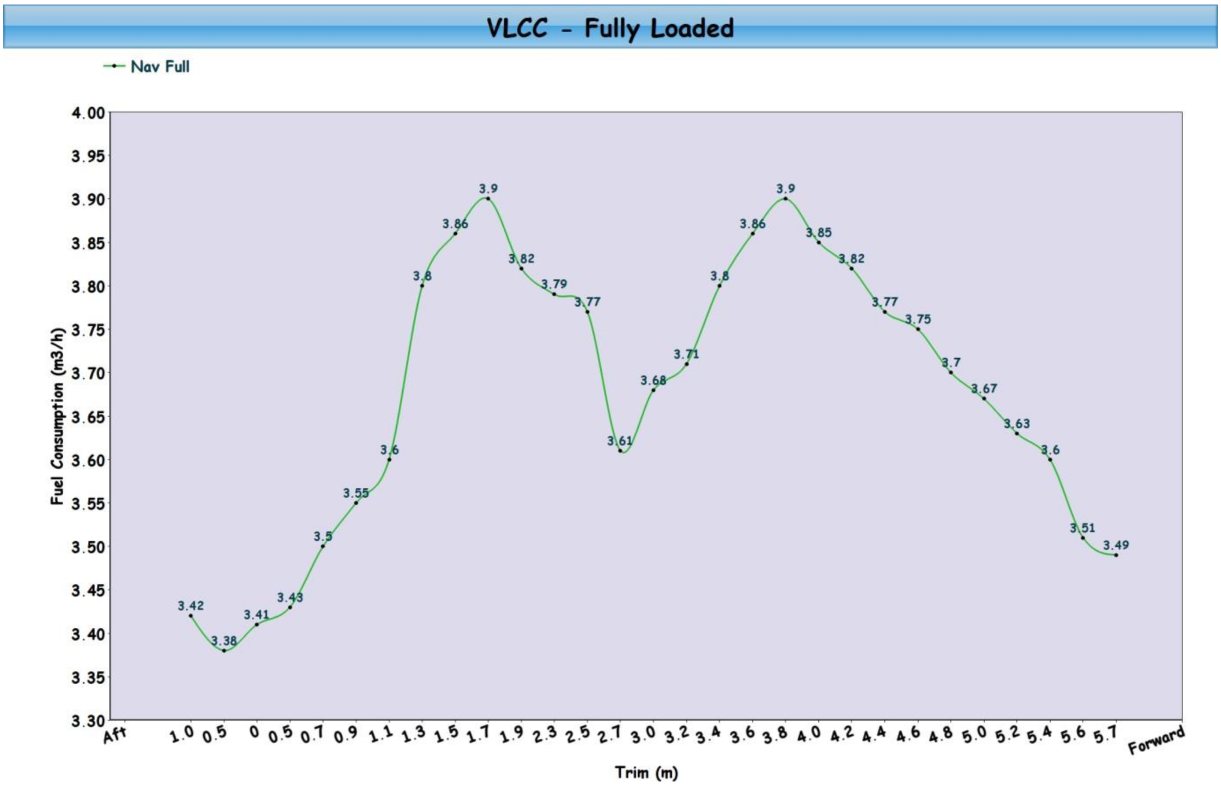


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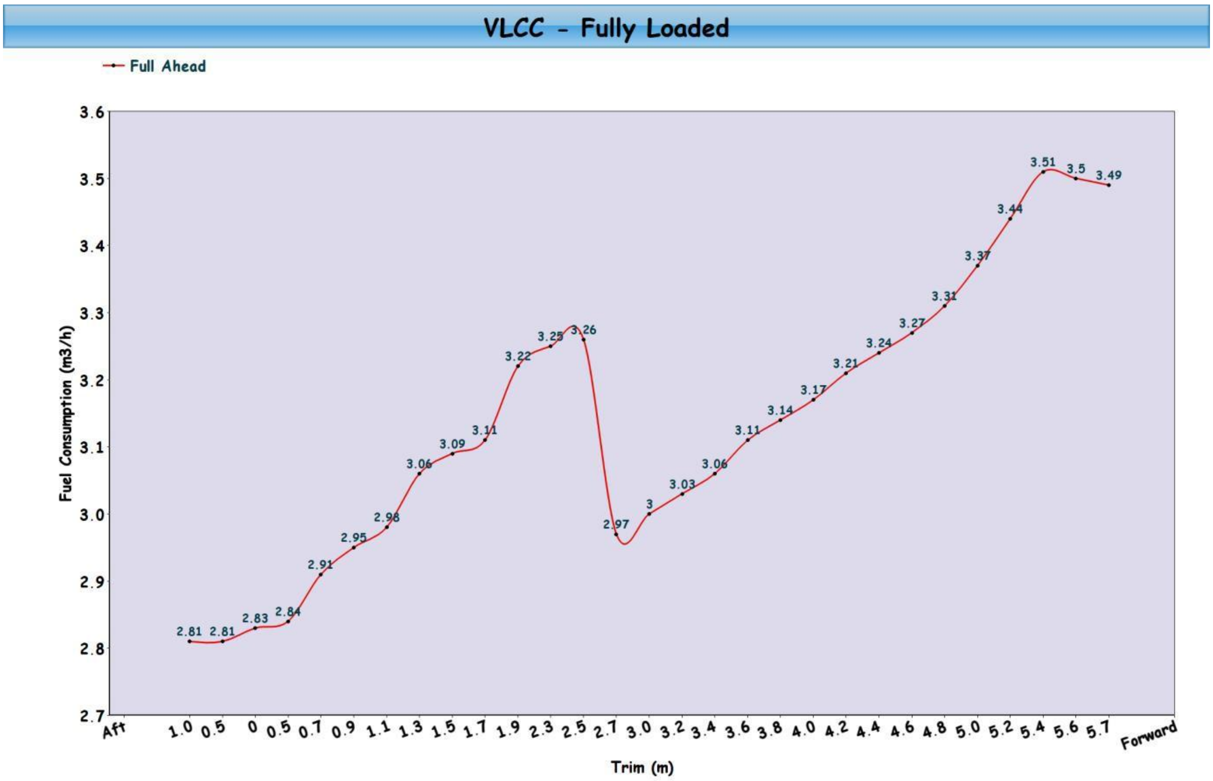


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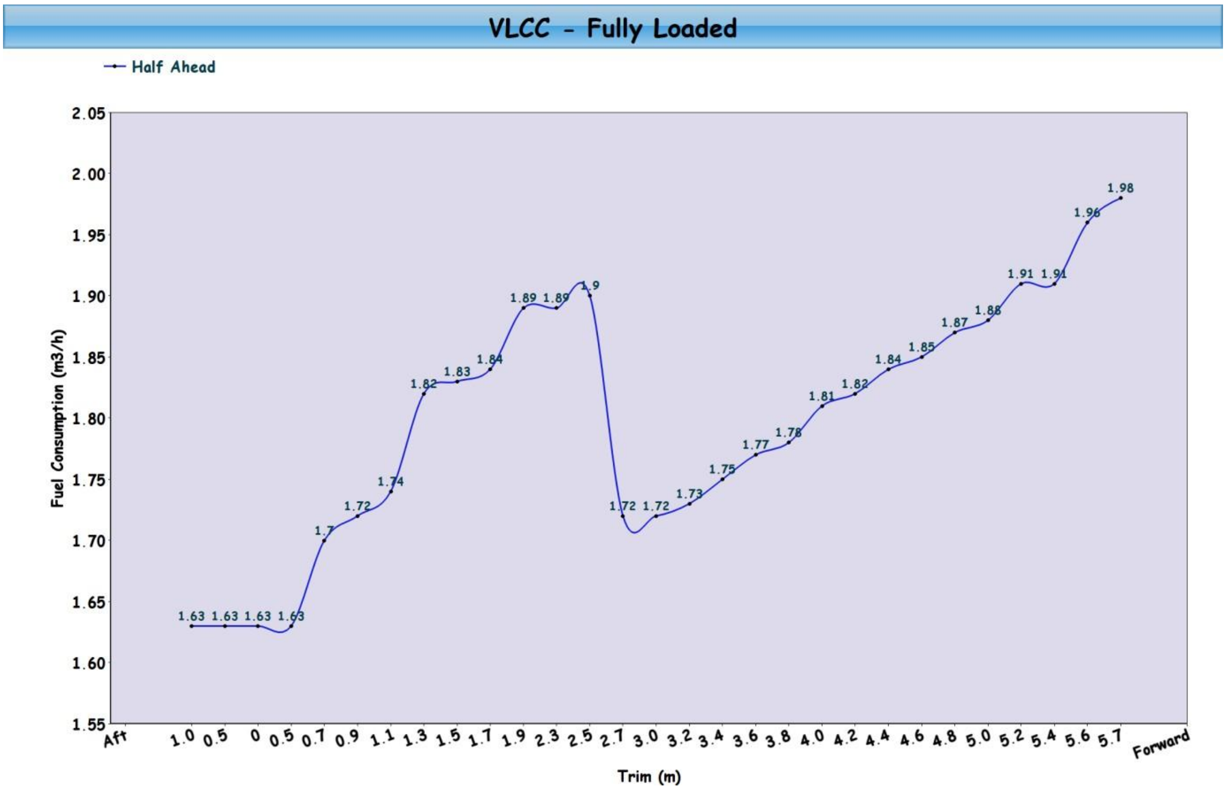


