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Position-related difference in surface salinity on board ro-ro vessels

A field study of corrosion sensitive cargo exposed to marine salts in the North Sea

Diploma thesis in the Master Mariner Programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The marine atmosphere is one of the most corrosive environments due to its high content of wind-transported salts and high relative humidity. Transporting vehicles with corrosion sensitive parts on open decks is advised against in cargo handling manuals however this recommendation contravenes with the transporter's need for flexibility regarding cargo placement on board. There is also a strong suspicion that regarding exposure to marine salts, some areas on the open decks can actually be compared to the fully closed main deck, where the vehicles are being transported today. The purpose of this study is to examine if this theory can be confirmed through surface salinity measurements, in order to provide the transporter with the knowledge needed as a ground for decision-making of whether it is possible to start shipping corrosion-sensitive cargo placed in such areas or not. This report contains results from a field study made during September-November 2015 on ro-ro vessels transporting vehicles in the North Sea. Using the Bresle method the surface salinity at predetermined cargo spaces is measured before departure and after arrival. These values are then compared to evaluate if there is a difference pre and post the sea voyages and if there are any variations between the cargo space areas. The measured salinity values are supplemented by results from weather observations during the voyages for the purpose of identifying eventual relationships. The results show that most of the areas on board that were considered for shipping of the vehicles have a very small increase in surface salinity. These areas are deemed as suitable for transportation under calm weather conditions. During more severe weather conditions most areas appeared to be unsuitable for transportation as they had a high increase in surface salinity.

Keywords: Bresle, salinity, salt, ro-ro vessel, shipping, corrosion, aluminium, vehicles, transport

Sammanfattning

Den marina atmosfären är en av de mest korrosiva miljöerna på grund av dess höga halter av luftburna salter och dess höga relativa luftfuktighet. Att transportera fordon med korrosionskänsliga delar på öppna däck avråds i lasthanteringsmanualer men dessa rekommendationer går stick i stäv med transportörens behov av flexibilitet när det gäller lastplacering ombord. Det finns också en stark misstanke att, med avseende på exponering för marina salter, vissa områden på de öppna däcken kan jämföras med det helt stängda huvuddäcket där fordonen transporteras i nuläget. Syftet med denna studie är att undersöka om denna teori kan bekräftas genom mätningar av ytsalter, för att kunna tillhandahålla transportören den kunskap som behövs som underlag för beslutsfattandet om det är möjligt att börja frakta korrosionskänsliga fordon placerade i dessa områden eller inte. Denna rapport innehåller resultat från en fältstudie som gjordes i september-november 2015 på ro-ro-fartyg som transporterar fordon i Nordsjön. Breslemetoden användes för att mäta salthalten på ytor placerade i förutbestämda lastutrymmen före avgång och efter ankomst. Dessa värden jämfördes sedan för att ta reda på om det fanns en skillnad efter sjöresan och om några variationer mellan områdena kunde påvisas. De uppmätta saltvärdena kompletterades med resultat från väderobservationer under resorna för att kunna identifiera eventuella relationer. Resultaten visar att de flesta av de områden ombord som antagits passa för placering av fordonen hade en mycket liten ökning av ytsalter. Dessa anses vara lämpliga för transporten under lugna väderförhållanden. Under svårare väderförhållanden verkade de flesta områden vara olämpliga för transport eftersom de hade en stor ökning av ytsalter.

Nyckelord: Bresle, salthalt, salt, ro-ro fartyg, sjöfart, korrosion, aluminum, fordon, transport

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Abbreviations

A	Aft
Bf	Beaufort - Scale for wind measurement
BVK	Port of Brevik, Norway
ECG	The European Car-Transport Group of Interest
FWD	Forward
GD	Garage deck - Open deck located below Weather deck, partially exposed to weather
GNE	Port of Ghent, Belgium
GOT	Port of Gothenburg, Sweden
IMO	International Maritime Organization
MD	Main deck - Fully closed cargo deck
MS	Midship
PS	Port side
RH	Relative humidity
SB	Starboard side
WD	Weather deck - Uppermost deck, exposed to weather

1 Introduction

Transportation of newly fabricated vehicles is a worldwide and complex business. When shipping new trucks and chassis the transporter follows detailed handling procedures stated by an European organization network for vehicle logistics companies (ECG). According to The ECG Operations Quality Manual for Commercial Vehicles (2015), *"All vehicles must be stored under deck. Any exception to this rule must be accepted by the manufacturer by way of a written contract, agreement or instruction."* The manual is intended to be used as guidelines without any legal obligation. Nevertheless, the purpose of this recommendation is that the cargo should not be exposed to the sometimes rough weather, winds and salts of the sea.

