A Study of Energy Efficiency in Articulating Tug and Barge Design

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Abstract

This paper provides research and analysis in the field of articulating tug and barge (ATB) design with an emphasis on energy efficiency. Topics researched include: 1) Hull Design, 2) Bow Design, 3) Bulbus Bows, 4) The Tug Barge Interface, 5) Hull Coatings, 6) Propulsion Efficiency, 7) Alternative Fuels, 8) Power Generation Efficiency, and 9) Operational Efficiency. The importance of designing for efficiency is discussed and analysis is provided for each category in the form of best practice suggestions focused on energy efficient ATB design.

Maximizing the energy efficiency potential of an ATB is a complex and dynamic endeavor. Beginning with design, through the build out process, and finally operation of an ATB, energy efficient choices must be weighed against the monetary cost of pursuing them, the economic benefit they may provide and the environmental impact of not pursuing them.

*Keywords:* Articulating Tug and Barge, ATB, Competitive Advantage, Designing for Efficiency, Energy Efficiency, Environmental Stewardship, Fuel Consumption, Marine Engineering, Marine Transportation, Operational Efficiency, Vessel Design
Introduction

Fuel is the lifeblood of many industries. This is especially true for the marine transportation industry. Fuel costs represent as much as 50-60% of a ship’s operating costs. Any marine transportation company that can achieve greater fuel efficiencies than competitors will develop a competitive advantage. Fuel efficiencies can take the form of cost advantage, efficiency of equipment, efficiency of operation or efficiency of vessel routing/scheduling.

In the United States, a unique industry utilizing articulating tug and barge units (ATB’s) for the coastwise transport of petrochemicals and refined fuels has formed due to the U.S. regulatory environment. Among seafarers, this industry is known as the Jones Act trade.

In the Jones Act trade there are a finite number of companies all competing for the same transportation contracts. There are limited fuel oil suppliers making it difficult for any one company to realize savings by purchasing fuel at a cheaper rate than competitors. All companies utilize the same routes making routing/scheduling a difficult arena to gain a fuel savings advantage.

Companies in this industry can best realize fuel cost savings in the areas of efficiency of hull/running gear, equipment selection, vessel maintenance and vessel/equipment operation. Unfortunately, many companies make decisions in these areas based on a ‘that’s how we have always done it’ mentality.

This project proposes to dispel that mentality by providing insight and best practice suggestions, for the design, operation, and maintenance of ATB units. Each suggestion will be offered with an approach towards maximizing fuel efficiency.
Literature Review

Tugboats to ATBs: A Historical Perspective

In 1736, recognizing the need for a small craft to aid in moving large ships in and out of harbor, an enterprising man named Jonathan Hulls from Gloucestershire, England patented the first tugboat. His design called for the use of a Newcomen steam engine for propulsion. The first tugboat built was named *Charlotte Dundas* and utilized a Watt engine and paddle wheel for propulsion. This vessel saw use in Scotland on the Forth and Clyde Canal (Britannica).

Fast forward 240 years to the 1970’s and tugboats are utilized around the world for everything from ship docking / escort work to inland and open ocean barge handling and transport work. In the United States many firms preferred utilizing tugboats to tow barges loaded with petrochemicals and liquid cargo rather than utilizing small tanker ships for interstate commerce. The U. S. regulatory environment created substantial economic benefits to this arrangement. In contrast to small coastal tankers, the tug and barge arrangement required considerably fewer crew, and were more economical to build and maintain. Where a small tanker would maintain a crew of 19-27, tug and barge units required a maximum crew of 7-10 while transporting the same capacity of cargo.

Despite the obvious economic benefits of utilizing tug and barge units over small coastal tankers, there are some significant drawbacks. Tug and barge petroleum transportation is largely weather dependent while towing. Historical annualized weather delays in the Gulf of Mexico averaged around 30%. In the Northeastern United States, these delays ran as high as 40-50% mostly in winter. Tug and barge transportation also averages a much slower speed than small coastal tankers (Ocean Tug/Barge Engineering).
During the 1970’s attempts were made to overcome these drawbacks by utilizing a ship/tug hybrid vessel known as an integrated tug and barge (ITB). For a myriad of reasons ITB’s fell out of favor among transportation companies. As the design characteristics, history, and reasons for failure of the ITB are beyond the scope of this work, we will not delve deeper into discussion of the ITB.

In 1980, John W. Gilbert Associates in Boston MA, began design work on an articulated tug and barge (ATB) chemical carrier for Sun Transport. Sun wanted a tug and barge unit that could operate in all weather, meet certain speed requirements, while still maintaining the economic benefits of a tug and barge arrangement. This required taking on regulatory issues. Out of Sun’s effort came the U.S. Coast Guard NVIC 2-81 (Ocean Tug/Barge Engineering). This document provided the first official policy that began the shift towards the ATB as a superior mode of transporting petrochemicals and liquid cargo in the U.S. interstate transportation market.

![Figure 1 - Typical ATB Design (Wolff, 2003)](image)

NVIC 2-81 states that if the tugboat meets all the regulatory and stability requirements of a towing vessel, it can be operated as a push boat 100% of the time and maintain the crewing and regulatory requirements of a traditional tugboat (Ocean Tug/Barge Engineering).
Efficiency of ATB Hull Design

Total hull resistance became important to vessel designers shortly after the invention of steam powered ships. Designers realized that ship speed was no longer wind speed/direction dependent. Once this realization was made, total hull resistance became an important factor in ship design. Total hull resistance combines the friction and viscous effects of water acting on the ship’s hull, the energy required to maintain the ship’s bow and stern waves, and the resistance of the unwetted portion of the ship moving through air. An important consideration of total hull resistance is that it is largely speed dependent. The faster a vessel travels through water the more resistance to forward motion will act against its hull (USNA, 2022).