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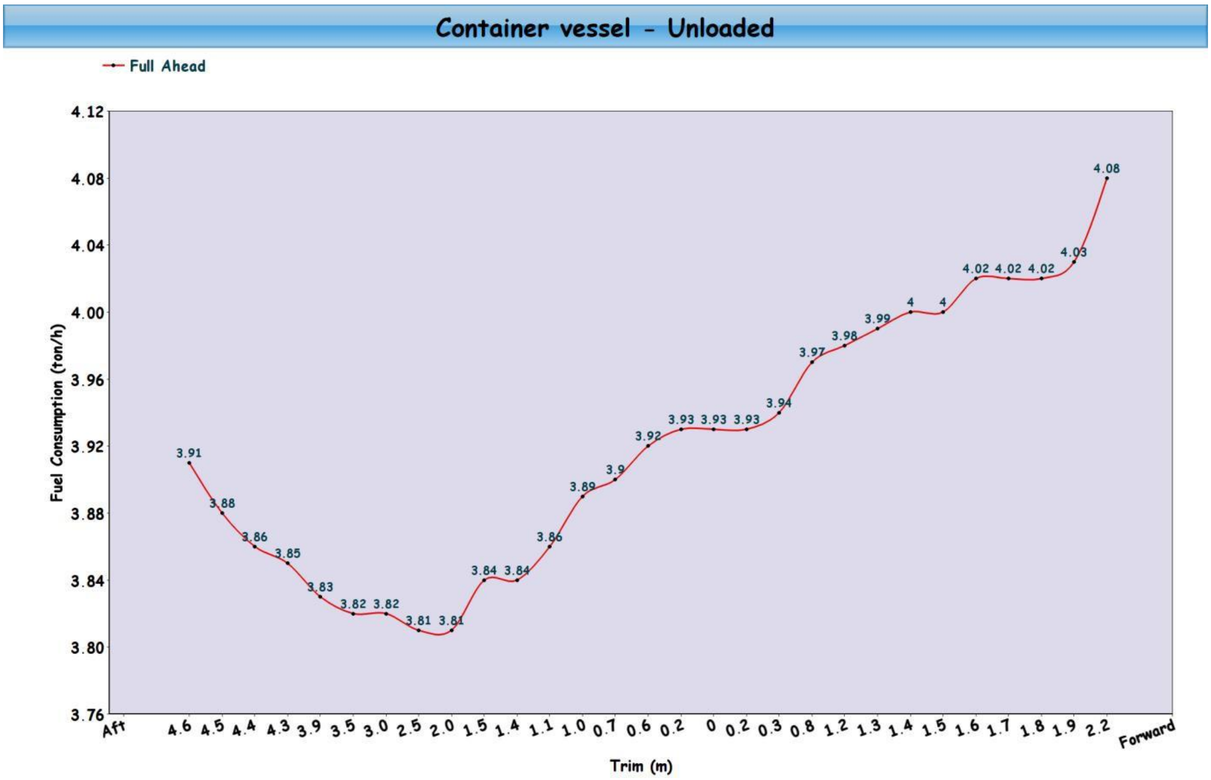


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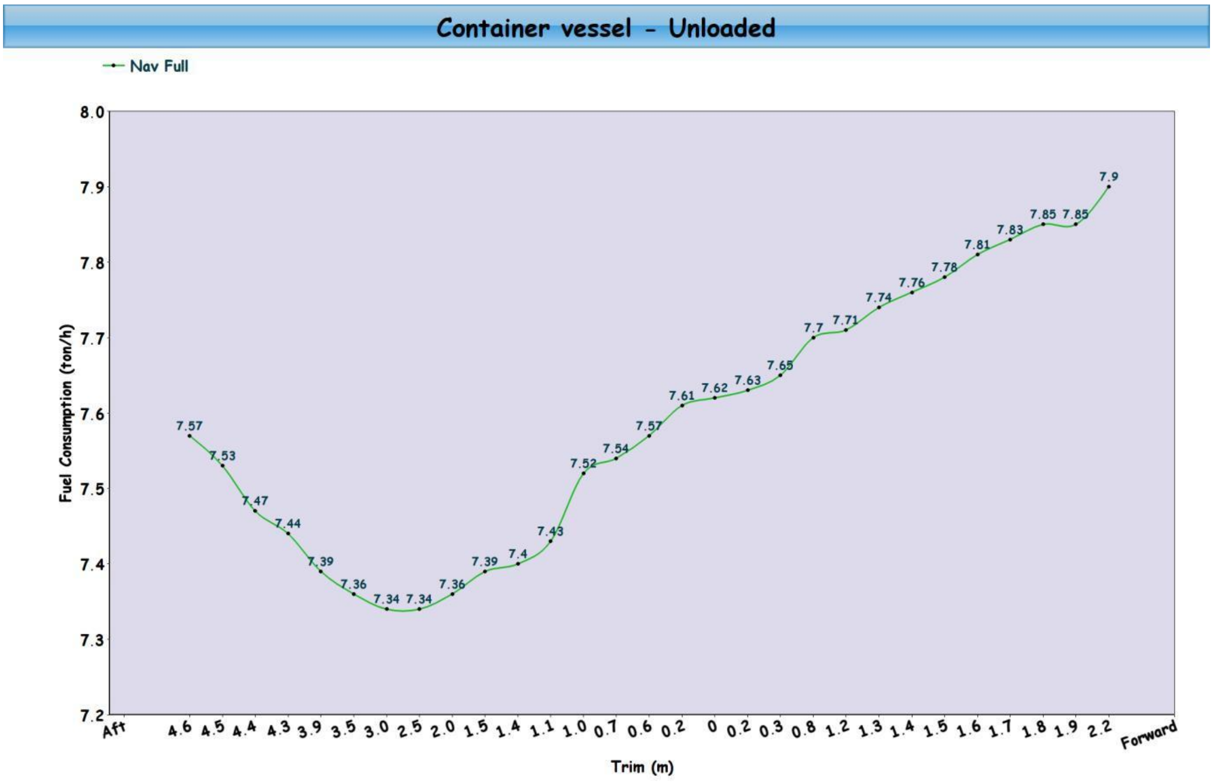


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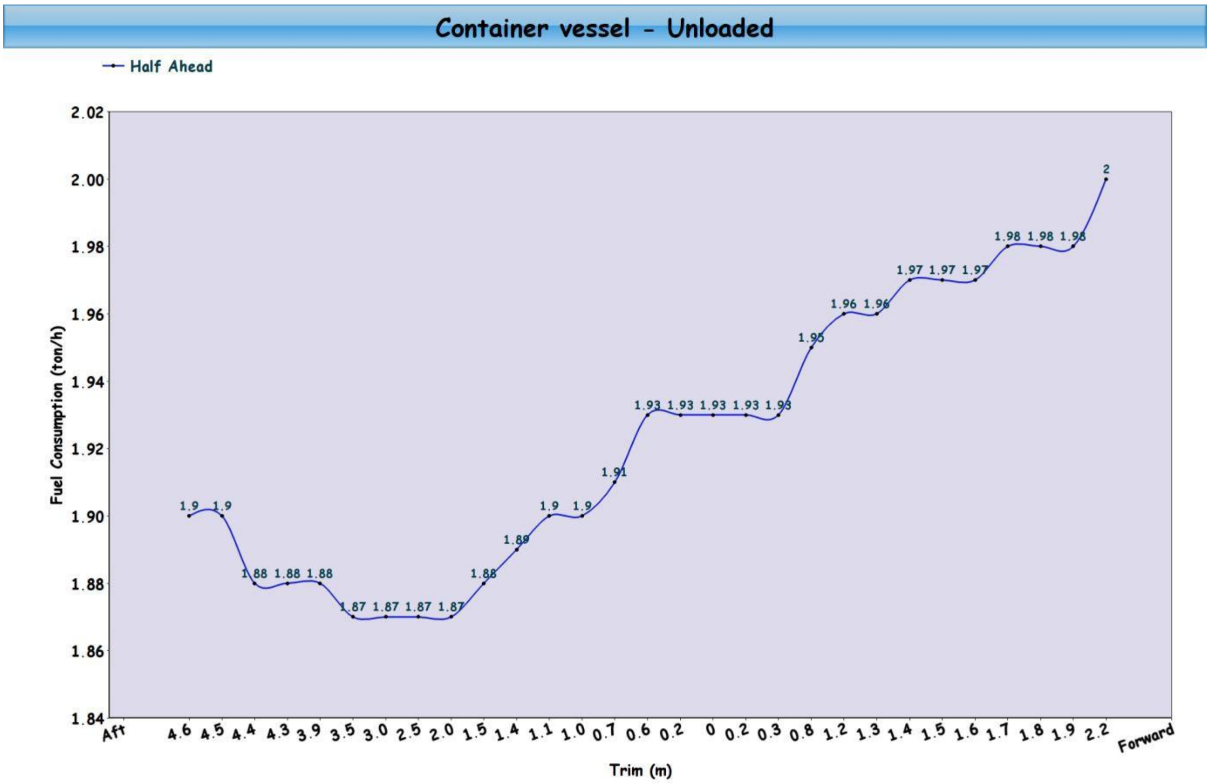