One shipping company that transports new vehicles across Europe is the Danish company Det Forenede Dampskib-Selskab (DFDS). It operates in several European countries with headquarters located in Copenhagen, Denmark and local branches spread throughout the World. DFDS is divided in one shipping branch (DFDS Seaways) and a logistics branch (DFDS Logistics). DFDS Seaways is currently shipping truck- and bus chassis for the European markets on board their Ro-Ro vessels, operating routes between Gothenburg and Ghent.

The weather- and garage decks have been deemed unsuitable for the transportation of new vehicles. This recommendation assumes that transportation on these decks would lead to an increased exposure to soluble salts. It is believed by the involved parties (the transporter and the carrier) that exposure during transport is connected to an increased risk of corrosion, mainly on the uncoated aluminium surfaces of the transported vehicles such as the gearboxes. The policy is in line with the recommendations given in the ECG Operations Quality Manual for Commercial Vehicles (2015).

This study was conducted in collaboration with DFDS and Volvo Group in order to determine how much salt the cargo located on weather deck and garage deck is exposed to compared with cargo transported on main deck. The knowledge of how the salt exposure differs on different positions on the cargo decks does not exist today, but a theory exists that some areas on upper deck and weather deck could be more suitable for the transportation of chassis than others. An evaluation of this hypothesis is central in order to assess which areas on which decks that are suitable for the transportation.

1.1 Purpose of the study

The purpose of this study is to compare the difference in surface salinity between cargo units placed in certain areas on the main-, garage- and weather decks on board DFDS' ro-ro vessels following transportion between Gothenburg/Brevik and Ghent. The goal is to provide the knowledge needed for decision making of whether it is possible to start transporting corrosion sensitive cargo on the garage- and weather decks, and to evaluate if there are any positions on these decks that are more suitable than others.

1.2 Questions

This report is based on the following questions:

- How does the difference in surface salinity on cargo units vary depending on what position they have on board during transportation?
- Which positions on the garage- and weather decks appear more suitable than other positions on board for transportation of cargo sensitive to surface salts?

1.3 Delimitations of the study

Due to time restrictions, the field studies are limited to three months; September, October and November 2015. The weather in the North Sea area varies greatly throughout the year and the results obtained can not with certainty be seen as representative for a full year regarding the weather and seasonal aspects. However, the results of a limited study could reveal trends of salt exposure which can be used as an indication of suitable positioning of cargo onboard.

To determine the environments on the different decks according to standardized corrosion classes would have been a relevant part of this study. However, a study of corrosive environments could be up to 2 years for satisfactory results. For this reason the subject of what corrosion classes the atmospheres on the different decks on board DFDS vessels belong to is beyond the scope of this report.

The exposure of metal surfaces to low pH values are also of interest when it comes to corrosion processes. However, due to lack of time and equipment no pH measurements were performed during this study.

2 Background

There is little scientific research on the subject of cargo placement in regard to salt exposure onboard ships. Much of the shipping industry's knowledge is derived from traditions and inherited experience in a thousands of years old business. Today, these traditions and "common knowledge" are reflected in shipping companies' cargo handling manuals, insurance companies' terms of coverage and maritime conventions and laws.

This chapter will cover the topics needed to understand the problematics with surface salinity on board. Firstly, the issues of corrosion, the term "surface salinity" and the marine atmosphere will be explained. Next, the particulars of the DFDS ro-ro ships and the transportation chain of the manufactured vehicles and parts will be described. The final parts of this chapter covers the subjects of metal composition of the involved materials and transportation liability, as well as defined limits of surface salinity.

