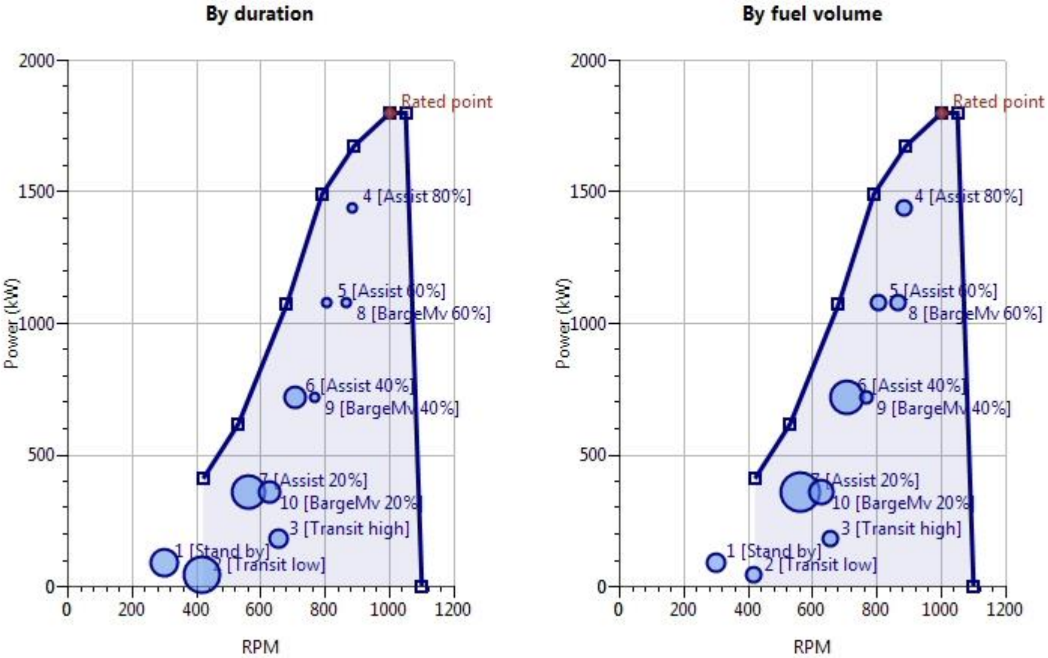
Understanding and Optimizing Vessel Propulsive Power and Fuel Use Using Duty Cycle Analysis Computations

Donald MacPherson[1] (M) and **Elizabeth Boyd**[2] (V)
1. HydroComp, Inc., Durham, New Hampshire
2. Nautican Research & Development Ltd, Vancouver, British Columbia



The maritime industry is in a mindset to save fuel and reduce emissions. How one achieves this end, however, can be a matter of some debate. While substantial industry effort is being placed on things that can be optimized, to achieve real benefit and financial return one must first understand the details about how the vessel consumes propulsive energy during its mission. This paper discusses a rational, simple, and effective systems engineering approach to identify power and fuel demands via computational propulsion analysis of the individual operating modes of a vessel's duty cycle. It explains sensible consumption metrics that can be used to evaluate and compare different physical systems, strategic plans, or helm decisions. A duty cycle operating mode analysis calculation for a tugboat in multi-role service (as a harbor tug and in long haul ocean barge towing) is demonstrated using COTS software, including examples of design-side and shipboard decision options and consequences.

KEY WORDS: Key performance indicators, duty cycle profile, fuel consumption, propulsion system optimization

INTRODUCTION

This paper puts forth a proposed approach for the optimum design of a vessel's propulsion system using a comprehensive analysis of alternatives. This is in contrast to the traditional "design spiral" design scenario, where the prime mover and propulsor are designed (or selected) based on a single reference design point. Further, it will focus on planning for design (strategic shore-side function) rather than for operation (a tactical on-board process). That being said, much of what is presented here can easily be extended for on-board operational planning.

Drive train design (or component selection) is traditionally based on selecting a single design point from a range of vessel operating modes, such as cruising speed; or by striking a balance between two competing objectives such as bollard pull and maximum free running speed. This "single design point" approach attempts to make an engineering decision without knowledge of the complete duty profile for the vessel. Of course, this approach was historically necessary because empirically-determined duty cycle data has been only sparsely available to designers. Therefore, without this data-driven understanding about a vessel's operating modes – and the duration of each of mode in the vessel's overall operation – designers will opt for some form of simple design objective even if it is based on limited data or anecdotal estimates.

The ability to optimize the drive train design using the all-inclusive duty cycle profile of the vessel is certainly advantageous. For vessel designers, the insight into the actual demands on the vessel in operation can lead to design scenarios that would not have been considered sensible using a single-point design approach. For example, the innovative use of a hybrid power plant in a tug [Faber 2008] was a clear step forward in how to think about the problem of optimizing fuel consumption and minimizing emissions in a harbor tug. This breakthrough was made possible in the context of a detailed study of the actual operations of a harbor tug, resulting in a clearly defined duty cycle profile for that vessel (and more broadly, for that vessel type). This knowledge allowed the designers to employ a new system given the demands of the vessel's duty profile.

Before proceeding further, we must define what is to be optimized. In simplest terms, the objective is to minimize "cost". Cost analysis is a complex discipline. So for the purposes of this paper, the cost function will be "operating expense" – more specifically, fuel consumption. In other words, the objective of the exercise is to minimize propulsion fuel consumption over a representative transit voyage or operational duration.

Individual operating "modes" are the fundamental pieces of the analysis. Each mode represents a unique way that the vessel will be operated. By collecting modes into a time-weighted "duty cycle" profile, one can develop a complete picture of how a vessel is to be operated in a particular type of service. A variety of "consumption" metrics are used for both the quantitative and qualitative assessment of energy efficiency, allowing rational comparison of different design alternatives and selection of the "optimum" system.

The vessel duty cycle profiles described in this paper are based on composites of both published and in-house data. They represent the "probabilistic" likelihood of vessel operation, and therefore reflect the real operating mission of the vessel. Functionally, the duty cycle profile is used to evaluate individual modes of operation as well as collective operating efficiencies and costs. Analysis of the modes (and their duty cycle profile summary) using contemporary computational techniques allows for realistic forecasting of potential fuel and financial savings from alternate design options.

One disadvantage of using a duty cycle design approach is that it requires a more complex and detailed analysis. It is necessary to employ a suitably valid duty cycle profile, whether from the vessel's own history or that of a similar vessel. Fortunately, the collection of operating data is becoming simpler and less expensive. Many contemporary engine models now include data logging, making it reasonably cost-effective to collect operating mode data as part of normal operations. This data not only can be used for optimizing operating efficiency, as is the discussion here, but also for observing operations or customizing maintenance routines.

The authors present the case for the duty cycle analysis of a general purpose tug for evaluation of energy efficiency, and illustrate its use to investigate minimum fuel use design alternatives.

SPEED AS A VARIABLE

Any model of ship operation, of course, must include speed as a variable. Using the well-known (albeit simple) model where propulsion energy (i.e., power and fuel) is related to speed cubed, one can easily see how reducing speed can save fuel. However, not all missions allow for speed reduction. All transit vessels have fixed starting and ending locations, so time increases as speed is reduced – and time is money. Only a business analysis can determine if reducing speed is viable for the mission.