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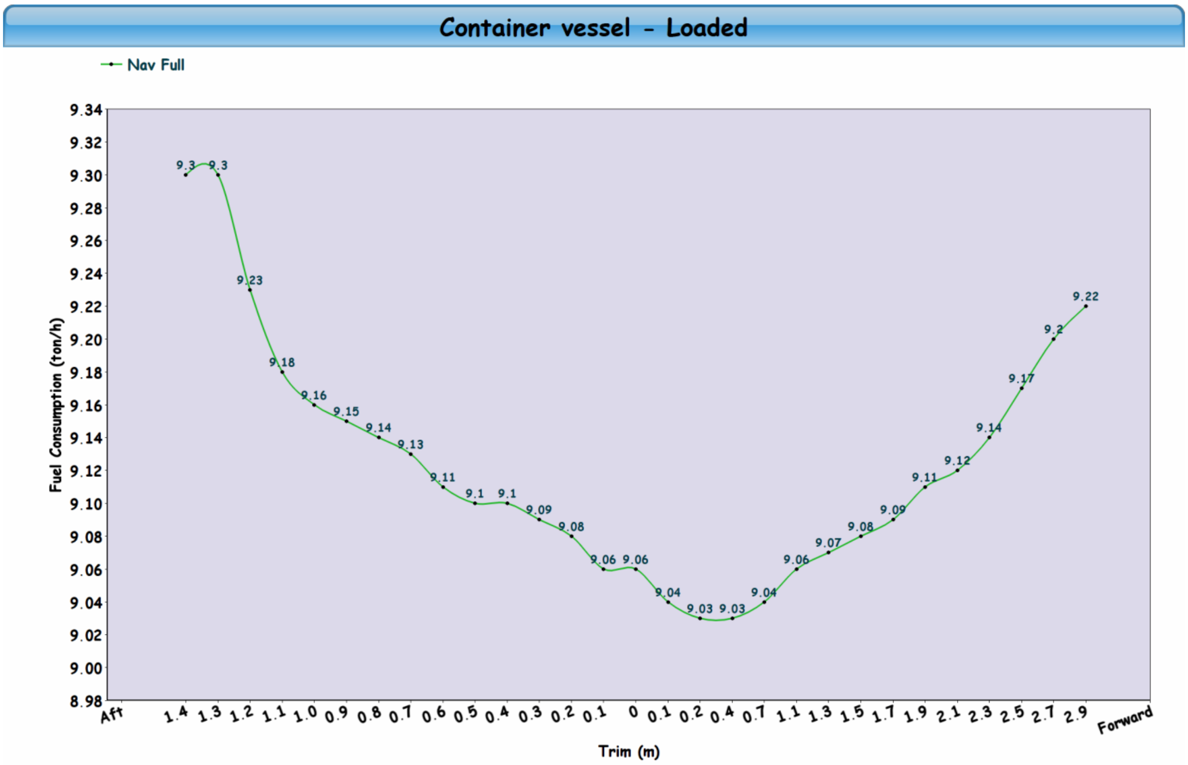


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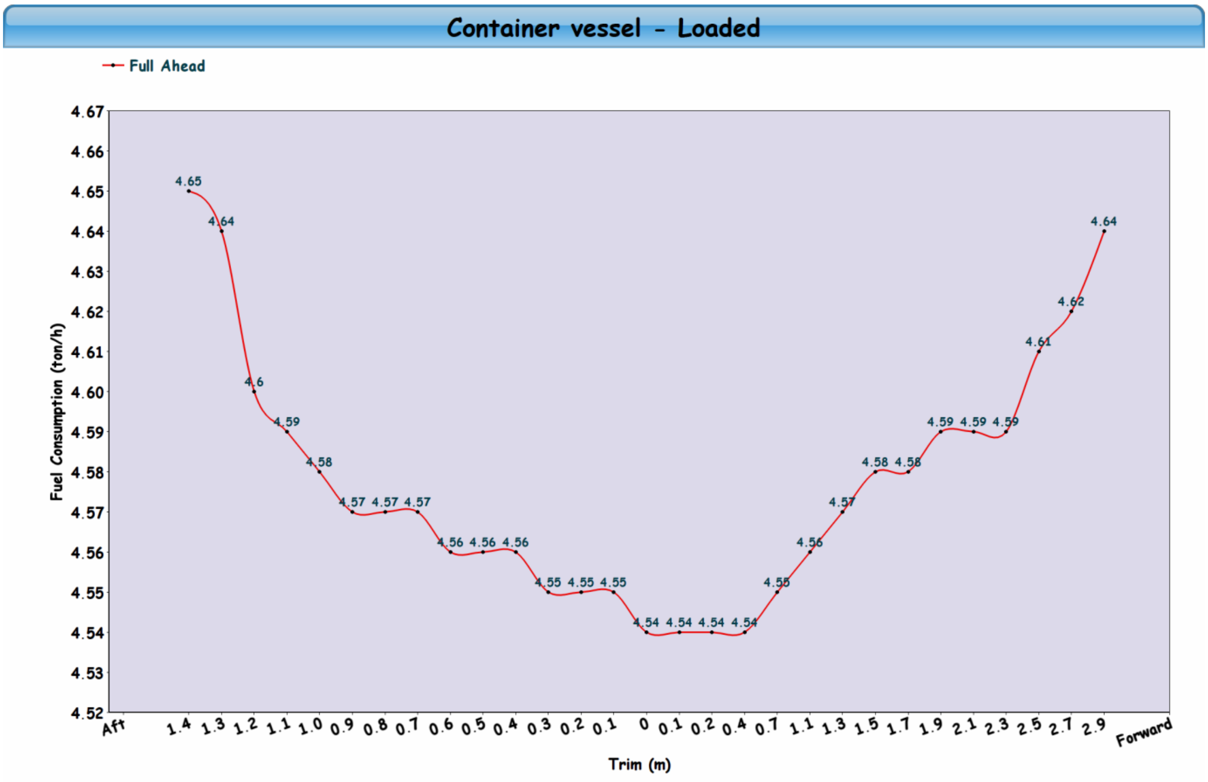


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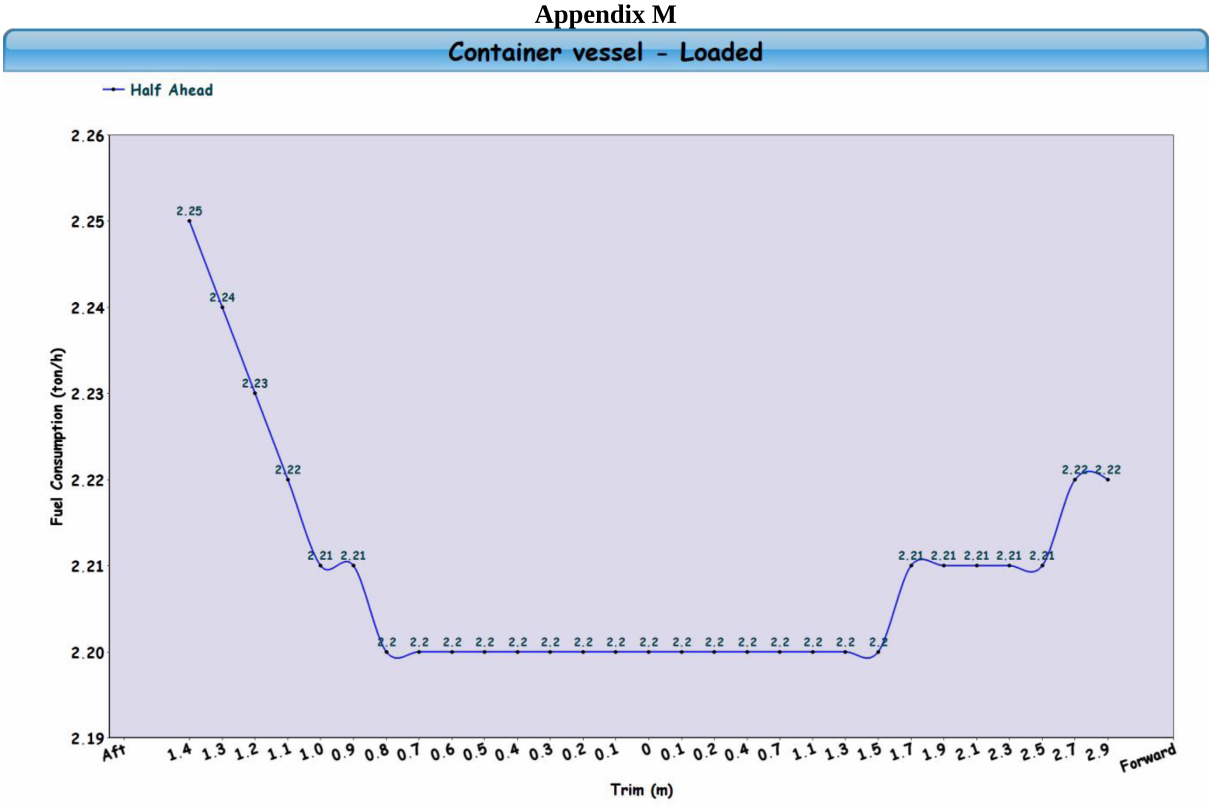


