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## ***RAptures: Resolving the Tugboat Energy Equation***

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### **SYNOPSIS**

With demands on all types of vessels to reduce emissions and fuel consumption, it is often difficult to separate the facts from the sales pitches. Faced with the frequent question of “How best to go green” (and also save some money), Robert Allan Ltd set about to create a tool to analyse a wide range of options for typical harbour tug propulsion systems. *RAptures* (Robert Allan Ltd: Powering Tugs for Real Energy Savings) is a straightforward analytical tool which can be used for both a high-level system comparison at the very early stages of a new design, and also for the latter design stage comparison of very specific machinery selection options. With basic tug power and an operating profile as input, a direct comparison of diverse propulsion system options is possible, with outputs of fuel consumption, emissions and installed costs.

### **INTRODUCTION**

Tugboat operators are looking for ways to make their vessels more efficient and friendlier to the environment, to reduce costs, meet regulatory requirements, cater to market demands for cleaner operations, or simply to improve ‘green’ credentials. Efficiency improvements that reduce fuel consumption generally reduce operating costs and emissions at the same time, a double bonus. The connection between fuel consumption and greenhouse gases is clear – CO<sub>2</sub> emissions are directly proportional to fuel consumption. But what about other emissions, such as unburned hydrocarbons, NO<sub>x</sub>, and particulates? For diesel prime movers these depend not only on fuel consumed, but also on how the equipment is operated and the emissions technology built into the engine, or added as off-engine equipment. As always there can be trade-offs to consider if new equipment requires significant capital investment.

On tugs, the power directed to propulsion is generally responsible for the bulk of fuel costs and emissions. With the exception of a relatively small number of diesel electric tugs, beginning with *Luna* (1930) and examples such as the US Navy’s YTB large yard tugs (1940s), the bulk of tugs today continue to be powered by diesel main engines coupled to propellers or, in the case of more modern tugs, azimuthing propulsors (Z-drives), or Voith Schneider Propellers (VSP drives). Electric power for hotel needs and auxiliary equipment is typically supplied by one or more small generator sets.

These systems have generally worked well and, until very recently, there has been little incentive to change. But the fuel-price rollercoaster ride and heightened consciousness of the environmental impact of greenhouse gases and other emissions have brought about a re-examination of the status

quo, and a new interest in alternative propulsion equipment configurations that offer some potential for improvements in fuel consumption and emissions – and preferably both.

Designers and operators of large anchor-handling tugs and other offshore support vessels have been quicker to embrace diesel electric power systems as an alternative to diesel mechanical. This is not only for the purported fuel savings, but also for the flexibility that a common power generation system offers in varying the power distribution between propulsion, dynamic positioning, pumps, and deck equipment loads as operations change. However, for smaller tugs that do not have the same variety of equipment or the need for extended dynamic positioning, any immediate advantages are not as obvious. Furthermore, the time has come to look beyond diesel electric to what is achievable with novel integrations of other commercially available technologies or the applications of more recent ‘alternative power’ technologies, such as alternate fuels or battery hybrids. Along with alternate equipment choices, operators may also achieve cost savings by simply changing how existing equipment is operated.

To make the best use of the opportunities alternative tug propulsion may offer, Robert Allan Ltd wanted to be equipped to efficiently and quantifiably answer the following basic questions when designing a new tug:

- What are the most practical powering options available for the application?
- How do these options compare in terms of fuel economy and emissions for the intended operations?
- What is the cost premium or savings?

- If operations change, what will be the impact on emissions and fuel consumption?

To that end, the *RAptures* programme was developed as a tool to make effective comparisons, evaluate the trade-offs, and generally zero in on the powering configuration that best fits the requirements and goals of the client. Appreciating that wide variations in vessel size, required performance, and duty profile mean there is no “one-size-fits-all” solution, the programme was designed at the outset to model diverse applications and configurations.

This paper gives an overview of the *RAptures* programme and discusses results from a hypothetical case-study for a typical Robert Allan Ltd 28m *RAmparts 2800* tug to illustrate the programme’s capabilities and potential.

## TERMS OF REFERENCE

*RAptures* was developed with these specific objectives in mind:

- To provide realistic estimates of fuel economy and emissions that are not based on guesses or supplier promises, but on reliable fuel consumption and emissions data that specifically takes into account the performance requirements for the vessel and the day-to-day operational profile;
- To model how the operating points of the machinery are linked to the activities of the vessel, whether it is idling, free-running, operating at BP, and what other power-consuming equipment, such as winches or pumps, is being operated at the same time;
- To recognise that, for tugs, both BP and hull resistance are critical aspects that dominate the power demand, and provide a means to predict BP and free-running resistance;
- To consider how fuel consumption and emissions of each installed prime mover varies with operating point, based on data from certified test results or other sources;
- To allow operating profiles to be defined that are realistic representations of an operator’s anticipated day-to-day usage of the vessel;

To accurately calculate fuel consumption and emissions totals for several candidate powering configurations operating under the same operational profile simultaneously, so that like-for-like comparisons can be made;

- To present cost comparisons that take into account equipment capital costs, and costs that vary with the operator’s duty profile, including fuel, equipment maintenance and overhaul;
- Make it easy to quickly evaluate ‘what-if’ scenarios.

## THE *RAptures* TOOL

The *RAptures* tool is a software program developed as a spreadsheet for maximum flexibility and transparency. The program is organised into several types of distinct modules (*Figure 1*): propulsion, duty and power, powering configuration, and equipment. This architecture makes it straightforward to establish new configurations and adjust parameters. In general, each module requires inputs regarding different aspects of the vessel, equipment or utilisation. Data for a specific vessel or its equipment details can be entered directly, or stock data from a pre-entered library can be referenced.

### Propulsion module

An essential element for predicting fuel consumption and emissions at different operation points is a model of how the ‘demand’ for power by the propellers varies with required static thrust, or free-running speed. Not only is power important, but also the corresponding rev/min since equipment efficiencies and prime mover fuel consumption and emissions are governed by both.

If the relationships between thrust, free-running speed, shaft power and shaft rev/min are already known, either from model tests or sea trials, this data can be entered directly into the duty and power module (see below). If unknown, the propulsion module can be used instead. The module combines a simple polynomial-based prediction of propeller and nozzle performance with a prediction of vessel resistance derived from an expansion of model test or trials data from similar vessels. These parameters establish the necessary static thrust and self-propulsion relationships. With the software currently oriented toward tugs, the propulsion predictions in the module are set up specifically for modelling Z-drives with Kaplan-style propellers in 19A nozzles. Other nozzle or propeller models can be built in.

### Duty and power module

Within the duty and power module, the user first defines a set of different possible ‘operating conditions’ which constitute all the states of significant interest in which the tug can operate. A variety of different conditions can be defined. These are typically idle, different free-running transit speeds, and different static thrust levels. The ‘operating profile’ is then defined by allocating the percentage of time spent at each condition within one standard operating period (typically a 24-hour day.) For each operating condition, the module uses the free-running and static thrust model parameters provided by the propulsion module to calculate propulsion power demands. Other loads, including hotel and deck machinery electrical power, are also entered. These powers, and the durations allocated in the operating profile, are then used by the powering configuration module.

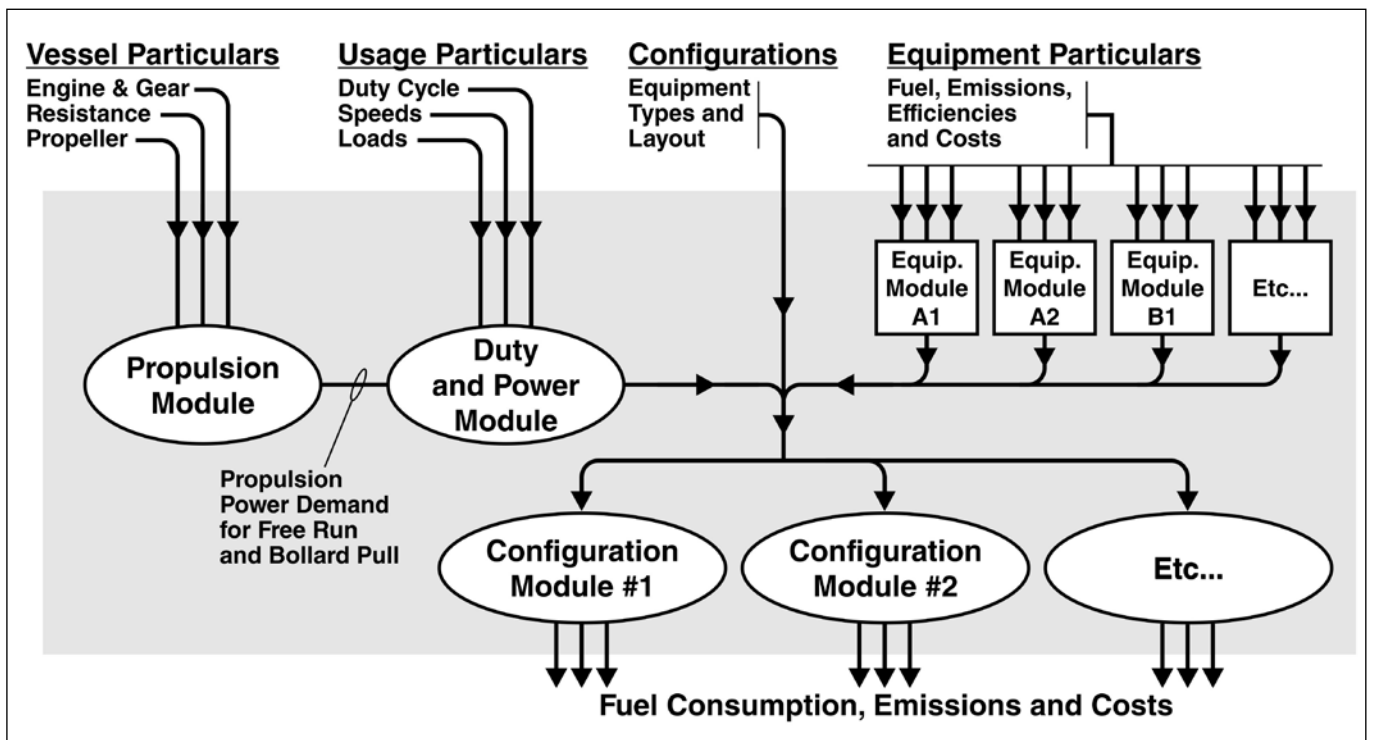


Figure 1: RAptures Architecture.