The coefficient of viscous resistance of a ship takes into account: hull form, vessel speed, and the water properties the vessel is traveling through. This coefficient is an important consideration when designing hull shape. The best means to reduce the total hull resistance of a vessel are to reduce the coefficient of viscous resistance, and the volume of wetted surface area of the hull. A long hull with reduced beam (width) will tend to reduce the coefficient of viscous resistance. However, this design will increase the wetted surface area of the hull for the same cargo volume (USNA, 2022).

![Figure 2 - Typical Hull Resistance Profile (USNA, 2022)](image)
Typical ATB service speeds are around 9 knots (Pike, 2011) with some transportation companies claiming service speeds up to 12 knots (Crowley, 2020). On average ATB’s travel at half the speed of self-propelled vessels. This decreased speed results in decreased hydrodynamic resistance on the hull. ATB’s can move the same volume of cargo the same distance at significant fuel savings when compared to self-propelled vessels. The increased efficiency of an ATB arrangement vs. traditional tug and barge represents a 25% reduction in fuel consumption (MarineLink, 2002).

Transportation companies disagree on barge bow design choices (Hill). Ship shape bows provide greater efficiency, while spoon bows track better (Beers, 2017). During this research no indication was found that transportation companies have utilized a bulbus bow design in ATB construction.

A bulbus bow has the distinguishing characteristic of a large protrusion at or just below the water line of the bow depending on vessel loading.
The purpose of a bulbus bow is to reduce the effects of wave making resistance on a ship’s hull. Most bulbus bows are “tuned” for a ship’s design speed and loading. The bulbus bow when tuned for design speed can reduce hull resistance by as much as 15% (USNA, 2022). The bulbus bow can have a negative effect by increasing fuel usage when a ship is partially loaded or operating at a speed that is different from designed speed (Lu et al, 2016). ATBs operate with a wide range of load conditions, and unless operating in open water, speeds can vary greatly.

Optimizing bulbus bow performance for multiple load and speed conditions that the vessel is likely to encounter is a recent concept. Tank testing of bulbus shapes designed utilizing algorithmic equations to optimize performance over multiple load and speed ranges has shown great promise. The slight reduction in efficiency of a multiple condition optimized bulbus bow, at full load and design speed, is more than made up for throughout the vessel load / speed range. Figure 5 (next page) depicts an example of hydrodynamic tank testing results of a hull optimized for one loaded / speed condition vs. a hull optimized utilizing algorithms for multiple conditions (Lu et al, 2016).
Figure 5 - Bulbus Bow Optimization (Lu et al, 2016)

The lower half of each image represents the original bow that was optimized for design speed / loading. The upper half represents optimization throughout a range of speed / loading conditions. Note the reduction in wave formation in the upper portion of each image.

The interface between the tug and barge of an ATB unit creates a complex hydrodynamic situation. Seemingly inconsequential design changes can result in drastic changes to maneuverability and efficiency (Hill). This research uncovered no definitive information regarding how to reduce hydrodynamic drag in this area. The barges stern must be designed to provide acceptable towing characteristics. This requires the barge stern to have steering skegs, which is an additional source of drag. This drag has the effect of increasing total hull resistance which decreases vessel fuel efficiency. Hydrodynamic tank testing of multiple design iterations
is the only current method of finding an acceptable balance of necessary drag vs. efficiency of the tug barge interface (Hill).

![Figure 6 - Tug Barge Interface (Hill)](image)

The tug bow shape does not greatly affect total hull resistance. This is caused by the notch of the barge (indent in the stern of the barge where the bow of the tug fits) creating eddying forces that negate much of the hydrodynamic resistance acting on the tug bow (Hill).

**Hull Coatings and Anti Fouling**

The two types of water flow along a ship’s hull are known as: laminar flow and turbulent flow the most efficient of these being laminar flow (USNA, 2022). Marine transportation companies employ hull coatings to reduce the negative effects of turbulent flow which result from the buildup of marine grown on a ship’s hull. As ships move through water, resistance to motion occurs as a product of the hulls wetted surface area (area below the water line), friction, and water viscosity. Hull coatings help reduce the friction element of this resistance by smoothing the hulls surface and slowing marine growth.

As marine growth builds on a ship’s hull, the volume of turbulent flow increases causing an increase in friction resistance. This increase in friction resistance has a direct negative effect on a ships total hull resistance (Lorie et al, 2021).
Significant research has been done in recent years utilizing machine learning to analyze and predict hull fouling related performance reduction (Lorie et al, 2021). Multiple studies found during this research have predicted, after cleaning heavily fouled hulls, an increase in effective power (the power to move a ship’s hull through the water at a given speed in the absence of propeller motion (USNA, 2022)) by 18.1%-39%. One study resulted in an increase in effective power of 25%-59%.