Likewise, it is clear that minimizing the variation of transit speed helps save energy and fuel – so long as the environmental conditions are similar. Within a uniform environment, constant speed along a transit leg will always use less fuel, for example, than running half of the trip at +10% and half at -10% (i.e., a "cubic penalty"). However, environmental conditions may be significantly different over a transit leg. For example, a significant period could be spent in shallow water, where there is a cost in power of operation in shallow water at high speed. In this case, an overall benefit might be found by varying speed (e.g., reducing speed in shallow water and increasing speed in deeper water). There also may be regulated speed constraints, such as low wake zones, that restrict constant speed operation.

All consideration of speed as a variable in this paper will be for the purposes of the design of the system. No attempt is made to discuss the tactical on-board decisions of speed management.

DRIVE TRAIN CONFIGURATION AS A VARIABLE

The key to success in design-side drive train optimization is in operational flexibility. This in turn requires variation in propulsion plant drive scenarios. The balance of the paper will focus on the strategic definition of the optimum drive train components of prime mover, transmission, and propulsor. It will further simplify the discussion by intentionally limiting the prime mover to conventional single-fuel (MDO) diesel engines driving propellers through a reducing gearbox. The models presented herein, however, are applicable to any prime mover (e.g., turbines, multi-fuel engines) and propulsor (e.g., waterjets).

The paper also will intentionally not discuss what some may consider exotic, complex, or "early adopter" technologies, such as hybrid drives, shaft generator/motor units, contra-rotating propellers, or various propulsor energy saving devices (ESDs). Due to limits of analytical fidelity, no consideration will be given to disabling an entire shaft line as a variable. This mode (often called "trail-shaft mode") requires assessment of the added drag of the "trailed" propeller, as well as the supplemental drag of rudders given a helm correction to account for the asymmetric applied thrust.

THE PROCESS OF OPTIMIZATION BY DUTY CYCLE ANALYSIS

Duty cycle optimization is a somewhat manual – and certainly iterative – "evaluate and review" process. With appropriate tools (such as the HydroComp NavCad® software, which is used for these examples), a variety of performance metrics and results for the various drive train options across the duty cycle profile can be quickly evaluated.

An optimization task generally requires four parts – a) variables (the equipment components), b) performance objective function (the propulsion performance results predicted by the software), c) the goal (minimum fuel use) , and d) its functional domain (including constraints).

Variables

The following describe the variables to be considered:

Main engines and gearboxes

- Gearbox reduction ratio

Propellers

- Type: Open, Ducted
- Blade count
- Blade area ratio

Speed

- Mode operational speed (as possible for transit studies)

The analysis described herein is simplified by pre-selecting the following: engine models, available gearbox ratios, shaft angle, and propeller diameter. All of these could be treated as additional variations in the study, of course.

Objective function

The algorithms that describe vessel performance given variables (components) and domain (duty cycle profile and constraints) are processed within the software tool to predict propulsion results, including fuel consumption and other performance measures. The selection of appropriate functions is critical to achieving a realistic performance prediction. The software used for this analysis provides a variety of techniques that correlates the prediction of resistance and propulsion to empirical model test or sea trial data. The fidelity of the prediction model is further enhanced by numerous user aids to help in the proper selection of methods, creation of a complete model of the physical system, and quantitative accuracy.

Goal

What is to be optimized? What is the calculation goal?

Typically, the goal is minimal cost. (A minimization goal in conjunction with a cost-based objective function is often called a "cost function".) Cost is the combination of fixed capital expense (CAPEX) and variable operating expense (OPEX). For many applications, the greatest OPEX cost is fuel – so minimizing total fuel consumption for the entire representative trip or duty cycle profile will be the objective of this optimization process.

Domain

The domain includes the scope of the optimization (which is the duty cycle profile), plus restrictions and constraints. Typical constraints include:

- Hydroacoustics (acceptable noise and vibration levels given the duration of each mode)
- Propeller or appendage cavitation damage (at high thrust, high power modes)
- Engine manufacturer restrictions (such as a minimum operational RPM)
- Minimum bollard pull or top speed
- Avoidance of cavitation breakdown at bollard or top speed (both for propellers and nozzles)
- Engine redundancy regulations (started and idle for emergency backup rather than shut down)
- Propeller manufacturing limitations (on blade count and blade area ratio)

Calculation procedure

With exception of some types of integrated propulsors, it is valid to approach each duty cycle optimization task in sequential steps looking at the propulsor first, then the drive train. Propeller efficiency (within the defined constraints, of course) is the important attribute of the propeller for a cost function optimization. If we accept that this type of optimization is a "qualitative" evaluation then it is more important to be sure that the performance algorithms deliver high-fidelity relational trends for the propeller performance. Additional "quantitative" accuracy can be gained by a second loop (or more) around the optimization process, but the resulting variable solutions and conclusions will not likely change.

Calculation steps (Conventional drive line)

1. Select propeller type (open or ducted).
2. Size highest efficiency propeller characteristics for highest thrust modes using software propeller component optimization module (choosing blade count, minimum BAR, and maximum shaft RPM for cavitation and hydroacoustic domain constraints).
3. Choose gearbox reduction ratio from the available options to provide the closest shaft RPM from defined above (rounding up to the next highest ratio, unless the step up is unusually large). Recalculate propeller pitch for the defined reduction gear ratio.
4. Run operating modes evaluation using software propulsion calculation. Review engine load and fuel significance plots.
5. Record the performance results, and loop to the next variable.

Efficiency Calculation

This methodology has been developed to allow for easily comparable measures of operating efficiency for specific duty profiles. Individual duty cycle modes are defined and used to assemble a time-weighted profile for a vessel. The vessel definition includes hull, engine and propulsor characteristics such that a reliable calculation of fuel consumption is achieved across the duty cycle profile using contemporary commercially-available software. From a given basis case, analysis of the variations in the proposed drive line configuration can be quickly made to get a assessment of operating efficiency for the duty cycle profile.

The current study is limited to analysis of propulsion. The analysis also does not include multi-engine configurations, such as compound (2-in/1-out) drives or the attachment of hybrid equipment. The authors will also not address operator culture as a contributor in vessel operating costs, although this certainly is a matter with potential for substantial savings.

MODAL ANALYSIS

The description of a vessel's complete duty profile is built from a collection of different operating modes. Duty profiles reflect the overall mission of the vessel, where each operating mode is a snapshot of a representative task within that mission. Over its life, a vessel will have many operating modes, but it also can have different duty profiles or missions. For example, a tugboat can have many different duties, from ship assist to harbor duty to long haul ocean towing.

Time-weighted operating modes

Each operating mode will be defined by a number of representative mission characteristics, as shown below in Table 1. The propulsion performance, fuel consumption, and key indicators will be calculated for this set of mode characteristics.

Table 1. Operating mode characteristics

TASK	Description of the mode task.
SERVICE	The operational service for the mode: *Idle, Transit, Towpull* (in various power levels)
SPEED	Vessel speed (for *Transit* and *Towpull* services).
TIME	The duration time of the mode.
DISTANCE	The distance traveled during the mode task.