2.1 Surface salinity - a simplified term

Measuring the actual amount of surface salts is challenging. There is currently no method for accurately collect salts that have congregated on a surface and, for example, weight them. Furthermore, there is a wide range of chemical substances that are categorized as "salts". The predominant salt that exists in a marine atmosphere is sodium chloride (NaCl) (Davis, 2000). However, there is no simple method of determining which composition of salts that are present on a particular surface. Instead of measuring the weight of the salts, one can determine the electrical conductivity (see section 2.2) in a brine consisting of a sample taken from the surface. With a fairly simple equation the conductivity value can represent the equivalent conductivity that would have been measured in a brine consisting of a specific amount of NaCl. An accurate description of the results of the calculation would be "surface density of soluble salts in mg/m^2 - measured as NaCl". The term "surface salinity" is used in this report for practical reasons and to simplify the concept for a better understanding. "Surface salinity difference" refers to the eventual increase or decrease in surface salinity between the two values measured and calculated before departure and at arrival (Frankhuizen, 2009a).

2.2 The effect of salts and relative humidity on corrosion rates

The corrosion rate on a metal surface is connected to several factors. According to Davis (2000), air temperature, pH, relative humidity (RH) and the concentration of corrodents are some of these factors. Corrosive agents are, according to ISO 12944-2 (SIS, 1998b), mainly gases like sulphur dioxide (SO_2) or salts. Chlorides and sulfates are among the main corrosive agents. Salts are present in marine atmosphere as an aerosol formed by salt water spray that is transported by winds. Lide (2005) defines salt as "*an ionic compound formed by the reaction of an acid and a base*". A salt is a neutral substance which when dissolved in water parts into a negatively charged particle (anion) and a positively charged particle (cation). The ions increases the electrical conductivity of the water and turns it into an electrolyte (Frankhuizen, 2009a). The corresponding amount of salt in a brine can be determined by measuring its electrical conductivity with the Bresle method.

ISO 12944-2 (SIS, 1998b) also states that increased corrosion rate is connected to RH and thin water films that appear on a material when it reaches the dew point of the atmosphere. Corrosion is likely to be more substantial in RH above 80%, although the presence of atmospheric pollutants and salts may increase the corrosion rate even at a lower RH. This fact is supported in a study by Rozenfeld et al. (1981), cited by Vargel (2004) which describes the influence of moisture on atmospheric corrosion of aluminium. It is shown that under the presence of 1% SO_2 and with a RH >90% the mass loss rate is 3 $mg/dm^2/day$ while when the RH is lower than 42% the mass loss rate is close to zero regardless of the presence of pollutants.

2.2.1 Types of corrosion

Corrosion is a degenerative process caused by electric currents flowing through a metal from a positively charged area (anode) to a negatively charged area (cathode). From the cathodic area an ionic current is present through a conductive medium to the anodic area. The anode and cathode together with the conductive medium is what constitutes a corrosive cell. The cathodic area is where the effects of the corrosion process is noticeable in form of degradation of the material (Davis, 2000).

There are several different types of corrosion, each with their own characteristics and origins. Davis (2000) has divided corrosion into eight different categories based on their appearance and underlying processes:

- *Uniform corrosion* forms when a metal area is equally exposed to a corrosive environment. This results in a corrosion that covers the whole exposed area. Pitting corrosion is a more localized form of corrosion, which is often characterized by small holes in the metal surface.

- *Crevice corrosion* occurs in narrow spaces and can come as a result of a difference in oxygen levels in narrow spaces and surrounding areas. A metal which has been eroded by external factors such as other metal objects or a water flow can be susceptible to *erosion-corrosion*. The worn-out areas of the metal suffers from an increased corrosion rate which can result in corroded areas of different shapes and forms.

- *Intergranular corrosion* is a corrosive process that can occur when for example two different pieces of metal are welded together. The presence of impurities introduced to the welded areas can lead to a difference in potential within the metals and result in a degenerative process.

- *Dealloying corrosion* can occur in metal alloys consisting of materials with different corrosion resistances. The less resistant materials, being more susceptible to degradation, are gradually removed from the alloy leaving only the more resistant materials. The effects of dealloying corrosion can be seen as more porous areas of the metal alloy.

- *Stress-corrosion* cracking is a result of stress forces acting on a metal alloy in conjunction with a corrosive environment. Not all metal alloys are susceptible to stress-corrosion cracking, but the presence of this process can lead to structural failure if left unmitigated.