**Propulsion Efficiency**

Figure 8 (below) depicts a representation of a typical ships propulsion system:

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Prime Mover  BHP  Reduction Gear  SHP  Shafting & Bearings  DHP  Propeller  THP  [Hull]
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**Figure 8 - Block Diagram Ships Propulsion (USNA, 2022)**

The prime mover (engine) provides power to the ships reduction gear (transmission). This power is known as BHP (brake horsepower). The reduction gear transmits BHP to the ships tail shaft SHP (shaft horsepower). The shaft is supported by bearings and delivers SHP to the propeller as DHP (delivered horsepower). The propeller converts DHP to thrust as THP (thrust...
horsepower). Thrust provides the ships relative motion. Each of these power deliveries constitute certain efficiency losses \( (BHP < SHP < DHP < THP) \) \( (USNA, 2022) \).

Figure 9 presents the typical efficiency losses in a ship’s propulsion system:

![Figure 9 - Typical Losses in Ships Propulsion System (USNA, 2022)](image)

**Prime Mover Efficiency**

Broken down to its most basic element, a ships propulsion engine converts thermal energy from the rapid oxidation (burning) of fuel to mechanical force. The thermal efficiency of an engine is a measure of how much thermal energy gets converted to actual work versus what is wasted. Wasted energy is lost as the heat of exhaust gasses and in engine cooling systems. A typical automotive diesel engine can have thermal efficiencies of 30-35%, large ship engines have thermal efficiencies over 50% with medium sized tugboat engine thermal efficiencies somewhere in the middle (Rahman et al, 1994).

The diesel engine has long been the standard ‘prime mover’ for ATBs. In recent years Diesel Electric drives have become a very common alternative mode of propulsion for tugboats.
This is especially true in vessels that are required to run at low speeds and varying loads for extended periods. Diesel Electric technology has been utilized to increase the efficiency of ship assist tugs with great success (Oceantime, 2018).

The optimum efficiency available from a diesel engine is usually achieved at roughly 85% MCR (max continuous rating). MCR is the amount of power an engine can produce 100% of the time (Oceantime, 2018).

Where diesel electric propulsion systems gain efficiency is in engine power scalability. These systems can be installed in multiple configurations. A popular option is a system that utilizes multiple prime movers to generate electrical power for propulsion with no mechanical connection between the prime movers and the ships propeller. Power is provided to the propeller by way of an electric motor of appropriate size. Diesel engines lose efficiency when operated below or above 85% MCR. This loss of efficiency increases linearly below 50% MCR. The above configuration of diesel electric drive maximizes the time each propulsion engine spends in its efficient range by cycling off one of the propulsion engines at periods of low load. All propulsion engines can provide power to each propeller simultaneously or individually (Oceantime, 2018).

**Running Gear Efficiency**

A ship’s running gear includes propellers, propeller shafts, struts, and rudders. Each of these items adds to total hull resistance. This added resistance is known as appendage resistance. Typical appendage resistance figures of ship’s propeller, strut and rudder combinations are around 8% of total hull resistance. The maximum appendage resistance of a ship’s hull including all appendages (Keel, Skegs, Shaft, Propeller and Rudder) can range as high as 28% of total hull
resistance (Mandru & Pacuraru, 2021). ATBs employ two sets of running gear and stabilizing skegs, therefore total hull resistance from running gear may run higher than this figure.

Kort nozzles consist of a shroud that is hydrodynamically designed to fit around a ship’s propeller. Kort nozzles increase propeller efficiency and provide up to a 30% increase in vessel pulling power (Bollard Pull) and thrust. This increase of pulling power and thrust is especially useful for vessels requiring high thrust at low speeds (i.e., tugboats). Kort nozzles typically become ineffective and increase total hull resistance at speeds greater than (10) knots (Bryant, 2012).

![Kort Nozzle](image)

*Figure 10 - Kort Nozzle (Bryant, 2012)*

Propeller choice can have a drastic effect on a ship’s efficiency. The size of a ship, propeller shaft rotational speed, engine power and ships operating speed are all considerations when choosing an efficient propeller. It is important to note that each of these conditions are interdependent. A ship’s speed is dependent on its size (total hull resistance), and a ship’s propulsion power required is dependent on desired speed (Techet, 2005).

The diameter of a propeller directly effects the thrust it can produce, the larger a propeller’s diameter, the more thrust it will produce. A propeller designed for slower rotational speeds will also increase thrust. Maximum efficiency for a given propeller design can be
calculated utilizing the Kramer Diagram for Ideal Propeller Efficiency (Techet, 2005). Through a series of calculations, propeller design choices can be utilized in conjunction with this diagram to find the maximum efficiency of each propeller in perfect laminar flow.

An alternative to utilizing a shaft-driven propeller for ship’s propulsion is the use of a Pod Drive. Pod Drives are characterized by a large electric motor inside the pod that rotates the propeller, and by its azimuthing operation (the entire unit rotates to provide thrust in any direction without the use of a rudder). Due to their high maneuverability and quiet operation, pods have been used extensively for propulsion in the cruise line industry (Mewis, 2001).

Figure 11 - Pod Drive (Mewis, 2001)

Pod Drive efficiency is slightly less than traditional propulsion. Although traditional shaft propeller arrangement can deliver greater thrust than Pod Drives at low speeds, they suffer increasing appendage losses as speeds increase. Pod Drive electric systems suffer from substantial electrical transmission losses which erodes propulsion system efficiency (Mewis, 2001).