### Powering configuration modules

The powering configuration modules form the heart of the software, taking input from the user and other modules to determine what equipment operates in any given condition and returning parameters related to fuel consumption, emissions and costs related to that condition. There is one module for each powering configuration of interest. All are all fed the same data from the duty and power module, but return different results so comparisons can be made. It is the same as running all configurations through the same virtual trials. The main purpose of each powering configuration module is to take the power demand associated with each operating condition and translate it into corresponding operating points (power and rev/min) for the prime movers, taking the intermediate efficiencies, losses, and gear reductions into account. With this information, the fuel consumption and emissions are determined at each operation condition through the equipment modules (see below) and summed up on the basis of the running times.

In the example considered in this paper, *RAptures* assumes fixed pitch Z-drives are used for all powering configurations, the differences being only in the equipment configuration supplying power to them. Mechanical losses in gears and bearings are modelled as fixed percentages of power within the powering configuration module. This is in accordance with typical engineering practice, although the program is amenable to accounting for speed-dependent or other linear or non-linear effects if needed.

Costs are also calculated within each powering configuration module. To make realistic and standardised comparisons between powering configurations, life-cycle costs are worked out for equipment purchase,

maintenance and fuel for 20 years. A Net Present Cost (NPC) is calculated for each configuration, which represents how much money would have to be invested in the market today at a given rate of return (interest rate) to create the cashflow to pay for 20 years of operation. Interest and predicted escalation (inflation) rates are adjustable to suit the client's accounting practices and economic projections. In the calculation of equipment-related costs, *RAptures* takes into account how the life-cycle costs are affected by specific vessel operating profiles. Fewer operating hours on equipment generally translates into lower annual maintenance costs and more years between overhauls.

Capturing this cost-saving effect is important, particularly where powering configurations allow machinery to be shut down when the power is not needed. Operating in this manner, however, could result in more wear and tear on the engines and starters due to more frequent starting and stopping, thermal stresses, and wear from start-up lube oil deficiencies. Generally, these aspects would typically have only a small effect, but should be subjectively evaluated in instances where there are only small differences between two contending arrangements. There are cases where *RAptures* needs to be supplemented with a combination of operating experience/preferences from owners, and intuitive input from designers.

In the case study presented below, *RAptures* considers those items related to the supply of power to the main propulsion shafting such as diesel engines, marine gears, generators, electric motors, drives and ancillaries. Costs for the shafting itself and the Z-drives are not included, these items being assumed more or less equal for all configurations.

## Equipment modules

A separate equipment module is established for each specific make and model of diesel engine, genset, electric motor or other equipment items that are used within the powering configurations. Data on fuel consumption, emissions, and cost (usually provided by the equipment supplier), is entered directly into its module. This data is then mapped with fitted polynomial curves so that predictions can be made on the basis of any given operating point and passed to the powering configuration. Where specific data is not available from equipment manufacturers, generic equipment modules with typical characteristics are created.

In the case study presented below, three equipment types are defined: main engines, VFD-driven propulsion motors and fixed speed generator sets. For main engines, specific fuel consumption as well as specific emissions (NO<sub>x</sub>, unburned hydrocarbons and particulate) in g/kWh is mapped according to engine rev/min and output power. For fixed speed gensets, data is mapped with respect to genset output power only. With the VFD-driven propulsion motors, drive and motor efficiency is mapped for motor speed and torque.

## CASE STUDY

The Robert Allan Ltd *RAmparts 2800* (Figure 2) is a relatively recent 28m design within the highly successful *RAmparts* series of tugs. To date, all of these tugs have been powered by conventional diesel mechanical powering arrangements. In light of the popularity of this type of tug, it is logical to wonder whether future versions could benefit from a switch to diesel electric or other alternative powering configurations. Furthermore, if there are benefits, how sensitive are these to the specific duty in which the tug will be engaged on a daily basis?

To answer these kinds of questions, *RAptures* is applied to a notional version of the *RAmparts 2800*, with the objective of comparing diesel mechanical to three alternative candidate-powering configurations. Given the dependency of the outcome on the specific



Figure 2: *RAmparts 2800* built by Cheoy Lee (2008).

characteristics of the candidate equipment and assumed tug operating profile, the intention is not to make a generalisation on the best arrangement for tugs in general, but rather to show how *RAptures* can provide results targeted to a specific case. The same type of analysis can be applied to any other vessels considering other equipment or operating profiles.

## Powering configuration options

In the case study, four powering configurations are examined for the *RAmparts 2800*:

- Diesel Mechanical (DM);
- Series Diesel Mechanical/Electrical (SDME);
- Diesel Electric – Running Standby (DERS);
- Diesel Electric – Cold Standby (DECS).

The outcome for two different operating profiles are compared:

- Harbour duty – In this duty the tug is primarily engaged in ship berthing/unberthing in a harbour environment, where transits are short. Between ship handling operations, the vessel spends a significant amount of time loitering.
- Ship assist duty – In addition to ship berthing/unberthing, the tug is tasked with accompanying ships entering and leaving the harbour over a greater distance for light escort operations. Overall, compared with the harbour duty, the tug spends more time at higher transit speeds and less time at operations involving high static thrust.

All powering configurations assume twin fixed pitch Z-drives. Hotel loads are 80kW and maximum peak deck machinery loads are 80kW. All deck machinery is assumed to be electrical or electric/hydraulic. Specific equipment data is obtained from a variety of specific manufacturers published data sheets. All engines are high-speed diesels from a common manufacturer and are EPA Tier II rated. Figure 3 (at end of paper) shows the specific fuel consumption of the prime movers as a function of the percent rated power.

The Diesel Mechanical configuration (Figure 4, at end of paper) has two 2,000kW main engines mechanically coupled to the Z-drives. Hotel and deck machinery loads are supplied by two 175kW ship's service generator sets arranged for independent operation.

The Series Diesel Mechanical/Electrical configuration (Figure 5, at end of paper) is an example of an alternative arrangement, but one that makes use of fairly conventional technology. It includes the same two 2,000kW main engines as the DM configuration, except that an electric motor is now installed between each of the main engines and Z-drives so that the motor is in series with the main engines. Power to the Z-drives is provided by either the electric motor or the main engines, but not to both at the same time. During

loiter or low speed transit, the electric motors drive the Z-drives from genset power; the main engines are declutched and not running. When higher power is required, the main engines are started up and clutched-in, and the electric motors are free-wheeled. Main engine power is passed through the electric motors so the motor shafts are sized accordingly.

This arrangement is similar to the one used in series hybrid systems, eg Foss's *Green Assist* hybrid tug, except that the motors are not also generators, and do not contribute torque to the propulsion shafting when the main engines are operating. The electric motors are AC-type controlled with Variable Frequency Drives (VFDs) rated for 250kW. Electric power for the motors and for the vessel's other electric loads is supplied by either one or two gensets, one of 560kWe, the other of 175kWe.

Both Diesel Electric configurations (*Figure 6*, at end of paper) have two 2,000kW electric propulsion motors directly driving the Z-drives. Electrical power is provided by a combination of the following gensets configured to allow staging and full load sharing: 2 x 2,200kWe; 1 x 560kWe; 1 x 175kW. The two DE configurations differ only in how the generators are operated.

In the Diesel Electric – Running Standby (DERS) configuration, when BP operations are anticipated, the two main generators are started up and paralleled (running standby) so that maximum power is available and the system can respond almost immediately to any demand fluctuations commanded from the bridge. However, during lower speed transits not involving bollard operations, one or more main gensets are shut down and the smaller ship's service generator(s) provides power.

In the Diesel Electric – Cold Standby (DECS) configuration, it is assumed that any generator operating surplus to the immediate power demand can be shut down immediately, even during bollard operations, and is only started up when needed (cold standby). While this would certainly reduce responsiveness substantially in comparison to DERS, especially during bollard operations, and is of questionable practicality, it is included for comparison.

## Tug operating profiles

The operating profiles (*Figure 7*, at end of paper) for both the harbour and ship assist duties are based on a 12-hour daily operation, 360 days per year. On harbour duty, the tug spends a significant amount of time idling and transiting at low speeds, mixed with short periods of high BP operations. On ship assist duty, more time is spent at higher speed transit to rendezvous/assist ships, and less time on BP operations. These scenarios are considered reasonably representative of typical duty for the purpose of this case study.

## RESULTS

Results for the harbour tug are presented in *Figures 8-11* (at end of paper). The nine operating conditions that comprise each operating profile (duty) are shown along the x-axis. The wider translucent bars indicate the percentage of time allocated for each. The narrower solid bars are fuel or emissions quantities for each Powering Configuration. Totals are given on the right.