The influence or significance of each mode is determined by a time-based weighting. The duration of the mode of operation is normalized into a percentage, which is used to calculate summary figures of overall performance. As opposed to single design-point comparisons of performance, it will be these time-weighted Summary parameters that are used to qualitatively compare the relative effectiveness of different configurations for the complete duty profile.

Service types

Each mode is characterized by a service type, whose definition includes the particular equilibrium propulsion condition. Calculation of the propulsion analysis in the software used for this analysis requires definition of the particular analysis type (e.g., Free run, Towing), and the service definition points the mode to the proper option.

Transit

A Transit service type describes the typical operation of ferries or cargo-carrying vessels, for example. The engine's responsibility is to drive the propulsor so that it produces just the right amount of thrust to meet a steady-state speed. The equilibrium is principally between the hull and the propulsor.

To find the proper thrust-based equilibrium, the analysis needs the total resistance at that speed. The software calculation will predict the total resistance using the defined hull and added-drag information, and then run a Free run analysis to find the proper engine RPM (and CPP pitch, if applicable) where delivered thrust (i.e., less thrust deduction) equals total resistance.

An example of how the engine relates to a Free run analysis Transit service is shown in Figure 1. A collection of steady-state speeds (e.g., 7-10 kts) is evaluated for the RPM needed to match thrust, and the power is derived at that RPM. The mode's developed power is not related to the engine's rated power and RPM, nor to its maximum power curve. It is solely related to the amount needed by the propeller.

Idle

The Idle service is simply one where the engine is doing no work for the mission, but is in a standby setting. The engines are using fuel to keep themselves running, but none of the power is being delivered to the propulsor for any useful purpose. The definition of the RPM and power at Idle are defined in the software engine definition. Figures for Idle RPM are often defined by the manufacturer (such as how Cummins states the "Minimum idle speed setting" on their product brochures. The range of Idle RPM typically varies between 25% and 35% of rated RPM for fixed pitch propeller and waterjet applications, and as high as 50% rated RPM for CPP systems. No such figures for Idle Power are offered in manufacturer's product literature, but measurements suggest that the Idle power for a conventional marine diesel engine power plant is 5% to 7% rated power [Jayaram 2010]. A representative Idle point is shown on Figure 1.

Towpull

Many working vessels, such as trawlers, tugs, and supply craft, are required to push or pull at various levels of intensity as part of their working duty profile. These are Towpull services, where the propulsion equilibrium is not between the hull and propulsor, but between the engine and propulsor. Once the power equilibrium has been met, the amount of towpull (total delivered thrust less the vessel's resistance) can be calculated.

A full power “bollard” condition (*Towpull [max]*) will find that point where the propulsor’s power-RPM curve intersects the engine’s power curve. The developed power is a function of the propeller’s requirement and the engine’s potential, and it may not be the full rated power but it will always be the full power available at that RPM (i.e., on the maximum power curve).

Selected *Towpull [partial]* options (i.e., Towpull 80%, Towpull 40%) are for cases where a Towing analysis is required, but not at full available power. The analysis limits the power used for towing to a proportion of rated power. Figure 1 shows a Towpull 60% limit.

It is very important to remember that the weighting of a Towpull mode may need to be altered when comparing different propulsion systems. The important comparative figure is the towpull thrust and not the power used. For example, a ducted propeller would be expected to generate more thrust per unit of power than an open propeller. So, it may be perfectly appropriate to shift the weighting of a Towpull mode to a lower power percentage for a comparable towpull thrust, or to define a basis towpull explicitly.

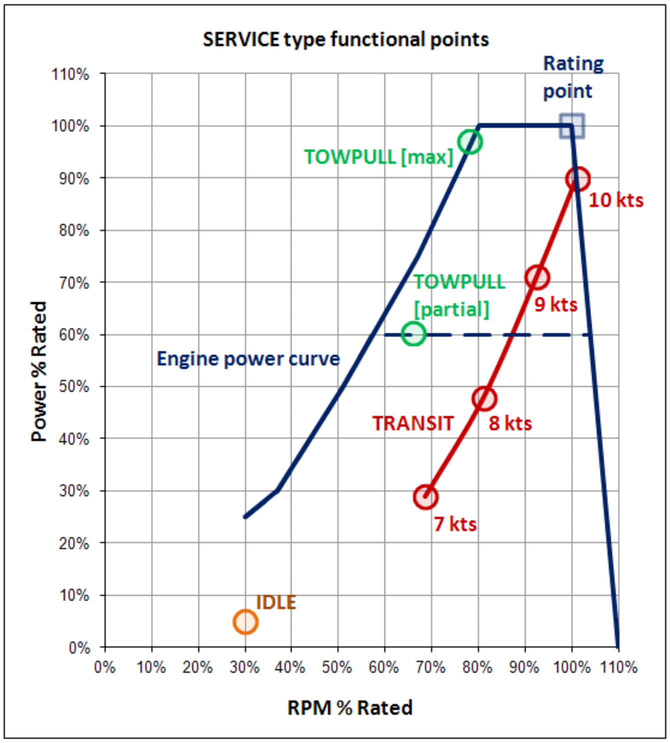


Figure 1. SERVICE type engine function points

Prediction of fuel consumption

Once a power and RPM pairing has been found, it is a relatively simple matter to predict fuel rate and consumption using the engine manufacture’s published data. The fuel rate data for the maximum power curve is typically provided. For most contemporary marine diesel engines, another intermediate “defined load curve” – sometimes called a “prop curve” or “cubic curve” (for the frequently-used RPM-cubed power function of these curves) – is also shown. In rare cases, a full fuel map is given. Accurate interpolation is possible with the full fuel map or with special manipulation of the fuel rate figures for the maximum power curve with a defined load curve. Fuel consumption (fuel rate) is provided by engine manufacturers as a volumetric rate (e.g., l/hr) or a mass specific rate (e.g., g/kW-hr). The data should also list corresponding heating value HV (a measure of the “energy” in the fuel, typically identified by a “lower” heating value LHV) and density figures.

The manufacturers determine fuel rate for their engines via empirical engine tests and publish this data on their product specification sheets. However, the published data is based on a particular fuel density and heating value specification, as noted above. Unfortunately, not all fuel is created equal and can vary in density and heating value depending on its composition (such as for sulphur content). If the fuel that is actually burned is significantly different than the fuel used for the engine tests, then an equivalent-energy conversion may be necessary to calculate the proper magnitude of volumetric and mass fuel rate during the mode task.

This study is limited to marine diesel engines using marine diesel oil (MDO). Operation with other fuels, such as heavy fuel oil (HFO) will also require a proper conversion to correctly determine actual fuel rates.

Duty profile examples

Of course, properly identifying the real mission duty profile is important to an operating modes analysis. This can be a challenge and requires disciplined measurement over the course of time. For the purposes of this paper, the authors have developed two duty profiles for a contemporary diesel-driven tug (as represented by the Ramparts 2800 design from Robert Allan Ltd) [Hertog 2009]. These profiles for harbor tug operation and ocean towing service are composites constructed from in-house data and multiple published sources [Hertog 2009] [Linden 2010] [Jayaram 2010].