An alternative to Pod Drives is the Z-Drive propulsion system. Z-Drives share similar azimuthing characteristics of a Pod Drive but utilize a shaft with two gearboxes to rotate the
propeller instead of the electric motors found in a Pod Drive. Like Pod Drives, Z-Drives can be optimized to maximize thrust or speed and any combination of the two.

![Z Drive Cutaway Showing Mechanical Arrangement](image)

*Figure 12 - Z Drive Cutaway Showing Mechanical Arrangement - (Thrustmaster, 2015)*

Z-Drives do not suffer from the same electrical power transmission losses as a Pod Drive. A 2018 study (Waterways, 2018) comparing Z-Drive propulsion to traditional propulsion found that: 1) Ahead efficiency is approximately equal. 2) Z-Drive can produce 55% more steering momentum (rate of turn). 3) Z-Drive can stop the vessel 38% faster.

Propeller performance can be negatively affected by the buildup of corrosion, impingement attack, cavitation erosion and fouling. Corrosion can be combatted using corrosion resistant alloys for propeller construction. Impingement attack usually occurs on the leading edge and outer edge of a propeller blade. Cavitation erosion and fouling usually occur on the trailing edge of a propeller blade (International Marine, 2022).

Some ship owners clean and polish propellers during dry-docking intervals of up to 5 years, others perform these tasks at regular intervals of 6 to 9 months (International Marine, 2022). Biocides are not a viable alternative for propeller anti fouling coatings due to the high sheer stresses created by a propellers motion through water. Foul release coatings work best to protect from fouling on propellers by smoothing the propeller’s surface enough to not allow
marine growth attachment under the sheer stresses experienced by a ship’s propeller. Foul release coatings can protect a propeller from marine growth build up for up to one year and do not negatively affect propeller performance (Korkut & Altar, 2009)

Alternative Fuels

Figure 13 presents the energy density and weight density of diesel fuel as compared to alternative fuels:

![Figure 13 - Energy and Weight Density Comparison of Fuel Alternatives (Ryste, 2019)](image)

When comparing alternative fuels for maximum efficiency, volumetric and gravimetric energy density are important considerations. A fuel with greater volumetric energy density will require less space for storage. Alternatively, a fuel with greater gravimetric energy density will add less weight to the vessel. In the above comparison (Figure 13), energy density is presented in MJ/kg for gravimetric and MJ/liter for volumetric.

With few exceptions, MDO (marine diesel oil) is the standard fuel source for ATB propulsion. When comparing alternative fuels, fuel weight, energy density, storage considerations, availability and price are all important factors to consider. LPG (liquified petroleum gas) and LNG (liquified natural gas) are two alternative fuels that may become
competitive, or at least comparable, to MDO from an operational cost standpoint in the near future (Ryste, 2019).

**Power Generation**

Optimization of a ship’s power generation system for efficiency is an important design consideration. Properly estimating electrical loads is a critical factor in sizing electrical generators. Reserve spinning power is a measure of the reserve capacity in a running power generation unit. Excess reserve spinning power negatively effects the efficiency of a ship’s power generation system (Leem et al, 2021).

The traditional method of determining a ship’s power generation requirements is in performing an ELPA (electrical power load analysis). To perform this analysis three inputs are necessary: 1) data from at sea trials. 2) the ship’s load factor (ratio between power utilization and maximum demand). 3) auxiliary documentation. With these three inputs generator sizing can be determined (Boveri et al, 2016).

![Figure 14 - Flow diagram using EPLA in generator selection (Bovere et al, 2016)](image.png)

Utilizing this information and accounting for regulation, ship owners can make informed decisions regarding power generation equipment sizing and number of units. Some ship owners opt to reduce the efficiency loss of reserve spinning power by utilizing different capacity
generators in parallel to meet peak demand. One generator is sized for most of the vessel’s power demands and a second smaller generator comes online in parallel to power peak demand. Another arrangement is to have three equally sized generators, each generator is sized to supply all but peak demand and all are capable of auto starting and synchronizing to meet peak demand (Bovere et al, 2016).

Shaft generators have long been used to increase electrical power generation efficiency aboard ships. Shaft generators are attached to the ship’s propeller shaft or propulsion engine output shaft and provide electrical power generation with much greater efficiency than the ship’s dedicated generator sets. (Landtao et al, 2020)

Traditionally, shaft generators have required constant propulsion engine speed to retain synchronization with the ship’s electrical bus. As ATBs are generally operated in short sea shipping routes, constant shaft speeds for extended periods are uncharacteristic of ATB operations.

Due to recent advances in power generation control systems, asynchronous shaft generators have become widely available. These systems offer benefits not found on synchronous systems, they are not reliant on constant shaft speed and they automatically adjust for power factor, load, and frequency, yet they provide similar power generation efficiency as synchronous systems. Some manufacturers have added the ability to provide power to the ship’s propeller at low loads using the ship’s power generation system, thus providing the ability to maneuver the vessel without running propulsion engines. Also advertised is the ability to provide an assist to the ship’s propulsion system in periods of high demand such as the high loads produced when accelerating a vessel up to sea speed (theswitch, 2013).
Bottoming cycles have been used with great success in many applications. The principal characteristic of a bottoming cycle is in utilizing waste heat from a mechanical process to produce usable electrical power. Bottoming cycles for electrical power generation aboard ships use waste heat to generate steam which provides rotation to a turbine generator. The turbine generator produces electrical power which is fed to the ship’s electrical systems. Bottoming cycle electrical power generation units, using a ship’s engine waste heat (exhaust heat), have not been a commercially viable option for shipowners. The primary reason for this is the relatively low exhaust gas temperatures of marine engines especially in turbocharged applications (Lebedevas & Cepaitis, 2021).

