NOWDRC Agreement #103

Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry:

Weather Downtime Based on Metocean Data & Frequency Domain Motions FINAL Technical Report

Milestone Number 5.5 (Rev 0)

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Abstract

The Cargo Feeder System (CFS) solution examined in this study is a tight-line operation consisting of a lead tug, a barge loaded with the components of one (1) wind turbine generator (WTG) and a support tug transporting WTGs to Empire Wind from either Salem, MA or Brooklyn, NY.

This report provides a weather down time study that incorporates vessel and cargo motions and accelerations. The study includes a base case that compares the throughput of a Foreign WTIV supported by a Jones Act compliant Cargo Feeder System to a Jones Act compliant WTIV working alone. It also describes how sensitive the system is to changes in (1) cargo acceleration limits during transit, (2) maximum landing velocity permitted when the feeder comes alongside the WTIV, (3) wind speed and direction during approach to the WTIV, (4) cargo top & base motion limits which might be mitigated by motion compensation equipment, and (5) cargo configuration and ballast condition. Relative cost between the two WTG delivery and installation systems is also examined.

This report also describes a tool that can be used to include vessel and cargo motions in a weather downtime simulation that yields system throughput by month reported with statistically significant confidence levels.

Keywords

Feeder barge, tight-line operation, wind turbine generator installation, wind turbine installation vessel, discrete event simulation, weather downtime, frequency domain motions, P50 and P90 confidence levels.

Acknowledgments

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Acronyms and Abbreviations

CES	Crowley Engineering Services
CF	Cargo Feeder (prefix to identify tug or barge that is part of CFS)
CFS	Cargo Feeder System (including lead tug, barge, and support vessel(s), if required)
CFV	Cargo Feeder Vessel (any vessel or assembly that deliver WTG components offshore)
CGS	Crowley Government Services
CMS	Crowley Marine Services
DES	Discrete Event Simulation
DNV GL	Det Norske Veritas / Germanischer Lloyd
DOF	degrees of freedom
ft	feet
Hs	significant wave height
IEA	International Energy Agency
JA	Jones Act (46 U.S.C. § 55102)
kJ	kilojoules
kWh	kilowatt hours
m/s	meters per second
MW	megawatts
MWS	marine warranty survey
N	newtons
NDA	Non-Disclosure Agreement
NDBC	National Data Buoy Center
NM	nautical miles
NOAA	National Oceanic and Atmospheric Administration (U.S. Department of Commerce)
NOWRDC	The National Offshore Wind Research and Development Consortium
NREL	National Renewable Energy Laboratory
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
OCMI	Officer in Charge, Marine Inspection
OEM	Original Equipment Manufacturer
OMS	Operational Motions Study
P50	Statistical Confidence Level indicating 50% of sample cases are completed in the time reported or less time. It indicates a moderate level of confidence.
P90	Statistical Confidence Level indicating 90% of sample cases are completed in the time reported or less time. It indicates a high level of confidence.
Phi (ϕ)	Wave Direction
POI	Points of Interest
PUP	Pick-up Point

RAO	Response Amplitude Operator
RTV	Round Trip Voyage
SRAO	Spectral Response Amplitude Operator
TBD	to be determined
Tp	wave period, peak
VOI	Variables of Interest
W	watts
WDT	weather downtime
WDTX	Weather Downtime Express
WTIV	Wind Turbine Installation Vessel
WTG	Wind Turbine Generator

1 Executive Summary

1.1 Overview

Wind Turbine Installation Vessels (WTIV) are high value, high day-rate equipment whose primary role is installing wind turbine generators on site. Only one Jones Act-compliant WTIV is under currently under construction. Using WTIVs to ferry equipment to the installation site may not be cost effective if that operation can be conducted by a fleet of low-cost cargo feeder vessels (CFV). Feeders allow the WTIVs to remain on site and continually erect wind generators.

The overall study examines WTIV feeder system feasibility using a minimally modified deck cargo barge accompanied by the appropriate tugs. The analysis includes:

- Dynamic Motions Analysis – under tow and alongside the WTIV
- Maneuvering Simulation – bringing CF barge to standoff zone and to make "soft landing"
- WTIV/Feeder Weather Down Time (WDT) Simulation – based on motions and maneuvering

This report evaluates the performance of a Cargo Feeder System (CFS) solution consisting of a lead tug, a barge loaded with the components of one (1) wind turbine generator (WTG) and a support tug or similar system delivering and installing WTGs at Empire Wind. This study compares the throughput of load ports in Salem and Brooklyn and assumes the load port is always available to load cargo and, when more than one barge is in service, a barge is loaded and ready to depart when the other barge returns to port.

This report provides a weather down time study that incorporates vessel and cargo motions and accelerations. The study includes a base case that compares the throughput of a Foreign WTIV supported by a Jones Act compliant Cargo Feeder System. It also describes how sensitive the system is to changes in (1) cargo acceleration limits during transit, (2) maximum landing velocity permitted when the feeder comes alongside the WTIV, (3) wind speed and direction during approach to the WTIV, (4) cargo top & base motion limits which might be mitigated by motion compensation equipment, and (5) cargo configuration and ballast condition.

This report also describes a tool that is used to include vessel and cargo motions in a weather downtime simulation that yields system throughput by month reported with statistically significant confidence levels.

Like all simulations of systems, the results may contain abrupt discontinuities associated with sudden changes in limiting constraints, therefore, the reader is cautioned not to apply the findings of this study to other systems without further evaluation. In addition, it should be noted that this simulation is based on hindcast data. It does not account for climate change.

The load conditions evaluated are described in Reference 6.1.1. The simulation task lists for each vessel type are summarized in Appendix A. The method used to incorporate vessel and cargo motions with metocean data is summarized in Appendix B.

1.2 Summary of Findings

1.2.1 Base Case System Performance

1.2.1.1 Cycle Time without Weather Down Time

Without interruptions due to weather as described in Section A.1.2, the time required for an average cycle to deliver and/or install one WTG at Empire wind from the indicated load port is shown in Table 1 below:

Salem		
Foreign WTIV	**Barge**	**JA WTIV***
2.1 days	4.8 days	2.9 days
* Average time for one WTG.		

Brooklyn		
Foreign WTIV	**Barge**	**JA WTIV***
2.1 days	1.6 days	1.3 days
* Average time for one WTG.		

Table 1 –Time Required to Install One WTG without Weather Down Time (WDT)

A CF feeder barge is assumed to transport one WTG per trip, a Foreign WTIV is assumed to install one WTG per cycle and a JA WTIV is assumed to transport and install four WTGs per trip.

1.2.1.2 Comparing Weather Delays by Season

Wind turbine installation is a highly seasonal task. For example, one can have a high level of confidence (P90) that a Cargo Feeder System (CFS) supported WTIV can transport and install one WTG from Brooklyn to Empire Wind in 2.9 days in July but may require up to 7.6 days in January as described in Section 3.1.1 and Table 2 below:

Month with Weather that is	Moderate Confidence (P50)		High Confidence (P90)	
	WTIV w/2 Barges	**JA WTIV**	**WTIV w/2 Barges**	**JA WTIV**
Worst	5.2 days	4.8 days	7.6 days	6.4 days
Spring/Fall Average	3.8 days	3.9 days	5.4 days	5.0 days
Best	2.5 days	3.1 days	2.9 days	3.6 days

Table 2 – Maximum Number of Days Required to Install One WTG from Brooklyn in Months with Best and Worst Weather

1.2.1.3 Minimizing Installation Cost over the Long Term

The number of days it takes to install each WTG is a significant driver of the cost of a wind farm. For example, the installation cost in a year with bad weather (a “P90 year) will be about 30% more than the cost in an average weather year (a “P50 year) as shown in Table 3 below.

	Salem				Brooklyn			
	WTIV w/2 Barges		JA WTIV		WTIV w/2 Barges		JA WTIV	
	P90	P50	P90	P50	P90	P50	P90	P50
WTGs Installed in One Year	75	101	65	82	75	103	76	96
Relative Cost to Install Each WTG	137%	102%	158%	126%	137%	100%	136%	107%

Table 3 – Portion of Year Required to Install Target Number of WTGs with Relative Cost

Since the installation contractor cannot predict the weather when the bid is submitted, the bid price is likely to be based on the cost of a year with bad weather and the level of risk they will accept. However, over the long term, the installation time, and therefore the cost, should approach the P50 level. The savings would be substantial if the utility could structure their contracts to minimizes weather risk for the installation contractors.

1.2.1.4 Comparing Distances to Load Ports

Two barges can keep a WTIV supplied from either Salem (389 NM) or Brooklyn (81 NM) and maintain nearly the same throughput. However, a Jones Act WTIV must pick up cargo at a nearby load port or the throughput suffers. For example, if a Jones Act WTIV must pick up cargo from Salem rather than Brooklyn, the days required to install one WTG increases from 3.1 to 3.2 days in the best month (at P50, or 3.6 to 3.8 days at P90) and it increases from or 4.8 to 6.5 days in the worst month (at P50, or 6.4 to 8.4 days at P90).

1.2.1.5 Comparing Installation Capacity

During an actual WTG installation campaign, the installer will have a target number of WTGs to install and WTIVs and support vessels all require maintenance periods every year or two. Those variations cannot be captured here so the installation capacity over a full year is generally reported.

To get a sense of how shorter campaigns compare when working when the weather is best, the portion of the year required to install the target number of WTGs is compared in Table 4 below.

	Salem				Brooklyn			
Installation Target	WTIV w/2 Barges		JA WTIV		WTIV w/2 Barges		JA WTIV	
	P90	P50	P90	P50	P90	P50	P90	P50
64	79%	50%	98%	68%	79%	49%	79%	60%
75	100%	64%	N/A	87%	100%	62%	97%	73%
85	N/A	77%	N/A	N/A	N/A	74%	N/A	86%
95	N/A	91%	N/A	N/A	N/A	88%	N/A	99%
Full Year	**75**	**101**	**65**	**82**	**75**	**103**	**76**	**96**

Table 4 – Portion of Year Required to Install Target Number of WTGs

1.2.1.6 Comparing Cost

Based on relative costs described in Appendix A1.4, for the Salem to Empire route and an installation target of 60 WTGs or more, the WTIV with two CF barges will be the least expensive option if the JA WTIV's day rate is greater than the foreign WTIV's day rate plus 13% or 6% at P90 or P50 respectively.

For the Brooklyn to Empire route and an installation target of 65 WTGs or more, the WTIV with two CF barges will be the least expensive option if the JA WTIV's day rate is greater than the foreign WTIV's day rate plus 44% or 18% at P90 or P50 respectively.

1.2.2 Sensitivity to Acceleration during Transit

The WTG manufacturers set limits on component accelerations during transit. OEMs have expressed concern that component acceleration limits will be reduced for larger turbines. Since the reference turbine has not yet been designed, a reduced acceleration limit is possible. It may be necessary to add motion compensation systems to vessels that transport next generation turbines.

In the case described in Section 3.1.2 and the relative costs described in Appendix A1.4, for a CF barge supported WTIV out of Salem with an installation target of 70 WTGs, if the acceleration limit is reduced by 50% from standard limits, the cost of installation will increase by 23% and 13% at P90 and P50 respectively.

1.2.3 Sensitivity to Maximum Landing Velocity

When cargo is transported to the WTIV by CF barge, the feeder will be brought alongside the WTIV after it is jacked up. To avoid damage to the legs, it is critical that the feeder approaches slowly so it does not apply large side forces into the WTIV. Once the barge is close to the WTIV, large waves can accelerate the barge even if the tugs are moving very slowly. This study includes the effect of wave motions on barge transverse acceleration. Fenders can absorb some of the landing force so WTIV load limits and landing velocity limits should be considered when selecting the fender size, quantity, and arrangement.

In the case described in Section 3.1.3 and the relative costs described in Appendix A1.4, for either route and an installation target of 68 WTGs, if the landing velocity limit is reduced from 0.6 m/s to 0.3 m/s, the cost of installation will increase by 13% or 8% at P90 or P50 respectively.

1.2.4 Sensitivity to Wind Speed and Direction during Approach to WTIV

A barge loaded with WTG components has a very large sail area which can make it too difficult to control the barge or the components while they are being lifted off the barge by the WTIV's crane. Therefore, the operators must wait for winds to drop below acceptable levels before proceeding.

During the *maritime navigation mission simulations* described in Reference 6.1.3, the operators demonstrated that they could safely land the barge against the WTIV in wind speeds up to 20 knots on beam or 25 knots on bow. In the case described in Section 3.1.4, as before, a feeder supported WTIV, with the limit wind speeds of up to 20 knots on beam or 25 knots on bow, can install 75 WTGs per year at P90 or 101 at P50; if wind speed limits are reduced to 64% of that level, capacity is reduced to 74 WTGs per year at P90 or 100 at P50; and for wind speed limits reduced to 41% of the maximum level, capacity is reduced to 67 WTGs per year at P90 or 92 at P50.

1.2.5 Sensitivity to Cargo Top & Base Motions

When the feeder is in position to off-load cargo, the top and base motions of each cargo item is critical. If the top of a tall tower section is moving too much, it might hit the crane, or the crane may not be able to lift it without hitting other cargo items. There are lifting appliances that can increase motion limits, but they are expensive. If the lifting appliances cost less than the cost of vessel time while waiting for lower motions, it makes sense to purchase them.

In the case described in Section 3.1.5 and the relative costs described in Appendix A1.4, for the Salem to Empire route, an installation target of 59 WTGs and the top/base motions limit being relaxed from 1.0 m to 1.5 m, the cost of installation decreases by 26% or 15% at P90 or P50 respectively. If the top/base motions limit is relaxed from 1.5 m to 2.5 m, the cost of installation decreases by 4% at both P90 and P50. If the top/base motions limit is relaxed from 1.0 m to 2.5 m, the cost of installation decreases by 30% or 19% at P90 or P50 respectively. The cost decrease is due to a shorter installation period.

1.2.6 Sensitivity to Cargo Configuration and Ballast Condition

In the case described in Section 3.1.6, light and DNV ballast conditions and cargo configurations with two and three tower sections were analyzed. In general, system throughput with three tower sections is slightly better than conditions with two tower sections (3% at P90 and 2% at P50). Also, light ballast conditions have slightly better throughput than heavier conditions (4% at P90 and 2% at P50).

2 Introduction

Europe presently has a total installed offshore wind capacity of 28.3 GW. That corresponds to 5,785 grid-connected wind turbines across 12 countries.[1] There are two projects totaling 42 MW in operation in the United States with an additional 35.3 GW in various stages of development.[2] The U.S. offshore wind industry is just transitioning from the pilot stage to utility-scale commercial development.

Fixed foundation offshore wind turbines are installed in water depths of up to about 160 ft (50 m). Wind Turbine Installation Vessels (WTIVs) are self-propelled with azimuthing thrusters, a ship-shaped hull, and a jack-up system to lift the hull out of the water providing a stable foundation for a very large crane. The first Jones Act-compliant vessel, the 472-ft (144 m) *WTIV CHARYBDIS,* is currently under construction at a cost of a half billion dollars[3] with a day rate assumed to be above a quarter of a million dollars. It is highly unlikely that there will be enough WTIVs available to meet the needs of all the projects in the pipeline due to the high cost of Jones Act-compliant WTIVs.

Foreign flag WTIVs may be used to install offshore wind turbine generators (WTGs) if they do not transport any cargo within the U.S. territorial sea (46 U.S. Code § 55102). Jones-Act qualified cargo vessels are available to transport cargo, and their day rates are much lower than WTIVs. In theory, a cargo feeder vessel (CFV) could improve the efficiency of a WTIV by eliminating the time spent traveling to and from port. The CFV would deliver cargo to the WTIV just-in-time for it to transload the cargo, install the WTG and move to the next installation site. CFVs may also be able to operate out of ports with restrictive bridge clearance or water depth limitations, thus offering more flexibility for marshalling site selection.

This study evaluates a cargo feeder system (CFS) comprised of a minimally modified deck cargo barge

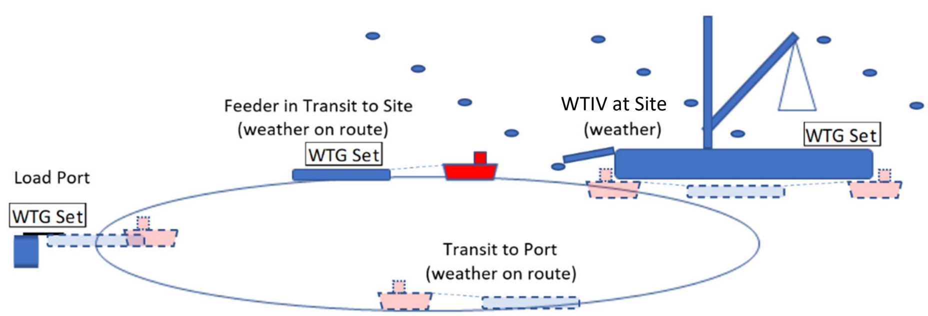


Figure 1 – WTIV with Feeder System

accompanied by the appropriate tugs in three key facets of the operation:

- Dynamic Motions Analysis – under tow and alongside the WTIV
- Maneuvering Simulation – bringing CF barge to standoff zone and to make “soft landing”
- WTIV/Feeder Weather Down Time (WDT) Simulation – based on motions and maneuvering

2.1 Background

Before existing U.S. flagged barges will be accepted as a cargo feeder vessel (CFV) solution, it must be demonstrated that they can safely deliver wind turbine generator (WTG) components to a Wind Turbine Installation Vessel (WTIV). The WTG components include very tall, heavy towers, heavy nacelles, and long blades. The components are subject to damage:

- During transit – if accelerations (x, y, z-directions) are beyond manufacturer specified limits, or
- During lift-off – if the top motions (lifting point) of a component are too large, the crane cannot hook the component and/or if the bottom motions are too great, the component might hit the CF barge structure or another component.

The feeder vessel or WTIV are subject to damage:

- Coming alongside – if the feeder athwartship velocity is too high and it lands hard, or
- While moored – if the feeder roll, pitch, and heave are too high, mooring line or fittings might fail or the cargo might hit the barge and damage it.

Before the cargo is loaded on the feeder, calculations must show that the feeder structure can support the cargo and acceleration loads and the cargo will not be damaged during transit.

Before the cargo can be removed from the feeder, it must be demonstrated that the feeder can be safely and securely moored to the WTIV, and the cargo can be safely lifted off.

2.2 Intent

The purpose of this *Weather Downtime Based on Metocean Data & Frequency Domain Motions* study is to predict the weather downtime (WDT) for the feeder and foreign-flag WTIV in a multi-unit WTG installation campaign. Different scenarios will be run to test the system's sensitivity to limit variations and how those changes affect installation costs.

2.3 Objective

There have been many studies examining the CF barge motions and the relative motions between the WTIV and CFVs but using the dynamic motions within the weather downtime analysis of a feeder in several load configurations is rarely done. Weather downtime studies are traditionally only including the Metocean data and not the responses from the vessels. The goal of this study is to apply the findings from the motions analysis (referenced in Section 6.1.3) to this weather downtime study. The motion study provides details about the computation of spectral response amplitude operators (SRAOs) so motion/acceleration responses can be predicted at vessel and cargo Points of Interest (POI) at each hourly timestep, and that data can be used to evaluate the various load configurations for overall system throughput.

2.4 Discrete Event Simulator

The Weather Downtime Express (WDTX) *discrete event simulator* used for this study is operated by ABPmer.

> *The ABPmer WDTX service uses the planned operational programme and associated working limits to realistically simulate the completion of all tasks, in sequence, over a wide range of historical conditions at the working site(s). The full operational programme is simulated many (typically hundreds of thousands of) times, which provides the basis for robust operation-specific statistical estimates of the operational programme, accounting for WDT*[4].

The functionality of the simulator is enhanced by the in-house Operational Motion Study (OMS) software package that adds acceleration and motions limits to the metocean limits included with WDTX. Details about the simulation are provided in Sections 3.2.2.3 and 3.2.2.4.

2.5 Limits of Study

2.5.1 Software Constraints

The single-agent simulator can model only one vessel in time, one task at a time, evaluating the motions and weather to either proceed or be delayed, and recording the time and reporting statistics for various confidence intervals. It cannot model multiple vessels, simultaneous tasks, or interactions between multiple vessels.

To model a multi-agent system with a single-agent simulator, two simulations must be run with identical limits for the activities that occur when the vessels interact. This method assures that there will be a period during each vessel's activity cycle when the transloading activities may occur, but because each vessel is acting independently, the operating windows when the joint activities occur may not be identical between models.

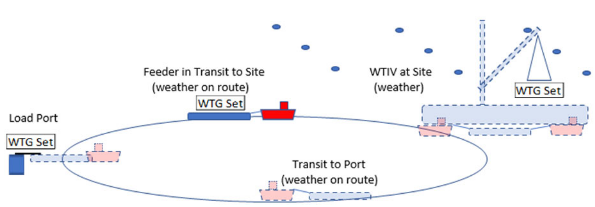


Figure 2 – Feeder Single-Agent

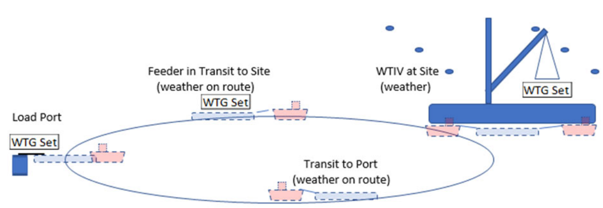


Figure 3 – WTIV Single-Agent

For example, the WTIV may be ready to receive cargo and a weather window may be available to do the transloading but, because the feeder is modeled separately, there is no way to know if a feeder would be on site. If a missing feeder would have caused a delay for the WTIV, no delay will be registered in a single agent simulation. With a single-agent feeder, the only way to compensate for this issue is to have “excess” feeder capacity. A single-agent model can provide a good estimate of the weather downtime for each vessel, but it cannot be used to optimize feeder capacity.

For this study, the discrete event, single-agent model is used to compare the performance of different feeder load cases, load ports and operational limits to maximize the utilization of the WTV.

2.5.2 Availability of WTG and WTIV Information

Information about WTG acceleration limits and WTIV crane capabilities and other vessel design details is protected by non-disclosure agreements (NDA). For this study, information subject to an NDAs is included within a range of variables and information that was not available was estimated.

3 Discussion

3.1 Findings

3.1.1 Base Case System Performance

3.1.1.1 Assumptions

The maneuvering simulation portion of this overall study (described in reference 6.1.2), the operators determined that landing velocities below 0.3 m/s were safe for everyday operations and may be safe up to 0.6 m/s. The operators also determined that they could confidently bring the CF barge alongside the WTIV in beam winds up to 20 knots, head winds up to 25 knots with quartering winds varying with angle from head to beam.

Unless described otherwise, the base case includes one complete WTG with the tower shipped in two sections loaded to the light ballast (LtBal-2T) condition. The task list and weather limits are described in Section A1.2 and other assumptions include: (1) a maximum landing velocity of 0.6 m/s, (2) 20 knots on beam / 25 knots on bow wind limits, (3) 2.0 m top and base motions, (4) 2 degree feeder roll or pitch and 2 m heave limits, and (5) standard cargo acceleration limits.

3.1.1.2 Cycle Time without Weather Down Time

Without interruptions due to weather as described in Section A.1.2, the time required for an average cycle to deliver and/or install one WTG at Empire Wind from the indicated load port is shown in Table 5 below:

Salem		
Foreign WTIV	**Barge**	**JA WTIV***
2.1 days	4.8 days	2.9 days
* Average time for one WTG.		

Brooklyn		
Foreign WTIV	**Barge**	**JA WTIV***
2.1 days	1.6 days	1.3 days
* Average time for one WTG.		

Table 5 –Time Required to Install One WTG without Weather Down Time (WDT)

A CF feeder barge is assumed to transport one WTG per trip, a Foreign WTIV is assumed to install one WTG per cycle and a JA WTIV is assumed to transport and install four WTGs per trip.

3.1.1.3 Comparing Weather Delays by Season

Wind turbine installation is a highly seasonal task. For example, one can have a high level of confidence (P90) that a Cargo Feeder System (CFS) supported WTIV can transport and install one WTG from Brooklyn to Empire Wind in 2.9 days in July but may require up to 7.6 days in January as described in the base case described in Section 3.1.1. In Table 6 below, the average number of days required to install one

WTG are shown for the months with the best and worst weather and are compared for a WTIV fed by two CF barges (with 1 WTG per trip) to a Jones Act WTIV that transports four WTGs delivering from Brooklyn.