Table 2a. Harbor Duty operating modes

ID	TASK	SERVICE	SPEED kt	TIME %
1	Stand by	Idle	0	15%
2	Transit low	Transit	6.6	30%
3	Transit high	Transit	10	7%
4	Assist 80%	Towpull 80%	1	1%
5	Assist 60%	Towpull 60%	1	1%
6	Assist 40%	Towpull 40%	1	9%
7	Assist 20%	Towpull 20%	1	26%
8	Brg mv 60%	Towpull 60%	5	1%
9	Brg mv 40%	Towpull 40%	5	1%
10	Brg mv 20%	Towpull 20%	5	9%

Table 2b. Ocean Towing operating modes

ID	TASK	SERVICE	SPEED kt	TIME %
1	10 kts	Transit	10	12%
2	8 kts	Transit	8	30%
3	6 kts	Transit	6	18%
4	4 kts	Transit	4	15%
5	2 kts	Transit	2	3%
6	Stand by	Idle	0	22%

KEY PERFORMANCE INDICATORS (KPI)

The purpose of a modal analysis, of course, is to get an idea of the effectiveness of the system over the range of tasks for a vessel's mission(s). Shore-side strategic planning, and even onboard tactical decision-making, requires useful and consistent metrics that can be used to qualitatively compare different design options (e.g., propeller versus waterjets), power plants (conventional versus compound), or propulsors (open versus ducted). Qualitative metrics can even be used for comparing entire vessels to investigate any benefits of proportional deadweight load sharing between vessels. We refer to these metrics as Key Performance Indicators (KPI).

GENERAL FORM FOR KEY PERFORMANCE INDICATORS (KPI)

KPI merit figures are principally used for qualitative comparisons of different "delivery" scenarios. They are ratios of "cost" to "capability". One important question is the way the ratio is to be handled: cost/capability or capability/cost? Examples of the treatment of this are widely varied:

- Miles per gallon for automobiles (capability/cost)
- Fuel rate gallons per hour traveled (cost/capability)
- True efficiency is capability/cost (e.g., thrust/power)

It may seem practical to use cost/capability ratio for transport vessels, where the problem being considered is one of the "costs" of fuel (whether that is financial cost or emissions cost), and to use capability/cost for towpull craft where the demand on the system varies and maximizing thrust/power or thrust/fuel is the design objective. However, it is to be expected that towing vessels with multiple operating modes may require transport-equivalent services (i.e., Transit to get on station), or conversely, for transport craft (e.g., Coast Guard vessels) to have significant Towpull modes. It is the opinion of the authors that one form of the "cost" and "capability" ratio should be followed for all modes.

A variety of KPI examples are available in the technical literature [Lloyds 2008], but one of the oldest KPI metrics is the Gabrielli and von Karman plot [Gabrielli 1950] which compares vessels using a ratio called "specific resistance". This is a cost/capability factor of: Power/(Weight*Speed). In recognition of the significant early contribution of this form to performance metrics, it was decided that the "cost/capability" form be used for the Operating Mode Analysis module in the analysis software as "consumption indices".

One popular KPI worth referencing is the Transport Factor (also called "Transport Efficiency", "Transport Effectiveness", or "Specific Power") [Kennel 1998]. This is calculated and displayed in the propulsion analysis, but is not used in the Operating Mode Analysis as it is a "capability/cost" metric.

CONSUMPTION INDICES

Three different Consumption Index (CI) forms are used for the analyses – Fuel (FCI), Energy (ECI), and Power (PCI).

Load

Each index requires a "load" variable, which will be the mass of ship displacement or deadweight, or by a towpull force. The choice for using displacement or deadweight should reflect the role of the vessel. For a commercial cargo-carrying service, where the business model depends on a cargo charge rate, using deadweight would make sense. In all other circumstances such as cruise ships or ferries, displacement would be used. The index acronym (FCI, for example) will be prefaced by "S" for ship displacement variant (SFCI), "D" for deadweight (DFCI), or "T" for towpull (TFCI).

Fuel Consumption Index (FCI)

FCI is a measure of the "cost" of fuel for a given action, as described by the fuel quantity needed to overcome a mass or force at a particular speed. This is not a true non-dimensional coefficient. The dimensional form of the index was established for the analysis software to use volumetric fuel rate, with units consistent with those chosen for the Operating Mode Analysis calculations (e.g., L/t-nm, gal/lbf-mi).

FCI = Fuel volume consumed / (Load [displacement, deadweight or towpull] * Distance traveled)

Energy Consumption Index (ECI)

ECI is a measure of the "cost" of energy for the mode. It further refines FCI to allow for differences in fuel energy delivery to move a load over a given distance. This provides for analysis with any particular fuel mix given the fuel's documented density and heating value. It is a non-dimensional factor, where the load is a true force (either the displacement or deadweight mass multiplied by gravity; or by the towpull force).

ECI = Mass fuel rate * Heating value / (Load force * Speed)

Power Consumption Index (PCI)

PCI offers the "cost" of total power delivery by incorporating the efficiency of an engine's conversion of fuel energy to developed power, as well as power train efficiency. However, PCI removes the engine's fuel use from the overall consumption assessment, so its principal value is in the qualitative evaluation of the hull-propulsor system. PCI is equivalent to a non-dimensional form of the Gabrielli & von Karman "specific resistance".

For the greatest system model fidelity, engine brake power should be used. However, given that shafts can be driven from a number of different configurations (e.g., diesel engine, electric motor), shaft power is often used.

PCI = Power / (Load force * Speed)

CASE STUDIES

The case studies presented herein are intended to show how operating mode analysis are a necessary part of the intelligent selection of propulsion system components for new construction or repower. The example tug and duty profiles (described above) over 1000 hours duration are used for the studies. The initial form of the tug is a conventional shaft-drive system for general-purpose usage.

INITIAL BASIS; GENERAL-PURPOSE TUG

The basis for the operating mode analyses and comparisons is the example tug with shaft-driven open-wheel fixed-pitch propellers. The sizing is based on the traditional strategy of balancing the competing objectives of maximum bollard pull and highest free-running speed [Gokarn 1969]. As we know, increasing one will decrease the other, so some “compromise” design point is needed. We will establish this point as full (100%) rated RPM, 85% rated power (i.e., 85% MCR), at a “compromise speed” of 6 knots.

The propeller has a maximum diameter of 2500 mm, and a blade form representative of a typical “workboat” style. The twin-screw vessel has a pair of 1800 kW/1000 RPM engines, whose specifications are a composite of a number of contemporary marine diesel engines. The propeller (of 2500 mm diameter) and gear ratio (4.0:1) were sized for this compromise design point.

PROPOSED ALTERNATIVE; PROPELLER AND GEAR RATIO

A proposed alternative system replaces the open propeller with a contemporary high-efficiency ducted propeller of the same diameter (2500 mm) and increases the reduction ratio (4.75:1) to shift the propulsor curve to slightly higher engine RPMs.

HARBOR DUTY PROFILE

For harbor duty service, the ducted propeller is able to generate substantially higher thrust per unit of power than the open propeller, so the specific towpull from the Basis was used for the Proposed case so that the towpull thrust was compatible between configurations. In other words, the proposed option met the towpull levels of the open propeller.