### Fuel consumption/CO<sub>2</sub> emissions

Since CO<sub>2</sub> emissions vary in proportion to fuel consumption, these aspects are intrinsically linked in comparing the configurations. Under the harbour duty, the two diesel electric options emerge as the least favourable. While there are some savings at lower powers, where the minimally loaded main engines of the Diesel Mechanical arrangement suffer from low specific fuel consumptions, the chart illustrates that most of the fuel is still consumed during static thrust operations. This is the case despite the fact that much more time is actually spent loitering or moving slowly. At the higher power operating points, the diesel electric configurations suffer from electrical system losses. Overall fuel consumption for diesel electric is higher by approximately 16 per cent.

Of the two diesel electric options, the Running Standby (DERS) system comes out worst since all generators are running continuously whenever BP operations are expected. This is in contrast with the Cold Standby (DECS) configuration where gensets are only started when needed and shut down again when not. In reality, operating gensets this way would be impractical for most typical harbour operations, as power demand varies rapidly where diesel gensets need time to start up and parallel. Nevertheless the comparison gives an indication of the potential savings in fuel, and underscores how batteries can have a beneficial role to play in providing a means to respond to short-term power fluctuation without the need to start up a genset each time.

With the SDME configuration, the situation is better. Slightly less fuel is consumed than with the Diesel Mechanical configuration. This is as one would hope, since the SDME arrangement is intended to avoid the pitfalls of the others: in the case of Diesel Mechanical, main engines operating unloaded at low power operating points; for the two Diesel Electric configurations, comparatively high electrical losses. However, the difference is fairly small, only 3 per cent less fuel than Diesel Mechanical and, on its own perhaps, not incentive enough to move to this configuration without the prospect of additional advantages of reduced emissions or lower costs, aspects which are discussed below. (*Figure 8*).

### NO<sub>x</sub>, Hydrocarbon (HC) and particulate emissions

With diesel prime movers, NO<sub>x</sub>, HC and particulate emissions vary with equipment design, fuel

management, off-engine measures, rate of power variations, and a host of other operational and environmental parameters. Data is not always easy to come by, the source often being the supplier, where possibly data was collected to prove conformance with regulatory requirements. For this case study, the emissions data was based on typical published values for the specific prime movers used in the case study. As the data is for steady state load conditions, it does not capture the effects of rapid transient load fluctuations. Nevertheless, comparing emissions on a quasi-steady state basis is a reasonable approach.

A common trend is seen in the emissions charts (*Figures 9-11*, at end of paper): where prime mover machinery is forced to operate away from its design operating point, specific emissions (emission per brake kW) tend to become worse. While improvements in emissions technology may reduce this sensitivity, it is characteristic of today's marine machinery. For this reason, at low powers the benchmark Diesel Mechanical configuration has the worst emissions of all the powering configurations due to the main engines running so far below their rated power. For the low- and mid-powers of idle and transit operations, diesel electric configurations fare better than Diesel Mechanical, as optimal loading points for smaller generators are possible. However, at the high-power BP conditions, diesel electric loses its advantage since the inherent electro-mechanical conversion losses reduce efficiency compared with Diesel Mechanical.

The ability of the SDME configuration to operate electrically at low power, optimally loading the gensets, but switching over to direct Diesel Mechanical for higher speed transit and BP conditions gives it the edge over the conventional Diesel Mechanical configuration. As the charts clearly indicate, the advantage is substantial as a result of the significant penalty Diesel Mechanical suffers under low-power loitering conditions. The net result is that emissions from the SDME configuration are the lowest overall.

## **COSTS**

Bar charts of the costs (*Figure 12*, at end of paper) comprise three components: fuel, equipment maintenance, and equipment purchase. Net Present Costs in this example are calculated on an interest rate of 5 per cent, an annual escalation of 2 per cent, at a fuel price of \$0.60/litre.

It is immediately apparent that the two diesel electric options are the most expensive owing to the relatively high capital cost of the four gensets, plus the costs for electric propulsion motors, switchgear and VFDs. The higher fuel consumption is also a factor, but to a lesser extent. As the breakdown in the chart shows, it is primarily the purchase cost of equipment that pushes the total cost beyond the other arrangements. Maintenance costs are less, particularly for the Cold Standby version, but not sufficiently to bring the total cost below the Diesel Mechanical and SDME configurations.

The comparison of Diesel Mechanical to SDME is interesting since the SDME configuration comes out as less expensive overall than Diesel Mechanical. The small difference in fuel consumption reduces fuel costs by approximately 3 per cent below Diesel Mechanical, but the real significance lies in the equipment purchase and maintenance costs. Although the equipment purchase cost is greater for the SDME configuration, as would be expected given relatively high cost for the electric motors, drives and generators, over time this is offset by considerably lower life-cycle maintenance costs. With the SDME arrangement, the main engines accumulate fewer running hours and this is an advantage since they are more expensive to maintain and overhaul than the gensets.

For an operator considering the SDME option, the fact that the lower maintenance cost more than compensates for the additional equipment purchase cost is a key conclusion that illustrates how all cost elements need to be considered collectively. Regrettably, making accurate predictions of per hour maintenance costs, time before overhaul, and the actual cost of overhaul can be a difficult proposition. Data from suppliers can be notoriously variable given the many factors that come into play, including how rigorously the equipment is operated, the maintenance skill level of the operator, and environmental and logistical aspects that can constrain servicing intervals. For this case study, data from various equipment suppliers was blended to arrive at values considered to be reasonably representative of equipment of the type under consideration. Of course, the best source of data is from the records of the operator itself for similar equipment and operational conditions, if available.

Despite the inherent uncertainty in maintenance cost projections, this does not detract from the key point that the case study results suggest that the SDME configuration could have a significant cost advantage over 20 years by saving maintenance on the main engines, at least for the subject vessel under the given duty profile.

## **COMPARISON TO SHIP ASSIST DUTY**

With *RAptures*, once the configuration options are defined, it is a matter of a few keystrokes to see how changing the operational profile influences fuel consumption, emissions and cost. To illustrate this, results for the same vessel, with the same four powering configuration options, are presented for the ship assist duty as defined above.

Looking at fuel consumption first (*Figure 13*, at end of paper), it is immediately clear that, with more of the working day spent in transit and less time loitering, fuel consumption is significantly higher than with the harbour tug duty. Most of the fuel is used for the high-speed transit at 12.5 knots, not during bollard pull, as is the case with the harbour duty.

It is worth noting that at the 12.5 knot transit, there is effectively little difference in how the Diesel Mechanical

and SDME configurations operate: both are using the main engines only, directly coupled to the propulsion shafting. The single difference is some loss of the shaft power passing through the inactive electric motor in the SDME configuration. The same situation exists between the two Diesel Electric configurations: the same number of generators is running in each case. For the Running Standby version, the standby generators are running only when bollard operations are anticipated, not for transit. Therefore the approximately 12 per cent greater fuel consumption of the Diesel Electric configuration is attributable mainly to the lower overall efficiency arising from electrical conversion losses.

The dominance of this 12.5 knot transit operating point also carries over into emissions (Figures 14-16, at end of paper). The general trend, when compared to the same results for harbour duty, is that the Diesel Electric configurations compare less favourably to the Diesel Mechanical and SDME configurations. At that power level, the electro-mechanical conversion losses outweigh the efficiency penalty in running the main engines at a lower load level.

In comparing the Diesel Mechanical and SDME configurations, with the ship assist duty there is a narrowing of the differences in all areas, including costs (Figure 17, at end of paper). Since more time and fuel is spent in transit in the ship assist duty, and less time loitering, the SDME loses some of the advantages it had in running more efficiently and producing less emissions at low power. However, overall it remains an attractive option.

## SUMMARY

For the case study for the *RAmparts 2800* tug there is little benefit to the two diesel electric configurations (DERS, DECS) over the other two configurations in terms of cost or emissions for either operational profile. Compared with the conventional Diesel Mechanical configuration, SDME appears to be a very attractive option, particularly for the harbour duty defined.

## CONCLUSIONS

The *RAptures* program is proving to be a versatile tool for assessing and comparing the fuel, emissions and cost performance of any alternative powering configurations that progressive tug operators may want to consider for reducing costs and emissions. The specific results from the program can be used to verify operational benefit claims, and can prevent investment in technologies that may prove disappointing. Its development is driven by Robert Allan Ltd's commitment to the design of cleaner, more efficient vessels and recognition that, in weighing the trade-offs between powering configuration options, the widely variable operational profiles of tugboats prevent any one solution from being a universally best one.

As illustrated by the case study, this type of analysis is essential to the process of properly weighing the potential improvements against the costs of alternative powering configurations. With *RAptures* as a tool, Robert Allan Ltd is ready to work with clients to achieve real energy and emissions savings.

Figure 3: Equipment specific fuel consumption.