Month with Weather that is	Moderate Confidence (P50)		High Confidence (P90)	
	WTIV w/2 Barges	JA WTIV	WTIV w/2 Barges	JA WTIV
Worst	5.2 days	4.8 days	7.6 days	6.4 days
Spring/Fall Average	3.8 days	3.9 days	5.4 days	5.0 days
Best	2.5 days	3.1 days	2.9 days	3.6 days

Table 6 – Maximum Number of Days Required to Install One WTG in Months from Brooklyn with Best and Worst Weather

For this base case with the task list and weather limits described in Sections A1.2 and A1.3, the days required to install one WTG by month is shown in Figure 4 and Figure 5 below.

Comparison between CFS supported Foreign Flag WTIV and Jones Act-compliant WTIV
Time to Install One WTG (by Month)

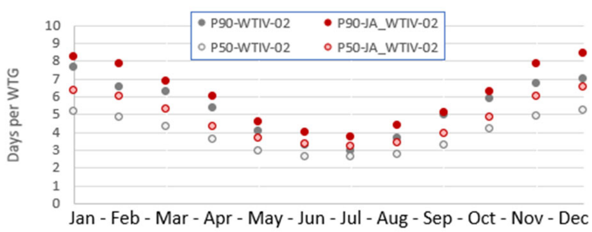


Figure 4 – WTIV Base Case - Salem to Empire

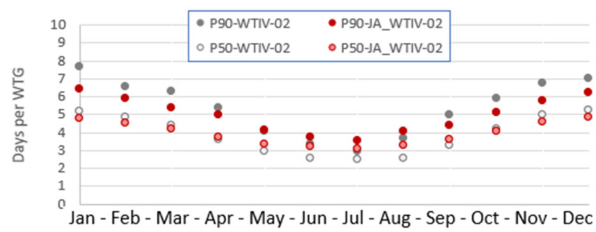


Figure 5 – WTIV Base Case - Brooklyn to Empire

The figures above compare the performance of the WTIVs in two configurations: (1) a foreign WTIV supported by two cargo feeder barges, and (2) a Jones Act WTIV working alone.

The performance of each part of the Cargo Feeder System (CFS) supported WTIV is also measured. For example, for a WTIV to perform a complete cycle consisting of transloading cargo, installing a WTG and moving to a new site, it takes 2.6 days in the best weather month (at P50, or 2.9 days at P90) and, for each of the two barges to make a complete round trip out of Salem, it takes 5.2 days in the best month (at P50 and 5.9 days at P90). Since there are two barges, a barge will arrive every 2.6 days in the best month.

The number of days required to complete one delivery round trip voyage for each component is described in a feeder barge OR to complete one installation cycle for the WTIV are:

Days Required for a CF Barge and WTIV to Complete One WTG Installation Cycle by Month

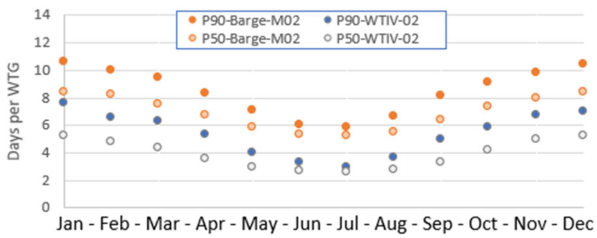


Figure 6 – Time to Install One WTG - Salem to Empire

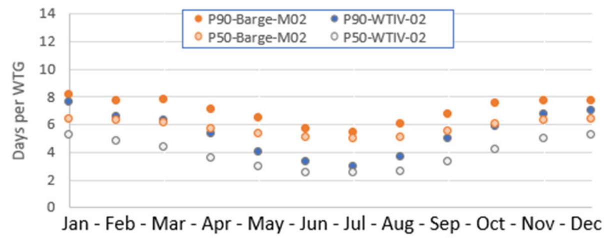


Figure 7 – Time to Install One WTG - Brooklyn to Empire

From Salem, a CF barge supported WTIV can install 75 WTGs per year at P90 or 101 at P50. A feeder that does not wait to load, can deliver 45 WTGs per year at P90 or 54 at P50. Therefore, two feeders are required. From Brooklyn, a feeder that does not wait to load, can deliver 53 WTGs per year at P90 or 64 at P50. Therefore, to maximize WTIV utilization, two feeders are required. If the barges provide excess capacity, the system should only be limited by the throughput of the WTIV.

3.1.1.4 Comparing Distances to Load Ports

Two barges can keep a WTIV supplied from either Salem (389 NM) or Brooklyn (81 NM) and maintain nearly the same throughput. However, a Jones Act WTIV that transports WTGs itself must pick up cargo at a nearby load port or the throughput suffers. For example, if a Jones Act WTIV picks up cargo from Salem rather than Brooklyn, the days required to install one WTG increases from 3.1 to 3.2 days in the best month (at P50, or 3.6 to 3.8 days at P90) and it increases from or 4.8 to 6.5 days in the worst month (at P50, or 6.4 to 8.4 days at P90). A comparison of maximum number of days required for a WTIV that transports WTGs itself for Brooklyn and Salem load ports is shown in Table 7 below:

Month with Weather that is	Moderate Confidence (P50)		High Confidence (P90)	
	Brooklyn	Salem	Brooklyn	Salem
Worst	4.8 days	6.5 days	6.4 days	8.4 days
Spring/Fall Average	3.9 days	4.7 days	5.0 days	6.1 days
Best	3.1 days	3.2 days	3.6 days	3.8 days

Table 7 – Maximum Number of Days Required for a JA WTIV transporting its own WTG cargo to Install One WTG in Months with Best and Worst Weather

In this base case in a full year, a feeder supported WTIV can install 75 WTGs from either port at P90 or 101 from Salem or 103 from Brooklyn at P50. A Jones Act-compliant WTIV can install 65 WTGs per year at P90 or 82 at P50 from Salem or 76 WTGs per year at P90 or 96 at P50 from Brooklyn.

3.1.1.5 Comparing Installation Capacity

In an actual WTG installation campaign, there are many variables including: (1) number of WTGs to be installed, (2) installation start date, and (3) breaks for WTIV and/or support vessel maintenance periods. Each of these variables can affect the system throughput. For example, during the four months of the year with the best weather about twice as many WTGs can be installed as in the four months with the worst weather.

During an actual WTG installation campaign, there will be a target number of WTGs to install and WTIVs and support vessels all require maintenance periods every year or two. Therefore, campaigns may require less than one year. To get a sense of how shorter campaigns compare when working when the weather is best, the portion of the year required to install the target number of WTGs is compared in Table 8 below.

	Salem				Brooklyn			
Installation Target	WTIV w/2 Barges		JA WTIV		WTIV w/2 Barges		JA WTIV	
	P90	P50	P90	P50	P90	P50	P90	P50
64	79%	50%	98%	68%	79%	49%	79%	60%
75	100%	64%	N/A	87%	100%	62%	97%	73%
85	N/A	77%	N/A	N/A	N/A	74%	N/A	86%
95	N/A	91%	N/A	N/A	N/A	88%	N/A	99%
Full Year	75	101	65	82	75	103	76	96

Table 8 – Portion of a Year Required to Install Target Number of WTGs

Since every variation in installation period and wind farm size cannot be analyzed here, performance over a full year will be used as a proxy for system performance.

3.1.1.6 Comparing Installation Cost

Based on relative costs described in Appendix A1.4 and the portion of the year required to install turbines described in Section 3.1.1.5, for the Salem to Empire route and an installation target of 60 WTGs or more, the WTIV w/two CF barges will be the least expensive option if the JA WTIV's day rate is greater than the foreign WTIV's day rate plus 13% or 6% at P90 or P50 respectively.

For the Brooklyn to Empire route and an installation target of 65 WTGs or more, the WTIV w/two CF barges will be the least expensive option if the JA WTIV's day rate is greater than the foreign WTIV's day rate plus 44% or 18% at P90 or P50 respectively.

3.1.1.7 Minimizing Installation Cost over the Long Term

The number of days it takes to install each WTG is a significant driver of the cost of a wind farm. For example, the installation cost in a year with bad weather (a "P90 year) will be about 30% more than the cost in an average weather year (a "P50 year). Or put another way, a WTIV can install a WTG faster in the worst month of a "P50 year" than it can in the seven best months of a "P90 year".

Since the installation contractor's bid on contracts at least a year in advance, they cannot know what the weather will be when they do the installation. Therefore, the bid is likely to be closer to the cost of a year with bad weather. The contractor's bid will reflect the level of risk they will accept. However, the savings could be substantial if the utility could structure contracts in a way that takes weather into account.

	Salem					Brooklyn			
	WTIV w/2 Barges		JA WTIV			WTIV w/2 Barges		JA WTIV	
	P90	P50	P90	P50		P90	P50	P90	P50
WTGs Installed in One Full Year	75	101	65	82		75	103	76	96
Relative Cost to Install Each WTG	137%	102%	158%	126%		137%	100%	136%	107%

Table 9 – WTGs Installed in a Full Year with Relative Costs

It may be possible to use this type of simulation to establish a baseline cost using the actual weather to reduce risk for the installation contractor thereby reducing the cost for the utility.

3.1.1.8 Comparing Barge Utilization between Load Ports

For a Cargo Feeder System (CFS), the load port affects barge utilization. For example, barge utilization by month is shown in Table 10 below.

Month with Weather that is	Moderate Confidence (P50)			High Confidence (P90)	
	From Brooklyn	From Salem		From Brooklyn	From Salem
Worst	61%	80%		54%	70%
Moderate	78%	92%		66%	79%
Best	100%	100%		92%	100%

Table 10 – Barge Utilization in months with Best and Worst Weather

As expected, the utilization is higher for barges that must travel further. However, the utilization may be lower in the winter because both the loaded barge and the WTIV must wait for a weather window to transload or place a WTG on the foundation, but an empty barge is not limited significantly by weather.

While high utilization is generally good, 100% utilization in the best month is of concern because, if the barge is delayed for any reason, the WTIV will also be delayed.

3.1.2 Sensitivity to Acceleration during Transit

For a multi-feeder system, in which one CF barge is loaded while the other is in transit, the transit time to the site accounts for 42% of an ideal round trip voyage (RTV) from Salem or 27% of an ideal RTV from Brooklyn. [See A2.3 for discussion of exposure periods.] The cargo acceleration limits apply to the cargo throughout the transit and approach to the WTIV.

If the same two tower-section / light ballast (LtBal-2T) case described in Section 3.1.1, is modified by changing to cargo acceleration limits to double or half of the base values, the number of days required to complete one delivery round trip voyage for a feeder OR to complete one installation cycle for the WTIV are:

Comparison of Performance over a Range of Cargo Acceleration Limits
Time to Install One WTG – Salem to Empire

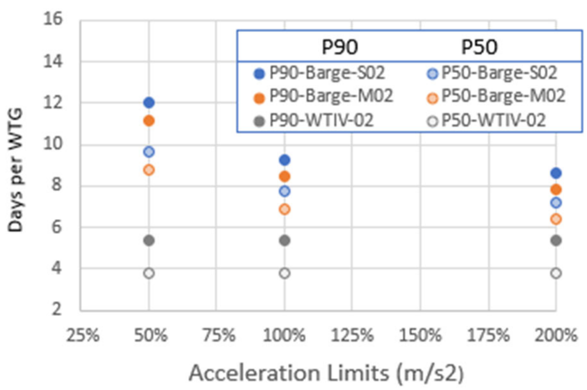


Figure 8 – Sensitivity to Cargo Accel Limits (Annual)

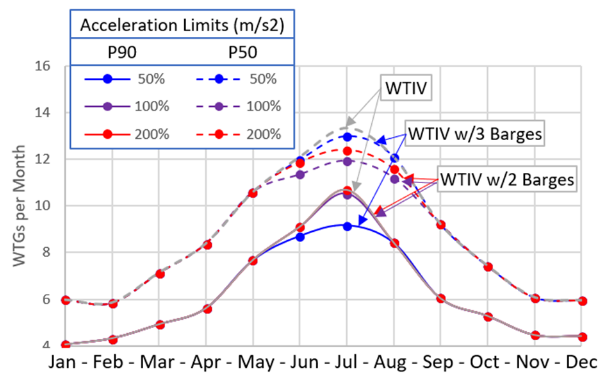


Figure 9 – Sensitivity to Cargo Accel Limits (Monthly)

In this case, as before, a feeder supported WTIV can install 75 WTGs per year at P90 or 104 at P50. From Salem, a feeder that does not wait to load, can deliver 45 WTGs per year at P90 or 54 at P50. If the acceleration limit is doubled, the feeder can deliver 48 WTGs per year at P90 or 58 at P50. If the acceleration limit is reduced by 50%, the feeder can deliver 33 WTGs per year at P90 or 42 at P50. For either the base case or the relaxed limits, two CF barges are required. If the acceleration limit is reduced by 50%, three CF barges are required to maintain WTIV efficiency. When three CF barges are required, an additional lead tug and assist tug are required to maintain system efficiency.

Based on relative costs described in Appendix A1.4, for the Salem to Empire route with a 70 WTG installation target, if the acceleration limit is reduced by 50%, the cost of installation increases by 23% and 13% at P90 and P50 respectively. Of the 23% cost increase (P90), 19% is due to the cost of the additional CF barge and tugs and 4% is due to the additional days required to do the installation. In a year with bad weather (when installations will be done at a P90 confidence level), it takes most of the year to install 70 WTGs.

Of the 13% cost increase (P50), +19% is due to the cost of the additional CF barge and –6% is due to the reduction in days required to do the installation because in a moderate weather year (when installations will be done at a P50 confidence level), the installation can be accomplished between April and mid-October. In a moderate weather year, it would make sense to install more WTGs because the equipment can install more WTGs per month in the worst month of a "P50 year" than can be installed in any of the worst seven months (October thru April) of a "P90 year".

It should be noted that this simulation is based on hindcast data, and it does not account for climate change.

3.1.3 Sensitivity to Maximum Landing Velocity

When cargo is transported to the WTIV by feeder, the feeder will be brought alongside the WTIV after it is jacked up. To avoid damage to the legs, it is critical that the feeder approaches slowly so it does not apply large side forces into the WTIV. Once the barge is close to the WTIV, large waves can accelerate the barge even if the tugs are moving very slowly. This study includes the effect of wave motions on barge transverse acceleration.

For a multi-feeder system, in which one CF barge is loaded while the other is in transit, the time required to move the feeder into position alongside the WTIV accounts for 0.4% of an ideal round trip voyage (RTV) from Salem or 1.3% of an ideal RTV from Brooklyn. [See A2.3 for discussion of exposure periods.] This thirty-minute operation is the most critical part of the operation because it is the period when the most limits apply to the vessel. [See 3.2.4.1 for description of limits.] The limits that apply during this period include:

- The cargo accelerations must remain below the OEM's limits,
- Feeder motions (roll, pitch and heave) must remain within limits,
- The feeder bow and stern athwartship velocity must remain below a limiting velocity, and
- The wind speed must be below a specified limit for beam seas and a different, less restrictive limit when the wind is from the bow (+/- 20 degrees).

It is possible to evaluate how sensitive the system is to each limit by changing the values of each variable and measuring the system throughput.

If the same two tower-section / light ballast (LtBal-2T) case described in Section 3.1.1, is modified by varying the maximum landing velocity, the number of days required to complete one delivery round trip voyage for a feeder OR to complete one installation cycle for the WTIV are:

Comparison of Performance over a Range of Maximum Landing Velocities
Time to Install One WTG

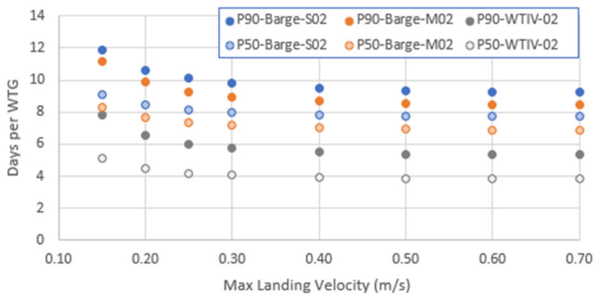


Figure 10 – Sensitivity to Max Landing Speed (Salem)

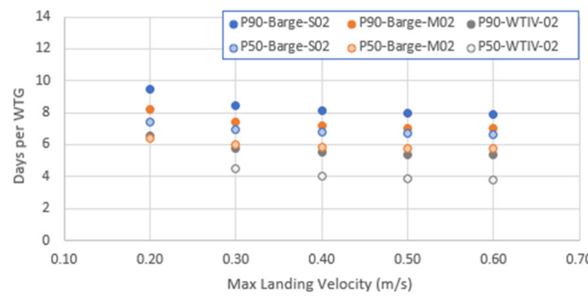


Figure 11 – Sensitivity to Max Landing Speed (Brooklyn)

In this case, as before, a feeder supported WTIV, with a maximum landing velocity of 0.6 m/s, can install 75 WTGs per year at P90 or 101 at P50 from Salem or 103 at P50 from Brooklyn. The variation in throughput for cases with landing velocities between 0.2 and 0.6 m/s are shown in Table 11 below:

Maximum Landing Velocity (m/sec)	WTIV w/2 Barges			
	Salem		Brooklyn	
	P90	P50	P90	P50
0.2	60	88	60	88
0.3	69	95	69	97
0.4	72	99	72	101
0.5	74	100	74	102
0.6	75	101	75	103
0.7	75	101	75	103
0.8	75	101	75	103

Table 11 – WTGs installed in a Year over a Range of Landing Velocities

Based on relative costs described in Appendix A1.4, for either route and an installation target of 68 WTGs, if the landing velocity limit is reduced from 0.6 m/s to 0.3 m/s, the cost of installation increases by 13% or 8% at P90 or P50 respectively. The cost increase is due to the cost of the additional days required to do the installation.

3.1.4 Sensitivity to Wind Speed and Direction during Approach to WTIV

A barge loaded with WTG components has a very large sail area which can make it difficult to control the barge or the components while they are being lifted off the barge by the WTIV's crane. Therefore, the operators must wait for winds to drop below acceptable levels before proceeding.

For a multi-feeder system, in which one CF barge is loaded while the other is in transit, the time required to move the feeder into position alongside the WTIV accounts for 0.4% of an ideal round trip voyage (RTV) from Salem or 1.3% of an ideal RTV from Brooklyn. [See A2.3 for discussion of exposure periods.]

During the *maritime navigation mission simulations* described in Reference 6.1.3, the operators demonstrated that they could safely bring the CF barge alongside the WTIV in wind speeds up to 20 knots on beam or 25 knots on bow.

If the same two tower-section / light ballast (LtBal-2T) case described in Section 3.1.1, is modified by varying the wind speed limits, the number of days required to complete one delivery round trip voyage for a feeder OR to complete one installation cycle for the WTIV are:

Comparison of Performance over a Range of Wind Speed Limits during Approach to the WTIV
Time to Install One WTG – Salem to Empire

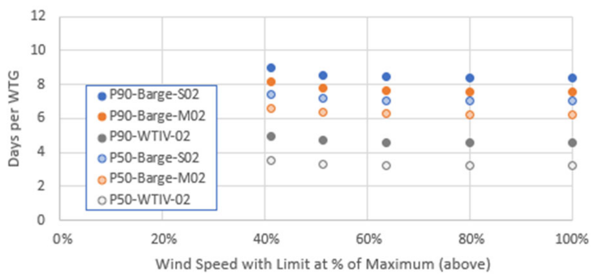


Figure 12 – Sensitivity to Wind Speed (Annual)

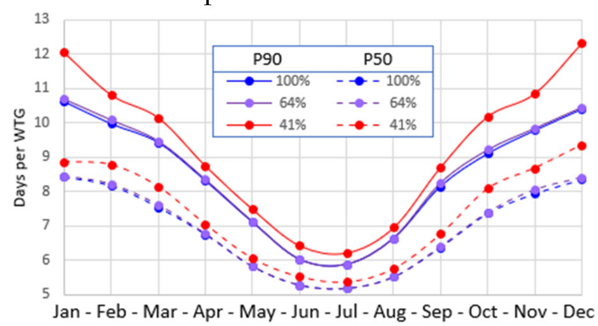


Figure 13 – Sensitivity to Wind Speed (Monthly)

In this case, as before, a feeder supported WTIV, with the maximum wind speed of up to 20 knots on beam or 25 knots on bow, can install 75 WTGs per year at P90 or 101 at P50; for wind speeds 64% of maximum, it can install 74 WTGs per year at P90 or 100 at P50; and for wind speeds 41% of maximum, it can install 67 WTGs per year at P90 or 92 at P50. From Salem, a feeder that does not wait to load, can deliver 45 WTGs per year at P90 or 54 at P50; for wind speeds 64% of maximum, it can install 44 WTGs per year at P90 or 54 at P50; and for wind speeds 41% of maximum, it can install 41 WTGs per year at P90 or 51 at P50.

For all cases with wind speeds during approach operations between 40% and 100%, two feeders are required.

3.1.5 Sensitivity to Cargo Top & Base Motions

When the feeder is in position to off-load cargo, the base and top motions of each cargo item is critical. If the top of a tall tower section is moving too much, it might hit the crane, or the crane may not be able to lift it without hitting other cargo items. There are lifting appliances that can increase motion limits, but they are expensive. If the lifting appliances cost less than the cost of vessel time while waiting for lower motions, it makes sense to purchase them.

For a multi-feeder system, in which one CF barge is loaded while the other is in transit, the time required to discharge cargo from the feeder to the WTIV accounts for 9.5% of an ideal round trip voyage (RTV) from Salem or 28.3% of an ideal RTV from Brooklyn. [See A2.3 for discussion of exposure periods.] The difference in installation time based on a range of cargo top & base motion limits is as follows:

Comparison of Performance over a Range of Cargo Top/Base Motion Limits during Transloading
Time to Install One WTG – Salem to Empire

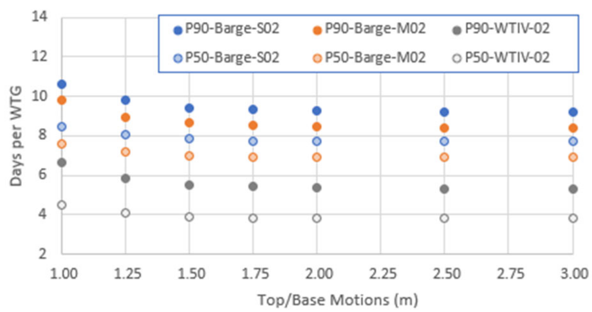


Figure 14 – Sensitivity to Top/Base Motions (Annual)

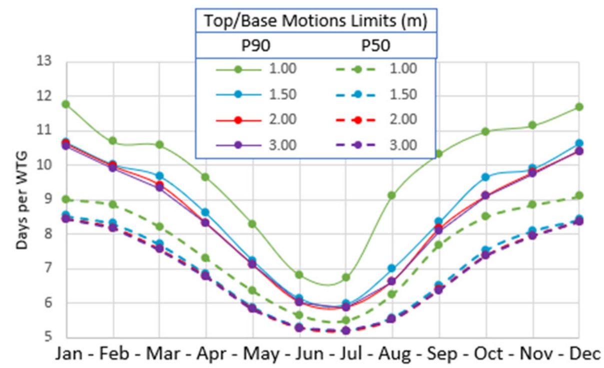


Figure 15 – Sensitivity to Top/Base Motions (Monthly)

In this case, as before, a feeder supported WTIV, annual system throughput changes with cargo top/base motions limits as shown in Table 12 below:

Confidence Level	Cargo Top / Base Motions Limit			
	1.0 m	1.5 m	2.0 m	3.0 m
P90	59	72	75	75
P50	88	102	104	104

Table 12 – WTGs Installed in One Full Year over a Range of Top/Base Motions Limits

For all cases with cargo top/base motions limit between 1 and 3 m, two feeders are required.