The complete operating mode analysis calculation reports are shown in Appendix A (Harbor Duty). The following plots (Figures 2 and 3), taken from the reports, show the comparative engine loading for the Basis and Proposed configurations. The marker area size reflects the fuel use at each mode. (Plots of duration at each engine loading are also available.)

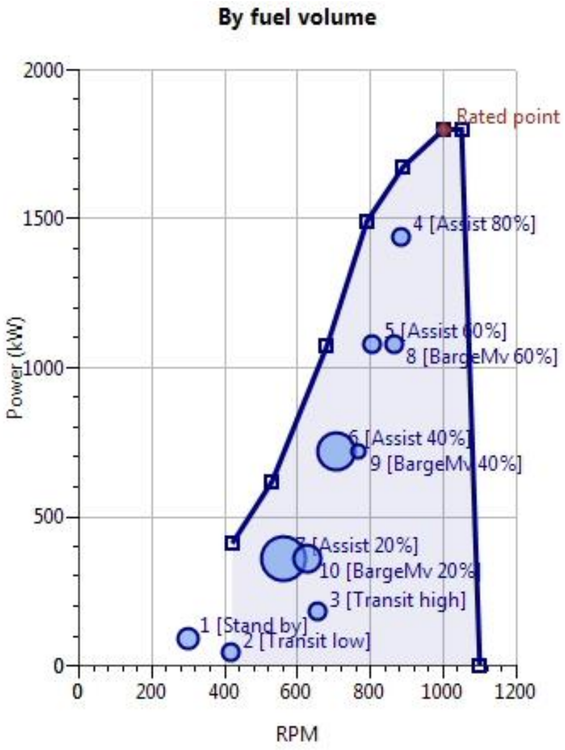


Figure 2. Basis configuration (Harbor Duty)

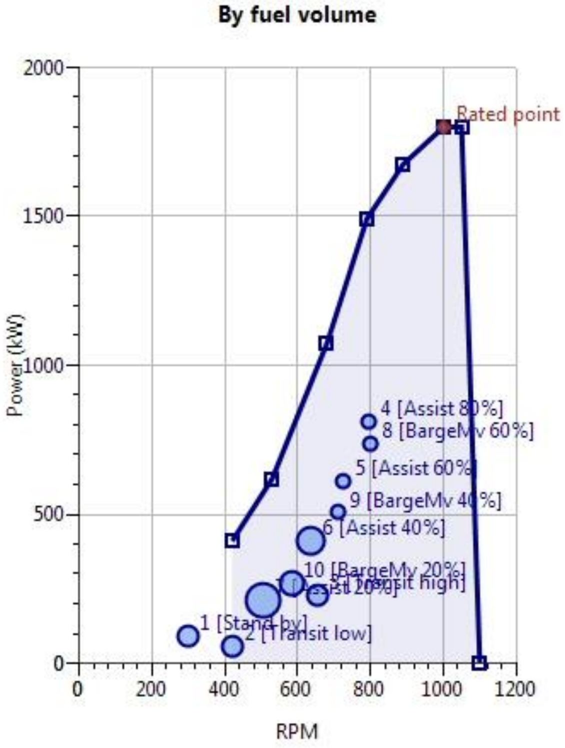


Figure 3. Proposed configuration (Harbor Duty)

The important fuel consumption metrics from the analyses are shown in Table 3 below. The overall conclusion is that the new proposed system offers some 29% overall fuel reduction – for the duty profile defined. While the free run transit fuel use is substantially larger with the new system, its fuel use in towpull operations offsets this. The smaller fraction of duration at transit (37% of the total time) means the towpull benefits dominate. Of course, for a different duty profile, the conclusions might be completely different. This might even suggest consideration of a different engine model if the boat is only for harbor duty.

Table 3. Operating mode analysis comparison (Harbor Duty)

	VOL FUEL L	MASS FUEL t	SHIP FUEL CI L/t-nm	TOW FUEL CI L/kN-nm
Basis	141548	118.90	0.007665	1.315
Proposed	100339	84.28	0.01007	0.7925
Change	-29%	-29%	+31%	-40%

OCEAN TOWING DUTY PROFILE

The duty profile for ocean towing modeled the added drag of a generic 400 ft towed barge. The proposed propellers are the same as for the previous example, except the pitch was sized for high-speed high-load operation. Since the functional modes were all Transit (i.e., the equilibrium thrust condition at the speed), no alteration of the mode duration figures were needed. Like the prior duty profile, the complete operating mode analysis calculation reports are shown in Appendix B (Ocean Towing). The following plots (Figures 4-5), show the comparative engine loading and fuel use for the Basis and Proposed configurations.

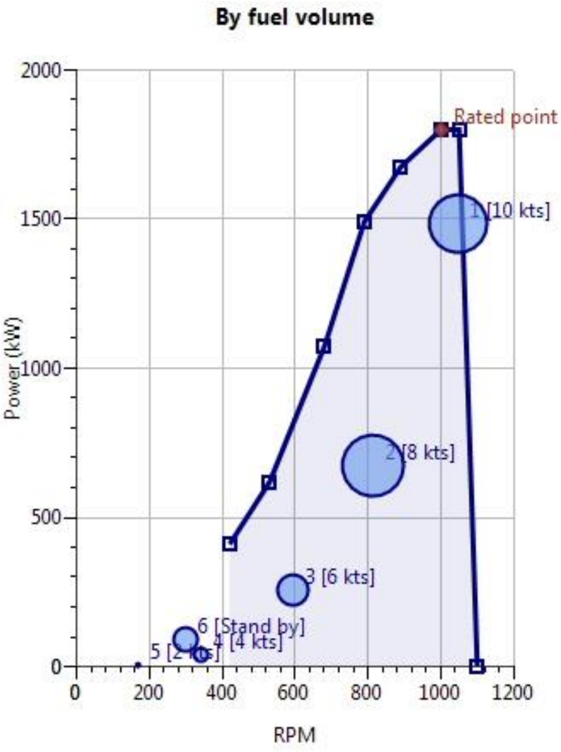


Figure 4. Basis configuration (Ocean Towing)

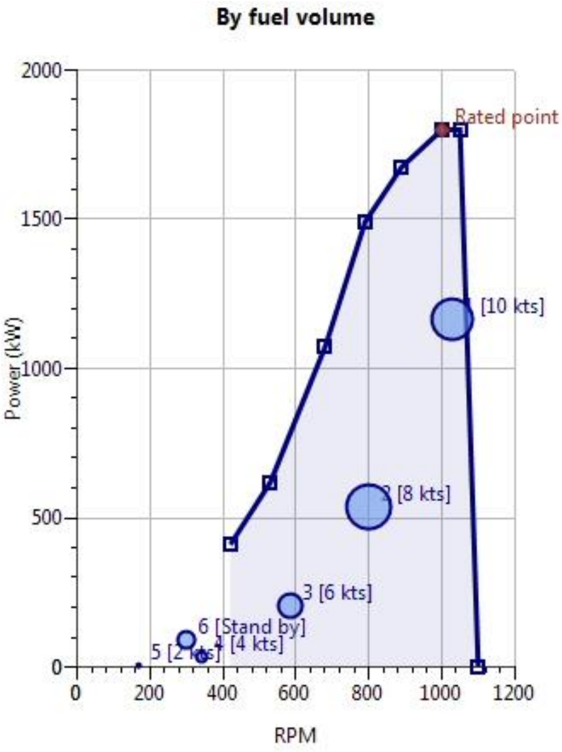


Figure 5. Proposed configuration (Ocean Towing)

It is remarkable how much better the proposed ducted propeller is than the basis open propeller, but given the significantly higher thrust loading requirement when towing, the benefits of a high-efficiency nozzle becomes less surprising. The fuel consumption merit figures are in Table 4 below. We can see that even in a duty that is traditionally popular for open-wheel applications, efficient ducted propeller design can offer significant savings.