A recent advancement in bottoming cycle technology is called an ORC (organic Rankine cycle). A Rankine cycle is a closed loop thermodynamic operating cycle wherein working fluid is constantly evaporated and condensed. In an ORC system the working fluid has a significantly lower boiling point than water and can be optimized for the exhaust gas temperature ranges compatible with medium speed marine diesel engines. An ORC system achieves this lower boiling point through the utilization of organic refrigerants instead of water (Lebedevas & Cepaitis, 2021).

Integrating wind turbine technology into a ship’s electrical generation system is a promising idea for the reduction of electrical power related fuel consumption. There are many options in wind turbine design / application. One application option is an on-grid application wherein the wind turbine provides supplemental power to the electrical generation or storage capacity of the vessel. On-grid applications are more suitable with smaller wind turbine generators, while off-grid applications are more suitable to large wind turbine generators. Wind
turbines for application on marine vessels have been developed from single digit KW outputs to as much as 30KW outputs (Paulson & Chacko, 2019).

Using modern electronic control systems, wind turbines can provide DC power, AC power or any combination of the two. Marine vessels have significant DC power loads. These are mostly found in the pilot house navigation equipment. AC loads are mostly found in hotel services and engine room pump and motor applications (Paulson & Chacko, 2019).

Figure 15 - Wind turbine connected to ship’s DC bus (Paulson & Chacko, 2019)

Figure 16 - Wind Turbine connected to ship’s AC bus (Paulson & Chacko, 2019)
Weather conditions are constantly changing. Wind turbines alone are not a viable alternative to installed power generating capacity; however, they do show promise in supplementing a ship’s power generating capacity.

**Operational Efficiency**

There are numerous methods to reduce a vessel’s fuel consumption through operationally efficient practices. Some of these methods include: 1) improved voyage planning, 2) optimal weather routing, 3) just-in-time port arrival / scheduling, 4) speed optimization, 5) shaft power optimization, 6) optimum ballast / trim, 7) rudder control systems (USCG, 2012). As this paper is focused on best practices of fuel-efficient ATB design, this research will be limited to design elements only.

Adaptive autopilot systems provide as much as a 1% operational efficiency improvement over traditional autopilot systems. Every rudder input adds drag to the vessel’s hull and load to its propulsion system. Adaptive autopilot systems can autotune to weather and load conditions and optimize rudder angle inputs for maximum efficiency (ABS).

Increasingly popular among shipping companies are advanced fuel management systems. These systems provide a vast amount of fuel consumption related data to the ship’s pilot house and to shoreside personnel. Typical fuel savings when utilizing fuel management systems range from 5% to 15% total voyage fuel consumption. Some systems rely on the vessel’s wheelhouse personnel utilizing the supplied data to optimize throttle settings. Other systems take throttle control out of the hands of wheelhouse personnel and optimize throttle control automatically (Professional Mariner, 2008).
Closing Remarks

While this research is extensive, it is by no means exhaustive. Designing vessels for efficiency is a complex and dynamic subject and many avenues of research may be followed in its pursuit.

Creative Element

Importance of Designing for Efficiency

“A pint of sweat will save a gallon of blood” - General George S. Patton (Business Insider, 2015)

In the United States, the interstate marine transport (Jones Act trade) of petrochemicals by articulating tug and barge (ATB) is a specialized industry with a limited number of companies all vying for a finite volume of trade. In 2009, there were 116 ATB units operating in the Jones Act trade (Barami & Dyer, 2009). By 2017, that number had risen to 167 ATB units (Marad, 2017). In 2016, RBN energy, an energy market data and analytics consultation firm, published an article warning of the looming oversupply of ATBs in the Jones Act trade (Amand, 2016). By September 2020, after 102 years in business, Bouchard Transportation the nation’s largest independently owned ocean-going barge transportation company filed for bankruptcy (Reuters, 2021).

While there were other contributing factors to Bouchard’s bankruptcy, the fact remains that the Jones Act ATB trade is a very competitive industry. Any transportation company in this industry that can reduce fixed costs by operating with greater energy efficiency than its competitors will develop a competitive advantage over those competitors.

Domestic marine transportation (freight, bulk cargo, passenger and fishing) accounts for 0.6% of global CO2 emissions, international marine transportation accounts for 2.7% (IMO,
On average, ships emit 16.8 grams of CO2 per kilometer for every tonne of cargo transported. In contrast, trucks emit 80 grams per kilometer for every tonne of cargo transported, and air cargo carriers emit 435 grams.

While marine transportation is the least greenhouse gas emitting alternative for transporting goods, focusing on reducing the greenhouse gas emissions of this industry remains an important consideration. This task is best accomplished through a concentrated effort to design the least energy consuming vessels as practical. As General Patton famously stated, “A pint of sweat will save a gallon of blood”, effort spent in designing for efficiency will save considerable expense in vessel operating costs and negative effects on the environment in the future.