Appendix N

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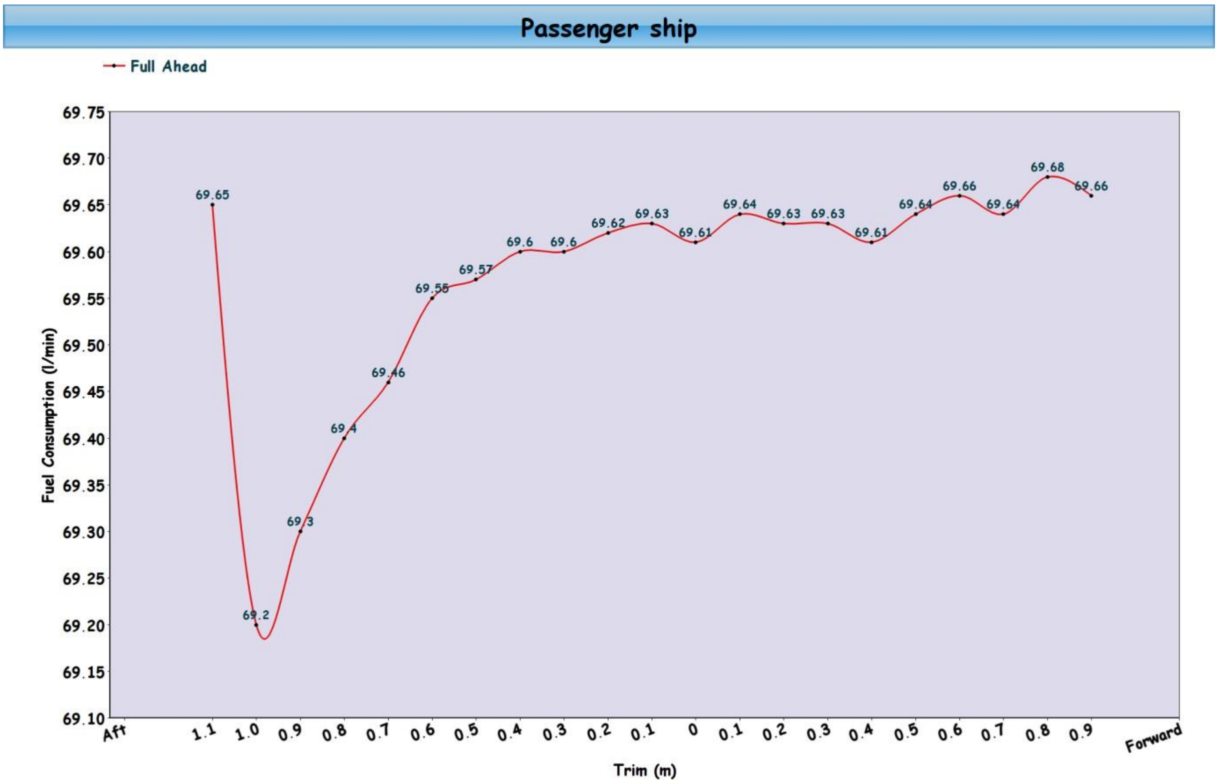


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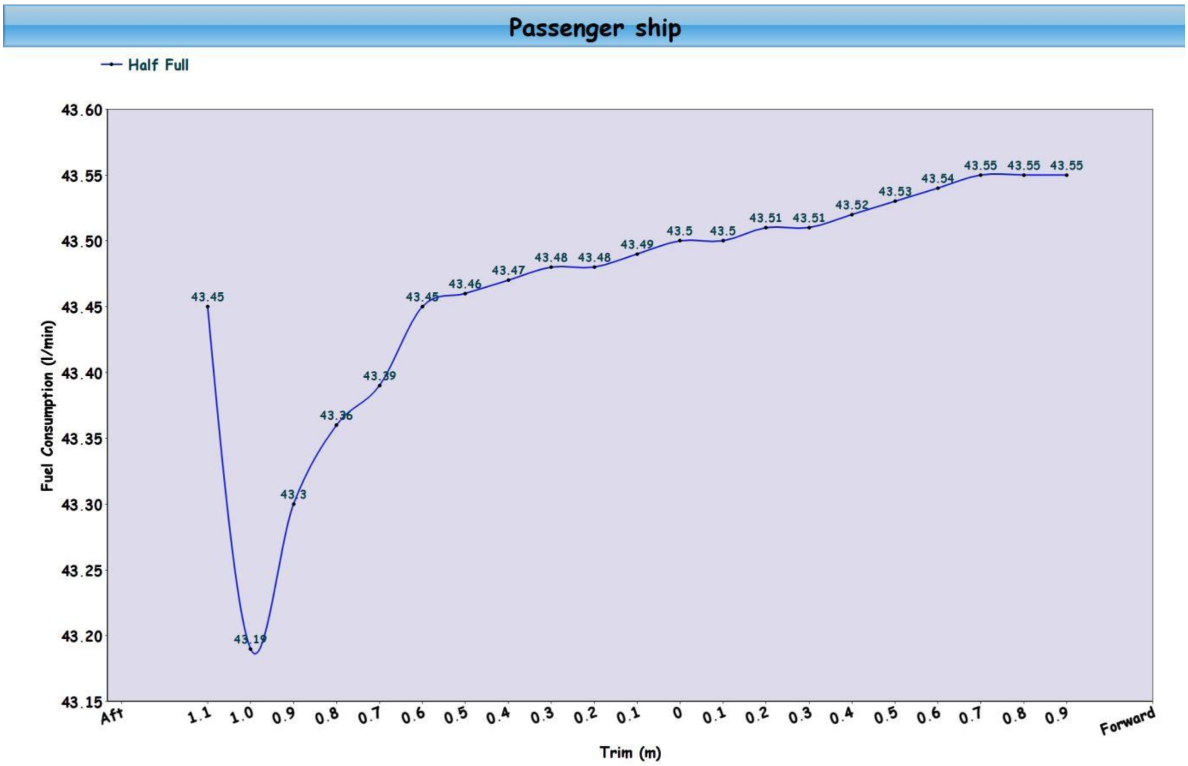


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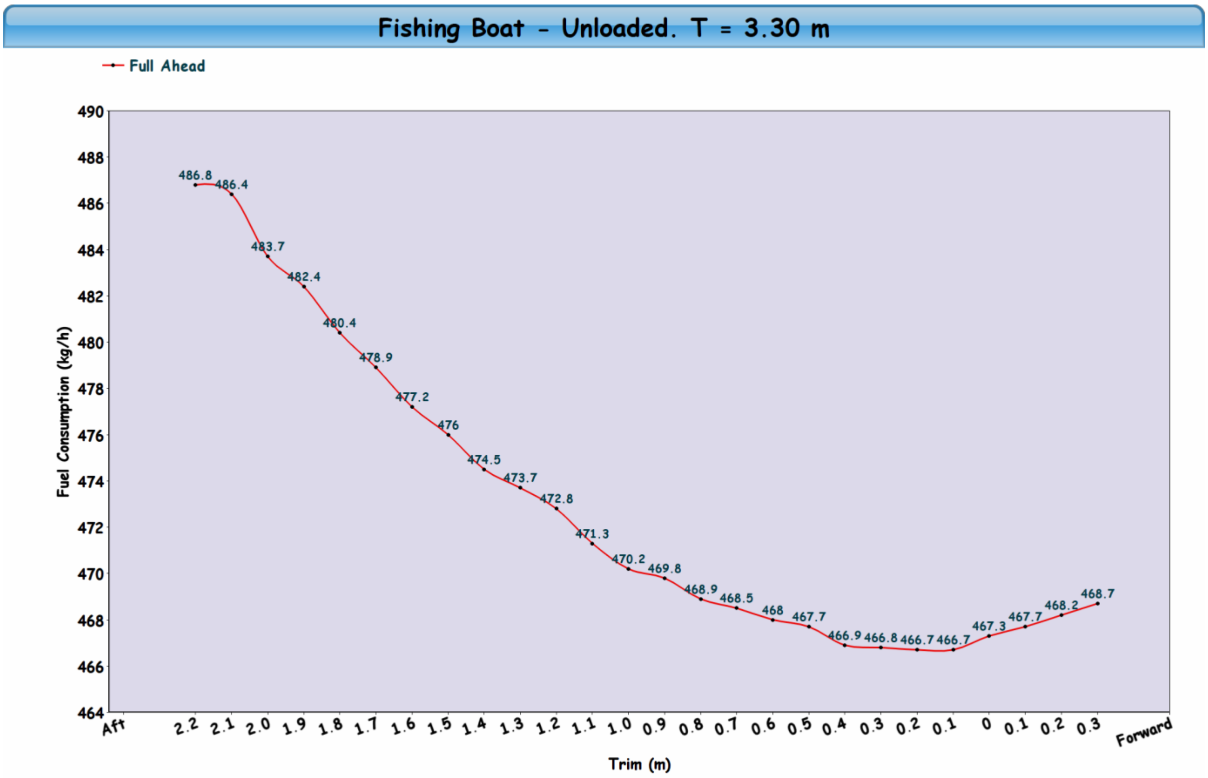