Table 4, Operating mode analysis comparison (Ocean Towing)

	VOL FUEL L	MASS FUEL t	SHIP FUEL CI L/t-nm
Basis	230289	193.44	0.05526
Proposed	186005	156.24	0.04427
Change	-19%	-19%	-19%

CONTINUING WORK

The current work demonstrates how vessel performance can be evaluated from the point of view of energy efficiency, using a multi-mode design approach that evaluates efficiency over a vessel's full duty profile. The current study is limited to an analysis of propulsive efficiency. This is applicable to most vessel types and operations, where efficiency losses due to maneuvering are small compared to the efficiency of the propulsion system. However, there are several areas where the authors plan to incorporate new analysis and capabilities in future work.

- Emissions
- Cumulative engine load for maintenance
- Multi-engine drives
- Effect of currents
- Heavy maneuvering operations (rivers)

REFERENCES

Faber, G. and J. Aspin, “The Foss Hybrid Tug: From Innovation to Implementation”, *ITS 2008*.

Gabrielli, G., and T. von Karman,, “What price speed? Specific power required for propulsion of vehicles”, *Mechanical Engineering*, Vol. 72, No. 10, 1950.

Gokarn, R.P., “Tug Propeller Design”, *Marine Technology*, April 1969.

Hertog, V. den; Harford, K., and R. Stapleton, “RAptures: Resolving the Tugboat Energy Equation”, *Tugnology ’09*, Amsterdam, 2009.

Jayaram, V., et al; “Evaluating Emission Benefits of a Hybrid Tug Boat”, Report to the California Air Resources Board, University of California Riverside, Riverside, CA, 2010.

Kennell, C.G., “Design Trends in High Speed Transport”, *Marine Technology*, Vol. 35, No. 3, 1998.

Linden, W. van der, et al, “Innovation in Tug Design”, *ITS 2010*, Vancouver, 2010.

Tozer, D., *Container ship speed matters*, Lloyds Register, 2008.

APPENDIX A1 – HARBOR DUTY CALCULATION (BASIS)

Operating Mode Analysis

1 Aug 2014 10:11 AM
HydroComp NavCad 2014 [Premium]

Project ID	**26 m multi- duty tug**
Description	**Basis open-wheel; Harbor duty**
File name	**HarborDuty_Basis.hcnc**

Vessel data

Hull		**Engine**	
Configuration:	**Monohull**	Engine data:	**Engine 1800 kW at 10...**
Length on WL:	**26.100 m**	Rated RPM:	**1000 RPM**
Max beam on WL:[LWL/BWL 2.270]	**11.500 m**	Rated power:	**1800.0 kW**
Max molded draft:[BWL/T 3.067]	**3.750 m**	**Fuel basis**	
Displacement:[CB 0.537]	**620.00 t**	Density:	**840.00 kg/m3**
Deadweight:		Heating value:	**42800 J/g**
Water properties		**Propulsor**	
Water type:	**Salt**	Propulsor count:	**2**
		Propulsor type:	**Propeller**

Prediction results

	DESCRIPTION				DUTY	
MODE ID	TASK	SPEED [kt]	TIME [hr]	SERVICE	TIME% [%]	DISTANCE [nm]
1	**Stand by**	**0.00**	**150.0**	**Idle**	**15.0**	**0.0**
2	**Transit low**	**6.60**	**300.0**	**Transit**	**30.0**	**1980.0**
3	**Transit high**	**10.00**	**70.0**	**Transit**	**7.0**	**700.0**
4	**Assist 80%**	**1.00**	**10.0**	**Tow-80%**	**1.0**	**10.0**
5	**Assist 60%**	**1.00**	**10.0**	**Tow-60%**	**1.0**	**10.0**
6	**Assist 40%**	**1.00**	**90.0**	**Tow-40%**	**9.0**	**90.0**
7	**Assist 20%**	**1.00**	**260.0**	**Tow-20%**	**26.0**	**260.0**
8	**BrgMv 60%**	**5.00**	**10.0**	**Tow-60%**	**1.0**	**50.0**
9	**BrgMv 40%**	**5.00**	**10.0**	**Tow-40%**	**1.0**	**50.0**
10	**BrgMv 20%**	**5.00**	**90.0**	**Tow-20%**	**9.0**	**450.0**
SUMMARY	**---**	**---**	**1000.0**	**---**	**100.0**	**3600.0**

	FUEL CONSUMPTION				PROPULSION PERFORMANCE			
MODE ID	VOLRATE [L/h]	MASSRATE [t/h]	FUELVOL [L]	FUELMASS [t]	RPMENG [RPM]	PBTOTAL [kW]	LOADENG [%]	TOWPULL [kN]
1	**49.00**	**0.041**	**7350**	**6.17**	**300**	**180.0**	**0.0**	**0.00**
2	**23.77**	**0.020**	**7130**	**5.99**	**417**	**86.8**	**2.4**	**0.00**
3	**96.85**	**0.081**	**6780**	**5.70**	**652**	**360.1**	**10.0**	**0.00**
4	**712.57**	**0.599**	**7126**	**5.99**	**883**	**2879.9**	**80.0**	**325.76**
5	**533.49**	**0.448**	**5335**	**4.48**	**804**	**2158.8**	**60.0**	**268.16**
6	**363.23**	**0.305**	**32691**	**27.46**	**704**	**1439.8**	**40.0**	**203.89**
7	**189.07**	**0.159**	**49158**	**41.29**	**561**	**719.8**	**20.0**	**127.35**
8	**533.59**	**0.448**	**5336**	**4.48**	**864**	**2159.3**	**60.0**	**232.05**
9	**363.13**	**0.305**	**3631**	**3.05**	**766**	**1439.3**	**40.0**	**170.96**
10	**189.03**	**0.159**	**17012**	**14.29**	**628**	**719.7**	**20.0**	**99.14**
SUMMARY	**141.55**	**0.119**	**141548**	**118.90**	**---**	**---**	**---**	**0.00**