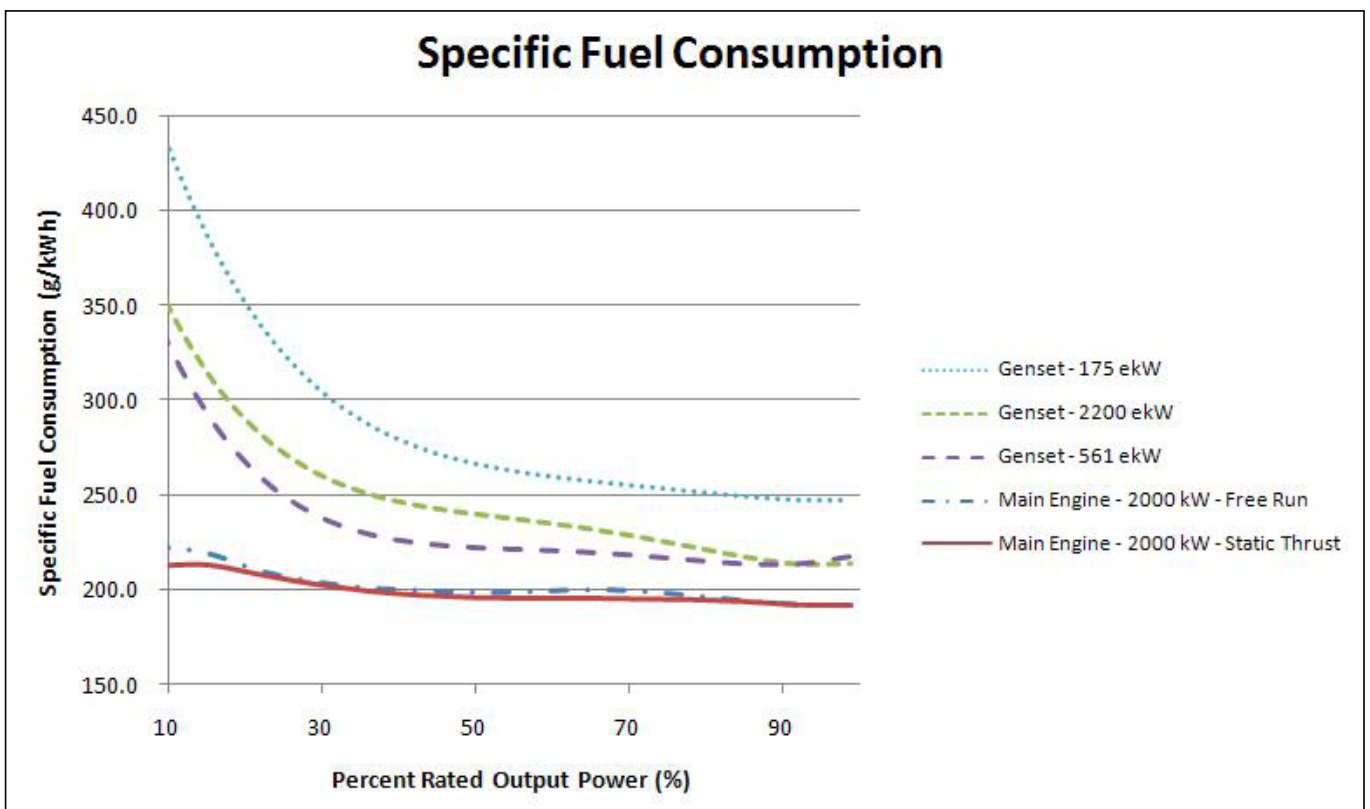


Figure 4: Diesel Mechanical (DM) Configuration.

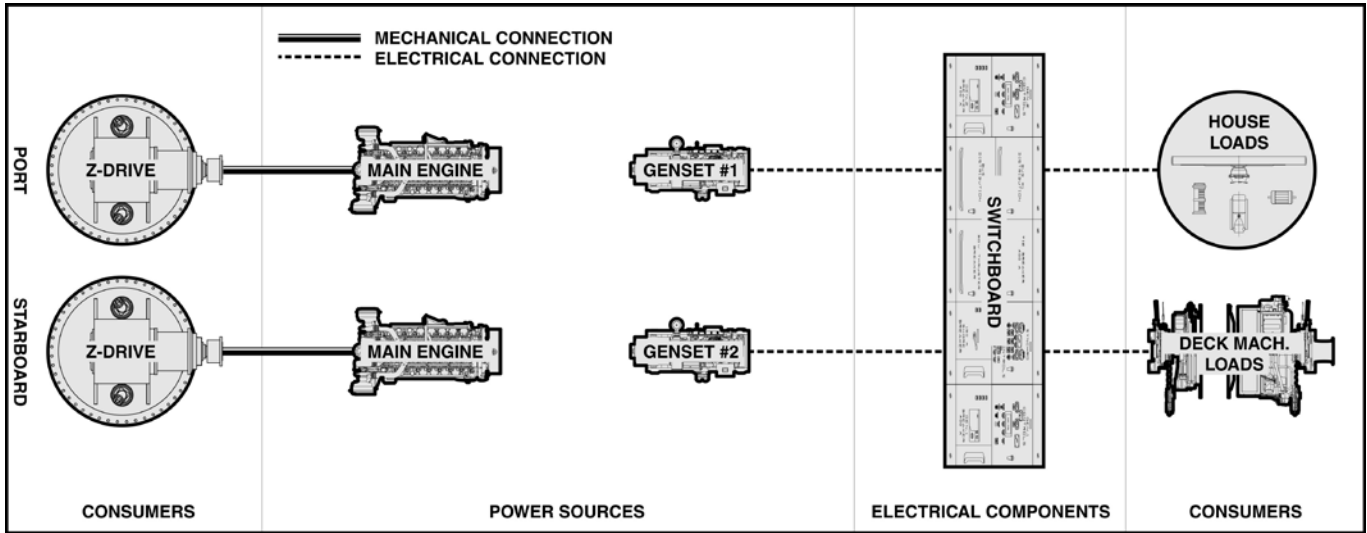


Figure 5: Series Diesel Mechanical/Electrical (SDME) Configuration.

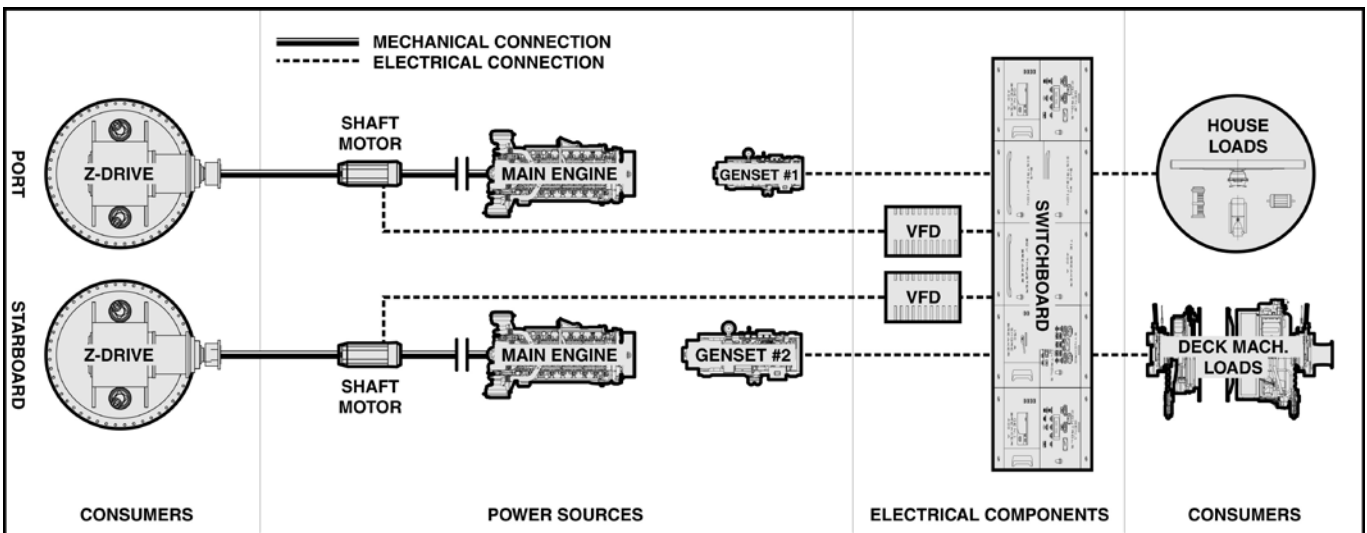


Figure 6: Diesel Electric Configurations (DERS, DECS).

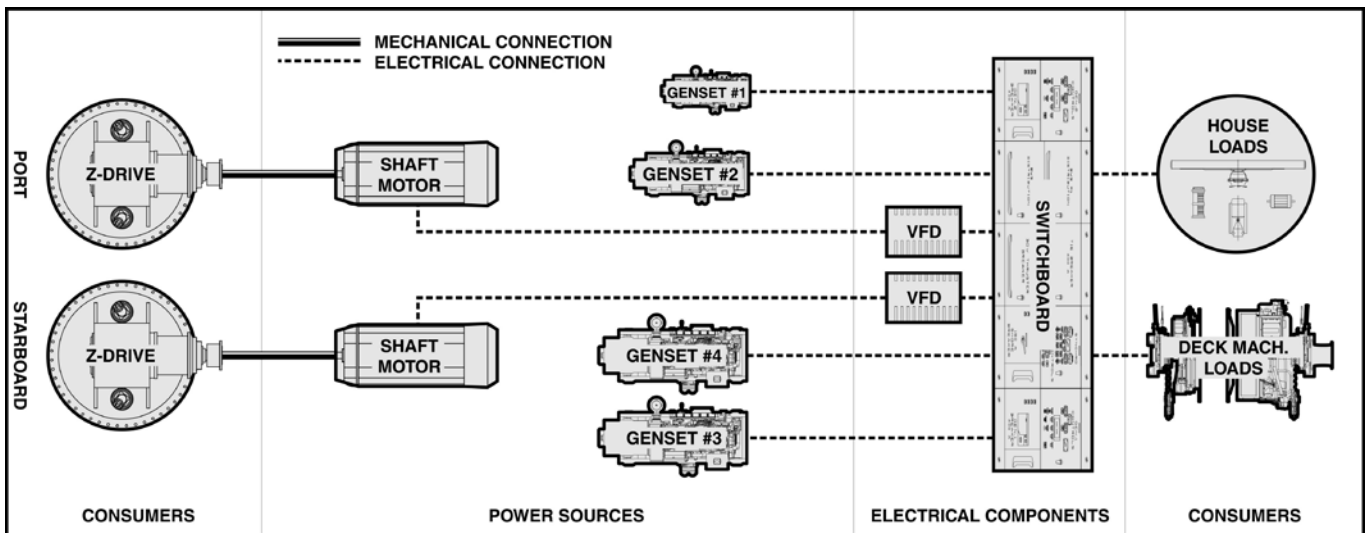




Figure 7: Operational Profiles Duty Cycles.