Based on relative costs described in Appendix A1.4, for the Salem to Empire route, an installation target of 59 WTGs and the top/base motions limit being relaxed from 1 m to 1.5 m, the cost of installation decreases by 26% or 15% at P90 or P50 respectively. If the top/base motions limit is relaxed from 1.5 m to 2.5 m, the cost of installation decreases by 4% at both P90 and P50. If the top/base motions limit is relaxed from 1.0 m to 2.5 m, the cost of installation decreases by 30% or 19% at P90 or P50 respectively. The cost decrease is due to a shorter installation period.

3.1.6 Sensitivity to Cargo Configuration and Ballast Condition

As described in Section 3.2.3.1 below, light and DNV ballast conditions and cargo configurations with two and three tower sections were analyzed. The average time to install one WTG for each load condition are shown in Figure 16 and Figure 17 below.

Comparison of Performance over a Range of Cargo & Ballast Configurations
Time to Install One WTG (Annual Average)

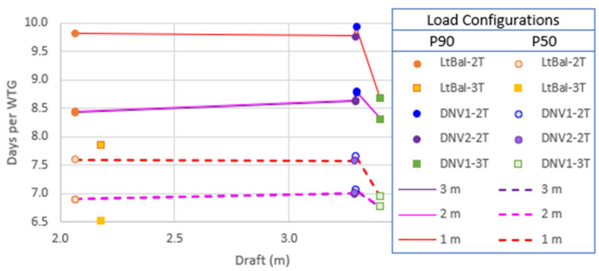


Figure 16 – Sensitivity to Load Condition (Salem)

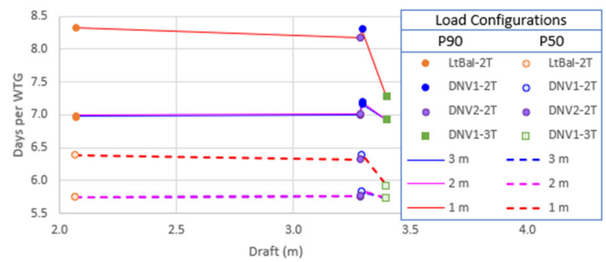


Figure 17 – Sensitivity to Load Condition (Brooklyn)

The number of WTGs that can be delivered with a multi-feeder system, in which one CF barge is loaded while the other is in transit, for each load condition, with a top/base motion limit of 2 m, is as follows:

Configuration	P90 Confidence Level				P50 Confidence Level			
	Full Year	Feb-Nov	Mar-Oct	Apr-Sep	Full Year	Feb-Nov	Mar-Oct	Apr-Sep
LtBal-2T	45	39	33	26	54	47	40	31
LtBal-3T	48	39	33	27	55	48	40	32
DNV1-2T	43	37	32	25	53	46	39	31
DNV2-2T	44	38	32	26	53	46	39	31
DNV1-3T	45	39	33	27	55	48	40	32

Table 13 – Sensitivity to Cargo Configuration and Ballast Condition

In general, system throughput with three tower sections is slightly better than conditions with two tower sections (3% at P90 and 2% at P50). Also, light ballast conditions have slightly better throughput than heavier conditions (4% at P90 and 2% at P50).

3.2 Methodology

3.2.1 Prediction Methods

Installing wind turbine generators on pre-installed towers is a capital- and labor-intensive activity. It is also highly dependent on weather conditions at the deployment site at sea. Disturbances along the supply chain can delay project completion and significantly increase installation costs. The magnitude of the delays in the operation can be estimated using either non-sequential or sequential methods. Non-sequential approaches compare operational requirements to weather persistence and/or exceedance/non-exceedance tables but because they do not take the order of weather windows into account, that method is likely to result in an underestimate of weather downtime (WDT). If results with a high (P90) statistical level of confidence is sought, typically P90 tables would be used for each task. This approach tends to result in an overestimate of weather downtime because the probability of consecutive periods of P90 weather occurring is under 10%[5].

Sequential task simulation methods break an operation into tasks (or discrete events) with a duration and operational limits assigned to each one. The simulation program steps through each task and compares the limits to the operational parameter (like wave height, waver period, wind speed) and either moves to the next step or waits for conditions that allows the operation to proceed. Sequential modeling tends to provide a more reliable measure and, when run thousands of times, can provide estimates over a range of confidence levels.

3.2.2 Discrete Event Simulation (DES)

Discrete event simulation (DES) is a method used to understand the behavior and performance of an existing or proposed real-world system as a series of events that occur over time. The simulation models distinct entities, tasks, resources and/or conditions required to perform each task, and controls. The simulation includes multiple passes through the complete task list to measure the probability distribution of the system performance.

Simulation makes it possible to test many scenarios in relatively little time. This allows decision-makers to understand how sensitive the system is to changes in resources or limits.

3.2.2.1 Systems vs. Processes

A system is more dynamic and complex than a process because a shortage of entities or a delay or bottleneck in an activity can alter the performance of the entire system.

- PROCESS – a collection of activities that create an output based on one or more inputs.
- SYSTEM – a collection of elements used to perform a process including:
  - Entities are the items processed (i.e. towers, nacelles, blades, frames)
  - Agents are autonomous decision-making entities that assess its situation and makes decisions using a set of rules
  - Activities are the tasks or actions that use resources & have a duration
  - Resources are supplies or conditions required to perform activities and have characteristics (frequency, duration, capacity, speed, reliability)
  - Controls govern how, when and where activities are performed.

3.2.2.2 System Performance Measures

System design and improvements are done to transform inputs into the desired outputs in the most timely, efficient, and cost-effective way.

Performance Measures used to gauge effectiveness of a system may include:

- Cycle time – time required for an entity to complete a pass through the system
- Resource utilization – percentage of time resources are in productive use
- Value-added time – time the entity spends operating or receiving services
- Waiting time – time that an entity (material or customer) waits for operations
- Processing rate – number of entities moved through system during a time period
- Quality – the percentage of parts produced that meet a standard
- Cost – operating cost of the system
- Flexibility – the ability of the system to adapt to fluctuations in volume.

3.2.2.3 Weather Downtime Express Service (WDTX)

For this study, ABPmer's Weather Downtime Express (WDTX) single-agent simulation engine was used to perform the discrete event simulation. For each task, the user may specify:

- Name of the task
- Location
- Duration (the actual period of time required to complete the task once started, or, if less than the weather window, the minimum period of time that the task would be worked on)
- Weather window (the period of sufficiently good weather required to start working on the task)
- Environmental and safety operational thresholds, including:
  - Wave height
  - Wave period
  - Wind speed (also the reference height and averaging period of the wind speed)
  - Current speed
  - Daylight working only, and
  - Not on rising/falling tides
- Whether consecutive tasks should be grouped (completed without any intervening WDT)[6]

WDTX steps through each task using weather hindcast data. The default hindcast model is NOAA WAVEWATCH III[7]. The weather files used for this study are described in Section 3.2.4.1 below.

The program starts the operation on every hour of the 31 years of data, excluding the cycles at the end that cannot be completed. The program runs hundreds of thousands of cycles and logs the waiting time or "weather downtime" for each run. It registers the cumulative distribution for operations starting in each month. A sample this large, makes it possible to calculate statistically significant statistics for each month and the whole year at any confidence level. The two statistics we are tracking are the 50 percent confidence interval (P50) and the 90 percent confidence interval (P90). They indicate how much the operation will be extended beyond the "Ideal Cycle Time".

The P50 confidence level is useful for understanding the time required for a RTV on average over a long period of time or the performance in an average weather year. The P90 confidence level is useful for understanding what is likely to be "worst case" for a RTV in any particular year.

3.2.2.4 Operational Motions Study (OMS)

The Operational Motions Study (OMS) combines the power of discrete event simulation with a frequency domain motions study. The OMS is a software package that consists of three in-house programs and WDTX:

- Step A – Develop the Hs-Tp-Phi transfer function database, as described in Section 3.2.3.2 below.
- Step B – Create up to four (4) master weather files that include 31 years of hourly data including:
  - Location specific NOAA Wave Watch III hindcast[8] weather records (Hs, Tp, wave direction, wind speed at 10m, wind direction), and
  - Route and heading specific vessel and cargo motions and accelerations calculated for the relative wave heading using the Hs-Tp-Phi database, as described in Sections 3.2.3.5 and 3.2.3.6 below.
- Step C – Apply acceleration and motion limits to the master weather files creating files that contain go/no-go instructions based on the limits for each leg of the route of the laden vessel, as described in Section 3.2.4.1 below.
- Step D – Discrete Event Simulation

3.2.3 Operational Motions Study Hydrodynamics – Steps A & B

Section 3.2.2.4 provides an overview of the OMS software package. This section describes the load, route, metocean, and other specific information related to the hydrodynamics portion of is study.

3.2.3.1 Stow Plans

Two stow plans to transport one 15 MW WTG were developed including:

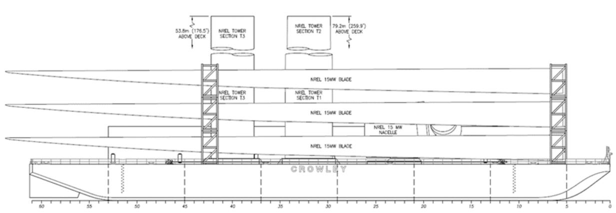


Figure 18 – Tower in Two Sections

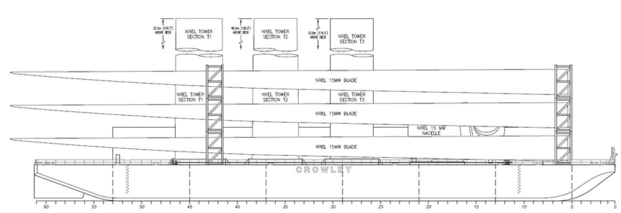


Figure 19 – Tower in Three Sections

Two ballast configurations were developed for each load configuration. The "Light" conditions represent the minimum ballast required to maintain level trim during offloading. The "DNV Drafts" are more heavily loaded conditions with a bow draft that complies with Section 11.10.9.4 of Reference 6.5.1.

			Base Case (T12-T3)				**Base Case (T3-T2-T1)**			
			0-0 Light		0-1 DNV Draft		1-0 Light		1-1 DNV Draft	
			Light	Full	Light	Full	Light	Full	Light	Full
Draft		[m]	1.5	2.1	2.7	3.3	1.6	2.2	2.8	3.4
Mass		[MT]	4,847	6,877	9,244	11,274	5,226	7,256	9,624	11,653
VCG (from keel)		[m]	4.7	10.9	3.7	7.7	4.5	9.2	3.6	6.7
VCG Corr for FSM		[m]	5.1	11.2	4.3	8.1	4.9	9.4	4.2	7.1
Radius of Gyration	Kxx	[m]	11.0	17.1	11.9	16.1	11.1	13.8	12.0	13.8
	Kyy	[m]	36.1	34.6	29.1	29.7	36.6	34.5	29.7	29.6
	Kzz	[m]	37.4	32.9	31.2	29.3	38.0	34.4	31.8	30.5
GMt*		[m]	55.9	33.2	30.2	21.2	51.7	32.9	29.1	21.4

* GMt includes true free surface.

Table 14 – Load Condition Characteristics

For more information about the stow plan, weight estimate, regulatory requirements, ballast plan, longitudinal strength, radius of gyration, and stability analysis, see Reference 6.6.1.

3.2.3.2 Spectral Response Amplitude Operators (SRAOs)

For each load condition, frequency domain vessel spectral response amplitude operators (SRAOs) were calculated using Orcaflex for a range of significant wave heights (Hs), wave periods (Tp) and wave directions (ϕ). The ITTC 2011 (Ikeda Method) was used to model viscous roll damping. The range covered in this Hs-Tp-Phi study includes:

- Wave heights, Hs: 1.0, 1.5, 2.0, 2.5 m
- Wave periods, Tp: 4 to 14 seconds in 0.25 second increments
- Wave direction, ϕ: 0 to 180 degrees in 10-degree increments with respect to vessel centerline

The Hs-Tp-Phi Study was run for all load cases in both full and empty cargo conditions. The spectral response amplitude operators (SRAOs) were computed, and the result is a 7-dimensional database for each load condition:

1 Phi – Wave direction
2 Hs – Significant wave height
3 Tp – Peak wave period
4 N exponent in $\cos^N$ for directional wave spreading – These dictates how tightly concentrated the wave energy is along the period direction.
5 Gamma (γ) for spectral wave spreading – These dictates how tightly concentrated the wave energy is near the dominant period.

6 19 response locations – These are used to determine cargo accelerations and top/bottom motions – The points of interest (POI) include the base, CG and top of up to six (6) cargo items (nacelle, tower in three sections, blade racks at root and blade) and the vessel origin.

7 Various statistics (response frequency (RMS), standard deviation of response magnitude, most probable maximum (MPM), spectral moments m0, m1, m2, m3, m4, etc.[9]) – These statistics are used to calculate the most probable maximum expected response for a given exposure period, such as 15 minutes during a lift.

An example of route and heading specific motions and accelerations calculated for the forward blade rack top motions calculated in Step B described in Section 3.2.2.4 above is shown in Figure 20.

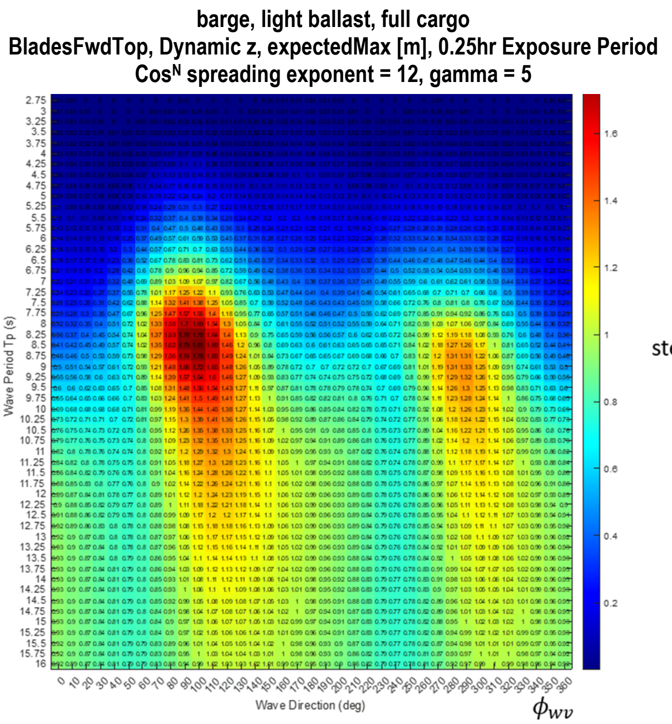


Figure 20 – Example SRAO Contours

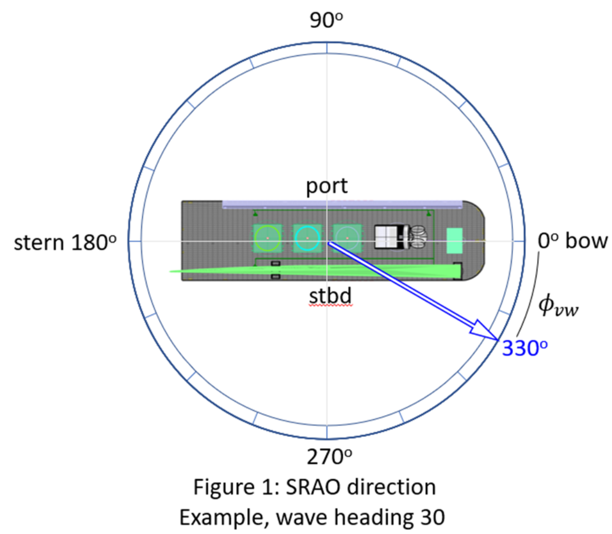


Figure 21 – Wave Direction (ϕ) with respect to Barge Coordinates

3.2.3.3 Local Metocean Conditions

Analysis of the metocean data collected at National Data Buoy Center (NDBC) Station 44025 near Empire Wind indicates that the range covered by the Hs-Tp-Phi study includes 50.2% of the measurements between January 1991 and December 2020. The significant wave height was less than 1 meter 41.9% of the time during the same period; operations would be governed by wind in seas of less than 1 meter. The significant wave height was greater than 2.5 m and/or the peak wave period was greater than 14 sec 7.5% of the time; no feeder operations would proceed in seas of more than 2.5 meters.

Total		Hs (m)															
		0-0.25	0.25-0.5	0.5-0.75	0.75-1	1-1.25	1.25-1.5	1.5-1.75	1.75-2	2-2.25	2.25-2.5	2.5-3	3-4	4-5	5-10	**Total**	**Exceedance**
Tp (s)	2- 4	0.06	0.84	2.63	1.59	0.31	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**5.44**	**94.56**
	4- 6	0.01	0.44	3.27	6.68	7.64	5.25	3.66	2.09	1.10	0.42	0.18	0.02	0.00	0.00	**30.78**	**63.78**
	6- 8	0.02	1.20	4.04	4.65	3.98	2.80	2.33	1.84	1.75	1.42	1.76	0.84	0.07	0.00	**26.69**	**37.09**
	8-10	0.02	1.48	4.49	3.55	2.65	1.74	1.32	0.95	0.73	0.52	0.76	0.73	0.24	0.03	**19.21**	**17.88**
	10-12	0.01	0.76	2.03	2.10	2.11	1.48	1.01	0.68	0.56	0.45	0.71	0.63	0.22	0.10	**12.85**	**5.03**
	12-14	0.00	0.29	0.51	0.49	0.49	0.40	0.37	0.23	0.16	0.11	0.16	0.23	0.07	0.04	**3.53**	**1.50**
	14-16	0.00	0.13	0.27	0.17	0.10	0.08	0.10	0.08	0.08	0.06	0.05	0.03	0.02	0.01	**1.19**	**0.31**
	16-18	0.00	0.02	0.09	0.04	0.03	0.02	0.02	0.01	0.02	0.02	0.03	0.01	0.00	0.00	**0.30**	**0.00**
	18-20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.00**
	20-22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.00**
total		0.13	5.16	17.32	19.28	17.30	11.79	8.80	5.88	4.40	3.00	3.65	2.48	0.61	0.19		
Exceedance		**99.87**	**94.71**	**77.39**	**58.10**	**40.80**	**29.02**	**20.21**	**14.33**	**9.93**	**6.93**	**3.28**	**0.80**	**0.19**	**0.00**		

Table 15 – Joint Probability Hs (m) - Tp (sec) at NDBC 44025

3.2.3.4 Route Planning and Metocean Data

Routes between the load ports and the wind farm sites were selected based on normal charted traffic lanes.

The routes between Salem, MA and Empire Wind, NY and between South Brooklyn, NY and Empire Wind, NY are shown in Figure 22 below. To account for differences in metocean conditions along the route, each route is defined by up to four (4) waypoints. For each load port (waypoint 1), metocean data at a point at the mouth of the harbor that is exposed to the ocean is selected. Along the route, two (2) waypoints are selected and metocean data is recorded from WWIII for these locations. At the wind farm site (waypoint 4), the seaward end of Empire Wind was selected for metocean data.

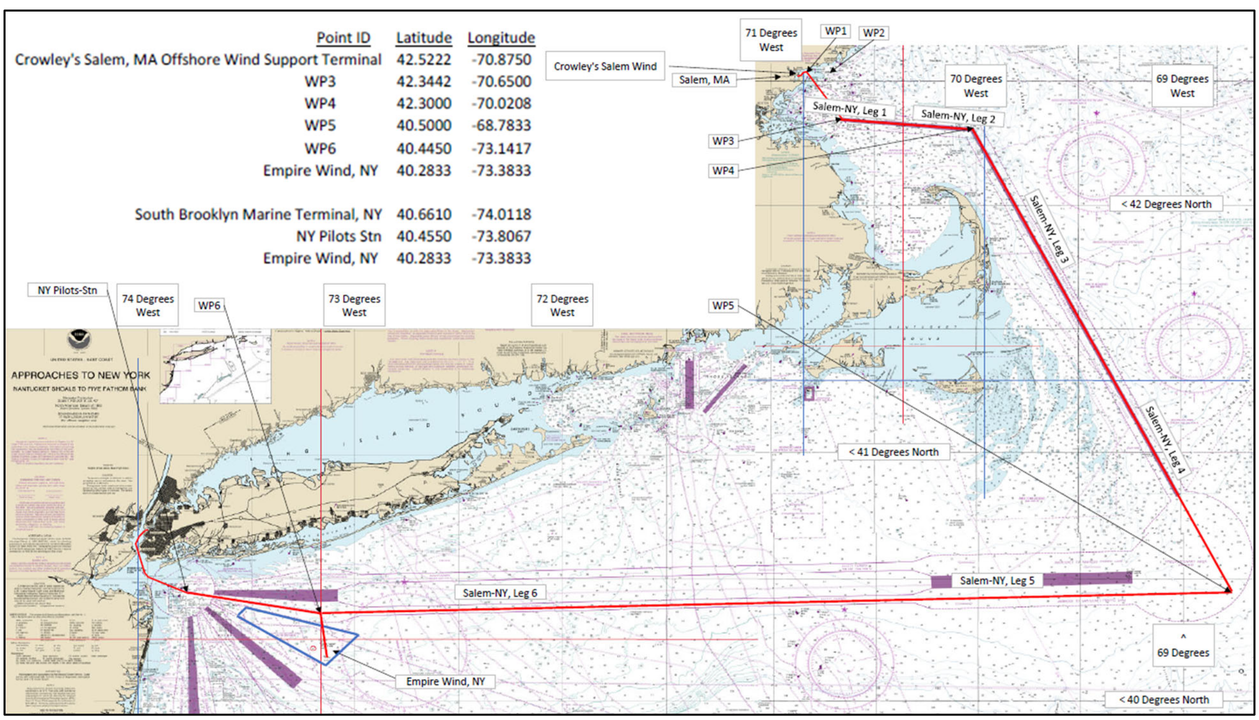


Figure 22 – Feeder Routes between Salem or South Brooklyn Load Ports and Empire Wind

The headings on the routes shown above are:

- Legs 1 & 2 outbound heading is 100 degrees
- Legs 3 & 4 outbound heading is 167 degrees
- Legs 5 & 6 outbound heading is 285 degrees
- NY Pilots Station to Way Point 6 heading is 120 degrees

For each of the four (4) waypoints, NOAA Wave Watch III hindcast weather were created as described in Step B in Section 3.2.2.4 above. Each file contains 31 years of hourly metocean data including significant wave height (Hs), peak wave period (Tp), dominant wave direction, wind speed at 10m, and wind direction.

3.2.3.5 Motions Along the Way

Once the transfer functions are calculated for each significant wave height (Hs), wave period (Tp) and relative wave direction (ϕ), and the heading is established, the real-world dominant wave direction is translated into the vessel's coordinate system and the motions at each hour are calculated based on wave height and period using the information in the Hs-Tp-Phi study. The motions/accelerations are written to the weather files as described in Step B in Section 3.2.2.4 above.

3.2.3.6 Motions at the WTIV Site

Once the WTIV reaches the wind farm site, it is assumed to come to a heading parallel to the direction of the dominant wave energy. The CF barge is assumed to be parallel to the WTIV. Again, the real-world dominant wave direction is translated into the vessel's coordinate system and the motions at each hour are calculated based on wave height and period using the information in the Hs-Tp-Phi study. The motions/accelerations are written to the weather files as described in Step B in Section 3.2.2.4 above.

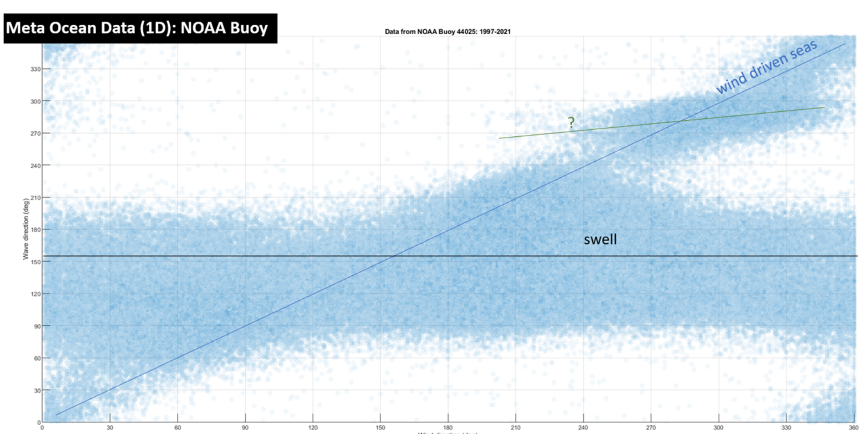


Figure 23 – Dominant Wave Energy by Direction

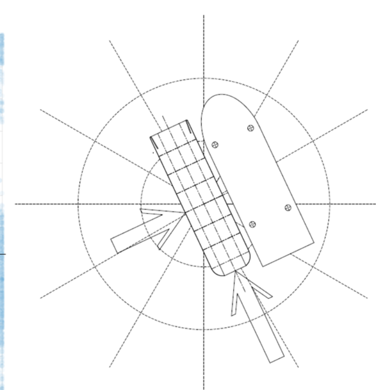


Figure 24 – CF Barge beside WTIV

Once the files created in Step B are complete, the effort changes from hydrodynamics to simulation.