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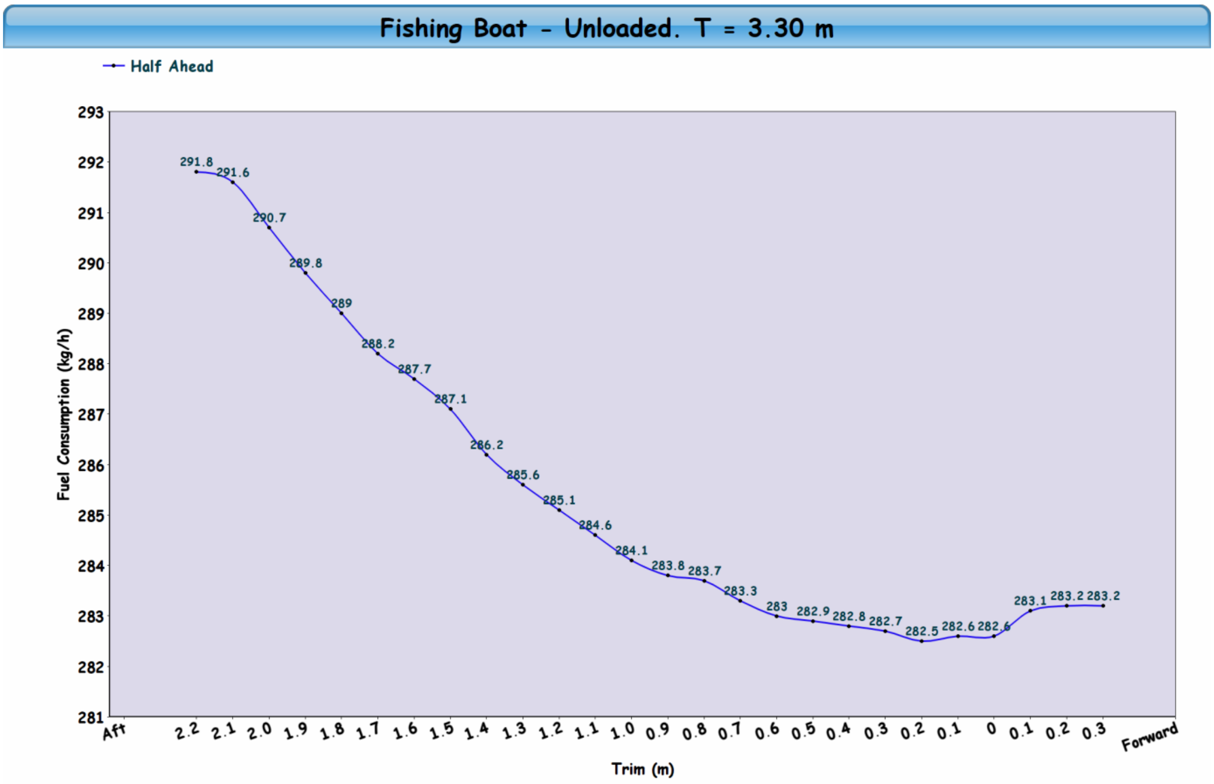


**Appendix R**

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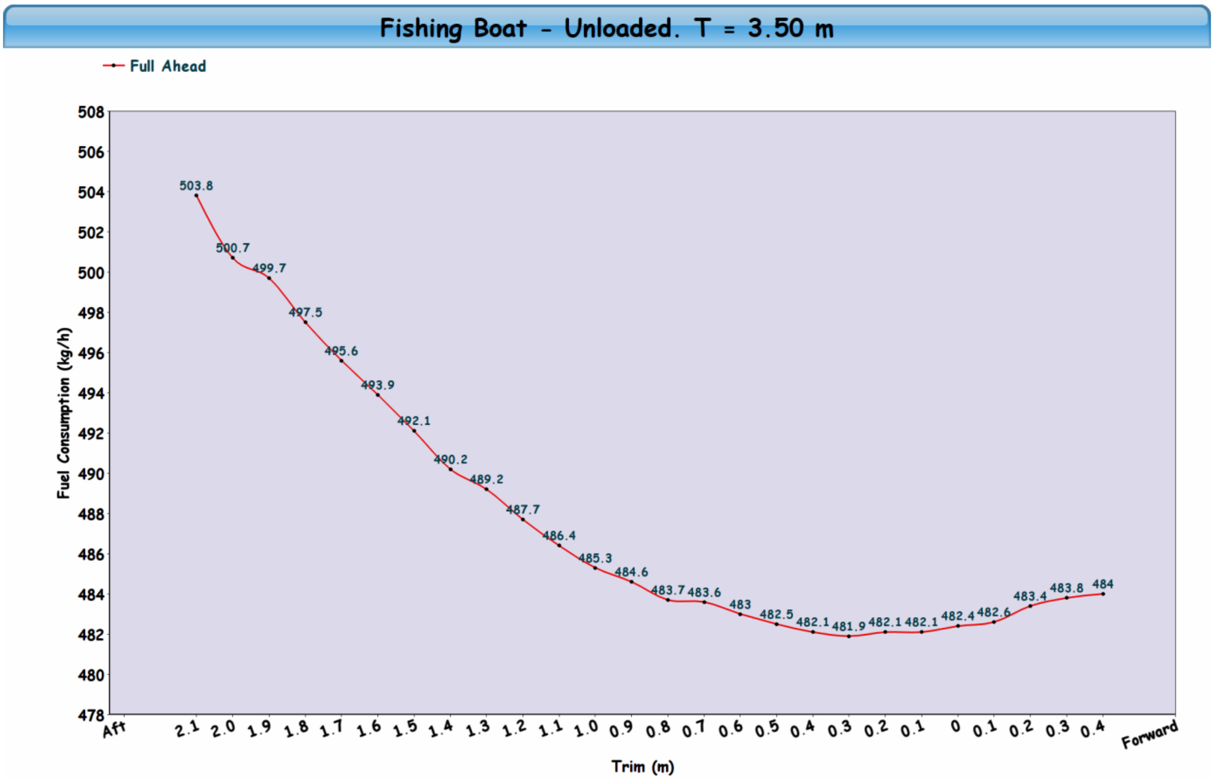


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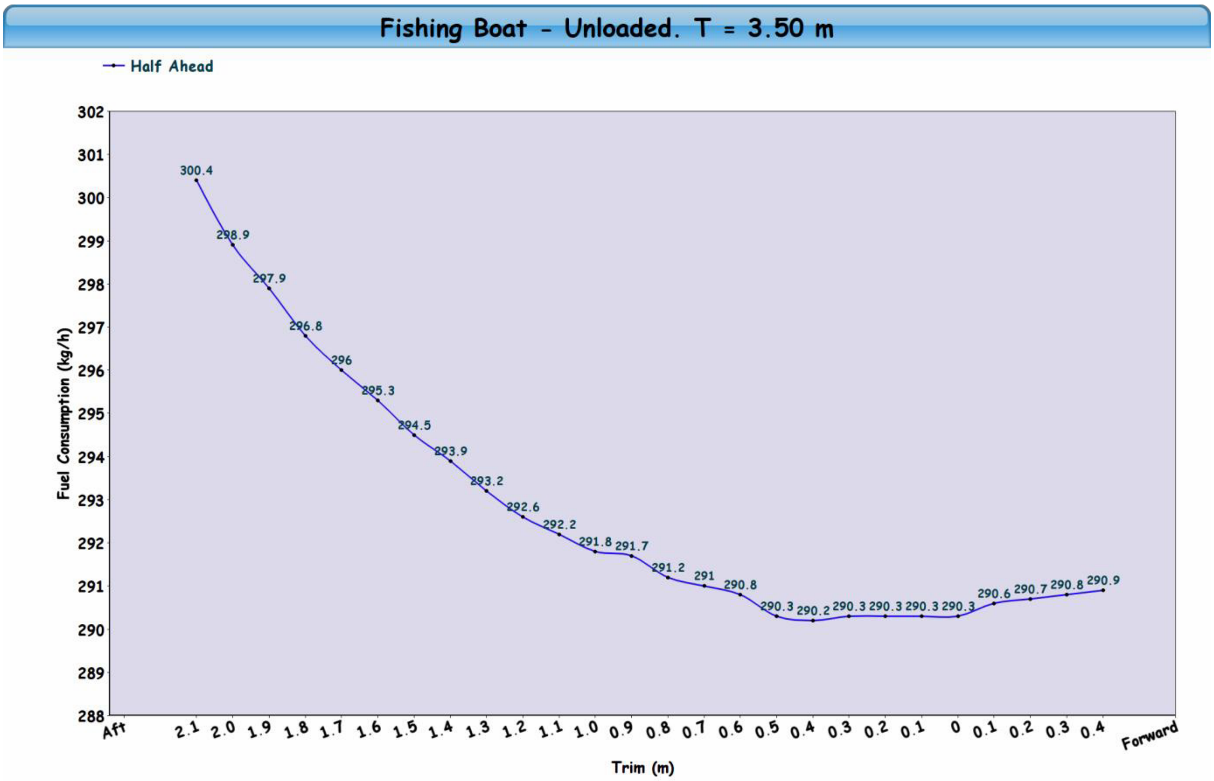