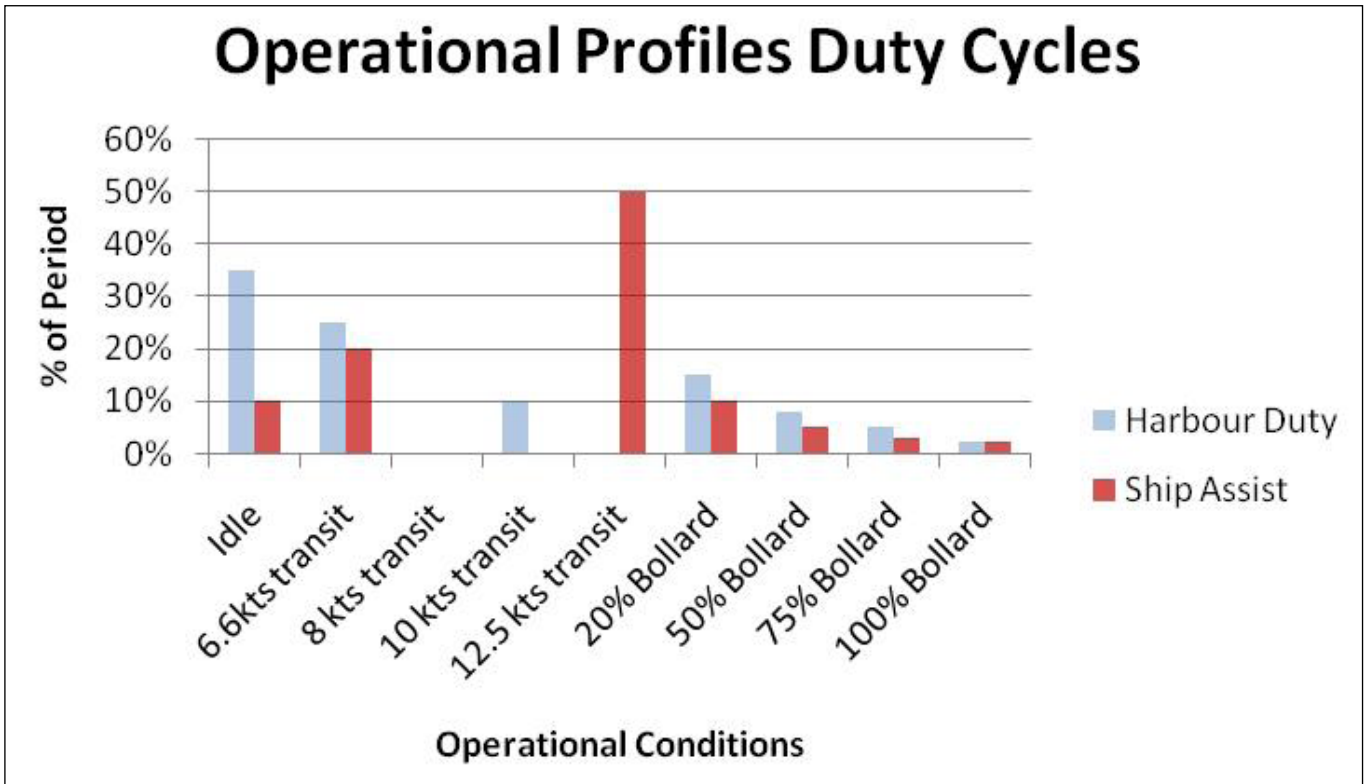


Figure 8: Fuel consumption – harbour duty.

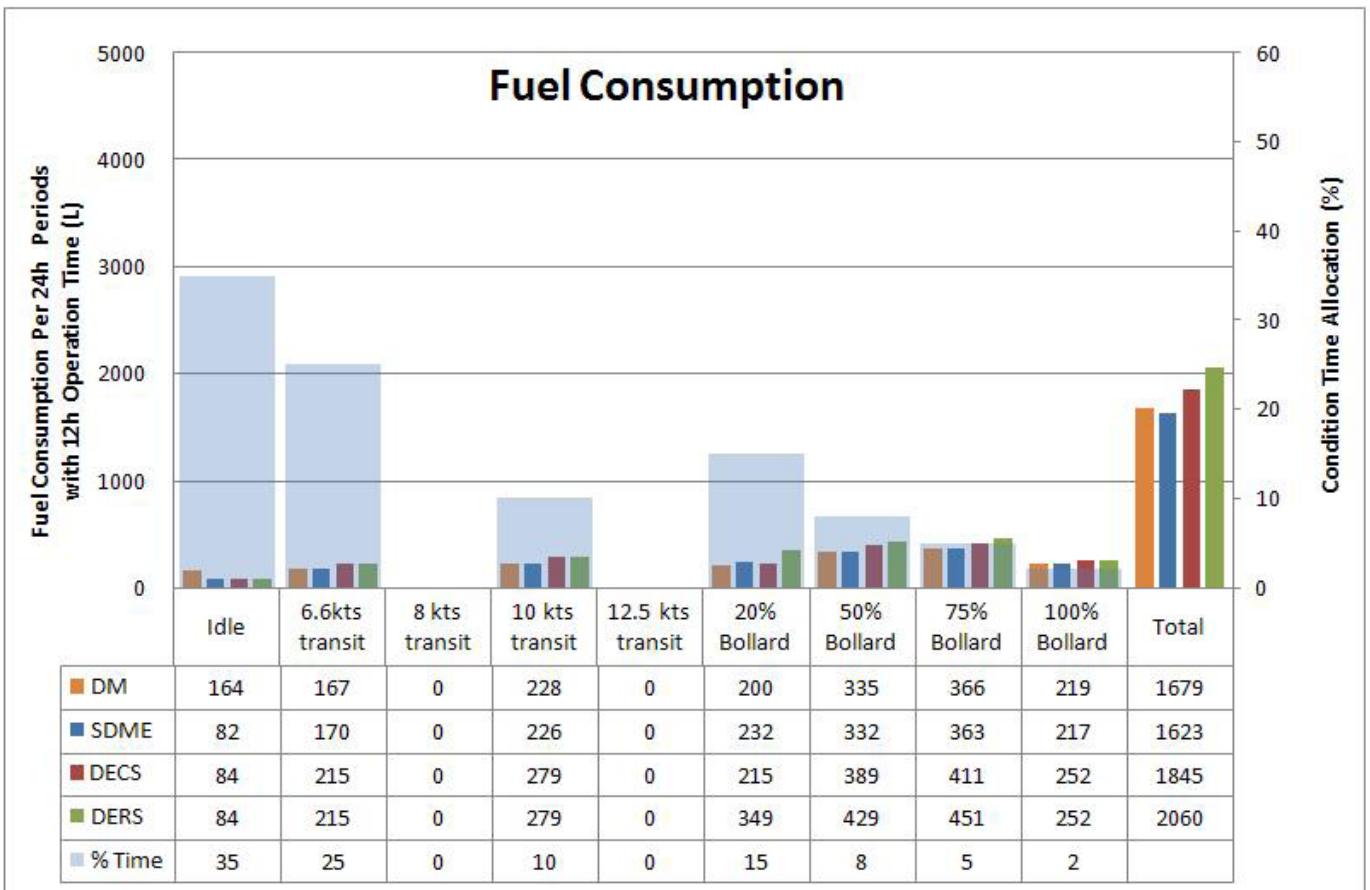


Figure 9: NOx emissions – harbour duty.