**Best Practice Suggestions for ATB Hull Design**

When designing an ATB for efficiency, total hull resistance is a very important consideration. Total hull resistance is a product of the friction and viscous effects of water acting on the ship’s hull, the energy required to maintain the ship’s bow and stern waves, and the resistance of the unwetted portion of the ship moving through air. Variables that significantly affect total hull resistance are design speed, bow shape, hull shape, shape and size of barge steering skegs, the hydrodynamic interface between tug and barge, and tug appendage resistance. Design choices that decrease wave making resistance, the coefficient of viscous resistance acting on the hull, the negative effects upon efficiency of the tug barge interface, and drag related to appendage resistance are critical. Furthermore, the use of anti-fouling coatings and performance of regular hull cleanings and maintenance are paramount to maintaining maximum efficiency of a given hull design.
Total hull resistance is largely speed dependent. One major advantage to ATBs over self-propelled vessels is their superior fuel efficiency. ATBs have a higher coefficient of viscous resistance than self-propelled vessels due to the addition of barge steering skegs, the tug barge interface and the use of multiple sets of running gear. They achieve higher fuel efficiency than self-propelled vessels for the same volume of cargo moved by operating at reduced speeds which effectively reduces total hull resistance. The trade off is that, due to the increased transit time from operating at reduced speeds, ATBs are less suitable for long voyages than self-propelled vessels and mostly thrive on short sea / inland shipping routes.

Marine transportation companies should pay close attention to anti-fouling hull coatings. These coatings protect a vessel's hull from marine growth which is a major contributor to increased total hull resistance. Periodic hull cleanings are expensive, but the increased coefficient of viscous resistance acting on the vessel's hull while in motion due to marine growth may justify the added maintenance expense.

Machine learning software that can predict hull fouling efficiency losses is a recent development that shows promise in assisting vessel operators with the decision of when to perform hull cleanings. Hull cleanings are an expensive, but necessary, maintenance item. Using machine learning software to accurately predict hull fouling efficiency losses can aid a vessel operator in deciding if the efficiency gained from hull cleanings can justify the expense.

Before the development of the ATB, most barges utilized a spoon bow for its greater lateral stability while being towed when compared to a ship shape bow. After the introduction of the ATB, ship shape bows became a more common design choice. Ship shape bows offer increased efficiency over spoon bows. ATBs are designed to remain in ‘push mode’ at all times, towing an ATB barge is very uncommon and only typically occurs in emergency situations. ATB
designers should choose a bow shape that reduces total hull resistance rather than focus on lateral stability characteristics under tow.

Use of a bulbus bow on an ATB has not thus far been advantageous due to the speed range and varying loads that are typical of ATB operations. Recent advances in bulbus bow design may change their suitability for ATB application. Using algorithmic equations to optimize bulbus bows for multiple speed and load ranges makes this possible and should be explored further.

A disadvantage of utilizing a bulbus bow for tug and barge work is in ‘handling’ the barge, coming on and off tow requires the tug stern to come in close quarters with the bow of the barge. The protruding appendage of a bulbus bow could contact the tug while performing this operation endangering both vessels. Bulbus bows are also more expensive to design and build than traditional barge bow designs. More research is necessary in determining the bulbus bow’s suitability for ATB application.

Barge steering skegs provide necessary lateral stability to the barge while being towed. They have the disadvantage of adding unneeded drag (increased total hull resistance) while operating in ATB mode. ATB designers should pay close attention to this necessary barge design feature and investigate methods of reducing drag while maintaining lateral stability while in ‘tow mode’. An option to reduce drag in ‘ATB mode’ would be the utilization of retractable steering skegs that would remain retracted into the barge stern while in ‘ATB mode’ and be lowered to provide lateral stability while in ‘tow mode’. Designers should investigate if the increased cost to produce and maintain retractable steering skegs would provide sufficient reduction in drag while in ‘ATB mode’ to justified the added expense.
The tug barge interface is of particular importance from a handling characteristic and efficiency standpoint. There is no current method to optimize the handling and efficiency of this critical feature without extensive hydrodynamic tank testing of scale models. Designers should pay close attention to this interface and extensively test each design iteration for expectable handling and efficiency characteristics.

**Best Practice Suggestions for ATB Propulsion**

An ATB’s propulsion engines constitute the vast majority of energy consumption associated with ATB operations. These engines provide rotational force to the vessel’s propellers which is converted to thrust that results in the vessel’s relative motion through water. Roughly 24% of the energy produced by a marine propulsion engine is converted to thrust. The remainder is lost through heat and friction related losses.

A rule-of-thumb that is common knowledge among tow boat operators is that every thousand horsepower in propulsion engine rating results in roughly a thousand gallons of fuel consumed per 24 hours when operating fully loaded. For example, a 4000HP tug and barge unit would be expected to consume 4000gals of fuel oil for every 24 run hours when loaded. Reducing this consumption will reduce operational costs and increase energy efficiency.

Diesel electric propulsion has been used to increase efficiency with great success in ship assist work. These systems have not been considered financially attractive for ATB operations in that ATBs are not subject to varying loads and running lightly loaded as frequently as assist tugs. Where diesel electric propulsion systems could benefit ATB operations is in areas where engine speed, engine load changes, running slow or lightly loaded are frequent operating characteristics.

It is critical that ATB designers choose a propulsion engine arrangement that maximizes the time each propulsion engine spends in its efficient range. For vessels designed to operate
mostly on long voyages at constant speeds (coastwise transport) a traditional propulsion system is preferable, for those operating mostly in rivers, harbors and inland waterways a diesel electric propulsion system may be advantageous.