- *Galvanic corrosion* forms when two metals with different corrosion resistance are connected by an electrolyte. The corrosion rate of the metal with more corrosion resistance decreases while the corrosion rate in the metal with lower corrosion resistance increases (Davis, 2000). The most common corrosion typse on aluminium alloys are pitting corrosion and galvanic corrosion. Galvanic corrosion of aluminium is especially aggressive in marine atmospheres (Vargel, 2004).

2.3 The corrosivity of the marine environment

The rate of corrosion depends on different factors in the environment as is mentioned in section 2.2. The standard ISO 12944-2 (SIS, 1998b) categorizes environments in six corrosion classes based on their effect on the corrosion rate. The classes range from from C1 (very low) to C5 (very high). There are two types of atmosphere labeled C5 with very high corrosivity. These are C5-I (industrial) and C5-M (marine). The corrosion classes have been established by measuring the material degradation of low-carbon steel and zinc after being exposed to the different environments for one year (SIS, 1998b).

Environments of corrosion class C5-M together with C5-I are the most corrosive environments of the ones categorized by SIS (1998b). C5-M can be found in coastal areas and out at sea, where a marine atmosphere is present. The marine atmosphere is not limited to the oceans, but can extend in over land. The corrosivity of the marine atmosphere is explained by Davis (2000) as a result of the existence of salt particles in the air. The salt particles are carried by winds and end up on the metal surfaces. The amount of salt in the marine atmosphere is strongly connected to the wind direction and strength in the area (Davis, 2000). The salts dissolves in the presence of water or humidity into ions and the contact with the resulting brine causes the metal to corrode and in the case of aluminium, also to tarnish (Vargel, 2004).

2.4 Description of the transportation chain and the operating ships

An order of a new vehicle marks the beginning of a complex assembly- and transportation process. The finished vehicle consists of many parts such as engine, cabin, gearbox and chassi. The parts are individually produced in several different factories in Sweden, transported to Gothenburg and either shipped to Ghent in covered trailers or, if it is a special order with more advanced features, first assembled in the factory in Gothenburg. The Gothenburg factory also produces vehicles intended for the Nordic and overseas market while the majority of the vehicles which are produced for the European and UK markets are assembled in Ghent and then transported onward via sea and land routes. (A. Lingårdsson, personal communication, 2015)

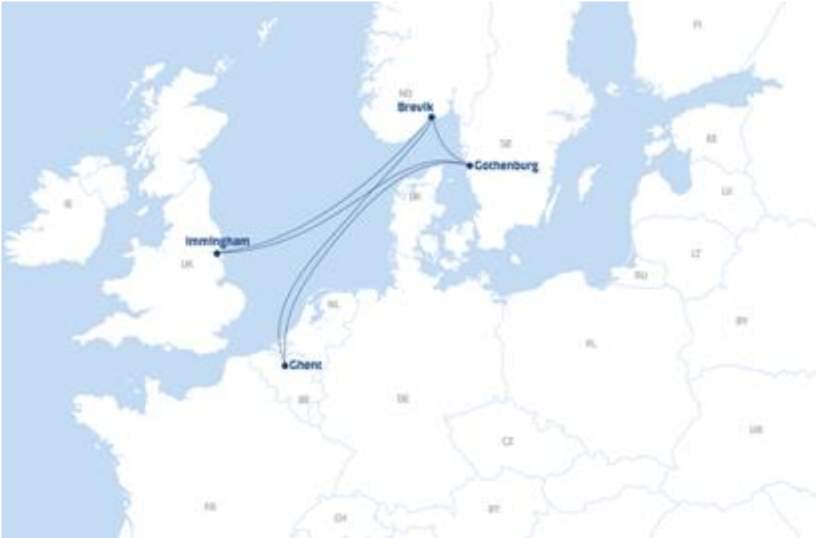

Figure 2.1 Map of the DFDS North Sea transportation chain (2015). DFDS A/S picture archive.