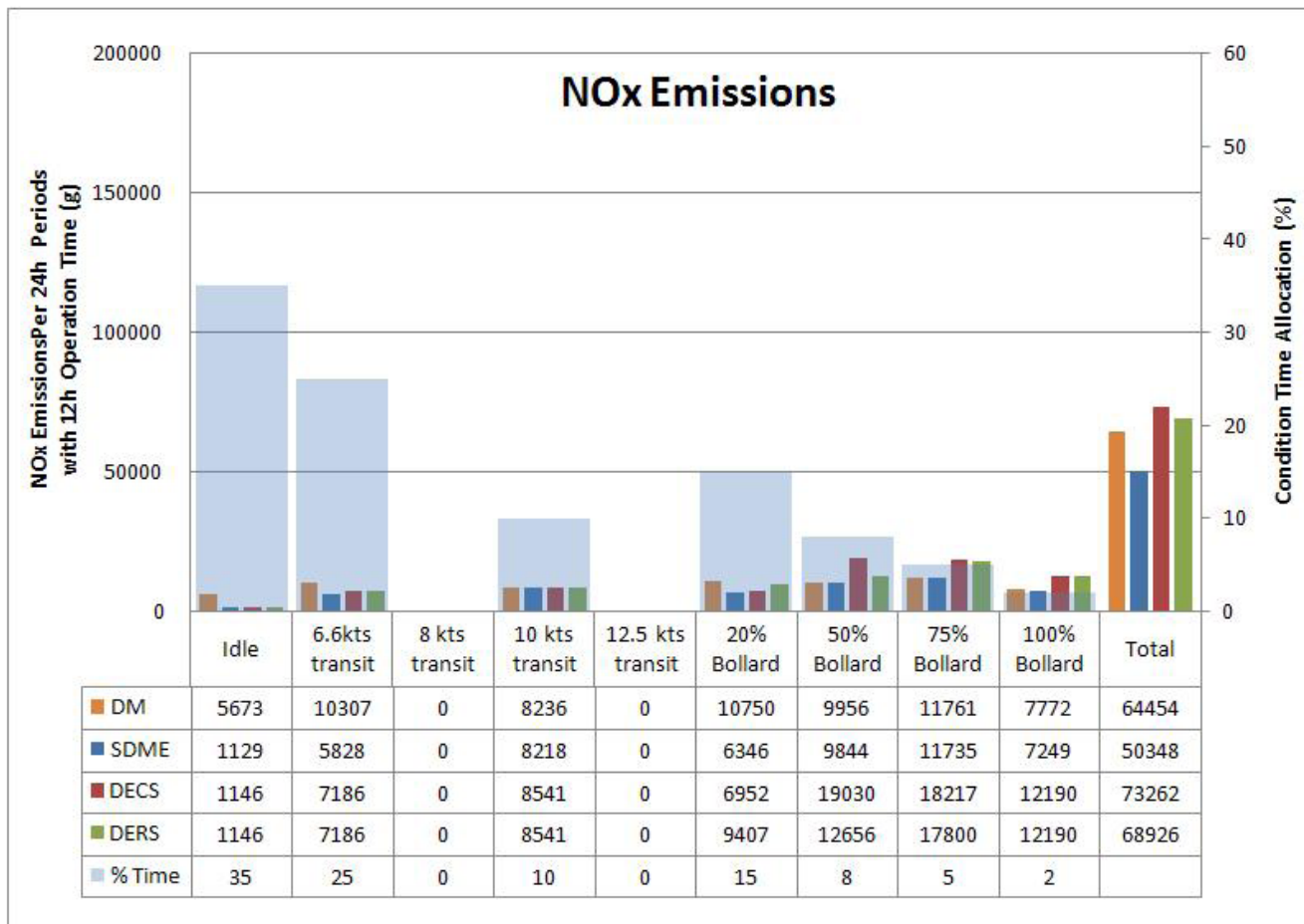


Figure 10: Hydrocarbon emissions – harbour duty.

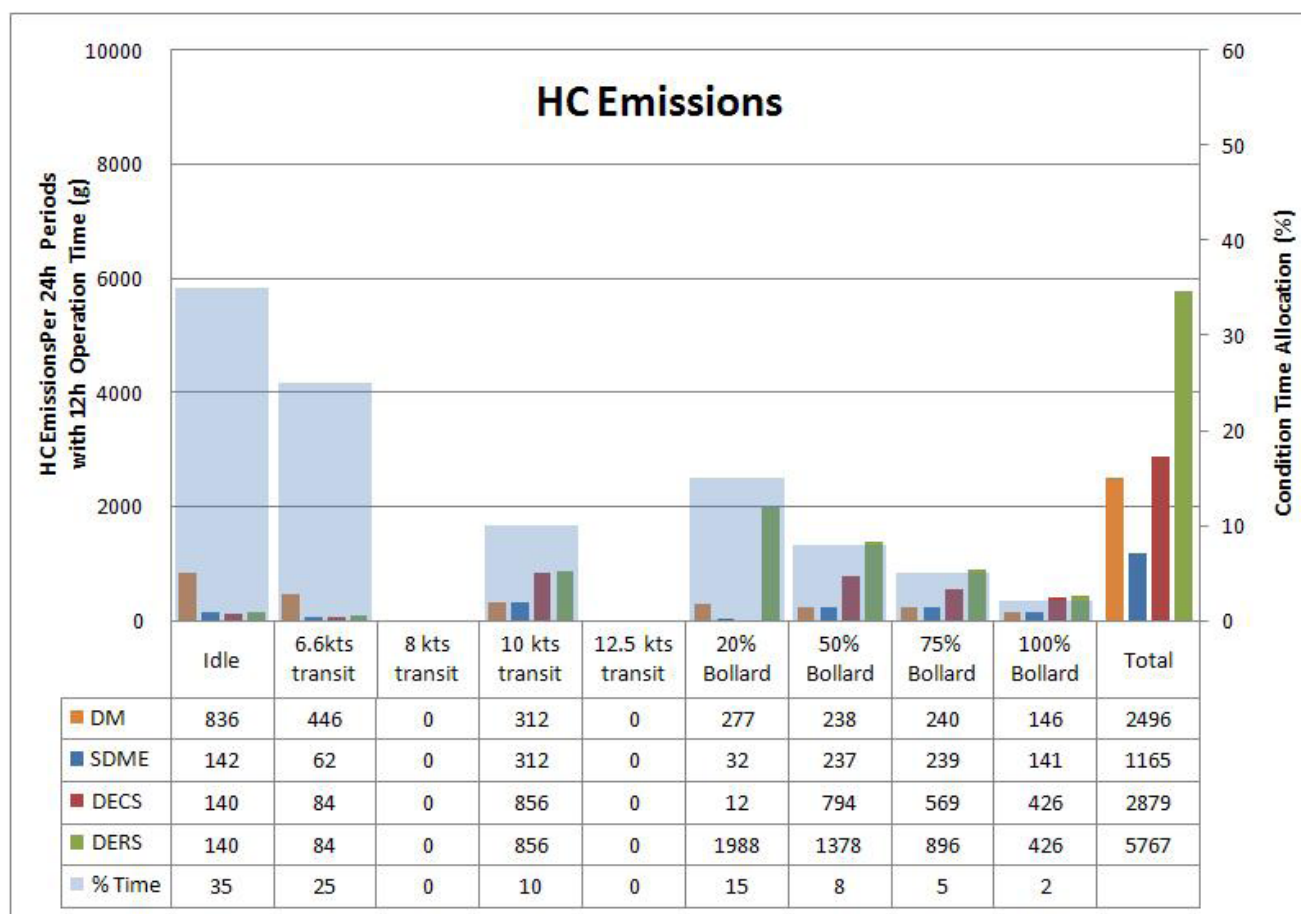


Figure 11. Particulate emissions – harbour duty.

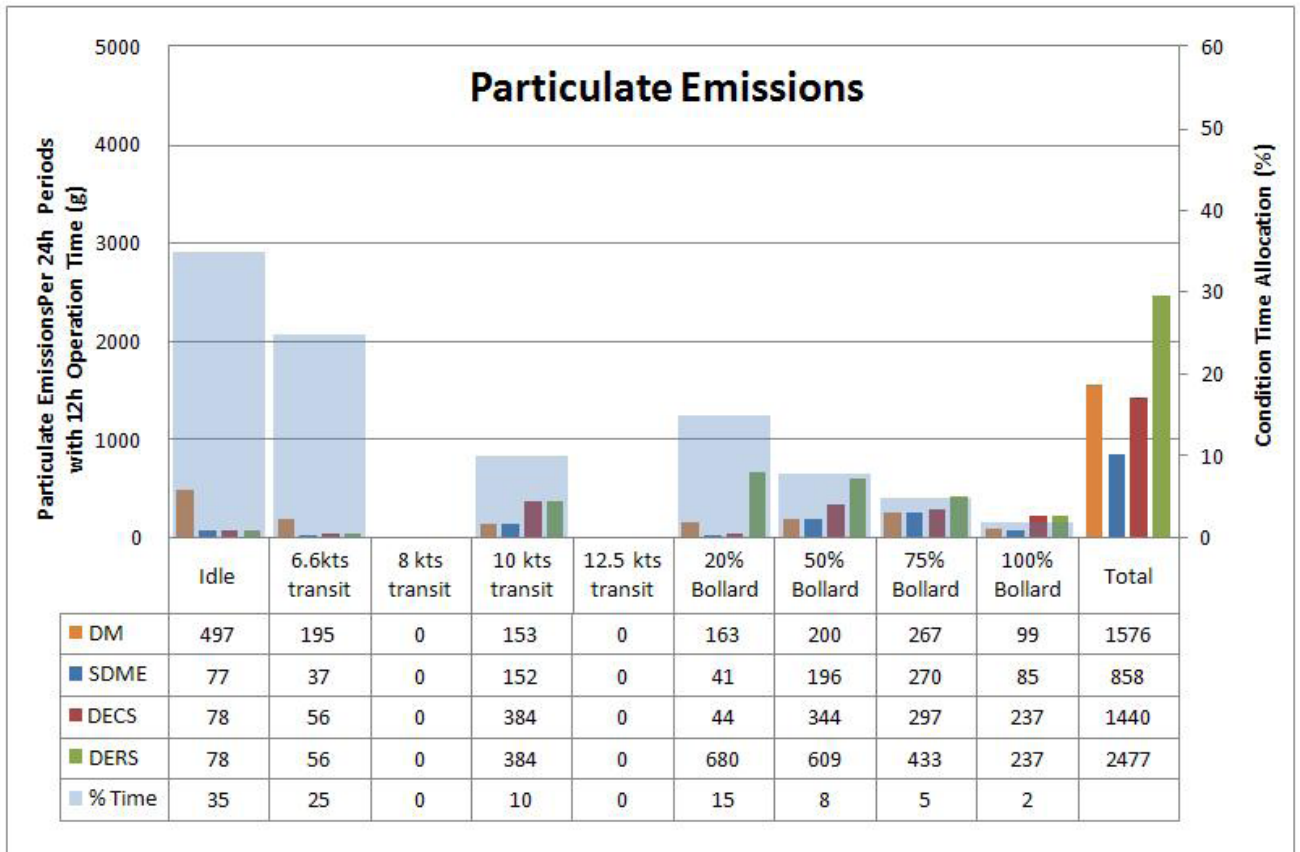


Figure 12: Costs – harbour duty.