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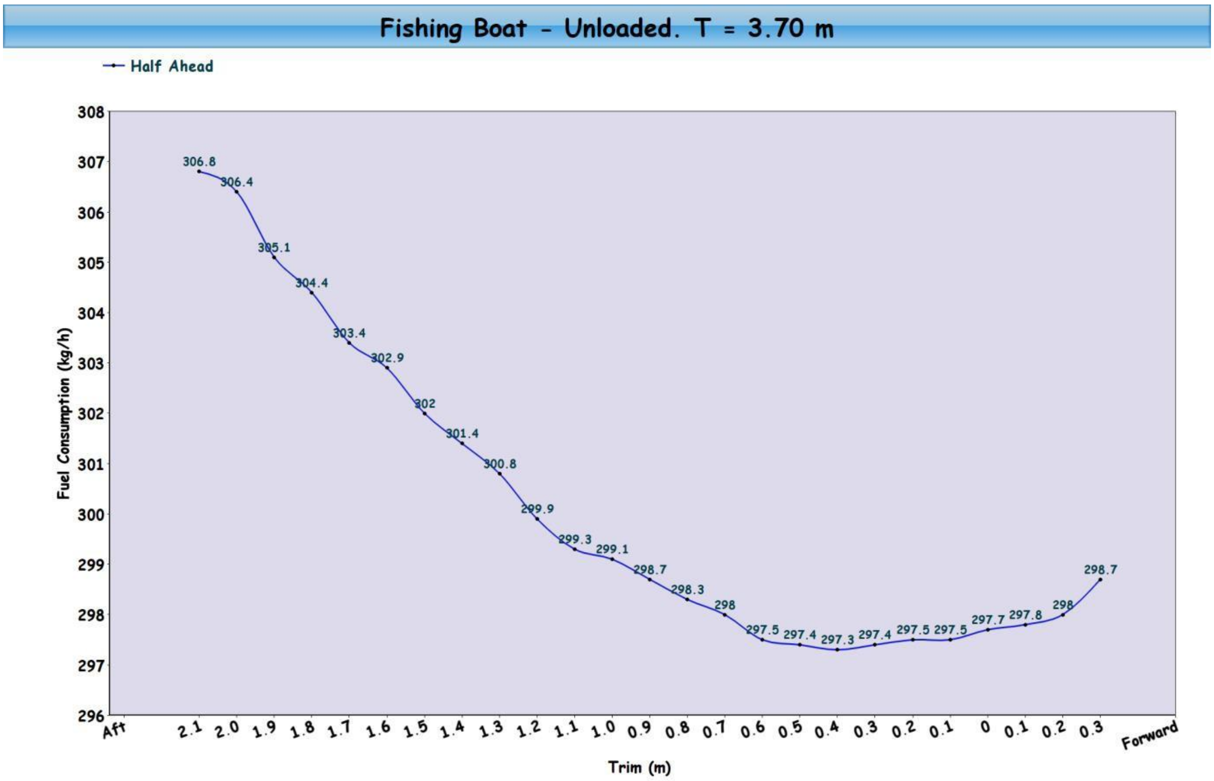


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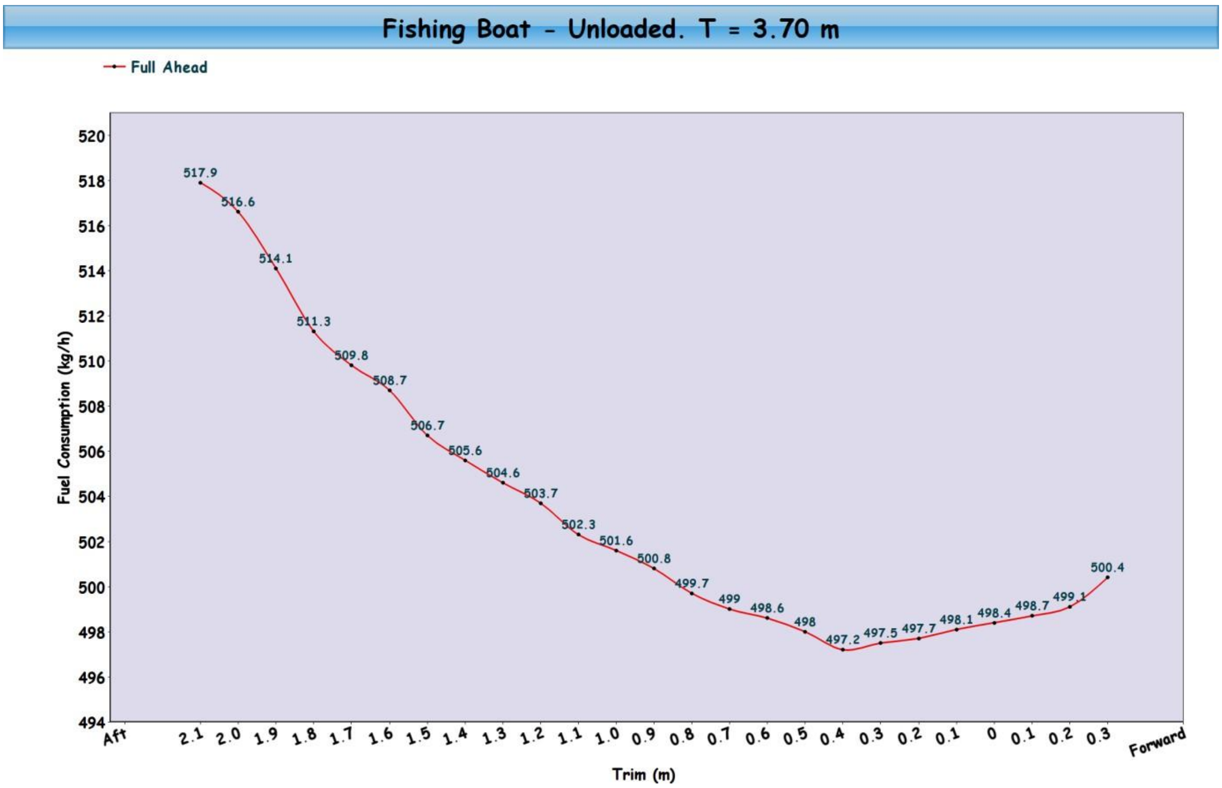