The North Sea routes between Gothenburg/Brevik and Ghent was at the time of this study operated by three of DFDS ro-ro vessels on a 29-34 hour voyage with six departures per week in each direction. The routes are shown in Figure 2.1. The three ships, Magnolia Seaways, Petunia Seaways and Primula Seaways were built in 2003-2004 as a part of a series of six vessels built for DFDS Tor Line at Flensburger Schiffbau Gesellschaft, Germany. They are 199,8 metres long, 26,5 metres wide and have four cargo decks. To meet the regulations of sulphur emission that entered into force in 2015 they are all fitted with sea water scrubbers. A scrubber is an exhaust after-treatment system that utilises sea-water in order to reduce the amount of sulphur dioxide (SO_2) in the exhaust gas (Karle I-M and Turner D., 2007). Figure 2.2 shows Magnolia Seaways at sea and a schematic figure of a DFDS vessel with ship-specific terms utilized in this report is provided in figure Figure 2.3.

Figure 2.2 DFDS vessel Magnolia Seaways under way (Photographer unknown, Year unknown). DFDS A/S picture archive.

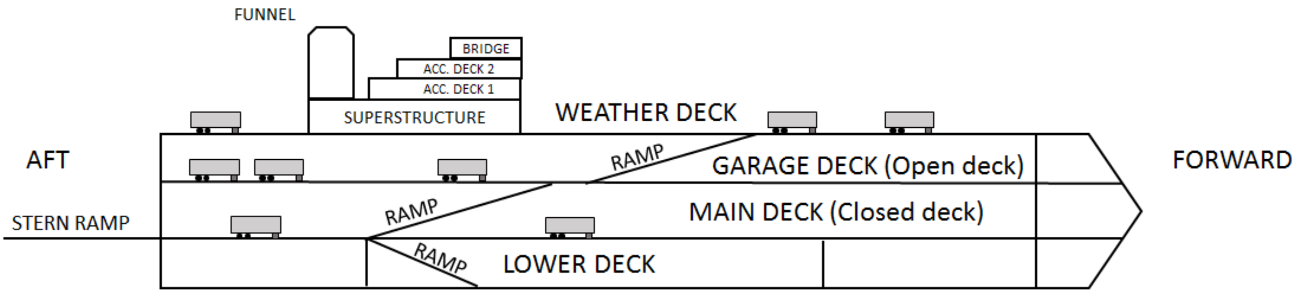

Figure 2.3 Schematic of a DFDS vessel showing different areas of the ship

As is shown in Figure 2.3, all DFDS vessels have four cargo decks. Lower deck and Main deck are fully closed decks while Garage deck and Weather deck are open to the outdoor elements. All decks are connected via cargo ramps with watertight cargo doors sealing off the closed decks.

2.4.1 Why do the ships have open decks?

There is a reason most ro-ro vessels have different types of decks. If all of the DFDS vessels' decks would have been closed (like main deck) the subject of cargo exposure to weather would not be a problem. The reason mentioned is that they also transport cargo classified as "*Dangerous Goods*" by The International Maritime Dangerous Goods Code (IMDG). Dangerous goods means inter alia explosives, flammable solids and liquids, poison and oxidizing agents. The handling of these items and the requirements of the transporting ships is regulated in detail by the IMDG code (IMO, 2012). The IMDG code lists and describes all materials, substances and articles that are classified as dangerous or hazardous, some of which needs to be transported on open decks or weather decks due to the hazards of the cargo (IMO, 2012).

IMO (2009) has stipulated in the International Convention for the Safety of Life at Sea (SOLAS) chapter VII that all carriage of dangerous goods on board ships is to be done according to the rules and guidelines given in the IMDG code. DFDS vessels have open ro-ro cargo spaces in form of a partly open deck located below weather deck in order to utilize more of the vessels cargo space for the transportation of dangerous goods (see Figure 2.3). IMO (2012) defines an open ro-ro cargo space as "*a ro-ro cargo space either open at both ends, or open at one end and provided with adequate natural ventilation effective over its entire length through permanent openings in the side plating or deckhead to the satisfaction of the Administration*". The term "weather deck" is defined by IMO (2012) as "*a deck which is completely exposed to the weather from above and from at least two sides*".