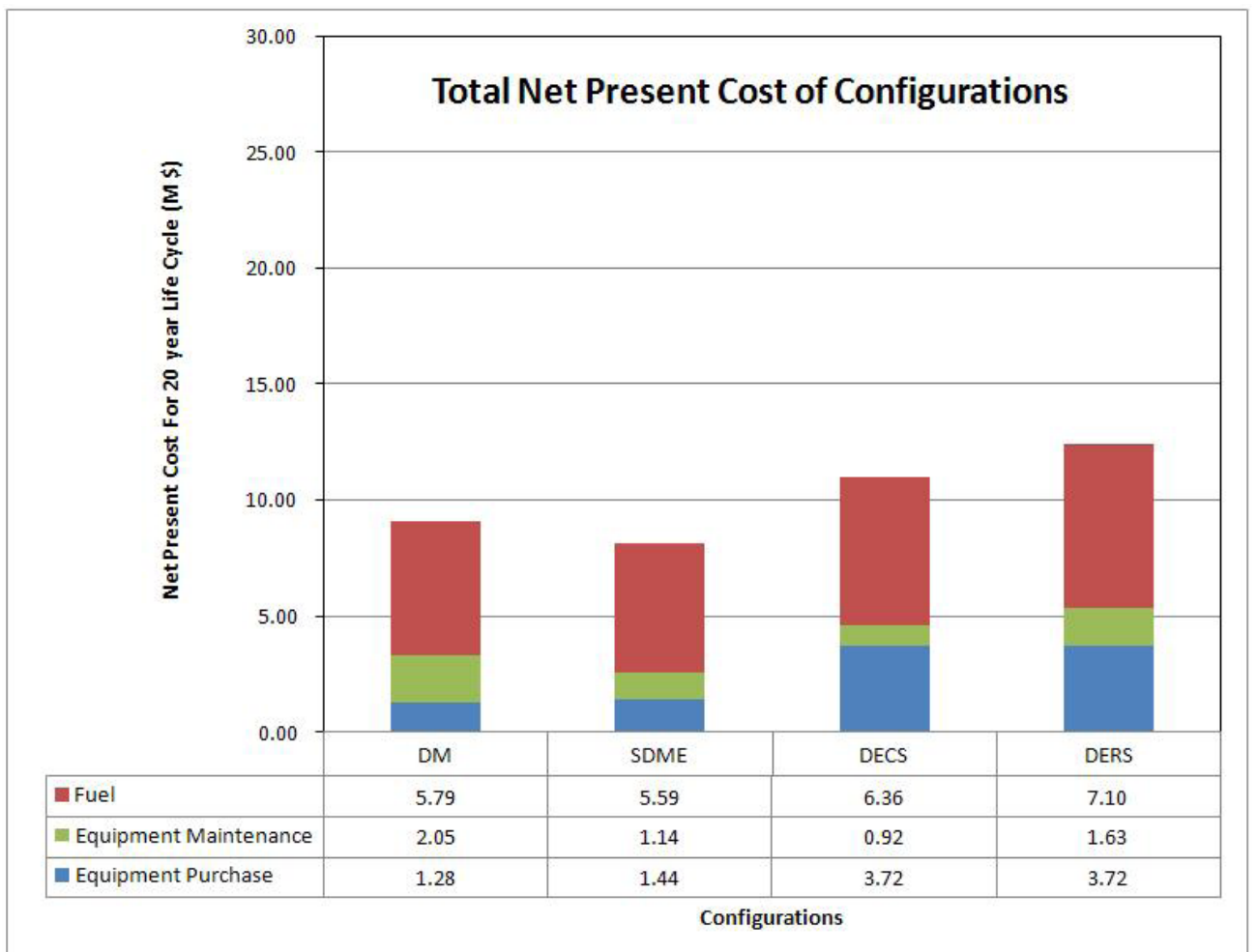


Figure 13: Fuel consumption – ship assist duty.

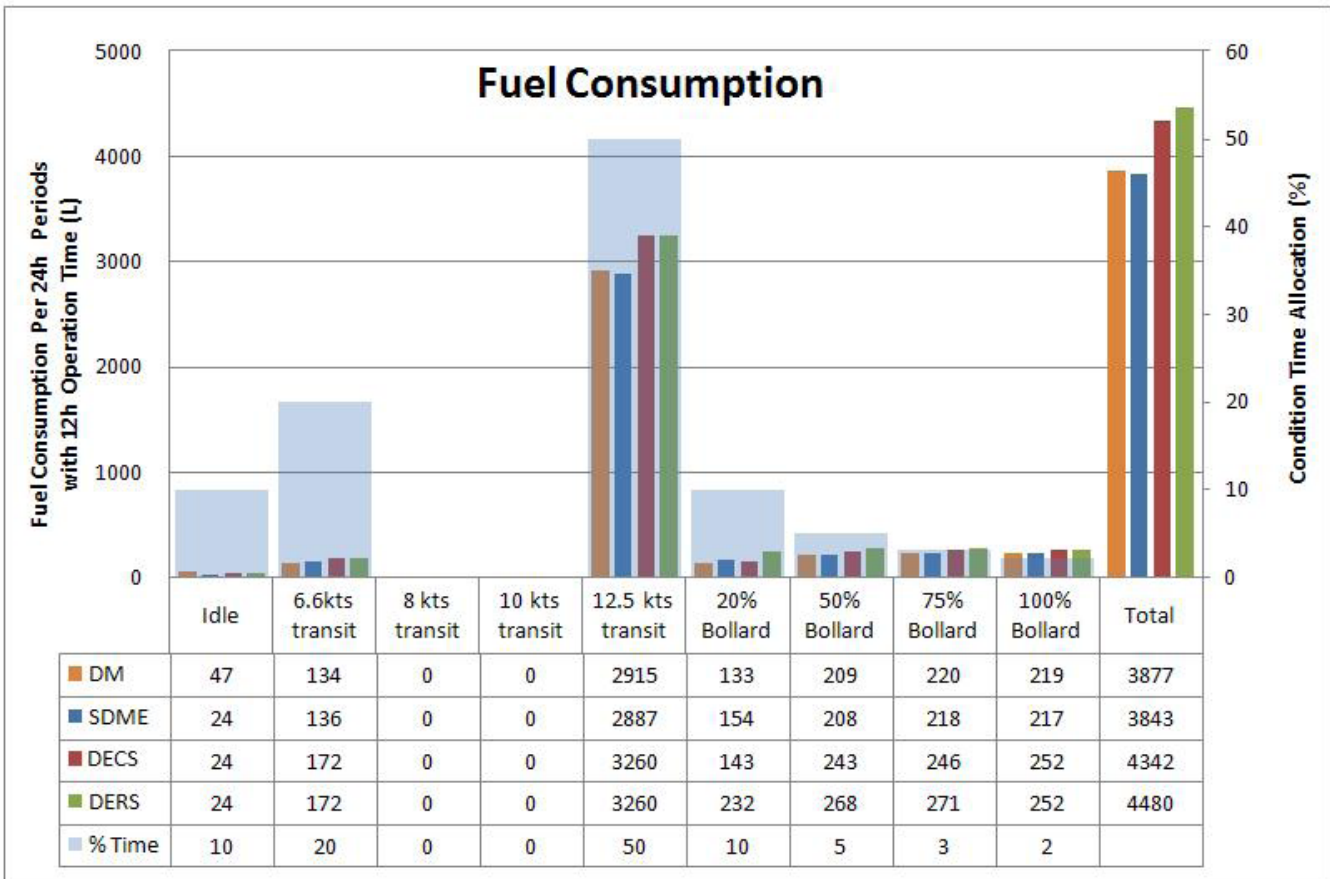


Figure 14: NOx emissions – Ship Assist Duty.