Typically, ATBs utilize a traditional running gear (propeller shaft, stabilizing struts, propeller, rudder) arrangement for propulsion. Given the similarities in efficiency and reduced operating / maintenance costs of traditional running gear over pod drives, traditional running gear remains the best arrangement for most ATB applications.

Due to its superior maneuverability (turning torque and backing power) a pod drive arrangement would be advantageous in confined waters. Designers should consider pod drives for application in vessels designed specifically for operation in rivers, harbors and inland waterways.

Pod drives (electric drive) should be used in vessels where the benefits of diesel electric propulsion systems are advantageous and pod running gear is also advantageous. In all other applications favoring pod running gear, Z-drive (mechanical drive) pods are best due to their superior energy transfer efficiency.

Marine Diesel Oil (MDO) remains the preferred fuel for ATB propulsion and power generation. Despite this fact, ATB designers should consider alternate fuels when and where appropriate. LNG and LPG are two fuels that may be competitive with MDO in the near future from an operational cost perspective. When considering alternative fuels, storage space and weight requirements are extremely important. LNG and LPG both require more storage space per BTU than MDO.

A possible storage solution for LNG and LPG applications could be on the barge of an ATB unit. LNG or LPG fuel could be stored on the barge and transferred to the tug when tug
stores become depleted. Typically, the tugboat of an ATB unit supplies the barge with fuel oil for consumption in its dedicated generators and pump engines. This is accomplished through utilizing transfer hoses coupled between the two units. The tug transfers a portion of its fuel reserves to a holding tank on the barge when needed. Designing the barge with storage capacity sufficient to supply supplemental fuel to the tug could be as simple as adding adequately sized tanks and reversing the transfer arrangement between units.

ATB operators should perform underwater hull surveys on an annual basis at minimum. This survey should note any underwater damage/corrosion on the vessel’s hull and running gear. Of particular importance for inspection are all wear items located under the waterline. These items include the leading edge of stabilizing struts, kort nozzles and bracing, corrosion inhibiting anodes, propeller shaft bearings and propellers.

During propeller inspection particular attention must be paid to the leading and outer propeller blade edges for impingement attack, and propeller blade trailing edges for cavitation erosion and fouling. Physical inspection is the only accurate way to verify propeller condition and will aid in making decisions as to when propeller polishing should be performed.

**Best Practice Suggestions for ATB Power Generation**

An ATB’s tug power generation system is the second largest energy consumer after propulsion engines. Other consumers of fuel oil on an ATB are barge pump engines and dedicated barge power generation systems.

Barge pump engines are utilized for transferring product from the barge to shoreside reception facilities. These engines should be sized appropriately to operate in their efficient range under designed load.
The barge’s electrical power generation system is utilized whenever the tug disconnects from the barge. Some operators rarely disconnect the tug from the barge while others do so regularly. As such, a barge’s electrical power generation system can be utilized often, in some instances, and infrequently in others. In either scenario, this system should be sized appropriately to operate in the efficient range of its generator engines.

Reserve spinning capacity is a measure of the reserve load capacity of each running generator. A diesel engine’s optimal efficiency is reached at roughly 85% max continuous rating (MCR). Meaning that, the optimal reserve spinning capacity for a given power generation system utilizing diesel engines as a prime mover is 15%.

With the exception of machinery space heating in cold weather, the electrical power demands of navigational equipment, engine room equipment, and lighting remain relatively constant on an ATB. In contrast, heating and air conditioning loads for hotel services change significantly depending on outside temperature which varies with time of year and vessel location. To meet the changing load conditions resulting from outside temperature fluctuations a scalable electrical power generation system is best.

This system should consist of multiple generators of equal size, each generator is sized to provide operational loads in its peak efficiency range during mild outside temperatures (spring and fall). The generator control system should be capable of starting, warming and placing online a second generator when loads demand. Multiple equal size generators are advantageous over a large primary and smaller secondary generator arrangement for continuity of operation reasons. Having three equal sized generators, where any combination of two are capable of supplying maximum demand, means any one generator can be out of service for maintenance without negatively effecting vessel operations.
Asynchronous shaft generators differ from traditional shaft generators in that they operate independent of propulsion engine speed. Shaft generators generate electrical power much more efficiently than dedicated generators by utilizing a fraction of the output power of a vessel’s propulsion engine to produce electricity. The increased load of a shaft generator on a vessel’s propulsion engine requires significantly less energy to maintain than a dedicated generator engine requires. However, when operating in short sea shipping routes and confined waters (the main operational areas of ATBs) traditional shaft generators have not been considered advantageous due to frequent engine speed adjustments.

Utilizing asynchronous shaft generators with modern control systems that are not dependent on consistent engine speeds would increase the efficiency of an ATB’s power generating capacity. The added cost of installing and maintaining these systems should be weighed against the fuel consumption savings they can create in deciding their viability for ATB application.

Similar to shaft generators, renewable energy sources such as wind and solar would reduce power generation related fuel consumption for ATBs. These systems could be utilized to supplement the entire vessel’s power production needs or for specific systems such as bridge navigational equipment. As is the case with shaft generators, the added cost of installing and maintaining these systems should be weighed against their benefits in deciding their viability for ATB application.

Utilizing an Organic Rankine Cycle (ORC) bottoming cycle for supplemental ATB power generation is another possible method of reducing power generation related fuel consumption. Unlike traditional bottoming cycle power generation units, ORCs utilize organic refrigerants for steam generation and can be optimized for medium speed diesel exhaust gas
temperatures. ATB operators should weigh the added cost of installing and maintaining an ORC bottoming cycle power generation system against its benefits in deciding its viability.