	SHIP CONSUMPTION INDICES			DWT CONSUMPTION INDICES			TOWPULL CONSUMPTION INDICES		
MODE ID	FUELCI [L/t-nm]	ENERGYCI	POWERCI	FUELCI [L/t-nm]	ENERGYCI	POWERCI	FUELCI [L/kN-nm]	ENERGYCI	POWERCI
1	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**
2	**0.005808**	**0.01150**	**0.004203**	**---**	**---**	**---**	**---**	**---**	**---**
3	**0.015622**	**0.03092**	**0.011512**	**---**	**---**	**---**	**---**	**---**	**---**
4	**---**	**---**	**---**	**---**	**---**	**---**	**2.187**	**42.46**	**17.185**
5	**---**	**---**	**---**	**---**	**---**	**---**	**1.989**	**38.62**	**15.649**
6	**---**	**---**	**---**	**---**	**---**	**---**	**1.782**	**34.58**	**13.727**
7	**---**	**---**	**---**	**---**	**---**	**---**	**1.485**	**28.82**	**10.987**
8	**---**	**---**	**---**	**---**	**---**	**---**	**0.460**	**8.93**	**3.618**
9	**---**	**---**	**---**	**---**	**---**	**---**	**0.425**	**8.25**	**3.273**
10	**---**	**---**	**---**	**---**	**---**	**---**	**0.381**	**7.40**	**2.822**
SUMMARY	**0.007665**	**0.01517**	**0.005586**	**---**	**---**	**---**	**1.315**	**25.53**	**9.882**

APPENDIX A2 – HARBOR DUTY CALCULATION (PROPOSED)

Operating Mode Analysis

1 Aug 2014 10:47 AM
HydroComp NavCad 2014 [Premium]

Project ID	**26 m multi- duty tug**
Description	**Basis open-wheel; Harbor duty**
File name	**HarborDuty_Proposed.hcnc**

Vessel data

Hull		**Engine**	
Configuration:	**Monohull**	Engine data:	**Engine 1800 kW at 10...**
Length on WL:	**26.100 m**	Rated RPM:	**1000 RPM**
Max beam on WL:[LWL/BWL 2.270]	**11.500 m**	Rated power:	**1800.0 kW**
Max molded draft:[BWL/T 3.067]	**3.750 m**	**Fuel basis**	
Displacement:[CB 0.537]	**620.00 t**	Density:	**840.00 kg/m3**
Deadweight:		Heating value:	**42800 J/g**
Water properties		**Propulsor**	
Water type:	**Salt**	Propulsor count:	**2**
		Propulsor type:	**Propeller**

Prediction results

	DESCRIPTION				DUTY		
MODE ID	TASK	SPEED [kt]	TIME [hr]	SERVICE	TIME% [%]	DISTANCE [nm]	
1	**Stand by**	**0.00**	**150.0**	**Idle**	**15.0**	**0.0**	
2	**Transit low**	**6.60**	**300.0**	**Transit**	**30.0**	**1980.0**	
3	**Transit high**	**10.00**	**70.0**	**Transit**	**7.0**	**700.0**	
4	**Assist 80%**	**1.00**	**10.0**	**Defined tow**	**1.0**	**10.0**	
5	**Assist 60%**	**1.00**	**10.0**	**Defined tow**	**1.0**	**10.0**	
6	**Assist 40%**	**1.00**	**90.0**	**Defined tow**	**9.0**	**90.0**	
7	**Assist 20%**	**1.00**	**260.0**	**Defined tow**	**26.0**	**260.0**	
8	**BrgMv 60%**	**5.00**	**10.0**	**Defined tow**	**1.0**	**50.0**	
9	**BrgMv 40%**	**5.00**	**10.0**	**Defined tow**	**1.0**	**50.0**	
10	**BrgMv 20%**	**5.00**	**90.0**	**Defined tow**	**9.0**	**450.0**	
SUMMARY	**---**	**---**	**1000.0**	**---**	**100.0**	**3600.0**	

	FUEL CONSUMPTION				PROPULSION PERFORMANCE			
MODE ID	VOLRATE [L/h]	MASSRATE [t/h]	FUELVOL [L]	FUELMASS [t]	RPMENG [RPM]	PBTOTAL [kW]	LOADENG [%]	TOWPULL [kN]
1	**49.00**	**0.041**	**7350**	**6.17**	**300**	**180.0**	**0.0**	**0.00**
2	**32.15**	**0.027**	**9646**	**8.10**	**423**	**117.6**	**3.3**	**0.00**
3	**121.20**	**0.102**	**8484**	**7.13**	**654**	**453.4**	**12.6**	**0.00**
4	**407.73**	**0.342**	**4077**	**3.42**	**794**	**1628.5**	**45.2**	**325.76**
5	**312.75**	**0.263**	**3128**	**2.63**	**723**	**1227.0**	**34.1**	**268.16**
6	**215.21**	**0.181**	**19369**	**16.27**	**634**	**824.9**	**22.9**	**203.89**
7	**112.27**	**0.094**	**29189**	**24.52**	**507**	**419.0**	**11.6**	**127.35**
8	**372.10**	**0.313**	**3721**	**3.13**	**798**	**1477.3**	**41.0**	**232.05**
9	**261.00**	**0.219**	**2610**	**2.19**	**709**	**1012.0**	**28.1**	**170.96**
10	**141.83**	**0.119**	**12765**	**10.72**	**584**	**533.4**	**14.8**	**99.14**
SUMMARY	**100.34**	**0.084**	**100339**	**84.28**	**---**	**---**	**---**	**0.00**

	SHIP CONSUMPTION INDICES			DWT CONSUMPTION INDICES			TOWPULL CONSUMPTION INDICES		
MODE ID	FUELCI [L/t-nm]	ENERGYCI	POWERCI	FUELCI [L/t-nm]	ENERGYCI	POWERCI	FUELCI [L/kN-nm]	ENERGYCI	POWERCI
1	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**
2	**0.00786**	**0.01556**	**0.005698**	**---**	**---**	**---**	**---**	**---**	**---**
3	**0.01955**	**0.03870**	**0.014495**	**---**	**---**	**---**	**---**	**---**	**---**
4	**---**	**---**	**---**	**---**	**---**	**---**	**1.2516**	**24.30**	**9.718**
5	**---**	**---**	**---**	**---**	**---**	**---**	**1.1663**	**22.64**	**8.895**
6	**---**	**---**	**---**	**---**	**---**	**---**	**1.0555**	**20.49**	**7.864**
7	**---**	**---**	**---**	**---**	**---**	**---**	**0.8816**	**17.11**	**6.396**
8	**---**	**---**	**---**	**---**	**---**	**---**	**0.3207**	**6.23**	**2.475**
9	**---**	**---**	**---**	**---**	**---**	**---**	**0.3053**	**5.93**	**2.301**
10	**---**	**---**	**---**	**---**	**---**	**---**	**0.2861**	**5.55**	**2.092**
SUMMARY	**0.01007**	**0.01993**	**0.007362**	**---**	**---**	**---**	**0.7925**	**15.38**	**5.818**

APPENDIX B1 – OCEAN TOWING CALCULATION (BASIS)

Operating Mode Analysis

1 Aug 2014 10:57 AM
HydroComp NavCad 2014 [Premium]

Project ID	**26 m multi- duty tug**
Description	**Basis open-wheel; Ocean towing**
File name	**OceanTowing_Basis.hcnc**

Vessel data

Hull		**Engine**	
Configuration:	**Monohull**	Engine data:	**Engine 1800 kW at 10...**
Length on WL:	**26.100 m**	Rated RPM:	**1000 RPM**
Max beam on WL:[LWL/BWL 2.270]	**11.500 m**	Rated power:	**1800.0 kW**
Max molded draft:[BWL/T 3.067]	**3.750 m**	**Fuel basis**	
Displacement:[CB 0.537]	**620.00 t**	Density:	**840.00 kg/m3**
Deadweight:		Heating value:	**42800 J/g**
Water properties		**Propulsor**	
Water type:	**Salt**	Propulsor count:	**2**
		Propulsor type:	**Propeller**