3.2.4 Operational Motion Study Simulation – Steps C & D

Section 3.2.2.4 provides an overview of the OMS software package. This section describes the operational limits, task list, and other specific information related to the simulation portion of is study.

3.2.4.1 Applying Motion/Acceleration Limits

At Step C, specific vessel and/or cargo motion/acceleration limits are compared to the Step B heading specific motions and accelerations and new files are written. For each limit, the new file contains hourly go/no-go instructions.

The heading in which the vessel is assumed to be traveling is based on the location of the vessel en route to the Site. For the return voyage, no cargo is aboard so only wave and wind conditions are limiting.

Once the feeder is preparing to dock, it is assumed to be aligned to the same heading as the WTIV.

The limits examined in this study include:

- In-Transit Cargo Acceleration Limits in X, Y or Z Directions – In transit, the acceleration at the center of gravity of each cargo item must not exceed Original Equipment Manufacturer (OEM) provided limits. As shown in Figure 22, the limits for each weather data point and heading are as follows:
    - fdr_f_nav1 Leg 1 - at Load Port, on Load Port to 1st Way Pt heading
    - fdr_f_nav2 Leg 2 - at 1st Way Pt, on Load Port to 1st Way Pt heading
    - fdr_f_nav3 Leg 3 - at 1st Way Pt, on 1st Way Pt to 2nd Way Pt heading
    - fdr_f_nav4 Leg 4 - at 2nd Way Pt, on 1st Way Pt to 2nd Way Pt heading
    - fdr_f_nav5 Leg 5 - at 2nd Way Pt, on 2nd Way Pt to Wind Farm Site heading
    - fdr_f_nav6 Leg 6 - at Wind Farm Site, on 2nd Way Pt to Wind Farm Site heading
- WTIV Jacking Limits - In Dynamic Positioning (DP) mode and when legs are being extended or retracted, WTIV operations are more sensitive to waves. This limit sets one wave height limit for beam seas and a different, less restrictive limit when the waves are from the bow or stern (+/- 22.5 degrees).
    - wiv_jackup - WTIV heading as described in Section 3.2.3.6 above.
- Feeder to WTIV - Approach/Mooring Limits – The period when the feeder approaches the WTIV has the most environmental limits in effect:
        - The cargo accelerations must remain below the OEM's limits,
        - Feeder motions (roll, pitch and heave) must remain within limits,
        - The bow and stern athwartship velocity must remain below a limiting velocity, and
        - The wind speed must be below a specified limit for beam seas and a different, less restrictive limit when the wind is from the bow (+/- 20 degrees)
    - fdr_f_approach2wiv
- Once the feeder is moored to the WTIV and cargo is being removed, the limits in effect are:
        - The cargo accelerations must remain below the OEM's limits for any cargo still aboard,
        - Feeder motions (roll, pitch, and heave) must remain within limits,

  - fdr_f_docked2wiv – fully loaded CF barge displacement & gyradius
  - fdr_f_docked2wiv_notowers – fully loaded CF barge displacement & gyradius without towers
  - fdr_e_docked2wiv_notowers – empty CF barge displacement & gyradius without towers
  - fdr_e_docked2wiv – empty CF barge displacement & gyradius

Note: After the towers are removed, both fdr_f_docked2wiv_notowers and fdr_e_docked2wiv_notowers limits are used together to bracket the actual displacement. This is a conservative assumption.

- Cargo Top & Base Motion Limits – As each cargo item is lifted, the Pick-Up Point (PUP) and base motions must remain within limits:
  - fdr_f_LiftTower1 base & top motions for Tower1 if lifted first (or nearly first)
  - fdr_e_LiftTower1 base & top motions for Tower1 if lifted last (or nearly last)
  - fdr_f_LiftTower2 base & top motions for Tower2 if lifted first (or nearly first)
  - fdr_e_LiftTower2 base & top motions for Tower2 if lifted last (or nearly last)
  - fdr_f_LiftTower3 base & top motions for Tower3 if lifted first (or nearly first)
  - fdr_e_LiftTower3 base & top motions for Tower3 if lifted last (or nearly last)
  - fdr_f_LiftNacelle base & top motions for Nacelle if lifted first (or nearly first)
  - fdr_e_LiftNacelle base & top motions for Nacelle if lifted last (or nearly last)
  - fdr_f_LiftBlades base & top motions for Blades if lifted first (or nearly first)
  - fdr_e_LiftBlades base & top motions for Blades if lifted last (or nearly last)

Note: "f" indicates full cargo load condition motions are used and "e" indicates the light cargo condition.

- Weather at Load Port, Wind Farm Site & In Between – In addition to the pre-processed motions-related limits, the weather files include wave height (Hs), wave period (Tp), and wind speed for each of the four locations of interest:
  - Load Port_metocean
  - 1st Way Pt_metocean
  - 2nd Way Pt_metocean
  - Wind Farm Site_metocean

See Section B2.3 for more information about limits and sub-limits.

3.2.4.2 Tasks for Discrete Event Simulation

For each vessel evaluated, a list that identifies every task necessary to complete a round trip voyage or installation cycle is assembled. Both the duration and required weather window were estimated and the weather or motion/acceleration limits being studied are recorded.

See Sections A1.2 & A1.3 for more information about the tasks to be performed by each vessel.

4 Concluding Remarks

4.1 Intersection of Findings

The mission to deliver cargo to the WTIV and be broken into two broad activities: transporting the cargo into the vicinity of the WTIV and bringing the cargo vessel alongside the WTIV for transloading. This study demonstrates that a Cargo Feeder System supported foreign WTIV is more efficient than a Jones Act-compliant WTIV for bringing the cargo to the vicinity of the WTIV. System performance during approach and transloading is quite sensitive to operational limits and the tool described herein allows the user to evaluate the change in system throughput and installation costs for a wide range of operational limits.

4.2 Evaluation of Method

4.2.1 Simulation Method Challenges

Using simulation to evaluate the performance of a system is a powerful way tool; however, the results sometimes include abrupt discontinuities because the constraint on the system can change suddenly, and it is not always obvious why. This is a strength of the method because it provides accurate insight into the system performance, but it means that the findings are often transferrable from one system to another.

The sensitivity to acceleration limits described in Section 3.1.2 is an example of this phenomenon.

Comparison of Performance over a Range of Cargo Acceleration Limits
Time to Install One WTG – Salem to Empire

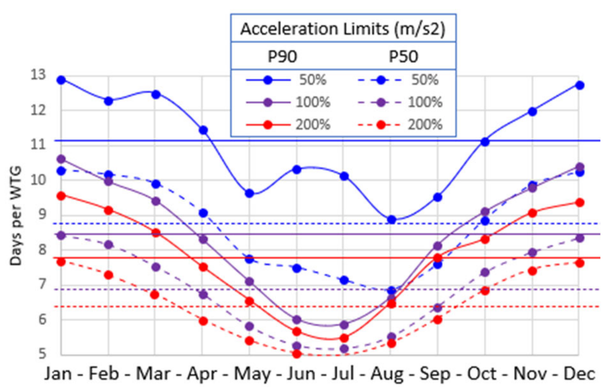


Figure 25 – Days to Deliver one WTG (Monthly)

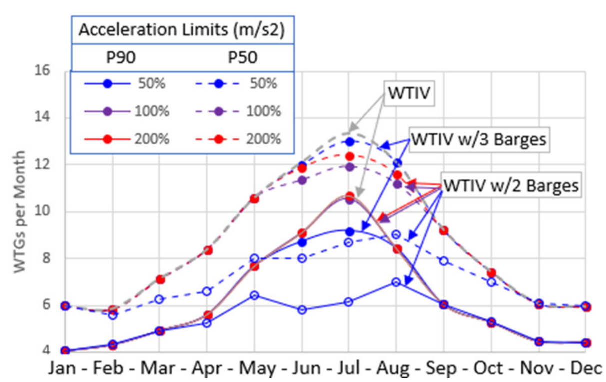


Figure 26 – WTGs installed per Month

In Figure 25 above, the most restrictive acceleration limit, which cuts the allowable accelerations by 50%, requires 2 days more than one might expect at P90 and 1/2 day more at P50 in June and July. Therefore, in April thru August in P90 years and February through October in P50 years, a third barge is required to maintain the supply of WTGs to the WTIV. This is an example of a limit abruptly shifting. It would require several more studies to determine which other limit is restricting throughput.

4.2.2 Simulation Method Strengths

The weather down time analysis is traditionally performed using only the weather (Metocean) data at locations along the voyage path, with limiting conditions being estimated based on generalized assumptions about the behavior of vessel or effects of motions on the cargo. Such simplifying assumptions usually correlate the response of the vessel to the incoming waves and wind in the dominant directions and set the wave height, wave period and wind speed limits without respect to relative direction. The limits are then used to run the WDT analysis. With this approach, the user can still study how sensitive the system is to different limits but there is no way to correlate weather to vessel or cargo motions and/or to allow limits to vary based on weather direction with respect to the vessel. Anyone who has ever sat in a canoe knows that a wave from the beam can cause vessel motions that would not even register if the wave was coming from the bow.

The conventional approach often results in underestimations of WDT but if limits are set so low as to exclude all waves that might cause excessive motions, WDT might be significantly over estimated. In contrast to the traditional approach, the presented study in this document, utilizes Spectral Response Amplitude Operators (SRAOs) derived from frequency domain motions analysis of the vessel with actual cargo and ballast load conditions. The combination of SRAO and weather data results in a motion /acceleration estimation at the POI, leading into a go/no go condition for each specific time step of the operation. This approach significantly improves the vessel behavior modeling and provides a more realistic basis for the WDT analysis.

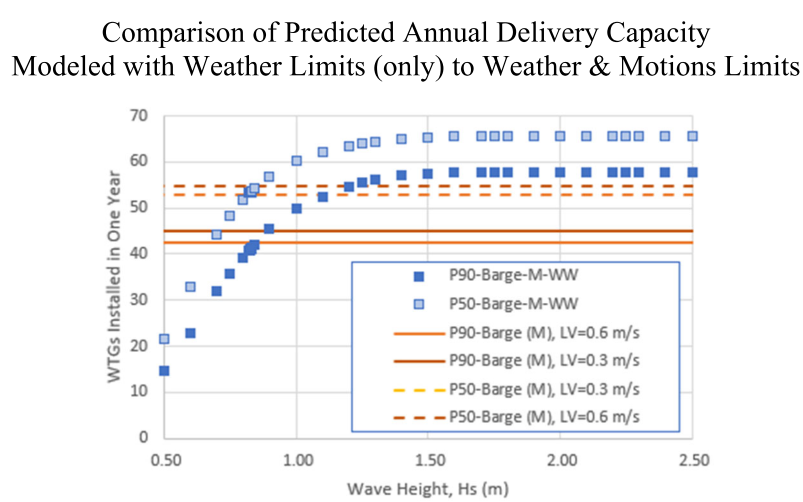


Figure 27 – WTGs Delivered by one Barge (M) per Year (Salem to Empire)

5 Areas for Further Study

5.1 Incorporate 2D Metocean Data

Some NDBC buoy stations measure full wave 2D spectrum and report the parameters need to regenerate the data. The NOAA Wave Watch III hindcast data is available as 1D which includes the significant wave height in the dominant direction and 2D data which includes the full 2D spectrum.

In some cases, the magnitude of secondary wave energy is only slightly less than the primary wave energy. A vessel exposed to a 2D spectrum behaves differently than one in a 1D wave field. The method to pre-process the motions/accelerations used within the OMS can be used with 2D spectra which would provide more realistic motions.

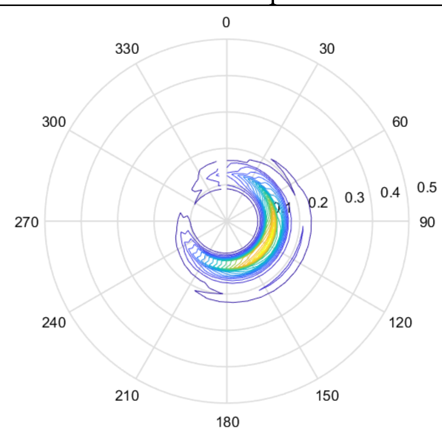
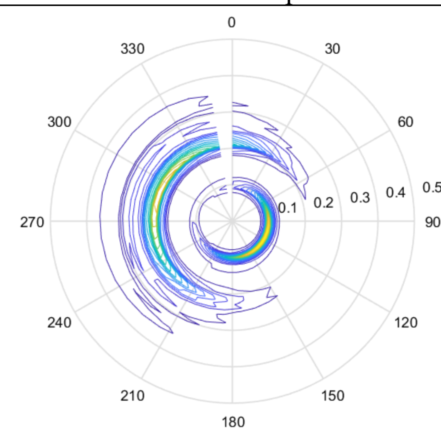
Uni-directional Spectrum	Multi-directional Spectrum
	
$Hs = 1.5\ m, Tp = 7.7\ s, Dir = 120°$	$Hs = 1.5\ m, Tp = 10\ s, Dir = 120°$

Figure 28 – Examples of Uni-directional & Multi-directional Wave Spectra

It is unclear whether the 2D response motions would change the results significantly as some periods with multi-directional waves may have larger motions in the non-dominant mode, but other cases may return dampened motions. If the full 2D spectrum is captured, the difference in direction between the local wind waves and swells can be quantified and seasonal differences can be analyzed as well.

5.2 Develop a Multi-Agent Simulator

As described in Section 2.5.1, the commercially available weather downtime simulator used in this study is a single agent model so interactions between the vessels are not modeled. If there is surplus feeder capacity, this is not a problem, however, minimizing surplus feeder capacity can drive down costs.

A simple multi-agent simulator could be built that includes the WTIV and many feeders. Feeders could be modeled as single vessels [like ships or articulated tug barges (ATB)] or multi-vessel units [like tugs towing barges]. The advantage of including multi-vessel units is that the simulation could permit a CF barge to be loaded while the tugs are out with another CF barge which would reduce the time that the more expensive assets are idle.

Over time, the simulator could be expanded to include the inventory in the load port, load port berth availability (for a port where WTGs come in from the OEM by vessel), or even harbors of refuge for feeders that are located at greater distance from the wind farm site.

As wind farm installations get started, the feeder supplied WTIV system being planned for the U.S. market is less likely to be subject to delays due to congestion, queuing or bunching because feeder departure will be controlled by a person with knowledge about the other vessels in the system and there isn't very much competition for the load port or WTG supply. However, as the industry builds, optimizing every part of the system becomes more important and simulation is the best way to predict the performance of capital improvements and optimize utilization.

5.3 Use Simulation to Estimate Return on Capital

Perform an exceedance/non-exceedance study to understand the availability of the CFS and the WTIV and to understand which specific tasks and limits slow overall system throughput. Compare performance improvements with the cost of the equipment to support capital improvement decisions.

5.4 Use Metocean Forecasting to Support Operations

Forecast weather models, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) or even the Global Forecast System (GFS), can provide fairly accurate forecast metocean data. [See www.PredictWind.com .] The OMS described in Section 3.2.2.4, can be used with forecast metocean data to predict performance as a decision support tool for route planning and operations. Feedback from operators could also be used to improve future simulations.

The forecast weather data could also be used with a time domain motions analysis to predict vessel motions for a specific CF feeder delivery which could provide valuable information for operators.

5.5 Examine the Effects of Climate Change

As mentioned in Section 3.1.2, this study is based on hindcast data and does not account for climate change. It may be possible to compare the weather patterns of the last few years to the 31-year database to determine how the results might skew as the weather patterns become more energetic.

5.6 Study Limits Related to Re-Hit

As mentioned in Sections 1.2.5 and 3.1.5, while the barge is beside the WTIV through lift-off, there is a danger of the cargo hitting the WTIV. This study examined top and base motions of the cargo which must be within limits so the crane can capture the lifting harness, however, the during a short period right after the cargo is lifted off the feeder, there is a danger that the cargo will make contact or “re-hit” the barge. This can happen because cranes cannot lift the cargo to a safe height instantaneously and as the heavy load is lifted from the barge, the barge will tend to pitch, roll and heave upward in response to the change in loading.

This period of rapid change in loading should be modeled separately and include barge motions in response to the most common weather patterns that occur within the weather limits for operations. The motions study should record the barge motions in the likely re-hit locations so the lifting speed and velocity required to avoid re-hit for each WTG component can be quantified. If the motions characteristics from the study, can be correlated to the barge motions in the load conditions that bracket each component’s moment of lift-off or weather limits for different lifting appliances or motion compensation systems options being considered. The limits could be incorporated into this simulation so the change in installation time can be measured, and the value of the various appliances or systems quantified.

6 References

6.1 NOWDRC Agreement #103 Reports

1. Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry: Barge, Cargo and WTIV Load Properties Technical Report, Milestone Number 1.3.
2. Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry: Maneuvering Simulation to Indicate Operational Limits Technical Report, Milestone Number 3.4.
3. Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry: Dynamic Barge Motions and Mooring Study Technical Report, Milestone Number 2.4.
4. Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry: Task and Weather/Motions Limits and Integration of Metocean Data for weather Downtime Study Technical Report, Milestone Number 4.3.

6.2 Barge Info

1. 400’ x 105’ x 26’ Deck Cargo Barge, GENERAL ARRANGEMENT, Dwg 73-03, Rev B
2. Crowley Spec Sheet: 455 Series – 400’ x 105’ x 25’
   [applicable to Barges: 455-1 (Marty J), 455-3, 455-4, 455-5, 455-6, 455-7. 455-8, 455-9]
3. 213025-833-1, Weight Estimate
4. 213025-034-01, 15 MW NREL Reference Turbine Stow Plan, Base Case – Two Tower Sections
5. 213025-034-02, 15 MW NREL Reference Turbine Stow Plan, Sens. Case 1 – Three Tower Sections
6. 213025-034-03, 15 MW NREL Reference Turbine Stow Towing & Mooring Arrangement
7. General HydroStatics (GHS) model: (21-11-29) 213025-455.gf

6.3 Tug Info

1. Crowley Spec Sheet: Ocean Class Tugs [applicable to DP1 Ocean Wind & Ocean Wave, and DP2 Ocean Sky & Ocean Sun]
2. Crowley Spec Sheet: Alert Class Tugs [applicable to Alert, Attentive & Aware which are outfitted with azimuthing drives (z-drive)/controllable pitch (CP) propellers]

6.4 Wind Turbine Generator Info

1. IEA Wind TCP Task 37, Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report, March 2020

6.5 Regulatory Documents

1. DNVGL Standard DNVGL-ST-N001, Marine Operations and Marine Warranty, September 2018.

6.6 Endnotes

[1] https://windeurope.org/intelligence-platform/

[2] https://www.energy.gov/eere/wind/wind-market-reports-2021-edition#offshore

[3] https://news.dominionenergy.com/2021-06-01-Dominion-Energy,-rsted-and-Eversource-Reach-Deal-on-Contract-to-Charter-Offshore-Wind-Turbine-Installation-Vessel

[4] ABPmer Weather Downtime Express Service - Technical Description, p. 1 (https://www.seastates.net/downloads/)

[5] ABPmer Weather Downtime Express Service - Technical Description, p. 5

[6] ABPmer Weather Downtime Express Service - Technical Description, p. 2

[7] NOAA WAVEWATCH III hindcast https://polar.ncep.noaa.gov/waves/hindcasts/nopp-phase2.php

[8] NOAA WAVEWATCH III hindcast https://polar.ncep.noaa.gov/waves/hindcasts/nopp-phase2.php

[9] https://www.orcina.com/webhelp/OrcaFlex/Content/html/Results,Statistics.htm

Appendix A. Operational Tasks & Limits

A1 Feeder and Installation Vessel Operations

A1.1 Feeder Vessel Routes

For this study, two routes are being evaluated:

- Salem to Empire Wind: 389 nm (long route)
- Brooklyn, NY to Empire Wind: 81 nm (short route)

See Figure 22.

A1.2 Feeder with Foreign Flag WTIV Tasks, Durations and Limits

A1.2.1 Feeder Tasks and Durations

A single feeder (S) will load in the load port, travel to the wind farm site, transload cargo to the WTIV and return to port to discharge the backhauled equipment and start again. For a system with multiple feeders (M), the tugs are assumed to pick-up a loaded barge and not wait for the loading operations:

Moored Tightline (w/1 WTG set/barge) Single Barge	(e) Task duration (hrs)	(f) Weather window (hrs)	(g) Wave height (m)	(h) Wave Period (s)	(j) Wind speed (m/s)
Come alongside in port	1.5	1.5			14.
Set gangway and ready for backloading	1.	1.			14.
Backload Equipment (Port)	3.	3.			14.
Loadout of Blades (1.5hrs/blade)	4.5	1.5			13.
Loadout of Towers (2.5hrs/tower section)	5.	2.5			14.
Loadout of Nacelles (3hrs/nacelle)	3.	3.			12.
Readying to sail	1.	1.			14.
Weather Check @ Empire	0.01	36.	10.		30.

Moored Tightline (w/1 WTG set/barge) Multiple Barges	(e) Task duration (hrs)	(f) Weather window (hrs)	(g) Wave height (m)	(h) Wave Period (s)	(j) Wind speed (m/s)
Come alongside in port	1.5	1.5			14.
Dropoff Barge 1	0.5	0.5			14.
Shifting/Pickup Barge 2	0.5	0.5			14.
Weather Check @ Empire	0.01	36.	10.		30.

Moored Tightline (w/1 WTG set/barge) Single Barge	(e) Task duration (hrs)	(f) Weather window (hrs)	(g) Wave height (m)	(h) Wave Period (s)	(j) Wind speed (m/s)
Leaving Salem, MA (SAL) (1.5 nm)	0.38	0.38	5.		14.
Sailing Port to Ocean: (20 nm) - Leg 1	2.5	2.5	5.		14.
Sailing To WP4: (28 nm) - Leg 2	3.5	3.5	5.		14.
Sailing From WP4: (61 nm) - Leg 3	7.63	7.63	5.		14.
Sailing To WP5: (61 nm) - Leg 4	7.63	7.63	5.		14.
Sailing From WP5: (100 nm) - Leg 5	12.5	12.5	5.		14.
Sailing Near Site: (120 nm) - Leg 6	15.	15.	5.		14.

Moored Tightline (w/1 WTG set/barge) Single Barge	(e) Task duration (hrs)	(f) Weather window (hrs)	(g) Wave height (m)	(h) Wave Period (s)	(j) Wind speed (m/s)
Move feeder in Safety Zone	0.25	0.25	3.	15.	12.86
Moving feeder into position	0.25	0.25	2.5	15.	10.29
Transfer Crew Over	0.25	0.25	2.5	15.	12.86
Secure mooring system	1.	1.	2.5	15.	14.
Ballast & Prep for Transloading	1.	1.	2.5	15.	14.
Lift Blade cassette (3 blades) from Feeder	0.5	0.5	2.5	15.	10.
Land blade cassette onto WTIV	1.5	1.5		15.	10.
Changing Rigging	0.5	0.5		15.	14.
Lift Top Tower Section from Feeder	0.5	0.5	2.5	15.	12.
Land Top Tower Section onto WTIV	1.5	1.5		15.	12.
Lift Bottom Tower Section from Feeder	0.5	0.5	2.5	15.	12.
Land Bottom Tower Section onto WTIV	1.5	1.5		15.	12.
Changing Rigging	0.5	0.5		15.	14.
Lift Nacelle from Feeder	0.5	0.5	2.5	15.	12.
Land Nacelle on WTIV	1.	1.		15.	12.
Changing Rigging	0.5	0.5		15.	14.
Backload Equipment (at Site)	2.	2.	2.5	15.	12.
Cast off mooring lines	0.5	0.5	2.5	15.	14.
Transfer Crew Back	0.25	0.25	2.5	15.	14.
Move feeder away from WTIV	1.	1.			
Sailing Near Site: (120 nm) - Leg 6	15.	15.	5.		15.
Sailing From WP5: (100 nm) - Leg 5	12.5	12.5	5.		15.
Sailing To WP5: (61 nm) - Leg 4	7.63	7.63	5.		15.
Sailing From WP4: (61 nm) - Leg 3	7.63	7.63	5.		15.
Sailing To WP4: (28 nm) - Leg 2	3.5	3.5	5.		15.
Sailing Port to Ocean: (20 nm) - Leg 1	2.5	2.5	5.		15.
Entering Salem, MA (SAL) (1.5 nm)	0.38	0.38	5.		15.