Neither shaft generators, renewable energy sources nor an ORC bottoming cycle should be considered as replacement for installed power generating capacity on an ATB. Each of these systems can only be used to provide supplemental power generation.

**Operating Efficiently Regardless of Design Elements**

Designing ATBs for fuel efficiency is only part of the equation. The vessel must be operated with energy efficiency in mind in order to maximize its efficiency potential. Two aids in operating efficiently that ATB designers should incorporate in every vessel design are advanced fuel management and adaptive autopilot systems.

Advanced fuel management systems provide fuel consumption related data to the pilot house and can provide this data to shoreside personnel as well. These systems can be set up to aid pilot house and shoreside personnel in refining throttle settings for efficiency or can take throttle control out of the hands of pilot house personnel altogether. ATB designers should incorporate fuel management systems in all new ATB designs. Further, ATB operators should consider the addition of an advanced fuel management system on all existing ATB platforms.

Adaptive autopilot systems work by reducing unnecessary rudder inputs along a given route. Each rudder input reduces the efficiency of the vessel traveling through water. Reducing unnecessary rudder inputs, will increase efficiency reducing the fuel required for each voyage. As with advanced fuel management systems, adaptive autopilot should be incorporated in every new ATB design and retrofitted to existing ATB platforms.
Conclusion

All corporations are depended on by their stakeholders. A corporate stakeholder is any person or entity with a direct or indirect financial, personal, or professional interest in the continued viability of a corporation. There are many types of stakeholders including (but not limited to) owners, suppliers, customers, employees, investors, and in many cases the general public.

To serve each stakeholder’s best interest, a corporation must take every step necessary to meet their financial and social responsibilities. Designing and operating ATBs in the most energy efficient way practical is an important step in this direction and will result in reduced fixed operational costs as well as reduced greenhouse gas emissions from vessel operations.

Designing ATBs with energy efficiency in mind is a complex and dynamic subject that can encompass many aspects of vessel design. Each incremental improvement in energy efficiency constitutes a percentage of the whole and although seemingly small, when combined throughout the entirety of an efficiency-oriented design, can add up to a significant energy consumption savings.

Efficiencies can be incorporated throughout every aspect of vessel design and operations. This paper focused on many key areas where efficient design and operational practices could be utilized in ATB design including:

1) Anti-Fouling Coatings – These coatings are critical to reduce hull fouling related efficiency losses.

2) Machine Learning Software to Predict Hull Fouling Efficiency Losses – This concept shows great promise in assisting vessel owners in decisions regarding when to perform hull cleanings.
3) Bow Shape – Ship shape bows are best as the lateral stability from a traditional barge spoon bow is not necessary on ATBs.

4) The Bulbus Bow – Recent developments in optimizing the bulbus bow for multiple speed and load conditions may make incorporation in ATB hull design a viable alternative and should be researched further.

5) Barge Steering Skegs – Vessel designers should investigate the viability of retractable steering skegs to reduce drag in ATB mode.

6) The Tug Barge Interface – The hydrodynamically complex relationship between the tug bow and notch of the barge should be tank tested extensively to assure acceptable vessel handling and efficiency characteristics.

7) Diesel Electric Propulsion – Diesel electric propulsion is the best option for ATBs that will spend the majority of time in areas where engine speed, engine load changes, running slow or lightly loaded are frequent operating characteristics.

8) Traditional Propulsion – Traditional propulsion systems remain the best choice for ATBs that operate primarily on open ocean (coastwise) voyages.

9) Traditional Running Gear – Traditional running gear (propeller shaft, stabilizing struts, propeller, rudder) remains the best running gear option for most ATB applications.

10) Pod Drive (Electric) – This drive system is best where diesel electric propulsion and pod running gear are advantageous such as where engine speed, engine load changes, running slow or lightly loaded are frequent operating characteristics and in confined waters (rivers, harbors and inland waterways).
11) Z-Drive (Mechanical) – This system is the best choice when designing an ATB to operate primarily in confined waters (rivers, harbors and inland waterways) and where diesel electric propulsion is not advantageous.

12) Fuel Choice – MDO remains the preferred energy source for ATB application, but LNG and LPG could become competitive, or at least comparable, with MDO from an operational cost perspective in the near future.

13) Propeller Inspection / Polishing – Perfuming propeller inspections, and subsequent polishing if found necessary, is critical to maintaining the optimal efficiency of a given propeller design.

14) Power Generation – A scalable power generation system is best as it provides the ability to reduce reserve spinning capacity during periods of low electrical load and maximize the time each generator engine can spend in its efficient load range.

15) Supplemental Power Generation – Generating power from asynchronous shaft generators, an ORC bottoming cycle, wind turbines and solar panels can reduce power generation related fuel consumption but should only be utilized to supplement an ATB’s power generating capacity.

16) Operational Equipment – Two items that should be included in ATB design to aid in efficient operation are an advanced fuel management system and adaptive autopilot.

Designing ATBs for efficiency is an important economic and socially responsible endeavor and should be pursued with vigor. Although not all of these key areas for improvement will apply to every ATB design, by maximizing efficient design and operational practices transportation companies will not only reap the financial rewards of reduced vessel operating costs but also help advance environmental conservatism for generations to come.
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