Prediction results

	DESCRIPTION				DUTY	
MODE ID	TASK	SPEED [kt]	TIME [hr]	SERVICE	TIME% [%]	DISTANCE [nm]
1	**10 kts**	**10.00**	**120.0**	**Transit**	**12.0**	**1200.0**
2	**8 kts**	**8.00**	**300.0**	**Transit**	**30.0**	**2400.0**
3	**6 kts**	**6.00**	**180.0**	**Transit**	**18.0**	**1080.0**
4	**4 kts**	**4.00**	**150.0**	**Transit**	**15.0**	**600.0**
5	**2 kts**	**2.00**	**30.0**	**Transit**	**3.0**	**60.0**
6	**Stand by**	**0.00**	**220.0**	**Idle**	**22.0**	**0.0**
SUMMARY	**---**	**---**	**1000.0**	**---**	**100.0**	**5340.0**

	FUEL CONSUMPTION				PROPULSION PERFORMANCE		
MODE ID	VOLRATE [L/h]	MASSRATE [t/h]	FUELVOL [L]	FUELMASS [t]	RPMENG [RPM]	PBTOTAL [kW]	LOADENG [%]
1	**736.52**	**0.619**	**88382**	**74.24**	**1050**	**2971.6**	**82.5**
2	**342.70**	**0.288**	**102811**	**86.36**	**814**	**1352.9**	**37.6**
3	**137.72**	**0.116**	**24790**	**20.82**	**595**	**517.4**	**14.4**
4	**22.94**	**0.019**	**3441**	**2.89**	**342**	**83.7**	**2.3**
5	**2.82**	**0.002**	**84**	**0.07**	**170**	**10.2**	**0.3**
6	**49.00**	**0.041**	**10780**	**9.06**	**300**	**180.0**	**0.0**
SUMMARY	**230.29**	**0.193**	**230289**	**193.44**	**---**	**---**	**---**

	SHIP CONSUMPTION INDICES			DWT CONSUMPTION INDICES			TOWPULL CONSUMPTION INDICES		
MODE ID	FUELCI [L/t-nm]	ENERGYCI	POWERCI	FUELCI [L/t-nm]	ENERGYCI	POWERCI	FUELCI [L/kN-nm]	ENERGYCI	POWERCI
1	**0.11879**	**0.2352**	**0.09500**	**---**	**---**	**---**	**---**	**---**	**---**
2	**0.06909**	**0.1368**	**0.05407**	**---**	**---**	**---**	**---**	**---**	**---**
3	**0.03702**	**0.0733**	**0.02757**	**---**	**---**	**---**	**---**	**---**	**---**
4	**0.00925**	**0.0183**	**0.00669**	**---**	**---**	**---**	**---**	**---**	**---**
5	**0.00227**	**0.0045**	**0.00163**	**---**	**---**	**---**	**---**	**---**	**---**
6	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**
SUMMARY	**0.05526**	**0.1094**	**0.04312**	**---**	**---**	**---**	**---**	**---**	**---**

APPENDIX B2 – OCEAN TOWING CALCULATION (PROPOSED)

Operating Mode Analysis

1 Aug 2014 11:12 AM

HydroComp NavCad 2014 [Premium]

Project ID	**26 m multi- duty tug**
Description	**Proposed ducted; Ocean towing**
File name	**OceanTowing_Proposed.hcnc**

Vessel data

Hull		**Engine**	
Configuration:	**Monohull**	Engine data:	**Engine 1800 kW at 10...**
Length on WL:	**26.100 m**	Rated RPM:	**1000 RPM**
Max beam on WL:[LWL/BWL 2.270]	**11.500 m**	Rated power:	**1800.0 kW**
Max molded draft:[BWL/T 3.067]	**3.750 m**	**Fuel basis**	
Displacement:[CB 0.537]	**620.00 t**	Density:	**840.00 kg/m3**
Deadweight:		Heating value:	**42800 J/g**
Water properties		**Propulsor**	
Water type:	**Salt**	Propulsor count:	**2**
		Propulsor type:	**Propeller**

Prediction results

	DESCRIPTION				DUTY	
MODE ID	TASK	SPEED [kt]	TIME [hr]	SERVICE	TIME% [%]	DISTANCE [nm]
1	**10 kts**	**10.00**	**120.0**	**Transit**	**12.0**	**1200.0**
2	**8 kts**	**8.00**	**300.0**	**Transit**	**30.0**	**2400.0**
3	**6 kts**	**6.00**	**180.0**	**Transit**	**18.0**	**1080.0**
4	**4 kts**	**4.00**	**150.0**	**Transit**	**15.0**	**600.0**
5	**2 kts**	**2.00**	**30.0**	**Transit**	**3.0**	**60.0**
6	**Stand by**	**0.00**	**220.0**	**Idle**	**22.0**	**0.0**
SUMMARY	**---**	**---**	**1000.0**	**---**	**100.0**	**5340.0**

	FUEL CONSUMPTION				PROPULSION PERFORMANCE		
MODE ID	VOLRATE [L/h]	MASSRATE [t/h]	FUELVOL [L]	FUELMASS [t]	RPMENG [RPM]	PBTOTAL [kW]	LOADENG [%]
1	**577.86**	**0.485**	**69344**	**58.25**	**1028**	**2330.8**	**64.7**
2	**275.90**	**0.232**	**82770**	**69.53**	**799**	**1074.3**	**29.8**
3	**111.31**	**0.093**	**20035**	**16.83**	**585**	**415.3**	**11.5**
4	**20.02**	**0.017**	**3002**	**2.52**	**339**	**73.0**	**2.0**
5	**2.46**	**0.002**	**74**	**0.06**	**169**	**8.9**	**0.2**
6	**49.00**	**0.041**	**10780**	**9.06**	**300**	**180.0**	**0.0**
SUMMARY	**186.01**	**0.156**	**186005**	**156.24**	**---**	**---**	**---**

	SHIP CONSUMPTION INDICES			DWT CONSUMPTION INDICES			TOWPULL CONSUMPTION INDICES		
MODE ID	FUELCI [L/t-nm]	ENERGYCI	POWERCI	FUELCI [L/t-nm]	ENERGYCI	POWERCI	FUELCI [L/kN-nm]	ENERGYCI	POWERCI
1	**0.09320**	**0.18450**	**0.07452**	**---**	**---**	**---**	**---**	**---**	**---**
2	**0.05563**	**0.11011**	**0.04293**	**---**	**---**	**---**	**---**	**---**	**---**
3	**0.02992**	**0.05923**	**0.02213**	**---**	**---**	**---**	**---**	**---**	**---**
4	**0.00807**	**0.01598**	**0.00584**	**---**	**---**	**---**	**---**	**---**	**---**
5	**0.00198**	**0.00393**	**0.00143**	**---**	**---**	**---**	**---**	**---**	**---**
6	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**	**---**
SUMMARY	**0.04427**	**0.08763**	**0.03426**	**---**	**---**	**---**	**---**	**---**	**---**