Figure 29 – Feeder Task List with Task Durations and Weather Limits (Tower in Two Sections)

With no weather downtime, the time for a feeder that doesn't wait for loading operations to make a round trip voyage is assumed to be:

Group of Tasks	Time (hrs) Salem, MA	 Brooklyn, NY
Load Cargo in Port	2.5	2.5
Travel from Load Port to Wind Farm Site	49.1	10.5
~~Approach Transition Piece Position & Jack Up~~	~~0.0~~	~~0.0~~
Move Feeder alongside WTIV / Transload Cargo	15.5	15.5
~~Install one WTG at Wind Farm Site~~	~~0.0~~	~~0.0~~
Return from Site to Load Port	49.1	10.5
Total Ideal Cycle Time (excluding WDT)	116.2 [4.8 days]	39.0 [1.6 days]

If the feeder must wait for loading operations, the time in port increases by 19.5 hours, so the total ideal cycle time (excluding WDT) for Salem to Empire is 135.7 hours [5.7 days] or Brooklyn, NY to Empire is 58.4 hours [2.4 days].

The task list described in Figure 29 is based on the tower being split into two (2) sections. If the tower is split into three (3) sections, the time required to transload cargo increases by 2 hours (which is 1.7% of a RTV from Salem or 5.1% of a RTV from Brooklyn). If the feeder must wait for loading operations, the time in port is increased by 2.5 hours when a third tower section must be loaded.

A1.2.2 Foreign Flag WTIV Tasks and Durations

Foreign flag wind turbine installation vessels (WTIVs) cannot be U.S. Coastwise-qualified under the Jones Act; therefore, they are not permitted to transport cargo within the United States. Once they are jacked up and are not acting as a vessel, they are permitted to lift cargo from a feeder vessel onto a pre-positioned foundation as part of the assembly process. A foreign flag WTIV will approach the foundation position and jack-up, transload cargo from the feeder, backload equipment for return to port, install the WTG, jack down and sail to the next site and start again.

Foreign WTIV **WTGs Brought by Feeder / WTIV Installs**	(e) Task duration (hrs)	(f) Weather window (hrs)	(g) Wave height (m)	(h) Wave Period (s)	(j) Wind speed (m/s)
Check Weather for WTIV @ Site	0.01	36.	10.		30
Approach Position	1.5	6.	1.8	15	14
Position DP Trial	0.5	0.5	1.8*	15	14
DP Mode + Lower Legs to Seabed	0.5	0.5	1.8*	15	14
Touchdown/Pre-load	3.	3.5	1.8*	15	14
Jack up #1	0.5	0.5	1.8	15	16
Move feeder in Safety Zone	0.25	0.25	3.	15	12.86
Moving Feeder into Position	0.25	0.25	2.5	15	10.29
Transfer Crew Over	0.25	0.25	2.5	15	12.86
Secure Mooring System	1.	1.	2.5	15	14
Readying for Transloading	1.	1.	2.5	15	14
Lift Blade Cassette (3 blades) from Feeder	0.5	0.5	2.5	15	10
Land Blade Cassette onto WTIV	1.5	1.5		15	10.
Change Rigging	0.5	0.5		15	14
Lift Top Tower Section from Feeder	0.5	0.5	2.5	15	12
Land Top Tower Section onto WTIV	1.5	1.5		15	12
Lift Bottom Tower Section from Feeder	0.5	0.5	2.5	15	12
Land Bottom Tower Section onto TP on MP	1.5	1.5		15	12
Change Rigging	0.5	0.5		15	14
Lift Nacelle from Feeder	0.5	0.5	2.5	15	12
Land Nacelle on WTIV	1.	1.		15	12

Foreign WTIV WTGs Brought by Feeder / WTIV Installs	(e) Task duration (hrs)	(f) Weather window (hrs)	(g) Wave height (m)	(h) Wave Period (s)	(j) Wind speed (m/s)
Change Rigging	0.5	0.5		15	14
Backload Equipment (at Site)	2.	2.	2.5	15	12
Cast Off Mooring Lines	0.5	0.5	2.5	15	14
Transfer Crew Back	0.25	0.25	2.5	15	14
Move feeder away from WTIV	0.25	0.25			14
Jack up #2	0.5	0.5	1.8	15	16
Readying for Installation	1.	**28.**	**3.**	15	14
Install Top Tower Section (Bottom Section(	5.	5.		15	12
Change Rigging	0.5	0.5		15	14
Installation of Nacelle	3.	3.		15	12
Change Rigging	0.5	0.5		15	14
Install Blade 1	3.	3.		15	10
Install Blade 2	3.	3.		15	10
Install Blade 3	3.	3.		15	10
End of Installation	1.	1.		15	14
Retraction / Jack Down	2.	2.	1.8*	15	13
Move from MP	0.5	0.5	1.8	15	14
Sail to next site	**0.5**	**0.5**	1.8	15	14

Figure 30 – Foreign Flag WTIV Task List with Task Durations and Weather Limits

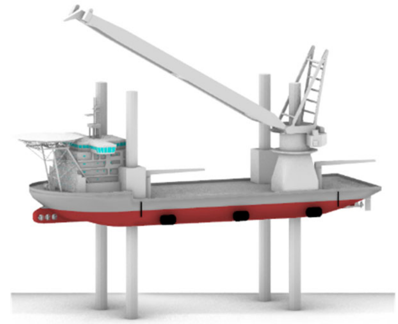
With no weather downtime, the time for a WTIV to make a complete installation cycle is assumed to be:

Group of Tasks	Time (hrs)
~~Load Cargo in Port~~	~~0.0~~
~~Travel from Load Port to Wind Farm Site~~	~~0.0~~
Approach Transition Piece Position & Jack Up	6.0
Move Feeder alongside WTIV / Transload Cargo	14.8
Install one WTG at Wind Farm Site	28.5
~~Return from Site to Load Port~~	~~0.0~~
Total Ideal Cycle Time (excluding WDT)	49.3 [2.1 days]

With no weather downtime, a foreign WTIV can install 177 WTGs per year. From Brooklyn, a single feeder can deliver 150 WTGs per year, and with a multi-feeder system, each vessel can deliver 225 WTGs per year. From Salem, a single feeder can deliver 64 WTGs per year, and with a multi-feeder system, each vessel can deliver 75 WTGs per year.

The task list described in Figure 30 is based on the tower being split into two (2) sections. If the tower is split into three (3) sections, the time required to transload cargo increases by 2 hours (which is 4% of an ideal installation cycle).

A1.3 U.S. Coastwise-Qualified WTIV



Wind turbine installation vessels that comply with the Jones Act (JA WTIVs) and are U.S. Coastwise-qualified are permitted to transport cargo within the United States. The cargo capacity of WTIVs varies, for this study, the WTIV can transport four (4) WTGs. A JA WTIV will load in the load port, travel to the wind farm site, will approach the foundation position and jack-up, install the WTG, jack down and sail to the next site, and repeat the installation cycle until all WTGs are installed, return to port to discharge the backhauled equipment, and start again. This task list is used as a sensitivity.

Jones Act WTIV					
Loads 4 WTG(s) in Port & Installs	(e)	(f)	(g)	(h)	(j)
	Task duration	Weather window	Wave height	Wave Period	Wind speed
	(hrs)	(hrs)	(m)	(s)	(m/s)
Come alongside in port	**1.5**	**1.5**			**14.**
Jack-up (in port)	1.	1.			14.
backload equipment	12.	12.			14.
Loadout of Blades (1.5hrs/blade)	18.	1.5			10.
Loadout of Towers (2.5hrs/tower section)	20.	2.5			12.
Loadout of Nacelles (3hrs/nacelle)	12.	3.			12.
Fuel/Provision	4.	1.			14.
Jack down	2.	2.			14.
Check Weather for WTIV @ Site	0.01	36.	10.		30.

Leaving Salem, MA (SAL) (1.5 nm)	0.38	0.38	3.5	15.	14.
Sailing Port to Ocean: (20 nm) - Leg 1	2.	2.	3.5	15.	14.
Sailing To WP4: (28 nm) - Leg 2	2.8	2.8	3.5	15.	14.
Sailing From WP4: (61 nm) - Leg 3	6.1	6.1	3.5	15.	14.
Sailing To WP5: (61 nm) - Leg 4	6.1	6.1	3.5	15.	14.
Sailing From WP5: (100 nm) - Leg 5	10.	10.	3.5	15.	14.
Sailing Near Site: (120 nm) - Leg 6	12.	12.	3.5	15.	14.

Leaving LwrNYBay (1.5 nm)	0.38	0.38	3.5	15.	14.
Sailing Port to Ocean: (9.54 nm) - Leg 1	0.95	0.95	3.5	15.	14.
Sailing To NYP: (11.33 nm) - Leg 2	1.13	1.13	3.5	15.	14.
Sailing From NYP: (24.84 nm) - Leg 3	2.48	2.48	3.5	15.	14.
Sailing Near Site: (35 nm) - Leg 6	3.5	3.5	3.5	15.	14.

Approach position	1.5	6.	1.8	15.	14.
Position DP Trial	0.5	0.5	1.8•	15.	14.
DP Mode + Lower Legs to Seabed	0.5	0.5	1.8•	15.	14.
Touchdown/Pre-load	3.	3.5	1.8•	15.	14.
Jack up	0.5	0.5	1.8	15.	16.
Readying for Installation	**0.5**	**27.5**		**15.**	14.
Install Top Tower Section	5.	5.		15.	12.
Changing Rigging	0.5	0.5		15.	14.
Install Nacelle	3.	3.		15.	12.
Changing Rigging	0.5	0.5		15.	14.
Install Blade 1	3.	3.		15.	10.
Install Blade 2	3.	3.		15.	10.
Install Blade 3	3.	3.		15.	10.

End of Installation	1.	1.		15.	14.
Retraction / Jack down	2.	2.	1.8*	15.	14.
Move from MP	0.5	0.5	1.8	15.	14.
Sail to next site	**0.5**	**0.5**	**1.8**	**15.**	**14.**
DUPLICATE	67				

Jones Act WTIV Loads 4 WTG(s) in Port & Installs	(e) Task duration (hrs)	(f) Weather window (hrs)	(g) Wave height (m)	(h) Wave Period (s)	(j) Wind speed (m/s)
Sailing Near Site: (120 nm) - Leg 6	12.	12.	3.5	15.	14.
Sailing From WP5: (100 nm) - Leg 5	10.	10.	3.5	15.	14.
Sailing To WP5: (61 nm) - Leg 4	6.1	6.1	3.5	15.	14.
Sailing From WP4: (61 nm) - Leg 3	6.1	6.1	3.5	15.	14.
Sailing To WP4: (28 nm) - Leg 2	2.8	2.8	3.5	15.	14.
Sailing Port to Ocean: (20 nm) - Leg 1	2.	2.	3.5	15.	14.
Entering Salem, MA (SAL) (1.5 nm)	0.38	0.38	3.5	15.	14.

Jones Act WTIV Loads 4 WTG(s) in Port & Installs	(e) Task duration (hrs)	(f) Weather window (hrs)	(g) Wave height (m)	(h) Wave Period (s)	(j) Wind speed (m/s)
Sailing Near Site: (35 nm) - Leg 6	3.5	3.5	3.5	15.	14.
Sailing From NYP: (24.84 nm) - Leg 3	2.48	2.48	3.5	15.	14.
Sailing To NYP: (11.33 nm) - Leg 2	1.13	1.13	3.5	15.	14.
Sailing Port to Ocean: (9.54 nm) - Leg 1	0.95	0.95	3.5	15.	14.
Entering LwrNYBay (1.5 nm)	0.38	0.38	3.5	15.	14.

Figure 31 – Jones Act WTIV Task List with Task Durations and Weather Limits

With no weather downtime, the time for a Jones Act-compliant (JA) WTIV to make a complete installation cycle is assumed to be:

Group of Tasks	Time (hrs) Salem, MA	Time (hrs) Brooklyn, NY
Load Cargo in Port	70.5	70.5
Travel from Load Port to Wind Farm Site	39.4	8.5
Approach Transition Piece Position & Jack Up	6.0	6.0
~~Move Feeder alongside WTIV / Transload Cargo~~	~~0.0~~	~~0.0~~
Install one WTG at Wind Farm Site	27.5	27.5
Repeat “Approach...Jack Up” and “Install one WTG…” until all cargo has been discharged	[6.0 + 27.5]	[6.0 + 27.5]
Return from Site to Load Port	39.4	8.5
Total Ideal Cycle Time (excluding WDT)	282.8 [11.8 days]	121.0 [9.2 days]

With no weather downtime, a Jones Act-compliant WTIV can install 158 WTGs per year out of a Brooklyn, NY port or 124 WTGs per year out of Salem, MA.

A1.4 Vessel Costs

For this study, the relative day rates of these vessels are assumed to be:

Vessel Combination	Day Rate ($/Day)
Foreign WTIV (only)	1.00 * X
Foreign WTIV w/Lead Tug, Assist Tug and 1 Barge	1.33 * X
Foreign WTIV w/Lead Tug, Assist Tug and 2 Barges	1.40 * X
Foreign WTIV w/2 Lead & 2 Assist Tugs and 3 Barges	1.67 * X
Foreign WTIV w/2 Lead & 2 Assist Tugs and 4 Barges	1.80 * X

Table 16 – Relative Day Rates

A2 Metocean and Motions Limits

A2.1 Metocean Limits

As described in Section 3.2.2.3, the discrete event simulator being used for this study evaluates environmental operational limits including wave height, wave period, and wind speed with wind reference heights. The base values used for this study are described with the task lists in Sections A.1.2 and A.1.3.

A2.2 Motion and Acceleration Limits

As described in Section 3.2.2.4, the Operational Motions Study (OMS) program pre-processes the environmental operational limits based on the vessel's motions at the specified heading at every time step for every limit. The route and headings are described in Section 3.2.3.4.

When the discrete event simulation is run, it checks the weather at each time step, and it checks each of the applicable motion/acceleration limit values. If both weather and motions are acceptable, the program proceeds to the next time step. If either weather or motions are not within limits, the program accumulates weather downtime until they are within limits again.

The base values used for this study are described in Section 3.1.1 above.

Transit speed for WTIVs is assumed to be 10 knots at sea or 4 knots in port; the feeder is assumed to travel at 8 knots at sea or 4 knots in port.

A2.3 Exposure Periods

The exposure time as a percent of the total cycle time is shown below.

	WTIV w/Feeder			JA WTIV	
Group of Tasks	Salem	WTIV	Brooklyn	Salem	Brooklyn
Load Cargo in Port	2-19%	N/A	6-57%	25%	58%
Travel from Load Port to Wind Farm Site	42%	N/A	27%	14%	7%
Approach Transition Piece Position + Jack Up	N/A	12%	N/A	8%	5%
Move Feeder alongside WTIV	0.4%	0.4-1%	1%	N/A	N/A
Transload Cargo	13%	29%	39%	N/A	N/A
Install WTG(s) at Wind Farm Site	N/A	58%	N/A	39%	23%
Return from Site to Load Port	42%	N/A	27%	14%	7%
Total Ideal Cycle Time (excluding WDT)	100-117%	100%	100-150%	100%	100%

Table 17 – Exposure Time as a Percent of Total Cycle Time

For the feeders, the ideal cycle time is assumed to be 100% for barges that don't wait to load or more than 100% for barges that do wait to load.

Appendix B. Operational Motion Study

B1 Frequency Domain Motion Analysis

B1.1 Load Conditions

Maximizing the performance of the feeder vessel supported WTIV installation system is critical to driving down the cost of WTG installation. There are trade-offs to each decision. For example, dividing the tower into three sections reduces the top motions of the towers which increases the weather windows available to off-load the towers, however, assembling three tower sections takes more time than assembling two. Another decision relates to ballast. A more heavily ballasted barge will tend to have less roll motions but higher cargo accelerations and will apply a higher force against the WTIV for a given landing velocity than a more lightly loaded vessel. It is important to examine all combinations throughout the delivery cycle to understand which combination offers the best system performance.

Load conditions studied include conditions with cargo loaded and discharged for the following cases:

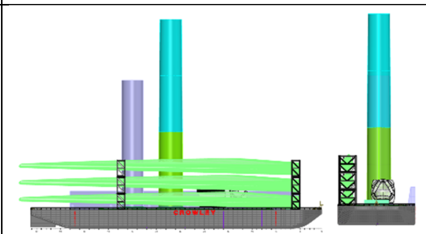
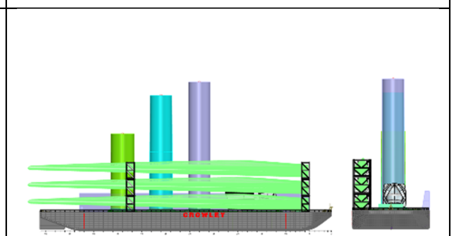
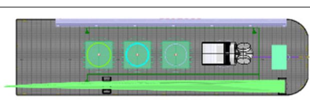
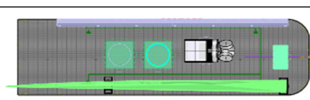
Towers / Ballast	Two Tower Sections	Three Tower Sections
		
		
Minimal Ballast	Draft = 27% of Hull Depth	Draft = 29% of Hull Depth
DNV1 (wing tks)	Draft = 43% of Hull Depth Minimum Free Surface	Draft = 45% of Hull Depth Minimum Free Surface
DNV2 (center tks)	Draft = 43% of Hull Depth Maximum Fred Surface	Draft = 45% of Hull Depth Maximum Fred Surface

Figure 32 – Cargo / Ballast Combinations

The load cases were developed to include:

- Stow plans,
- Weight estimates,
- Shear and bending moment values,
- Radius of gyration values,

- Ballast Plans for port-to-starboard and starboard-to-port cargo discharge,
- Maximum KG curves for each cargo transport and discharge step load condition, and
- Stability analysis.

Hydrostatics and other details about the load cases can be found in Table 18 below. More information can be found in Reference 6.1.1.

Case ID	project			213025											
	vessel			Crowley 455 barge											
	project case name			0-0 BaseCase		0-1 DNV		1-0 Sensitivity		1-1 DNV		0-1 DNV2		1-1 DNV2	
	vessel name			455	455	455	455	455	455	455	455	455	455	455	455
	study			1	1	1	1	1	1	1	1	1	1	1	1
	case subindex (motions study)			1	2	3	4	5	6	7	8	9	10	11	12
	case name (motion study)			V455S01C01	V455S01C02	V455S01C03	V455S01C04	V455S01C05	V455S01C06	V455S01C07	V455S01C08	V455S01C09	V455S01C10	V455S01C11	V455S01C12
	Melissa Manuever Sim Name			-	Cdn B	Cdn C	-	Cdn A	-	-	-	-	-	-	-
	MITAGS Manuever Sim Name			-	Case 1	Case 2	-	Main Ld	-	-	-	-	-	-	-
	ballast			light	light	DNV1	DNV1	light	light	DNV1	DNV1	DNV2	DNV2	DNV2	DNV2
	turbine			15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL R	15MW NREL Re
	turbine sets			1	1	1	1	1	1	1	1	1	1	1	1
	cargo load condition			full	empty	full	empty	full	empty	full	empty	full	empty	full	empty
	tower segments			2	2	2	2	3	3	3	3	2	2	3	3
Hydrostatic Model (imperial)	draft		ft	6.8	4.859	10.80	8.967	7.14	5.221	11.14	9.312	10.785	8.954	11.123	9.299
	Displacement		LT	6767	4770	11094	9098	7140	5143	11468	9471	11079	9083	11452	9456
	VCG		ft	35.72	15.49	25.04	12.09	29.85	14.81	21.74	11.86	24.235	11.082	20.949	10.887
	VCG Corr for FSM		ft	36.55	16.67	26.56	13.95	30.64	15.90	23.21	13.64	35.18	24.46	31.55	23.74
	Radius of Gyration	Kxx	ft	56.26	36.0	52.89	39.138	45.40	36.526	45.37	39.268	47.563	29.165	39.171	29.787
		Kyy	ft	113.95	118.86	97.60	95.716	113.59	120.145	97.59	97.577	97.764	95.781	97.724	97.639
		Kzz	ft	108.49	123.315	96.31	102.62	113.45	124.719	100.22	104.419	93.381	99.272	97.502	101.266

Table 18 – Hydrostatics for Load Conditions

B1.2 Frequency Domain Modeling

For each load condition, a mesh model of the hull below the load waterline is created. The models for the two DNV load conditions are the same for each cargo configuration because the quantity of ballast is the same. The difference between the two ballast conditions is that the ballast is in the wing tanks for the DNV cases and is in the centerline tanks for the DNV2 cases.

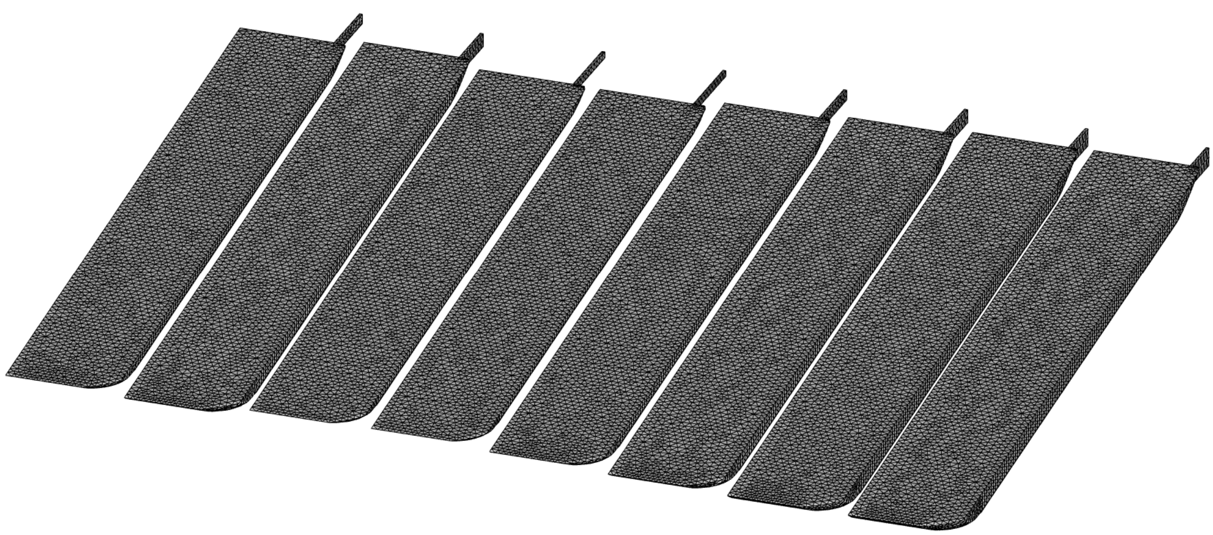


Figure 33 – Hull Mesh Models (Symmetry Assumed)

B1.3 Frequency Domain Analysis

The initial step in a frequency domain analysis is "system identification". During system identification, for each vessel load condition, the response amplitude operators (RAOs) are computed, representing a linear relation between the incoming ocean wave condition and the vessel responses for each of the six degrees of freedom (6-DoF). This frequency domain analysis was performed for all 12 load cases. Two software packages were implemented for this analysis:

- GHS-SK (Seakeeping)
- OrcaWave

Before running the frequency domain analysis, viscous roll damping and roll damping due to radiated waves must be addressed. The viscous roll damping computations were performed using ITTC 2011 (Ikeda Method) implemented in GHS seakeeping. The roll damping coefficients due to radiated waves are computed using the 3D panel code, OrcaWave. The viscous roll damping values where then applied within the OrcaWave model.