Appendix V

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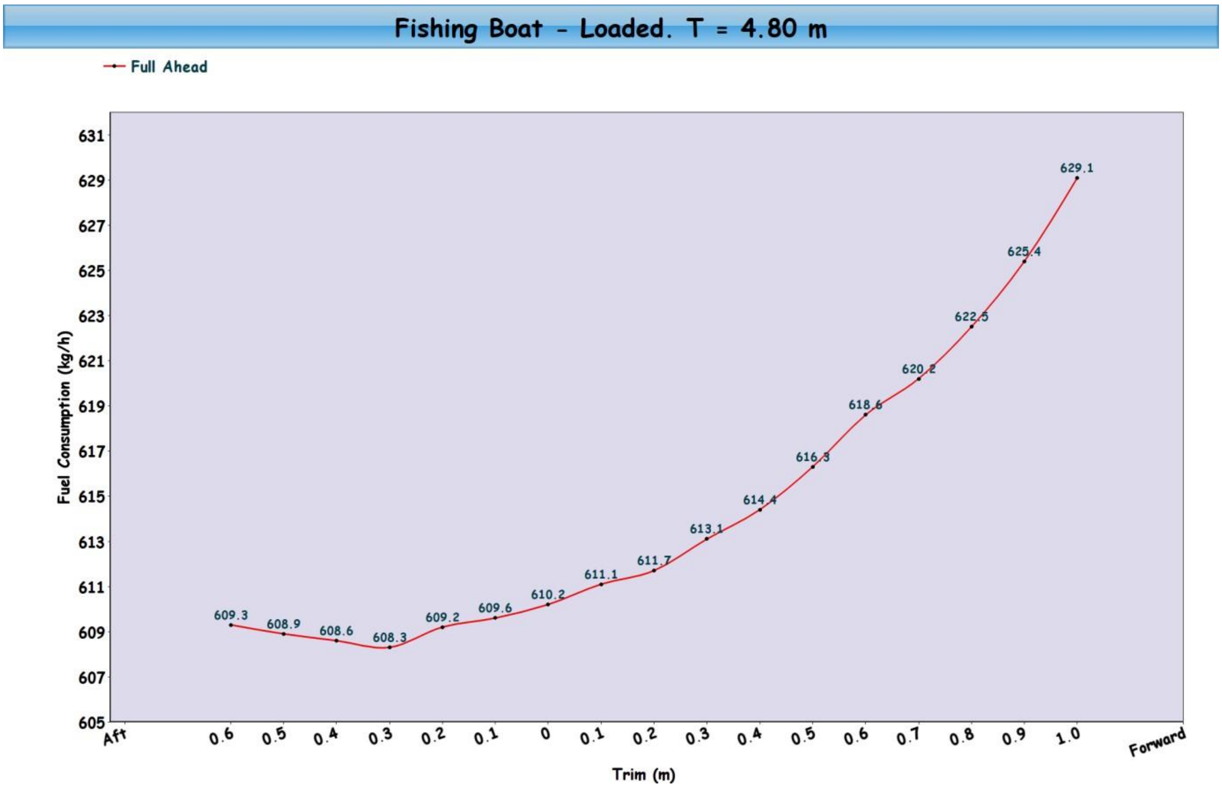


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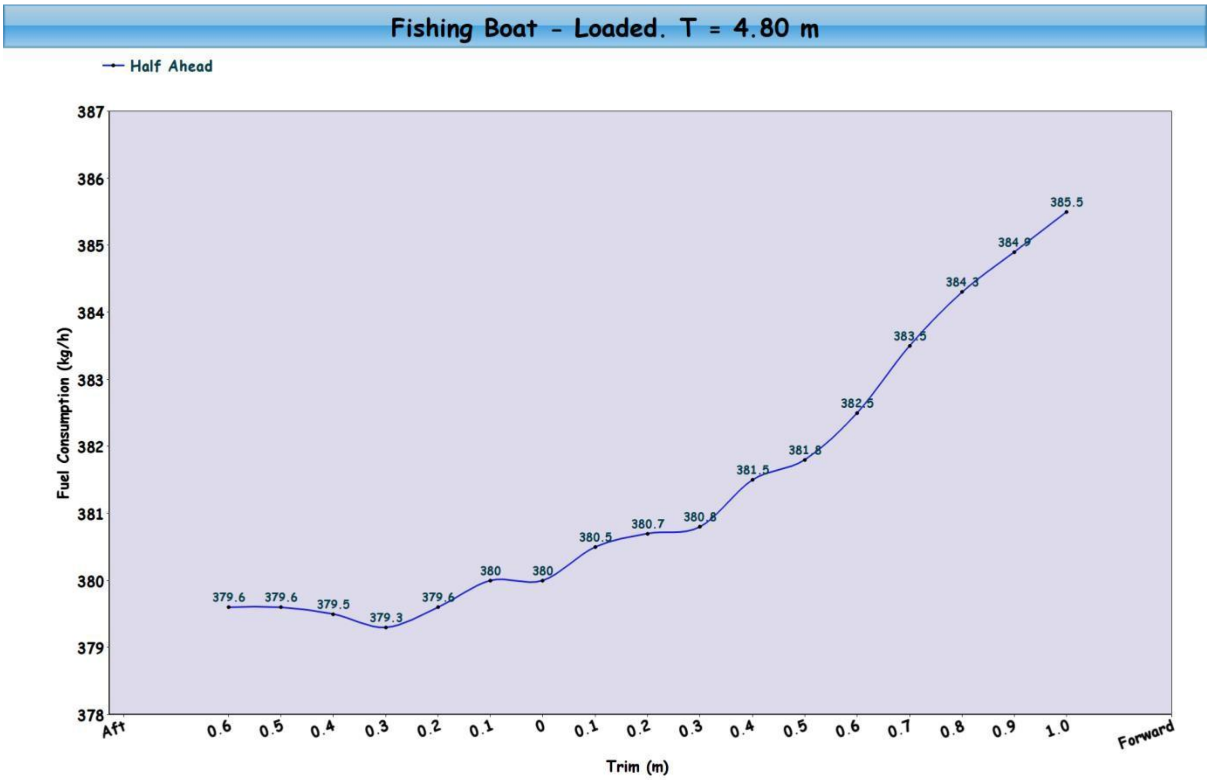


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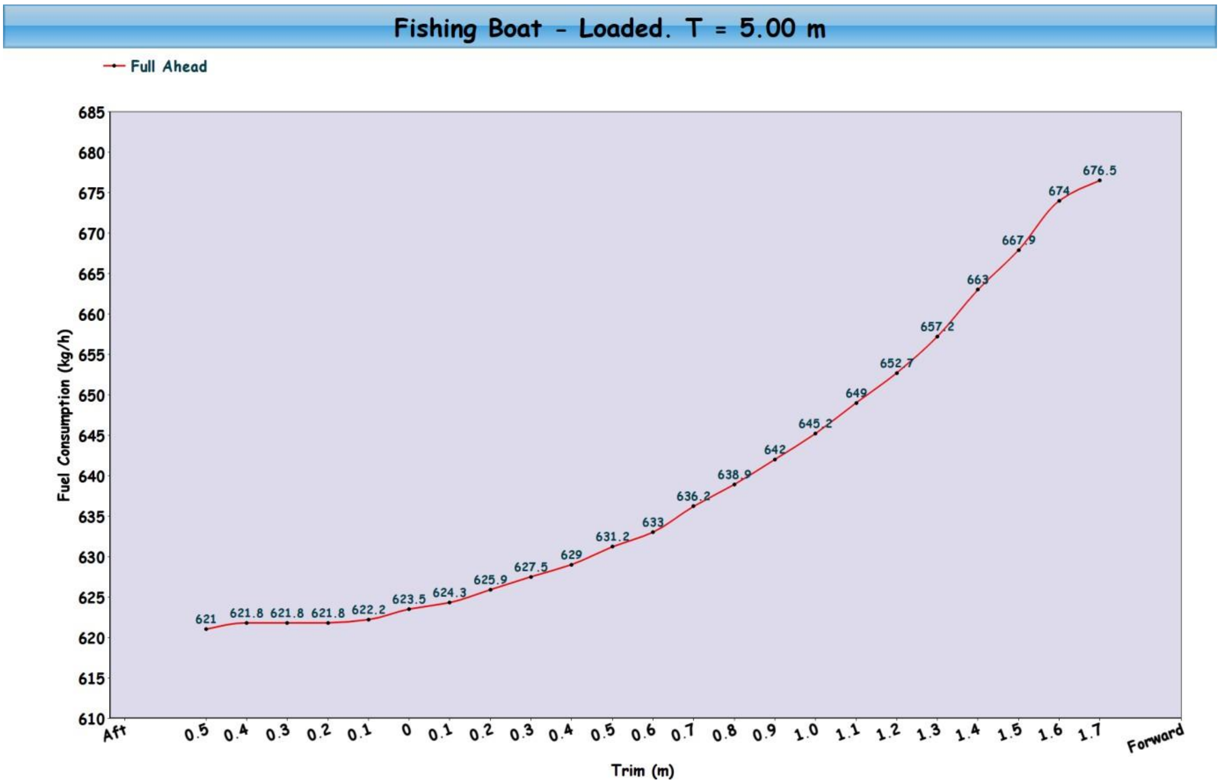