2.5 Alloy composition of the test plates and the sensitive parts of the vehicles

The gearboxes on the vehicles in this study are made of a copper-containing aluminium casting alloy of the 40000 series. The numerical name of the series and alloy is standardized and published by the Swedish Standards Institute (SIS) in SS-EN 1780 (2002) and depend on the composition of the alloy. In more detail, the European standard name for the particular alloy is AC-46000. In addition to aluminium, the main metals included are silicone (8-11%), copper (2-4%), zinc (maximum 3%) and magnesium (0,05-0,55%). Each component has its influence on the finished product and while copper improves some of the mechanical properties, it also decreases the resistance to corrosion (Vargel, 2004). Additionally, while aluminium generally has a good resistance to sodium chloride (NaCl) this does not include alloys with added copper such as AC-46000. When in contact with NaCl (which is present in a marine atmosphere, see section 2.3), the consequences according to Vargel (2004) are that aluminium will tarnish and be subject to pitting corrosion.

The test plates utilized in this study are made of aluminium alloy 5754 in the 5000 series. Similar to the 40000 series, its numerical name is standardized by SIS (2005). Besides aluminium, it contains magnesium (2,5-4%) and a smaller percentage of additives such as manganese and chromium (Vargel, p.64, 2004). It is among other things used for shipbuilding and because of its exceptional resistance to corrosion and NaCl reactions it can also be used in the food- and salt mining industry (Vargel, 2004). The surface features differ between the two materials described in the paragraphs above. While the gearboxes are rough, matte and somewhat porous the test plates utilized have smooth and shiny surfaces.

2.6 The shipper's and the carrier's cargo liabilities

Damage such as tarnishing, wet storage stains and corrosion can become grounds for legal claims from the recipient of the vehicle. *The International Convention for the Unification of Certain Rules of Law relating to Bills of Lading*, more commonly known as the "Hague-Visby Rules" is an international convention and set of transportation rules that are ratified in Nordic maritime law. The rules are referred to in the terms and conditions issued by both the carrier and the merchant in this study (DFDS, 2011 & Volvo Logistics Corporation and Associates, 2009). The Hague-Visby Rules regulates the division of cargo liability between the shipper and the carrier and is, when applicable, included in the transport document known as Bill of Lading (B/L). Generally, when any cargo that is intended for shipment is ordered a B/L is drawn and is issued in three copies, one for each party involved (the shipper, the carrier and the recipient). It works as a cargo receipt and an evidence for the contract of carriage (with the transportation rules as a clause or reference). The B/L also contains a detailed description of the condition of the cargo and its physical properties (Schelin & Severin, 2012). If a vehicle is damaged as mentioned above it does not match the original description and the recipient can claim compensation from the other parties. This often leads to extra expenses and is an affliction for all the involved parties worth making efforts to avoid.

2.7 Surface salinity limit on surfaces before coating

There are several areas in the maritime business where the density of surface salts is a subject of interest. One of these areas are preparation of steel surfaces before the application of paints and coatings. IMO has developed a performance standard for the preparation of steel surfaces in ballast tanks before coating. In this standard the maximum recommended surface density of soluble salts (measured as NaCl) is 50 mg/m^2. If the surface salinity is lower than 50 mg/m^2 the steel surface is regarded as clean enough for painting (IMO, 2006).

3 Method

This report is based on the result of six field studies performed on board DFDS vessels during their voyages on the North Sea. Surface salinity measurements using the Bresle method were performed on test plates which were placed on different locations on board the ship at the time of departure. The Bresle method is a standardized test of the conductivity of a sample taken from a surface to determine the surface salinity and is described in detail in section 3.5. On arrival at the destination the plates were collected and a second Bresle test was performed to establish the difference in surface salinity. Weather observations and excerpts from the ships' log books were taken in order to monitor the different weather states during the voyages. In addition to the onboard measurements, field studies were performed at the port of Gothenburg in one of the ro-ro terminals and at a production site for truck chassis. All collected surface salinity data was calculated into mean values for the different positions and voyages and compared in order to see which positions obtained the lowest average surface salinity difference during the voyages.

3.1 The positions of interest on board

To determine the most suitable locations for measurements on board a visit to the vessel Primula Seaways was made on the 18th of August 2015. Together with representatives from the two companies involved a visual inspection of the different cargo decks was performed and possible test locations were identified and noted. This visual inspection resulted in establishment of 16 pre-determined positions of interest. The testing locations were purposely chosen to represent different surroundings onboard. For example, seven positions were located at starboard side and equally many on port side, ten were covered from above by an upper deck and five were not, eight were partially sideways protected from weather by bulkheads and two were completely protected by the same. Ten of the locations were chosen under the assumption that they would be most suitable for the transportation of chassis. The remaining positions were chosen for the purpose of reference, at spots where heavy salt contamination was expected and also on the fully closed main deck where no or little contamination was anticipated. An illustrated figure of the positions chosen is provided in Figure 3.3.