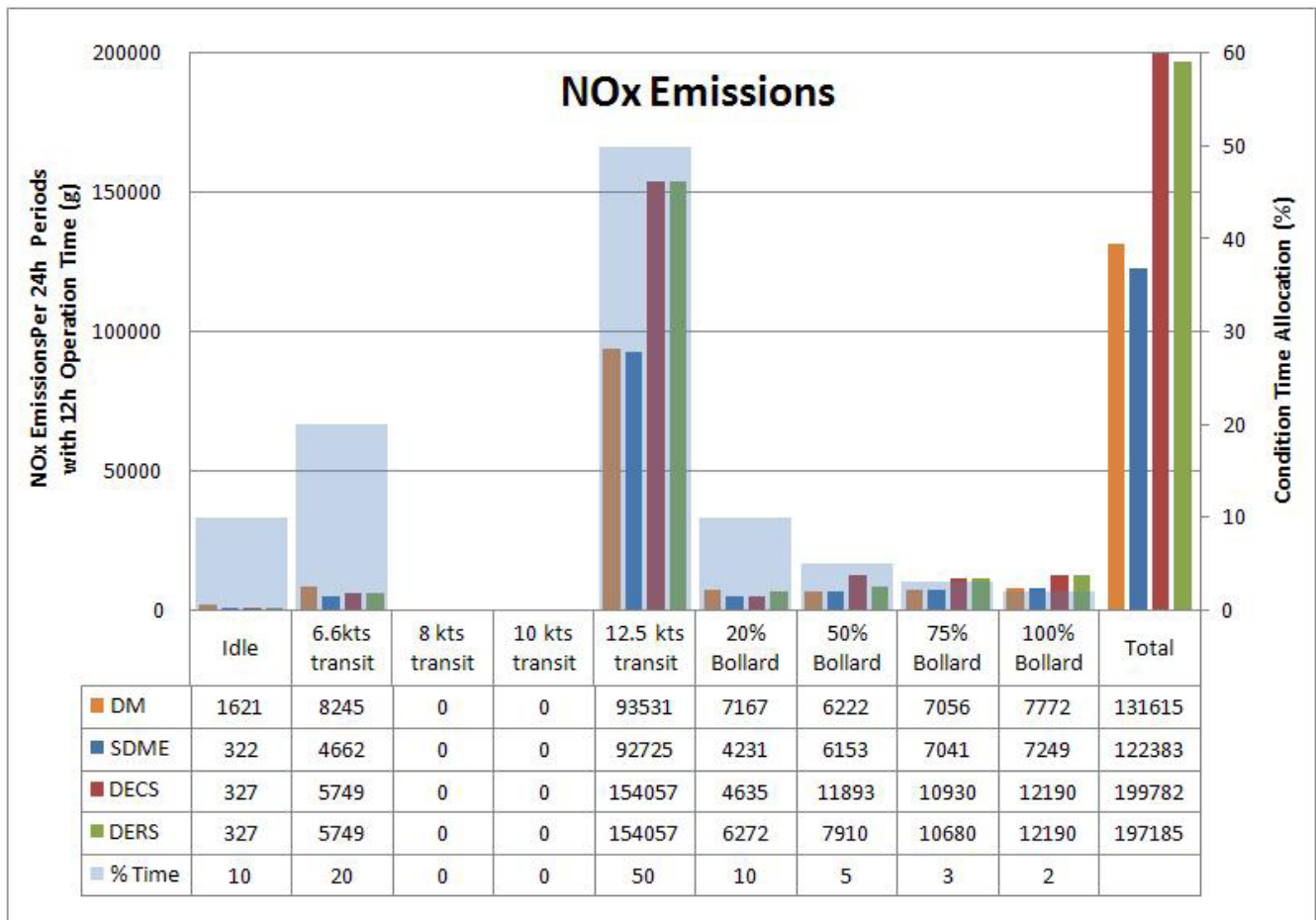


Figure 15: Hydrocarbon emissions – Ship Assist Duty.

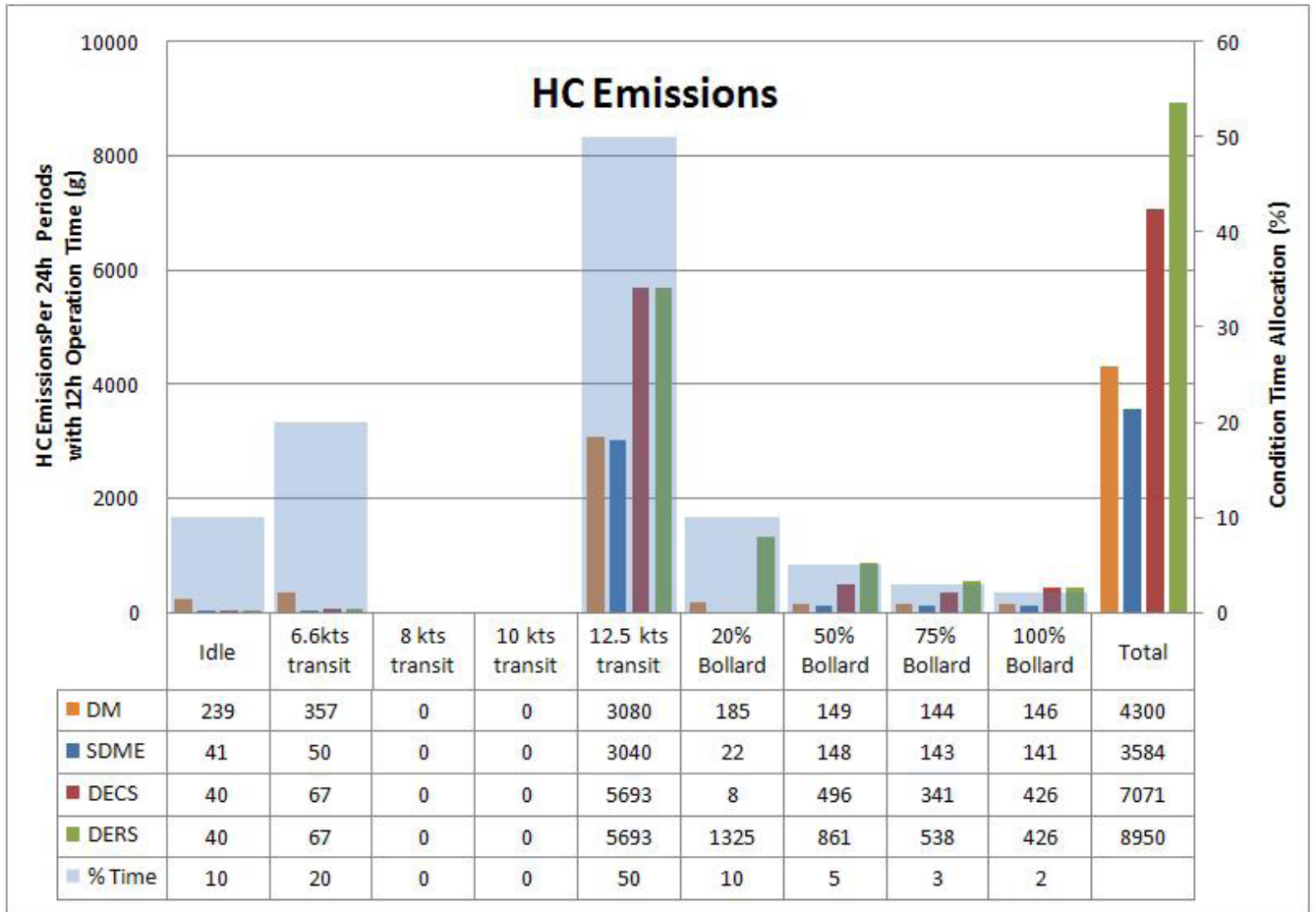


Figure 17: Costs – Ship Assist Duty.

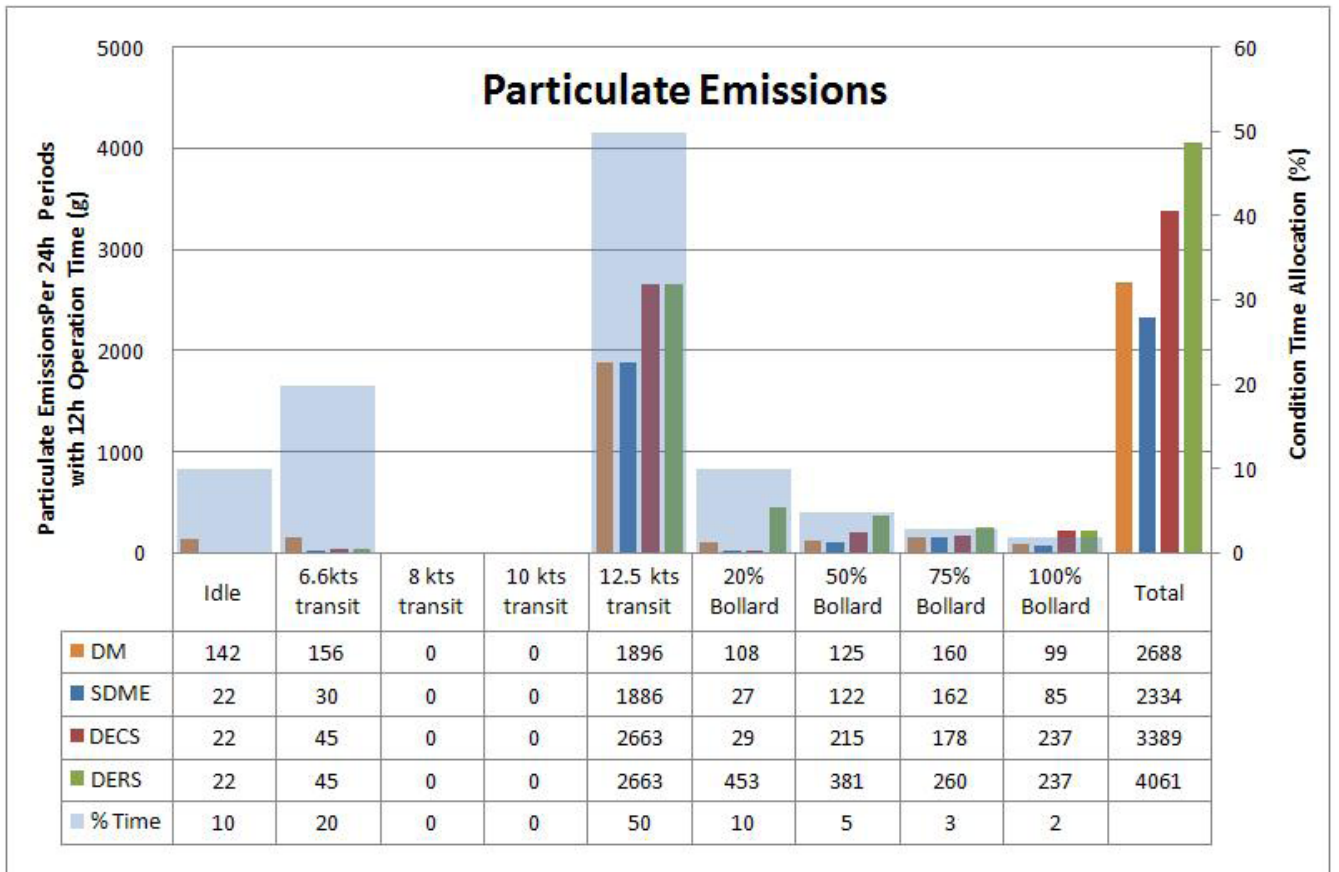


Figure 16: Particulate emissions – Ship Assist Duty.