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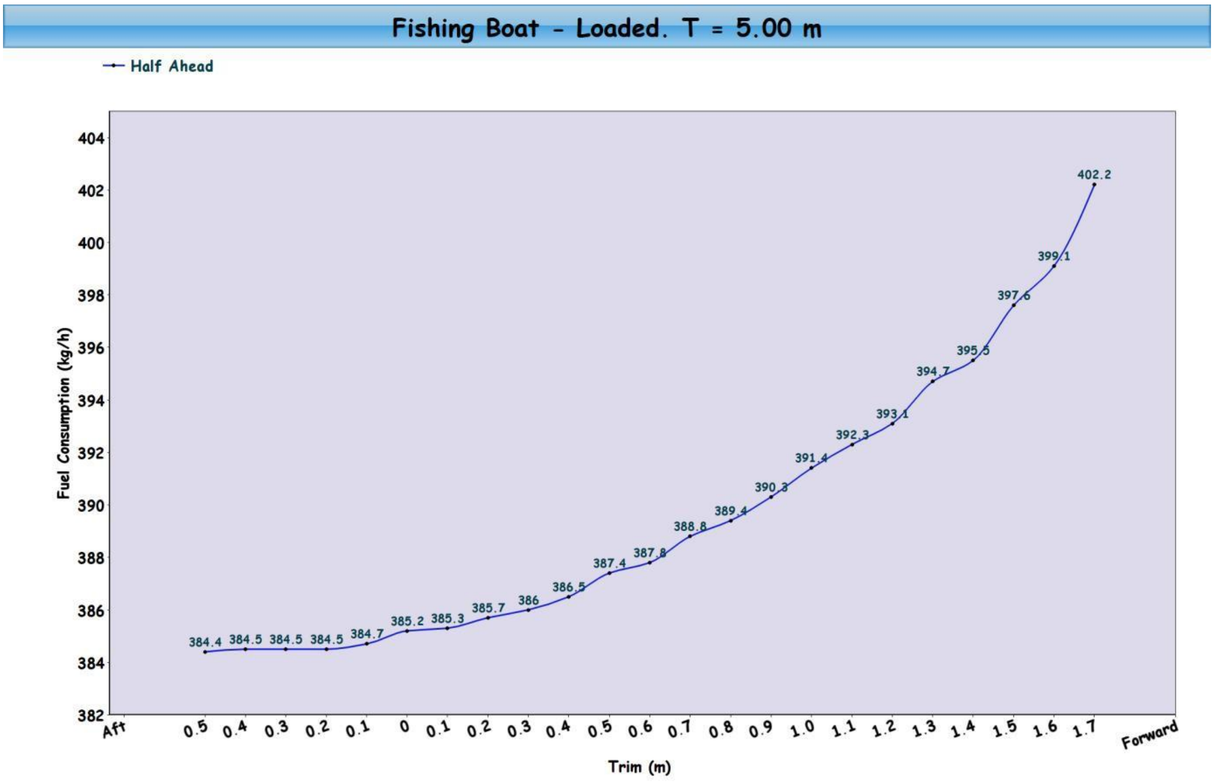


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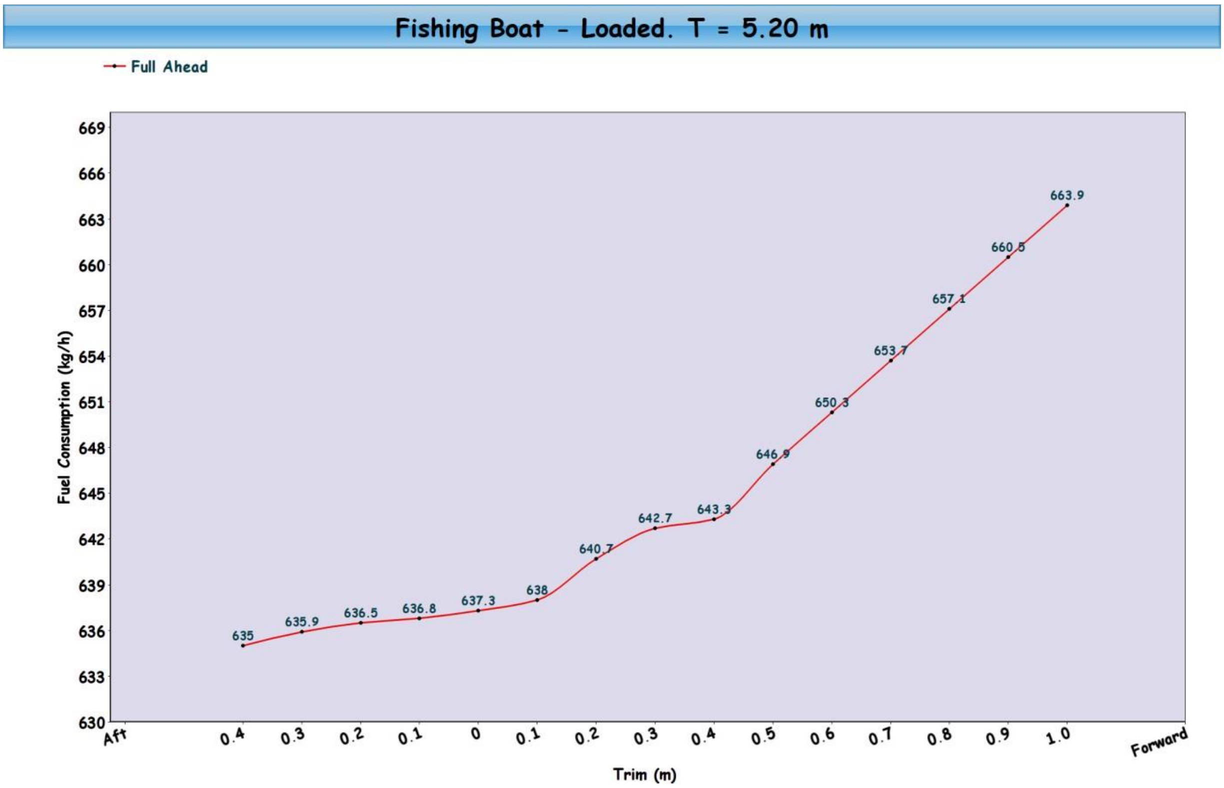
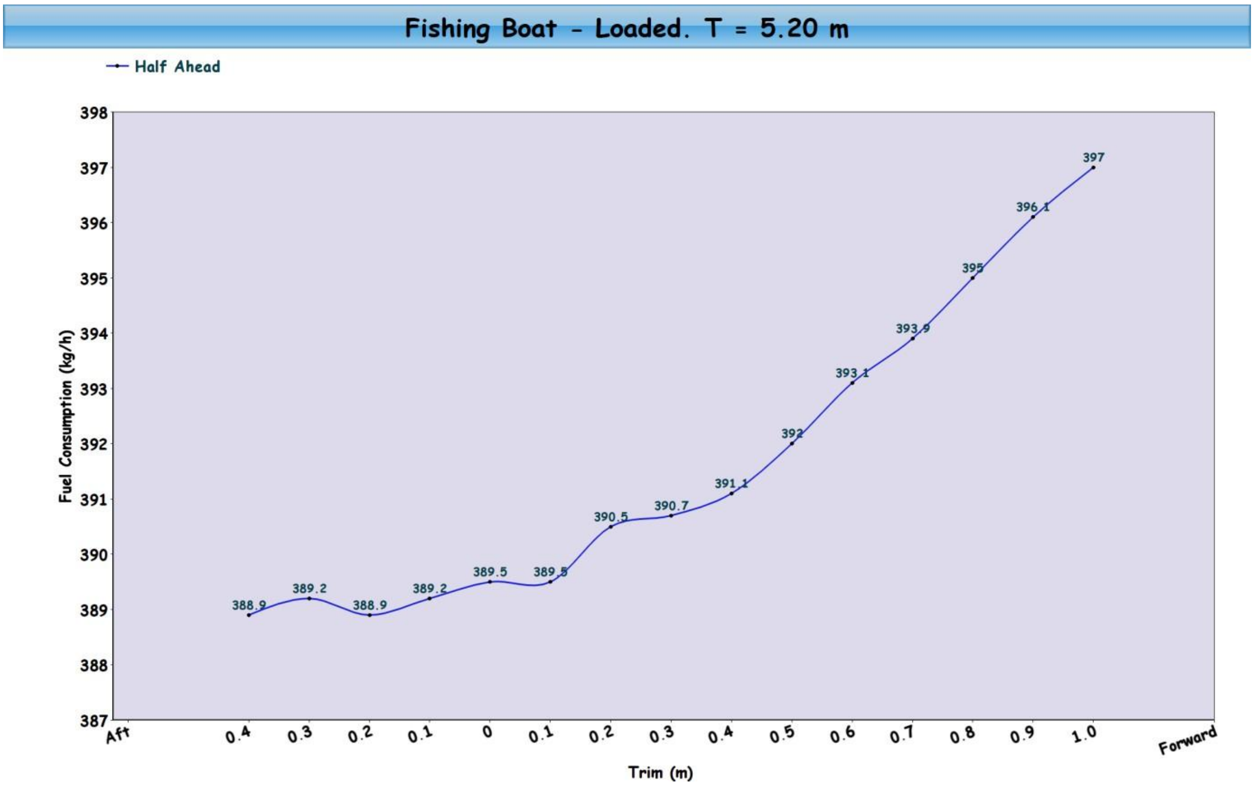



Appendix $Z_1$




Appendix $Z_2$

## AUTHORS' CONTRIBUTION STATEMENTS

Mahdi Birafane and Sarvar Khalikov supervised the project. Margulan Dairshenov selected vessels for investigation and tested them on the simulator of Kongsberg Company. Munojat Isakdjanova wrote the manuscript. Sarvar Khalikov and Munojat Isakdjanova provided critical feedback and did not participate in the final evaluation of the manuscript.

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