3.2 A pilot study

A pilot study was performed on the 6th to 8th of September 2015 on a round-trip with Magnolia Seaways between Gothenburg and Ghent in order to establish detailed routines before the first voyage. All equipment, including the Bresle kit and the measuring instrument for RH, temperature and air pressure (model Testo 480) was tested and collected data was evaluated.

With the experiences and lessons learned during the pilot study the need for further preparations before the main study was apparent. An estimate of the necessary complementary equipment was identified and listed. Furthermore, the trailers showed not to be optimal as testing spots due to heavy contamination. During the pilot study the surface salinity measurements were performed on actual cargo units, mostly trailers. The spot to be tested was wiped with a wet rag and then measured using the Bresle kit. Several of the cargo units were dirt stained and greasy (as trailers usually become over time) and the results from the tests were not quite as reliable as anticipated. A decision was made to manufacture test plates out of aluminium in order to obtain as uniform data as possible. These plates were to be used as substitutes for actual cargo units, their composition and similarities to the trailers are further described in chapter 2.5. The test plates were fabricated in Gothenburg and collected by a representative from DFDS, who made them available at the time of the next voyage.

3.3 The time, duration and other features of the voyages

One pilot study and three final round-trips were made hence a total of six final measurements on each predetermined location was completed. Each voyage took between 29 and 34 hours depending on the route and time schedule for the vessel, see Table 3.1 for details. Two of the studies was carried out on voyages between Ghent (GNE) and Brevik (BVK). Nevertheless the proximity in distance to Gothenburg (GOT) and its similar atmospheric properties renders it as an acceptable substitute for Gothenburg as a destination in this study. Voyage 1 and 2 were the round-trips where the pilot study was performed. The data obtained from voyages 1 and 2 are therefore not included in the results section of this report.

Table 3.1 List of voyages during the field study

	Vessel	Route	Departure	Arrival	Duration
Voyage 1 (pilot)	Magnolia Seaways	GOT-GNE	2015-09-06, 23:00	2015-09-08 06:00	31h
Voyage 2 (pilot)	Magnolia Seaways	GNE-GOT	2015-09-08, 13:00	2015-09-09 18:00	29h
Voyage 3	Petunia Seaways	GOT-GNE	2015-09-25, 04:00	2015-09-26 14:00	34h
Voyage 4	Petunia Seaways	GNE-GOT	2015-09-26, 22:00	2015-09-28 07:00	33h
Voyage 5	Magnolia Seaways	GOT-GNE	2015-10-08, 04:00	2015-10-09 14:00	34h
Voyage 6	Magnolia Seaways	GNE-BVK	2015-10-09, 22:00	2015-10-11 04:00	30h
Voyage 7	Magnolia Seaways	GOT-GNE	2015-11-05, 04:00	2015-11-06 14:00	34h
Voyage 8	Magnolia Seaways	GNE-BVK	2015-11-06, 22:00	2015-11-08 04:00	30h

3.4 Testing the surface salinity on units ashore

In addition to the round trips, measurements were taken ashore in order to compare the surface salinity difference *during transport* with the surface salinity *before transport.* On september 28th, a field study at a production site in Tuve, Gothenburg were performed in order to get values of surface salinity from the earliest stage in the transportation of chassis. Five Bresle tests were performed as described in section 3.5.1 on different units which had been positioned outside for varied periods of time.

Further measurements ashore were taken in port in order to compare the surface salinity difference *during transport* with the surface salinity difference on units *during the time awaiting transport*. A total of five test plates were placed at different locations at the ro-ro terminal in the port of Gothenburg on the 17th and 26th of november. Four plates were placed at the location where truck chassis are usually parked in the terminal before being loaded onto vessels bound for Ghent. Two plates were placed closer to the waterfront. The plates were left in the harbour for a period of 30 hours (to resemble the duration of a voyage) after which they were collected and tested for surface salinity differences. The weather data for these time periods was retrieved from a metorological website, www.smhi.se.