B1.4 Viscous Roll Damping

A comparison between the computed radiation and viscous roll damping, together and individually, are shown in Table 19 below.

Loading case	GHS		Orcaflex	
		damping ratio (damping sources)		
	Peak Visc. Damping (kg.m^2/s)	GHS radiation + visc.	Orcaflex radiation only	Orcaflex radiation + visc.
1	47,181,544	5%	5%	6%
2	25,994,950	11%	16%	17%
3	46,589,896	4%	2%	3%
4	33,610,284	9%	7%	8%
5	38,118,168	6%	6%	7%
6	26,684,000	10%	15%	16%
7	46,421,576	6%	3%	4%
8	34,253,868	9%	7%	8%
9	43,616,388	5%	2%	3%
10	29,945,054	9%	9%	9%
11	43,261,024	6%	3%	4%
12	30,858,576	9%	8%	9%

same loadout design, with and without cargo (cases 5 and 6)

light draft + small mass moment (case 6)

deep draft + high mass moment (case 9)

Table 19 – Comparison of Roll Damping Values

The values used for this study are shown in Table 20 below.

Load case	Critical Damping Ratio
V455S01C01	0.0506
V455S01C02	0.1075
V455S01C03	0.0446
V455S01C04	0.0878
V455S01C05	0.0624
V455S01C06	0.1046
V455S01C07	0.0552
V455S01C08	0.0866
V455S01C09	0.0508
V455S01C10	0.0918
V455S01C11	0.0604
V455S01C12	0.0906

Table 20 – Frequency Domain Analysis Critical Roll Damping Ratios

After computing the roll damping coefficients, a numerical free decay test was conducted for roll, pitch, and heave responses, the results of which are presented in Figure 34. It can be seen from this figure that only roll responses, both frequencies and amplitudes, are highly dependent on the loading conditions. To this end, the free decay roll damping curves/results were used to compute and compare the linearized decay assumption with curve fitting.

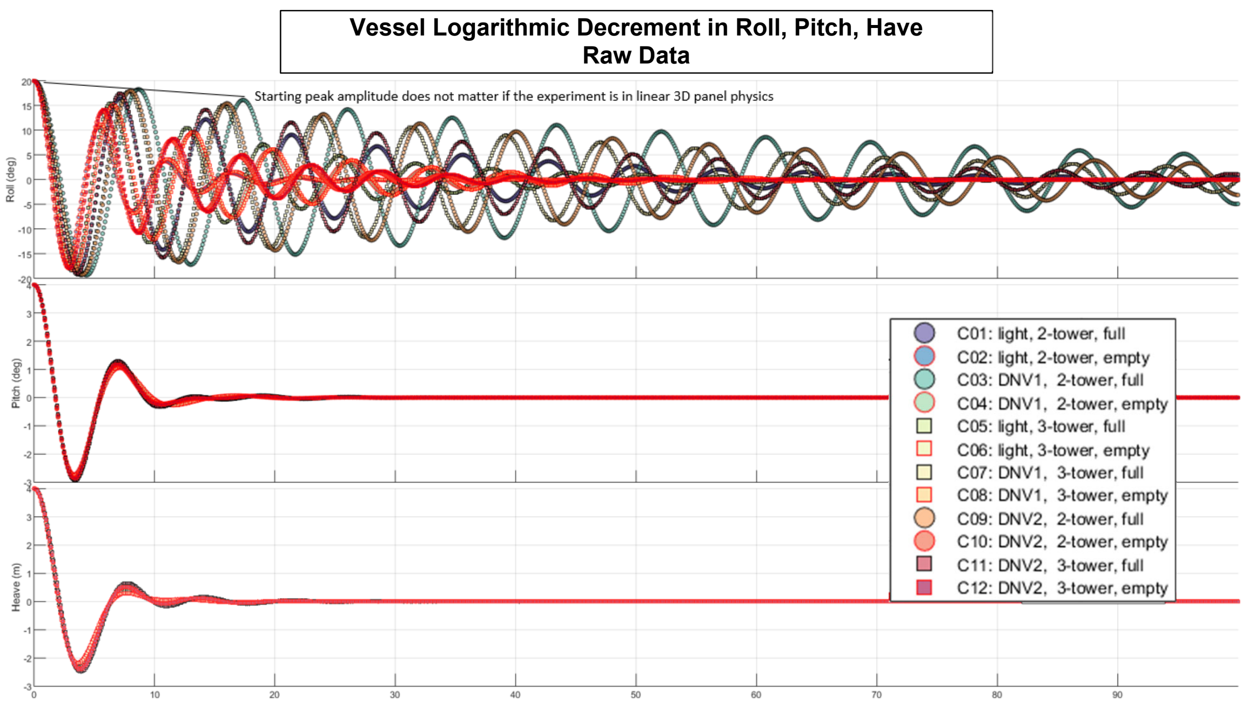


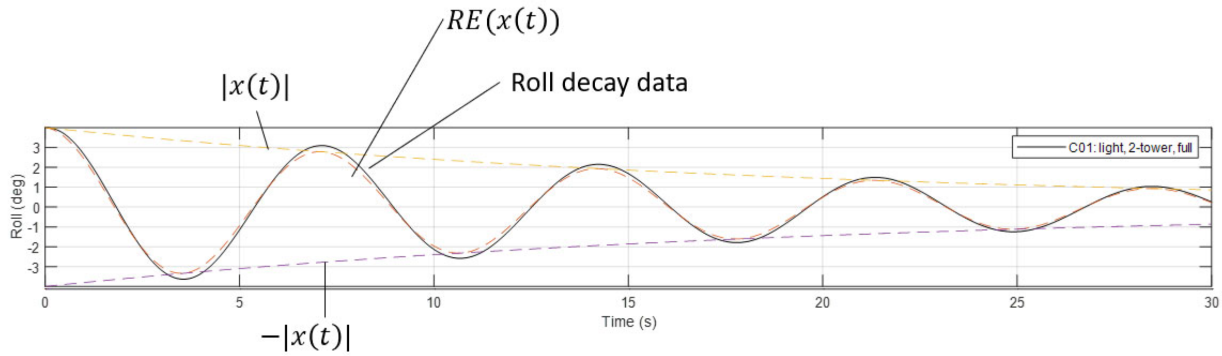
Figure 34 – Free Decay Test for Roll, Pitch, and Heave for Twelve Loading Conditions

The linearized roll damping coefficient can be computed using the free roll decay curve with the following equations:

$$\delta = \frac{1}{n}\ln\left(\frac{x(t)}{x(t+nT)}\right)$$

$$\zeta = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}}$$

$$x(t) = C_0 e^{-i\omega t\left(\zeta + i\sqrt{1-\delta}\right)} \quad \text{with } C_0 \rightarrow \text{starting amplitude}$$



The results of the linear curve fitting test, with the numerical free roll decay test, for all 12 vessel loading cases are presented in Figure 35 - Figure 37.

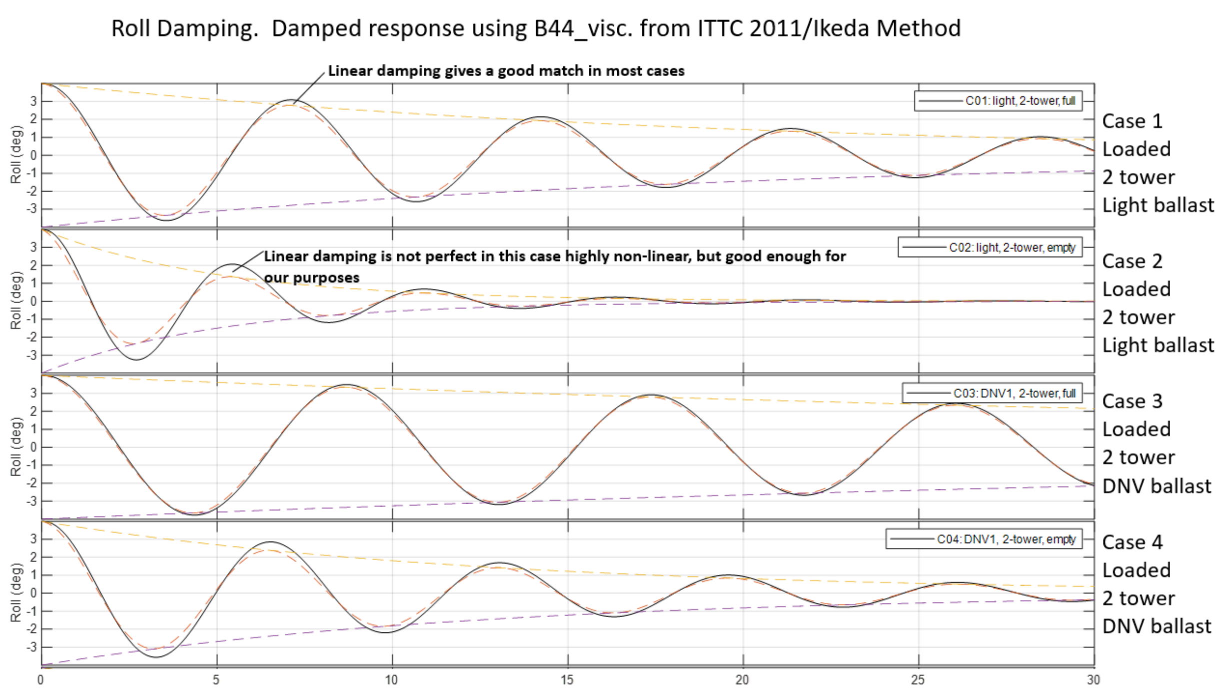


Figure 35 – Free Roll Decay assuming Linear Damping, Load Cases 1-4

Roll Damping. Damped response using B44_visc. from ITTC 2011/Ikeda Method

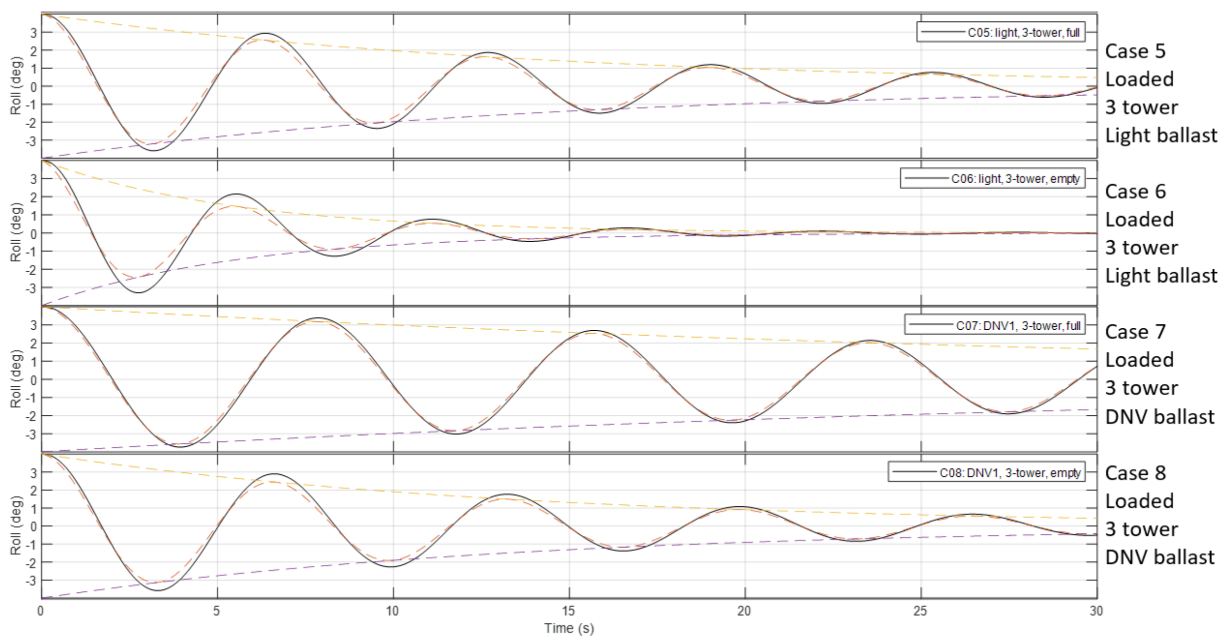


Figure 36 – Free Roll Decay assuming Linear Damping, Load Cases 5-8

Roll Damping. Damped response using B44_visc. from ITTC 2011/Ikeda Method

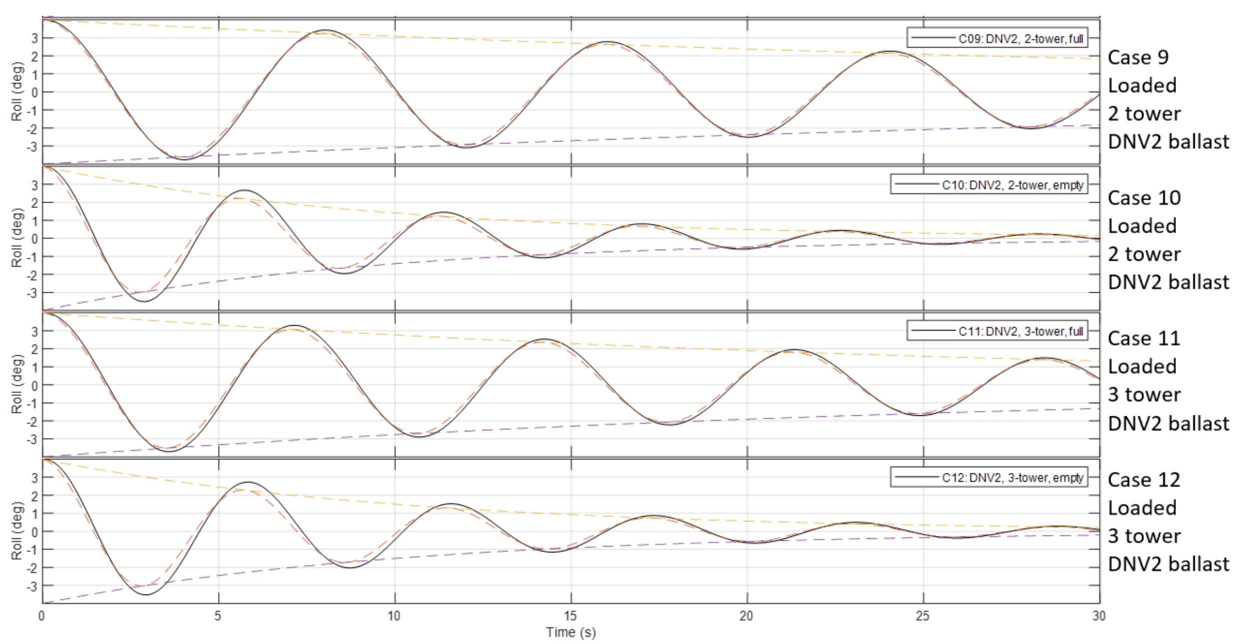


Figure 37 – Free Roll Decay assuming Linear Damping, Load Cases 9-12

B1.5 RAOs from the Frequency Domain Analysis

Response amplitude operators (RAOs) are transfer functions that are used to determine the effect that waves will have on the motion of the ship. An example of the hydrodynamic response amplitude operators (RAOs) is shown in Figure 38.

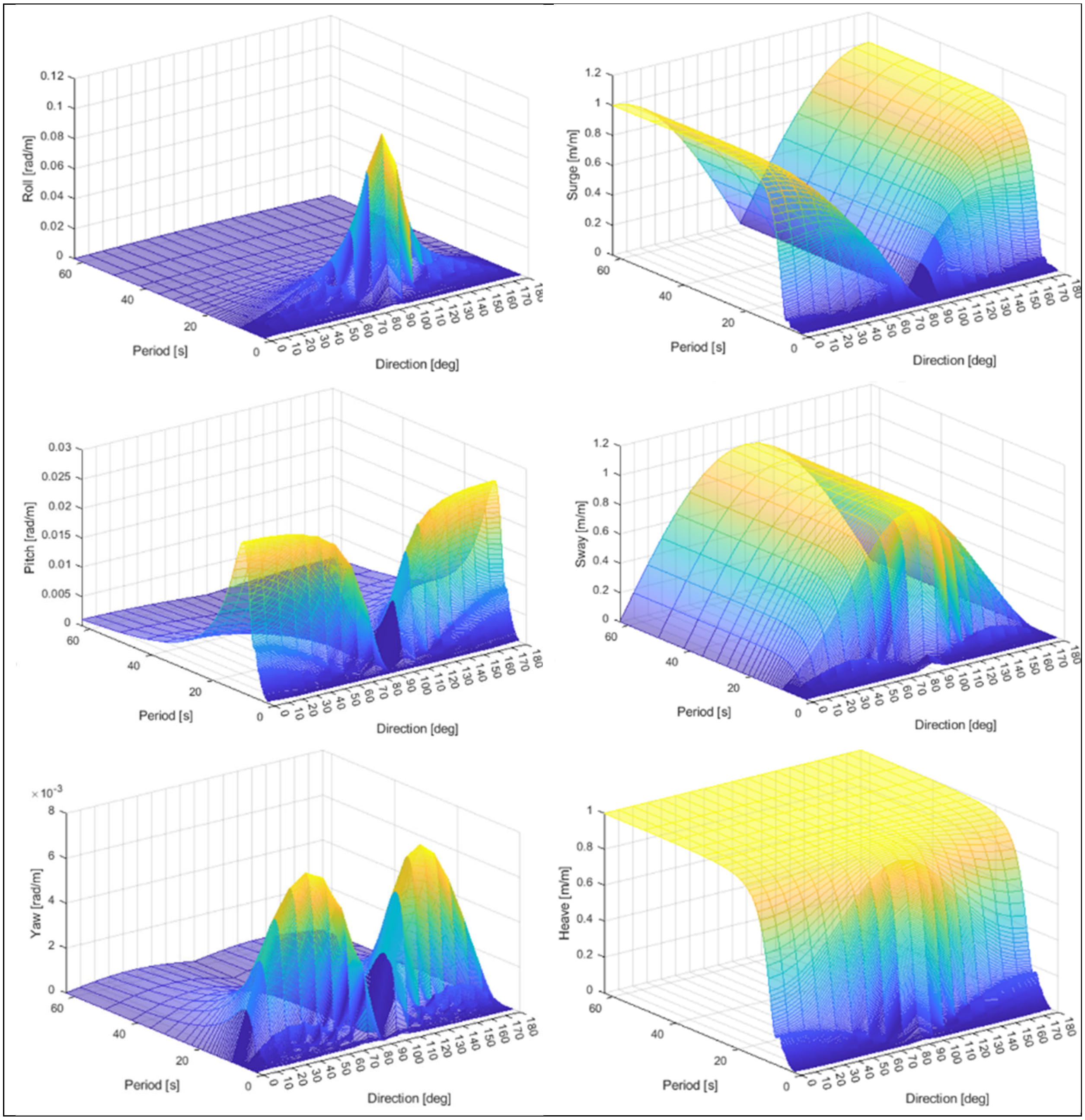


Figure 38 – Example of Hydrodynamic Response Amplitude Operators (RAOs)

The Response amplitude operators (RAOs) were computed using the viscous roll damping coefficients with the Orca software. Some examples of the RAOs resulting for 6 degrees of freedom for the Base Case (2 Towers, Light Ballast) are presented in Figure 39 with direction and frequency, and in Figure 40, for selected directions of 0, 10, and 20 degrees of incoming waves. Also, the added mass coefficients for 6 degrees of freedom are presented in Figure 41.

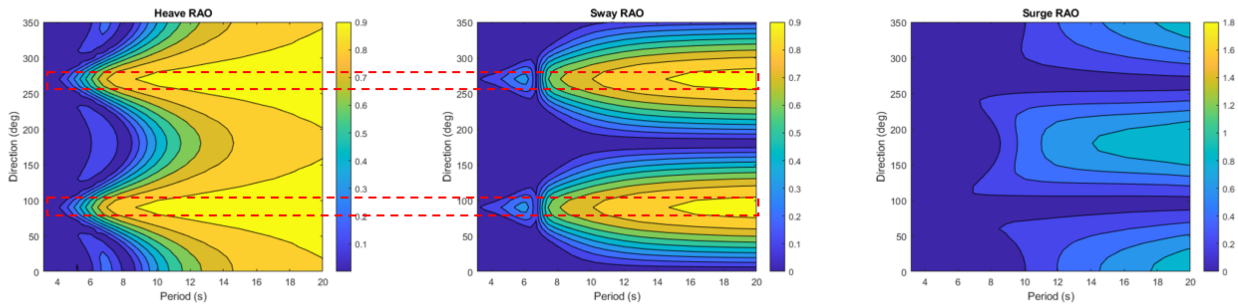
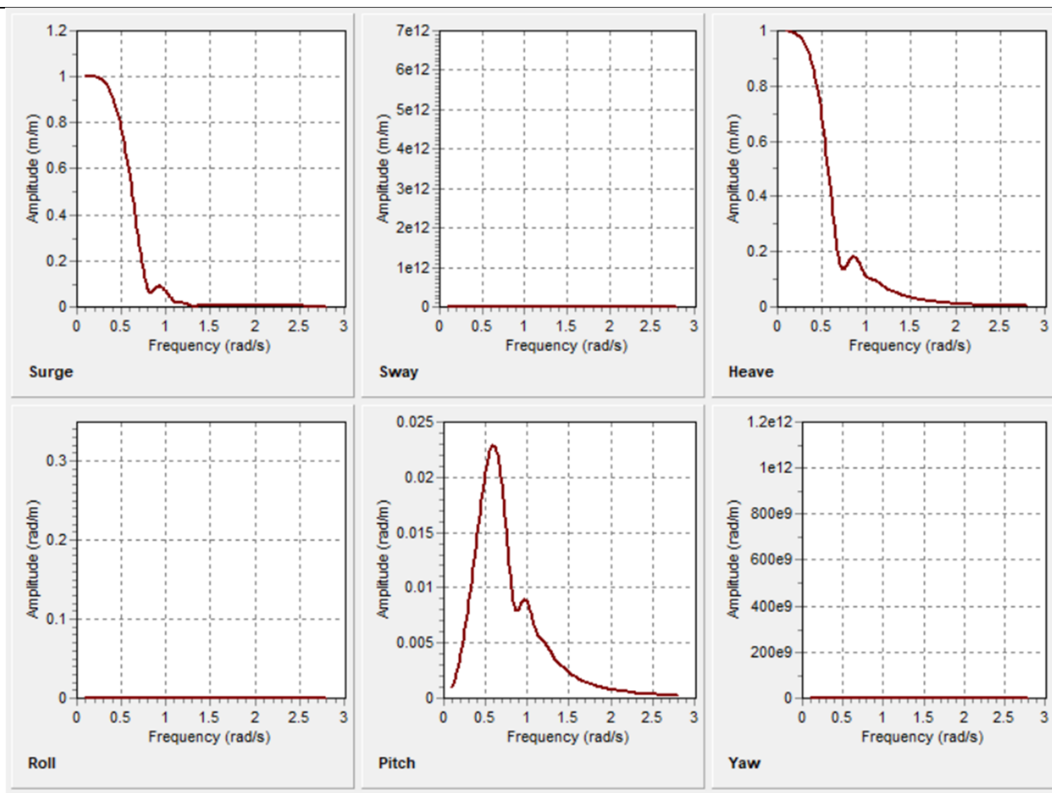


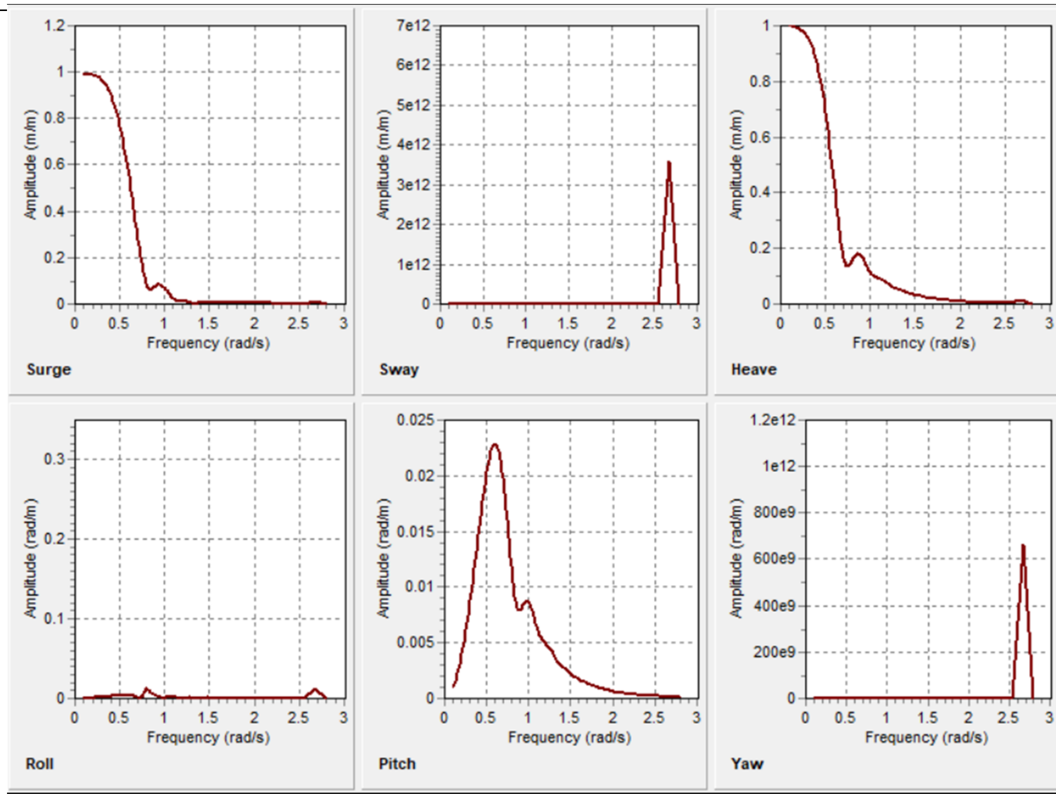
Figure 39 – RAO of the Base Case (2 Towers, Light Ballast), as a Function of Direction and Frequency

See Figure 21 for wave direction convention.

$\phi = 0$



$\phi = 10$



$\phi = 20$

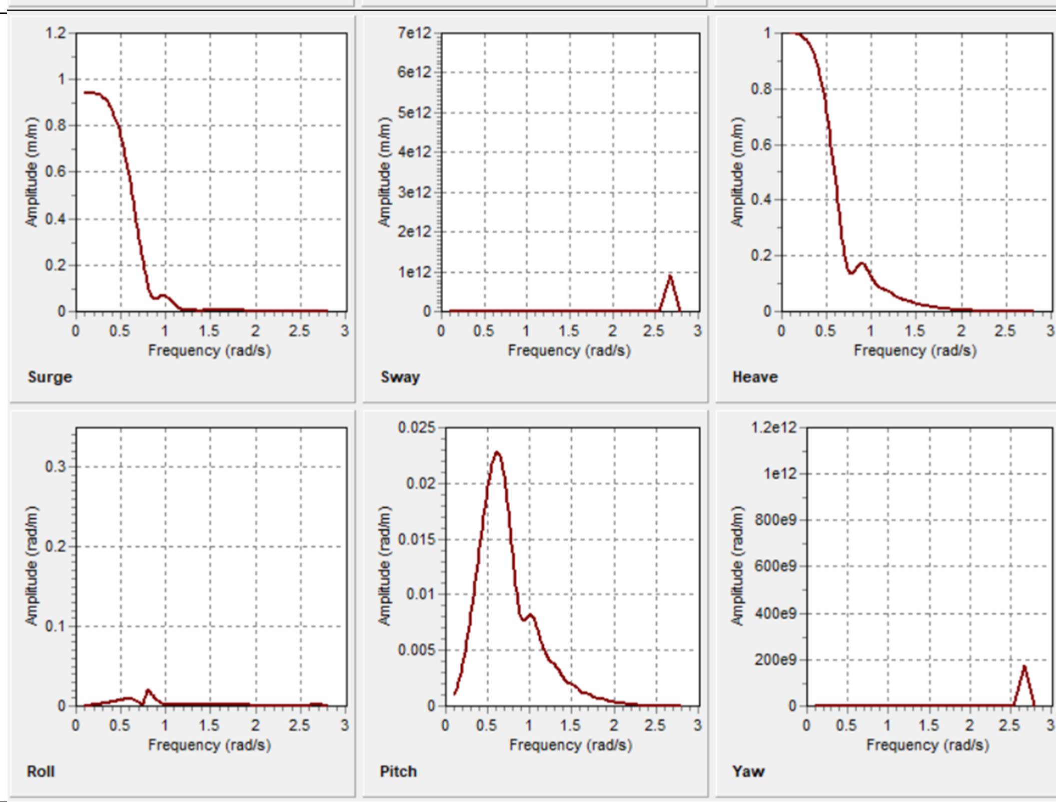


Figure 40 – RAO of the Feeder Base Case (2 Towers, Light Ballast) for three Wave Approach Directions

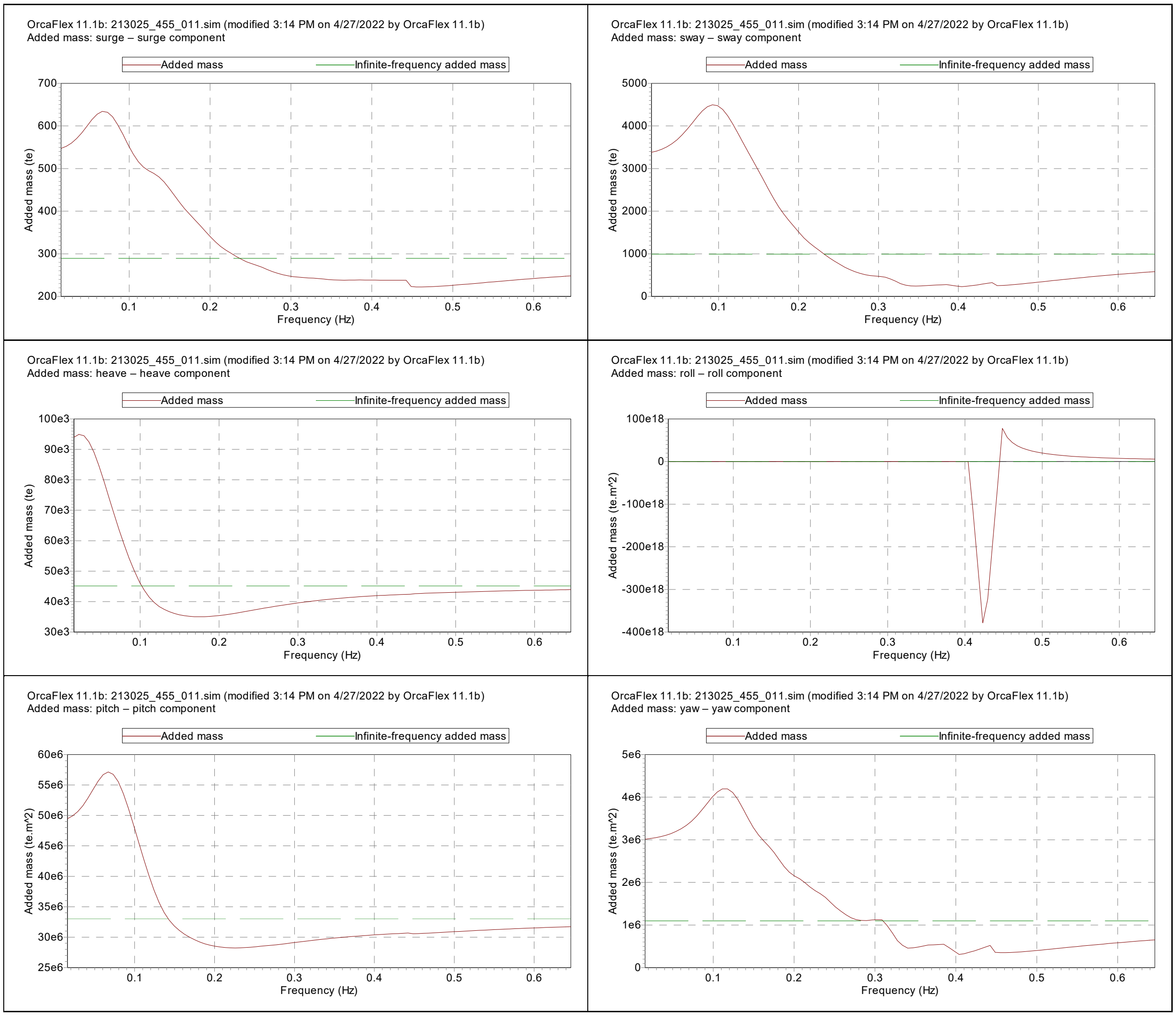


Figure 41 – Added Mass Coefficients as a Function of Frequency for 6 DoF

B2 Hs-Tp-Phi Study

B2.1 Spectral RAOs

Using the methods described above, a comprehensive motion study was conducted using the Orcaflex Frequency Domain Solver and the viscous damping (Ikeda method). The study is a systematic analysis of the six (6) load conditions, both with full cargo and loaded for return voyage, totaling twelve (12) different load conditions described in Section A.1.1.

The measured Variables of Interest (VoI) are displacement and acceleration which are measured the Points of Interest (PoI) including:

	Displacement (m)			Acceleration at CG (g)		
	Base	CG	Top	x	y	z
Tower 1	X	X	X	X	X	X
Tower 2	X	X	X	X	X	X
Tower 3*	X	X	X	X	X	X
Nacelle	X	X	X	X	X	X
Blades, Fwd	X	X	X	X	X	X
Blades, Aft	X	X	X	X	X	X
Feeder Vessel		X		X	X	X
* If tower is divided into three (3) sections.						

Table 21 – Variables of Interest at Points of Interest

Also, from each analysis, multiple statistical properties are computed as:

- RMS
- Most Probable Maximum
- Period
- Spectral moments m0, m1, m2, m3, m4

For each of the twelve load conditions, the motions were systematically evaluated by computing 3,116 SRAOs covering the range of four (4) significant wave heights from 1.0 to 2.5 m in 0.5 m intervals, forty one (41) peak wave periods from 4 to 14 seconds, in 0.25 sec intervals, and nineteen (19) wave directions from 0 to 180 degrees, in 10 degrees steps. In total, responses were collected at a total of 19 locations described in the Displacement portion of Table 21.

B2.2 Hs-Tp-Phi Study Raw Data

The initial Hs-Tp-Phi study was performed on relatively coarse mesh, both in direction and peak periods, with 1 second steps in periods and 30 degrees steps in direction. The results were found to be unsatisfactory because local extrema were not clearly defined. So, the intervals were refined to the levels described in Section A.2.1. The comparison between the results of the coarse and fine mesh, for the expected maximum displacement of the top of tower 1, for a 30-minute exposure period, is presented in Figure 42.

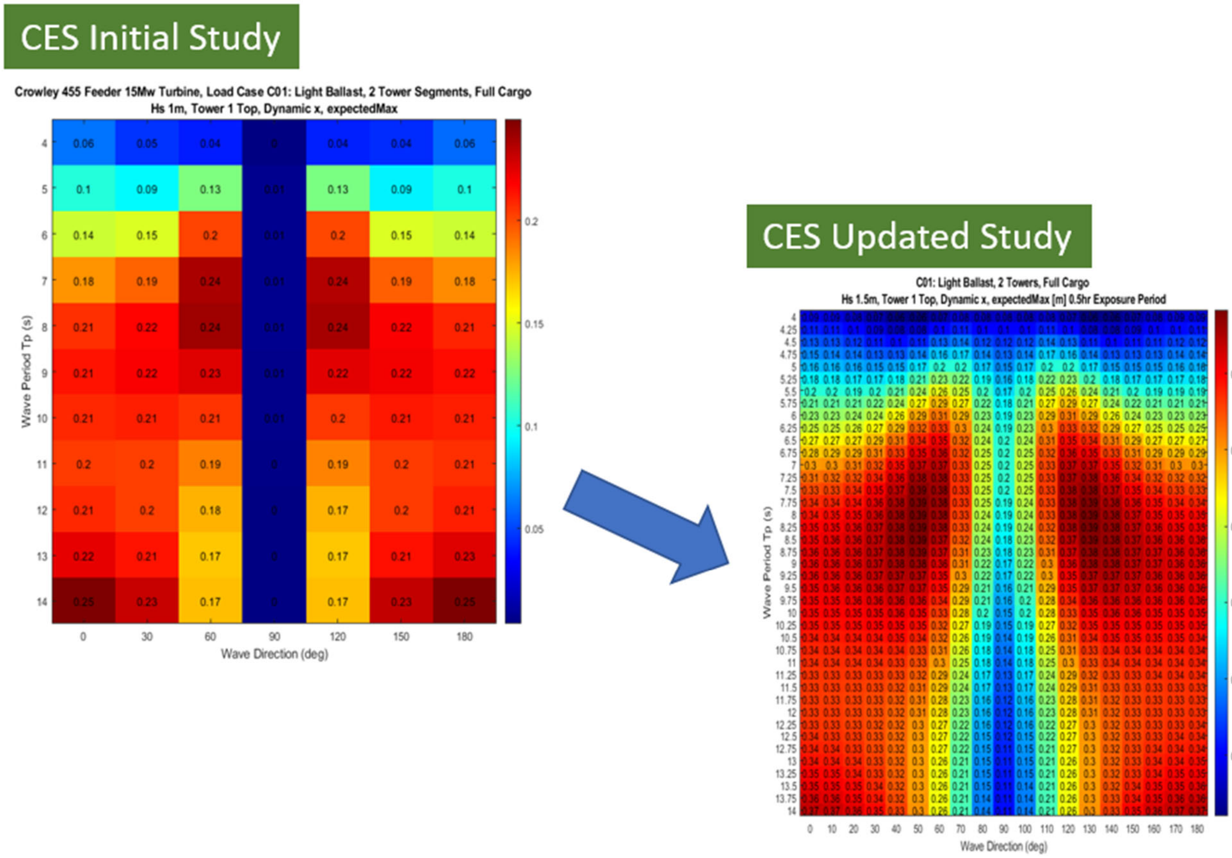


Figure 42 – Comparison between Course (7x11 points) and Fine Grid (19x41 points) for Analysis Case Grid

The database created by the Hs-Tp-Phi study, is very large, in fact, it is too large to be useful as a published document. However, this database as the basis of the weather file that will be used for the Weather Downtime (WDT) analysis to process the weather file into cargo acceleration and feeder motions limits. How this information is used is described briefly in Section A.2.3 and will be described in more detail in the Weather Downtime Report. As an example, the expected displacement motions in meters for a 30-minute exposure period in the x-, y- and z-directions for the Top of Tower 1 (which is one of eighteen points of interest) for the Light Ballast/2 Tower Segments/Full Cargo load condition (which is one of twelve loading conditions) for Hs = 1.5 m (which is one of four significant wave heights) are shown in Figure 43 through Figure 45 below:

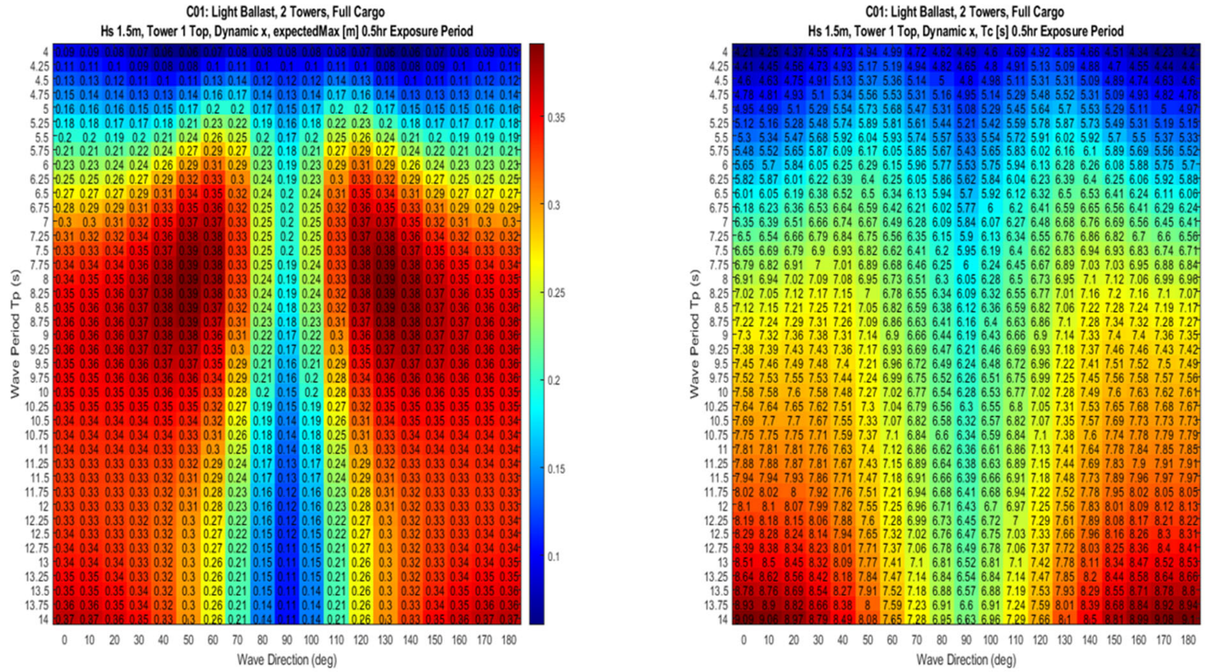


Figure 43 – Hs-Tp-Phi Sample Data for Motions in Longitudinal (x-direction)

As expected, Figure 43 shows, the most extreme longitudinal motions at the tower top occur when the vessel is in quartering seas (ϕ = 30 to 60 degrees or 120 to 150 degrees) and longitudinal motions are minimized when seas are directly on the beam and when the wave period is very small.

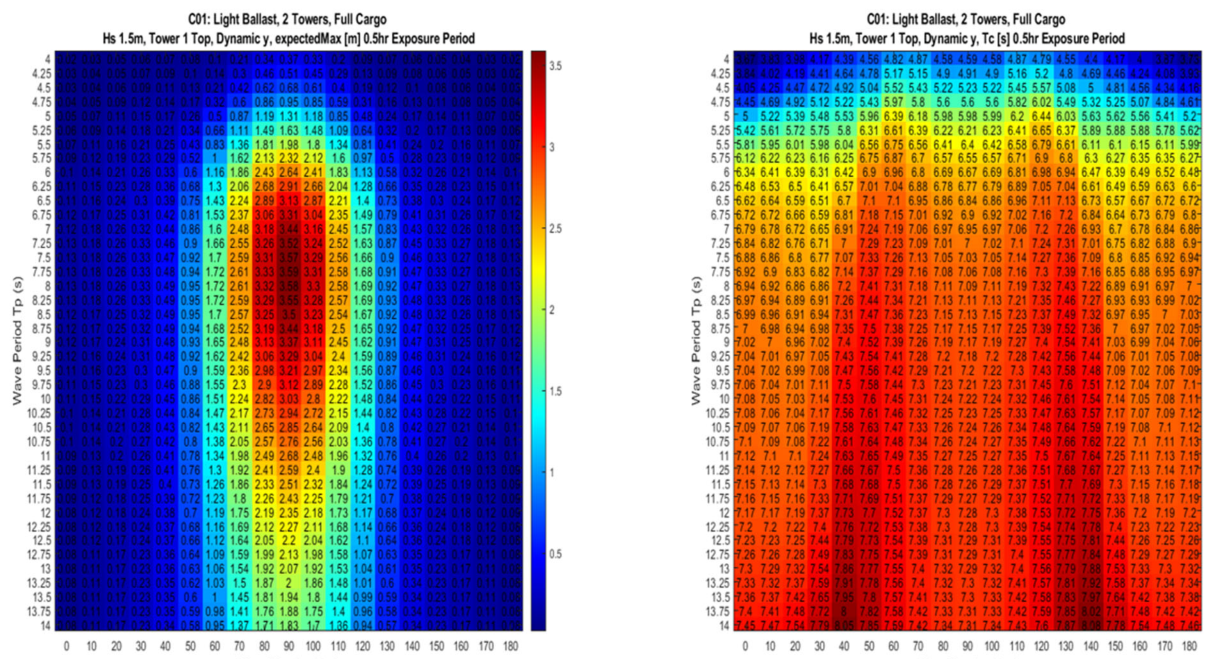


Figure 44 – Hs-Tp-Phi Sample Data for Motions in Transverse (y-direction)

Figure 44 shows, the most extreme transverse motions at the tower top occur when the vessel is in beam seas (ϕ = 90 degrees) and transverse motions are minimized when the vessel is aligned with the waves. The transverse motions are on the order of ten times the magnitude of the longitudinal motions.

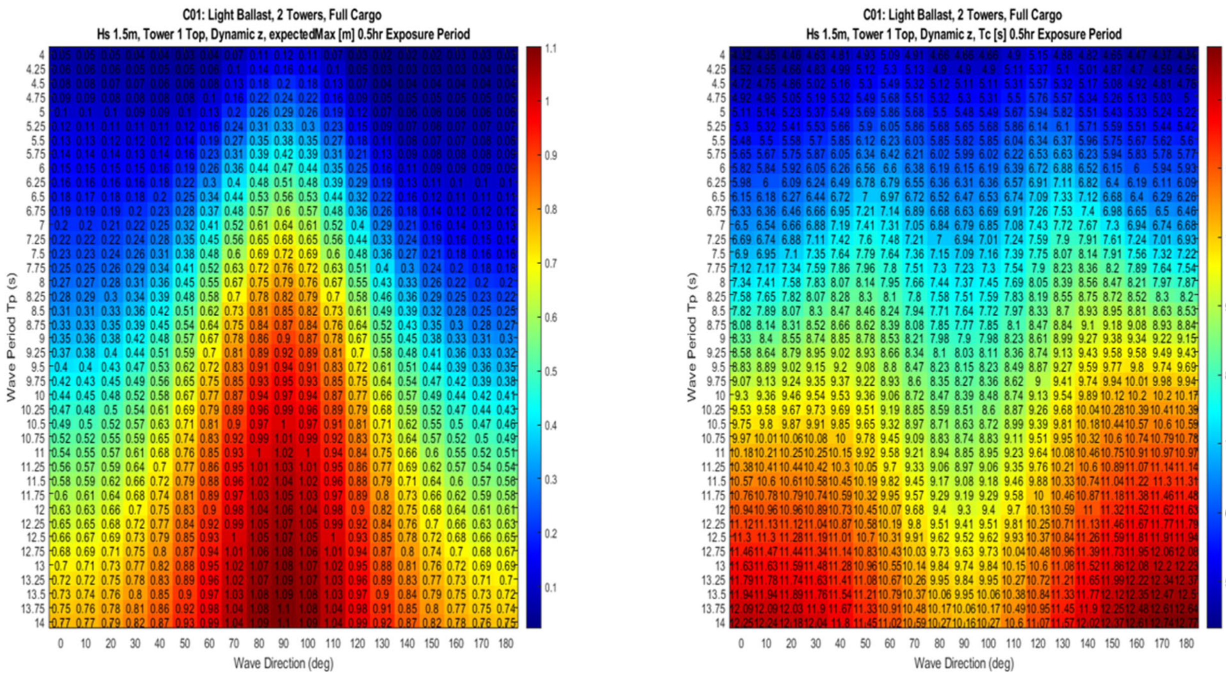


Figure 45 – Hs-Tp-Phi Sample Data for Motions in Vertical (z-direction)

Figure 45 shows, the most extreme vertical motions at the tower top occur when the vessel is in long period beam seas (Tp > 11 sec and ϕ = 90 degrees) and vertical motions are minimized when vessel is aligned with the waves, or the wave period is shorter. The transverse motions are on the order of three times the magnitude of the longitudinal motions.

Figure 46 shows the variation of longitudinal, transverse, and vertical displacement motions in meters for a 30-minute exposure period over a range of wave heights and wave directions for a given wave period. The Tower 1 Top point of interest represents a point in space for each empty cargo position and are only included for illustrative purposes. As expected, the cargo top motions increase as the overall displacement of the feeder is reduced. For this reason, consideration should be given to removing the tallest tower first.

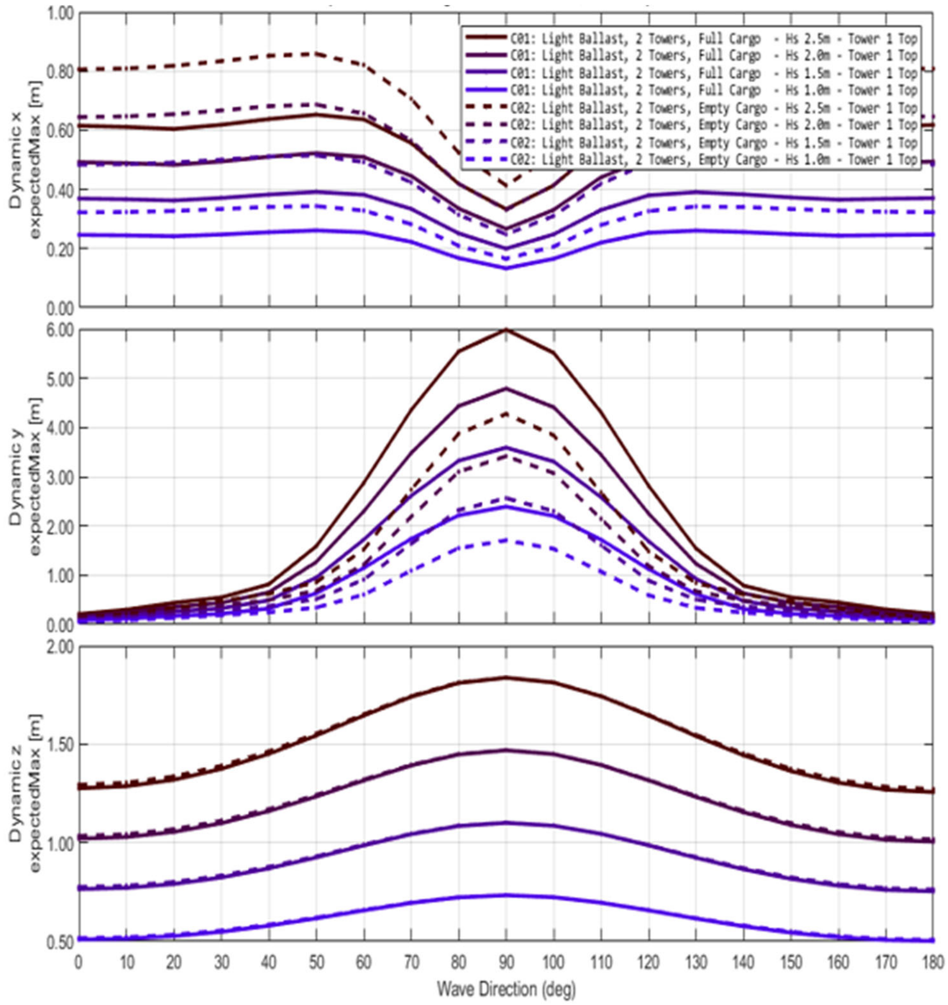
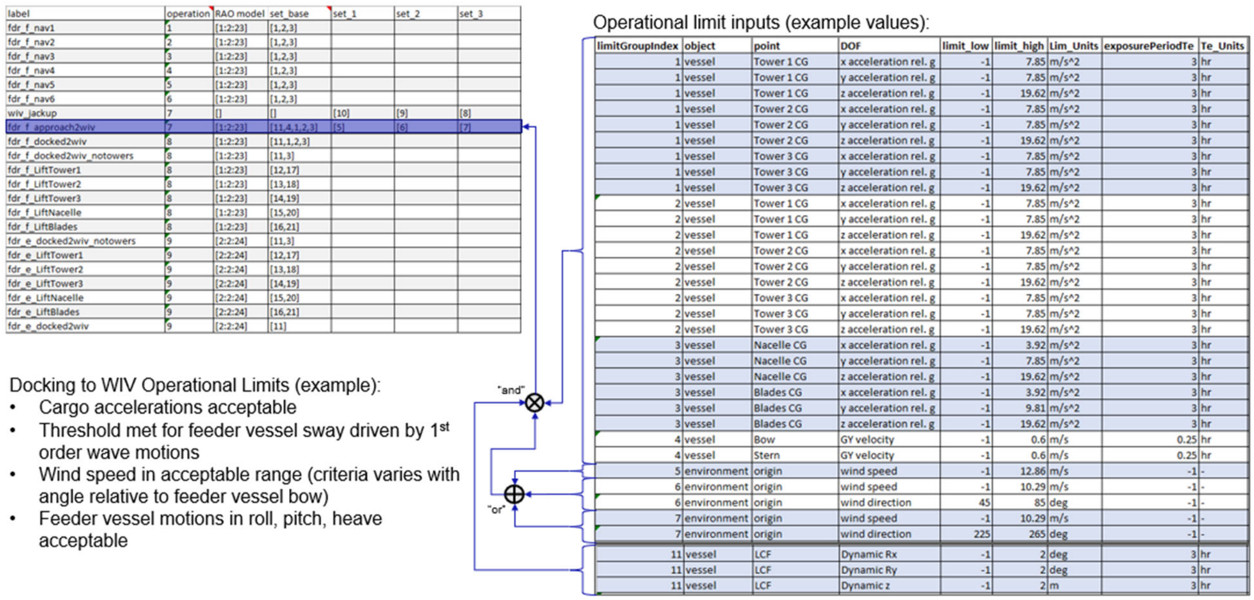


Figure 46 – Hs-Tp-Phi Sample Data for Range of Wave Heights

B2.3 Motions Limits in Weather Downtime Study

As described in Section 3.2.4.1, the Hs-Tp-Phi database is used to pre-process the environmental data to provide a go/no go condition based on weather conditions at each hour for a specified location. The twenty-two composite limits described are created from seventy-five sub-limits. Each sublimit is a variable set by the user:



label	operation	RAO model	set_base	set_1	set_2	set_3
fdr_f_nav1	1	[1:2:23]	[1,2,3]			
fdr_f_nav2	2	[1:2:23]	[1,2,3]			
fdr_f_nav3	3	[1:2:23]	[1,2,3]			
fdr_f_nav4	4	[1:2:23]	[1,2,3]			
fdr_f_nav5	5	[1:2:23]	[1,2,3]			
fdr_f_nav6	6	[1:2:23]	[1,2,3]			
wiv_jackup	7	[]	[]	[10]	[9]	[8]
fdr_f_approach2wiv	7	[1:2:23]	[11,4,1,2,3]	[5]	[6]	[7]
fdr_f_docked2wiv	8	[1:2:23]	[11,1,2,3]			
fdr_f_docked2wiv_notowers	8	[1:2:23]	[11,3]			
fdr_f_LiftTower1	8	[1:2:23]	[12,17]			
fdr_f_LiftTower2	8	[1:2:23]	[13,18]			
fdr_f_LiftTower3	8	[1:2:23]	[14,19]			
fdr_f_LiftNacelle	8	[1:2:23]	[15,20]			
fdr_f_LiftBlades	8	[1:2:23]	[16,21]			
fdr_e_docked2wiv_notowers	9	[2:2:24]	[11,3]			
fdr_e_LiftTower1	9	[2:2:24]	[12,17]			
fdr_e_LiftTower2	9	[2:2:24]	[13,18]			
fdr_e_LiftTower3	9	[2:2:24]	[14,19]			
fdr_e_LiftNacelle	9	[2:2:24]	[15,20]			
fdr_e_LiftBlades	9	[2:2:24]	[16,21]			
fdr_e_docked2wiv	9	[2:2:24]	[11]			

Operational limit inputs (example values):

limitGroupIndex	object	point	DOF	limit_low	limit_high	Lim_Units	exposurePeriodTe	Te_Units
1	vessel	Tower 1 CG	x acceleration rel. g	-1	7.85	m/s^2	3	hr
1	vessel	Tower 1 CG	y acceleration rel. g	-1	7.85	m/s^2	3	hr
1	vessel	Tower 1 CG	z acceleration rel. g	-1	19.62	m/s^2	3	hr
1	vessel	Tower 2 CG	x acceleration rel. g	-1	7.85	m/s^2	3	hr
1	vessel	Tower 2 CG	y acceleration rel. g	-1	7.85	m/s^2	3	hr
1	vessel	Tower 2 CG	z acceleration rel. g	-1	19.62	m/s^2	3	hr
1	vessel	Tower 3 CG	x acceleration rel. g	-1	7.85	m/s^2	3	hr
1	vessel	Tower 3 CG	y acceleration rel. g	-1	7.85	m/s^2	3	hr
1	vessel	Tower 3 CG	z acceleration rel. g	-1	19.62	m/s^2	3	hr
2	vessel	Tower 1 CG	x acceleration rel. g	-1	7.85	m/s^2	3	hr
2	vessel	Tower 1 CG	y acceleration rel. g	-1	7.85	m/s^2	3	hr
2	vessel	Tower 1 CG	z acceleration rel. g	-1	19.62	m/s^2	3	hr
2	vessel	Tower 2 CG	x acceleration rel. g	-1	7.85	m/s^2	3	hr
2	vessel	Tower 2 CG	y acceleration rel. g	-1	7.85	m/s^2	3	hr
2	vessel	Tower 2 CG	z acceleration rel. g	-1	19.62	m/s^2	3	hr
2	vessel	Tower 3 CG	x acceleration rel. g	-1	7.85	m/s^2	3	hr
2	vessel	Tower 3 CG	y acceleration rel. g	-1	7.85	m/s^2	3	hr
2	vessel	Tower 3 CG	z acceleration rel. g	-1	19.62	m/s^2	3	hr
3	vessel	Nacelle CG	x acceleration rel. g	-1	3.92	m/s^2	3	hr
3	vessel	Nacelle CG	y acceleration rel. g	-1	7.85	m/s^2	3	hr
3	vessel	Nacelle CG	z acceleration rel. g	-1	19.62	m/s^2	3	hr
3	vessel	Blades CG	x acceleration rel. g	-1	3.92	m/s^2	3	hr
3	vessel	Blades CG	y acceleration rel. g	-1	9.81	m/s^2	3	hr
3	vessel	Blades CG	z acceleration rel. g	-1	19.62	m/s^2	3	hr
4	vessel	Bow	GY velocity	-1	0.6	m/s	0.25	hr
4	vessel	Stern	GY velocity	-1	0.6	m/s	0.25	hr
5	environment	origin	wind speed	-1	12.86	m/s	-1	-
6	environment	origin	wind speed	-1	10.29	m/s	-1	-
6	environment	origin	wind direction	45	85	deg	-1	-
7	environment	origin	wind speed	-1	10.29	m/s	-1	-
7	environment	origin	wind direction	225	265	deg	-1	-
11	vessel	LCF	Dynamic Rx	-1	2	deg	3	hr
11	vessel	LCF	Dynamic Ry	-1	2	deg	3	hr
11	vessel	LCF	Dynamic z	-1	2	m	3	hr

Figure 47 – Example of Composite Operational Limit: Docking Feeder to WTIV

An example sensitivity analysis of a sublimit is described below.

B2.4 Motion Limit Sensitivity in Weather Downtime Study

The pre-processed motion and acceleration limits can be compared in two ways:

- DES Input – showing the percent of time the weather is below the limits as a raw value, and
- DES Output – showing how the operational availability affects the overall system throughput.

For example, by varying the maximum landing velocity between 0.2 and 0.6 m/s in 0.1 m/s increments, one can see how sensitive the system is to that limit. The available operating time at Empire (Input) is:

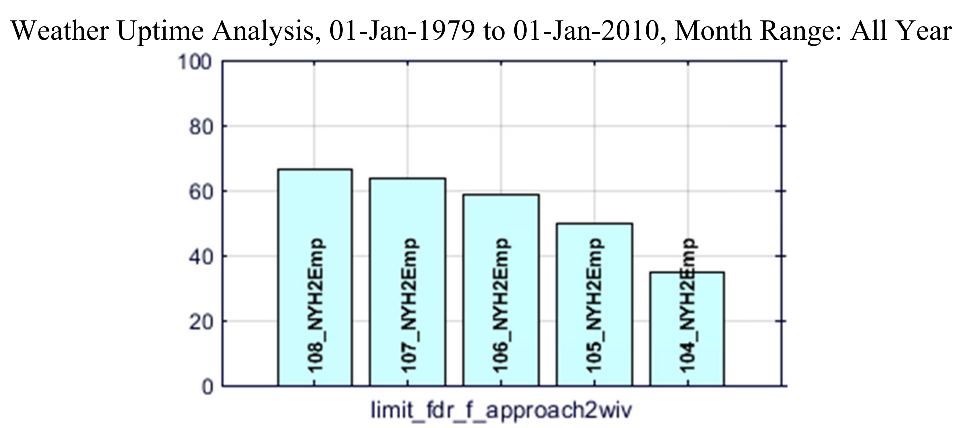


Figure 48 – Operational Availability for Landing Velocities of 0.2, 0.3, 0.4, 0.5 & 0.6 m/sec

The impact of changing the maximum landing velocity limit (between 0.2 and 0.6 m/s in 0.1 m/s increments), changes the overall system throughput at Empire (Output) as follows:

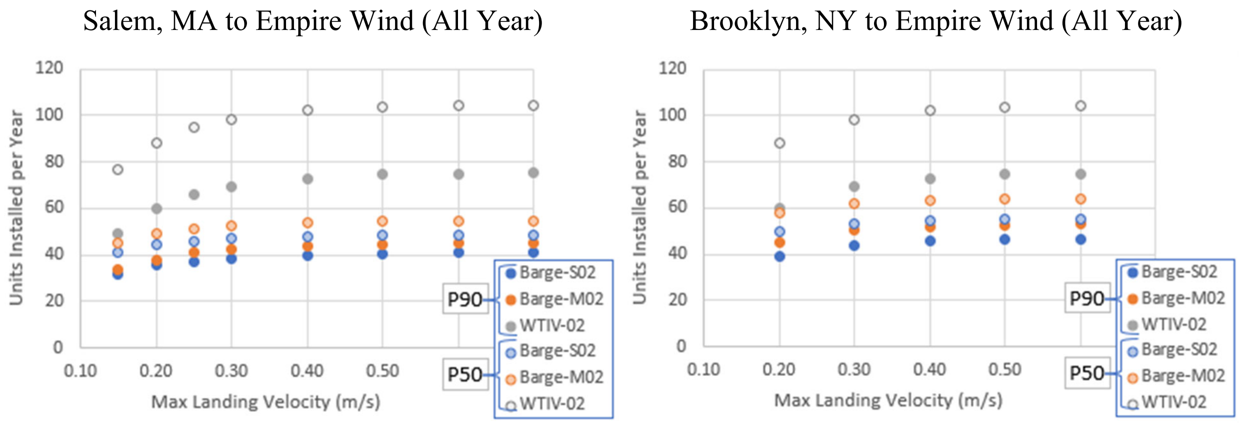


Figure 49 – System Throughput for Varying Landing Velocities

The effect of variation in landing velocity limit can also be seen by month:

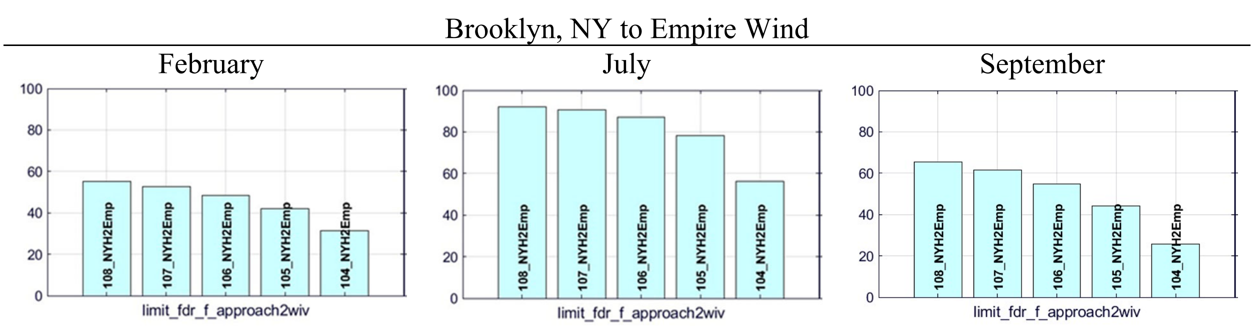


Figure 50 – Operational Availability for Select Months for Landing Velocities of 0.2, 0.3, 0.4, 0.5 & 0.6 m/sec

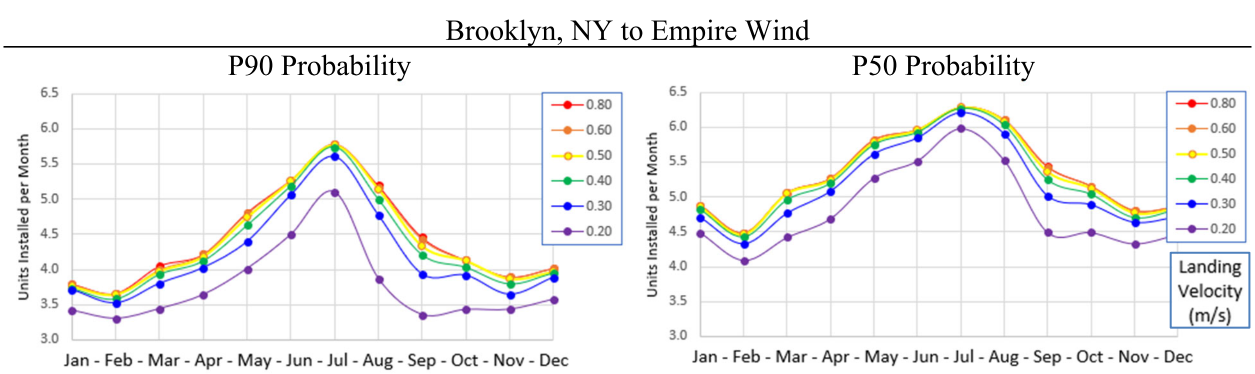


Figure 51 – Monthly System Throughput for Varying Landing Velocities (Units per Month)

As can be seen in Figure 51, the number of WTGs that can be installed in a month varies significantly. At a P90 probability and 0.6 m/s landing velocity, 5.8 units can be installed in July but only 3.7 can be installed in February.

Brooklyn, NY to Empire Wind

P90 Probability | P50 Probability

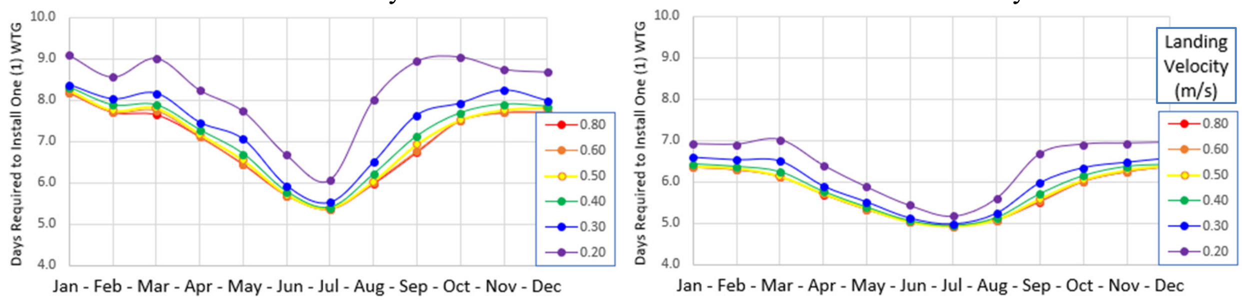


Figure 52 – Monthly System Throughput for Varying Landing Velocities (Days per WTG)

For the WDT study, the Hs-Tp-Phi database will be used in conjunction with the travel direction for the barge when pre-process the environmental data to provide a go/no go condition. For example, the route between Salem and Empire Wind is shown in Figure 53 below. The heading into the second way point (Leg 4) is 167 degrees. The heading away from the second way point (Leg 5) is 285 deg.

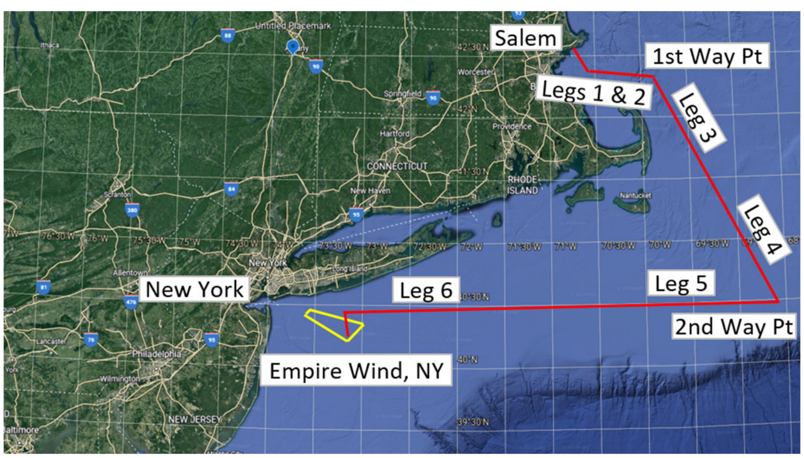


Figure 53 – Feeder Routes between Salem Load Port and Empire Wind

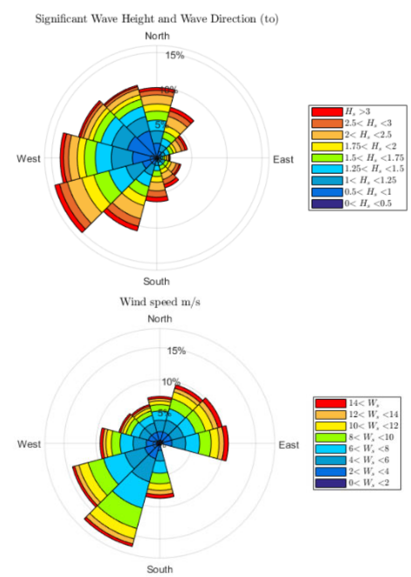


Figure 54 – Wave & Wind Roses at 2nd Way Point

For example, if the cargo acceleration limits are varied between typical limits and acceleration limits that are half or double the typical limits. The available operating time at the 2nd Way Point varies as follows:

Weather Uptime Analysis, 01-Jan-1979 to 01-Jan-2010, Month Range: All Year

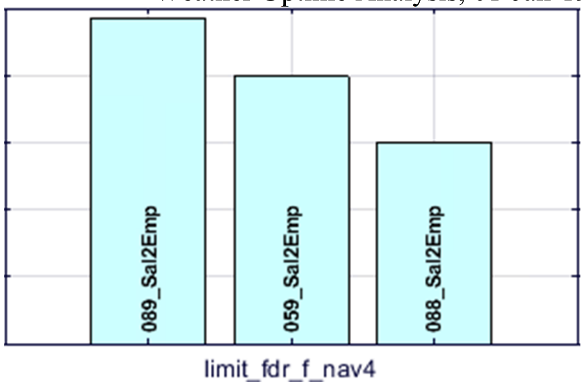


Figure 55 – Example Uptime Analysis for Cargo Accelerations, Leg 4

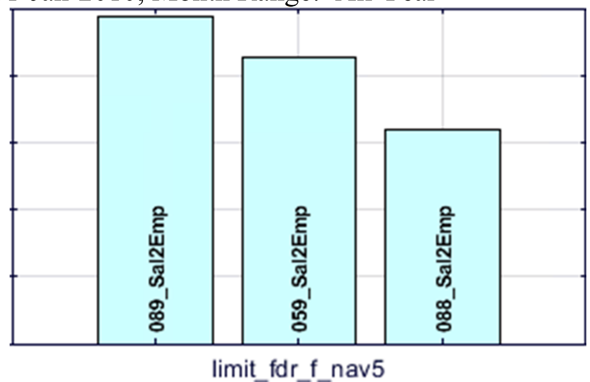


Figure 56 – Example Uptime Analysis for Cargo Accelerations, Leg 5

On Leg 4, with acceleration limits ranging from half the typical limits to twice the typical limits, the operational time varies from 96.7% to 79.8% to 60.1% and at Leg 5, the operational time varies from 97.4% to 85.3% to 64.0% as shown in Figure 55 and Figure 56 above.