3.5 The procedure and equipment utilized for surface salinity measurements

To determine the surface salinity differences on the different positions a field study using the Bresle method was conducted in September – November 2015. The measurements were performed on 20x20 cm test plates made of aluminium (see section 2.5). The plates were newly fabricated for the purpose of this study and therefore considered as clean. Before departure each plate was marked and catalogued before the Bresle test was performed. The plates were suspended using 4mm Ø polyester braided rope, one at each location described in section 3.1. Time, position, base value and plate value was noted. During the voyage all plates were checked repeatedly for any sign of suspension failure. On arrival to the destination the plates were collected and measured a second time with the same procedure as before departure and the difference in surface salinity was calculated using the equation described in section 3.7.1.

The Bresle testing kit is shown in Figure 3.1 and consists of a hard case containing the following:

- 1x Conductivity meter
- 1x Conductivity probe
- 25x Bresle patches
- 1x Syringe and needle
- 1x Test vial
- 1x Flask containing deionized water
- 1x Plastic brush
- 1x Magnetic square

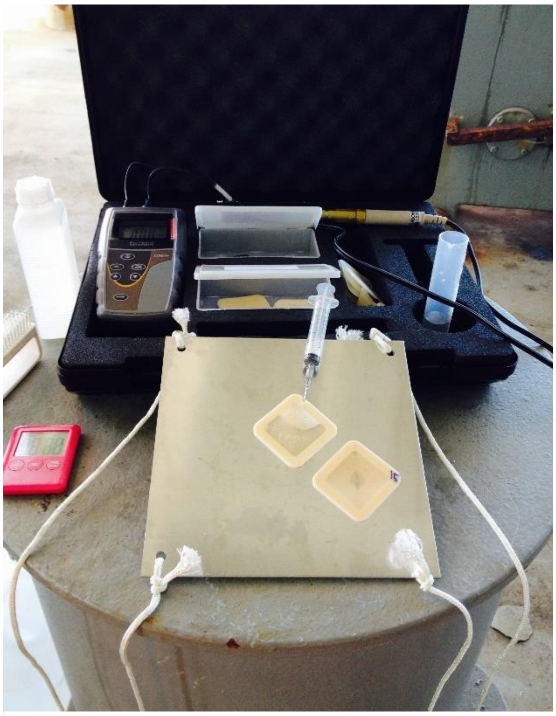

Figure 3.1 The Bresle test kit and one of the test plates during measurements on board (Anders Larsson, 2015). Private photo collection.

The equipment used to conduct the Bresle test and the procedure followed are standardized in ISO 8502-6 (SIS, 2006) and ISO 8502-9 (SIS, 1998a). It was originally developed for the purpose of determining the amount of water-soluble salts on steel surfaces prior to application of protective coating.

3.5.1 Base value and plate value explained

There are two values used to determine the surface salinity on the test plates in this study. What follows is a description of these two values and the procedure for obtaining them using the Bresle test kit. The values are utilized in the calculations described in section 3.7.1.

The base value is the conductivity value of the deionized water at the start of the testing procedure. The test begins with pouring 15 ml of deionized water into the test vial. The syringe and needle is filled with the water, and directly emptied again into the vial. This is to make sure that both syringe and needle are as clean as possible for the testing procedure. The conductivity probe is connected to the conductivity meter and the meter is turned on. The probe is placed in the liquid and the value is noted. If the shown value is above 5 µS (microSiemens) the conductivity in the water is, according to the ISO 8502-9 (SIS, 1998a) standard, too high to be acceptable as a base value and the probe needs to be rinsed in deionized water before performing the first steps again. This procedure is repeated until the base value shown is below 5 µS.

After the base value has been established and noted, the syringe is used to collect 3 ml of the deionized water. The water is injected into one of the adhesive Bresle patches that has been attached to a test plate or to a cargo unit. In order to dissolve as much of the soluble salts on the metal surface as possible, the water is repeatedly removed and injected into the Bresle patch using the syringe and needle. This procedure is continued for five minutes after which all of the water is collected in the syringe and returned to the test vial. The conductivity probe is then submerged in the water and the resulting value, the plate value, is calculated and noted.
The procedure is shown in Figure 3.2.

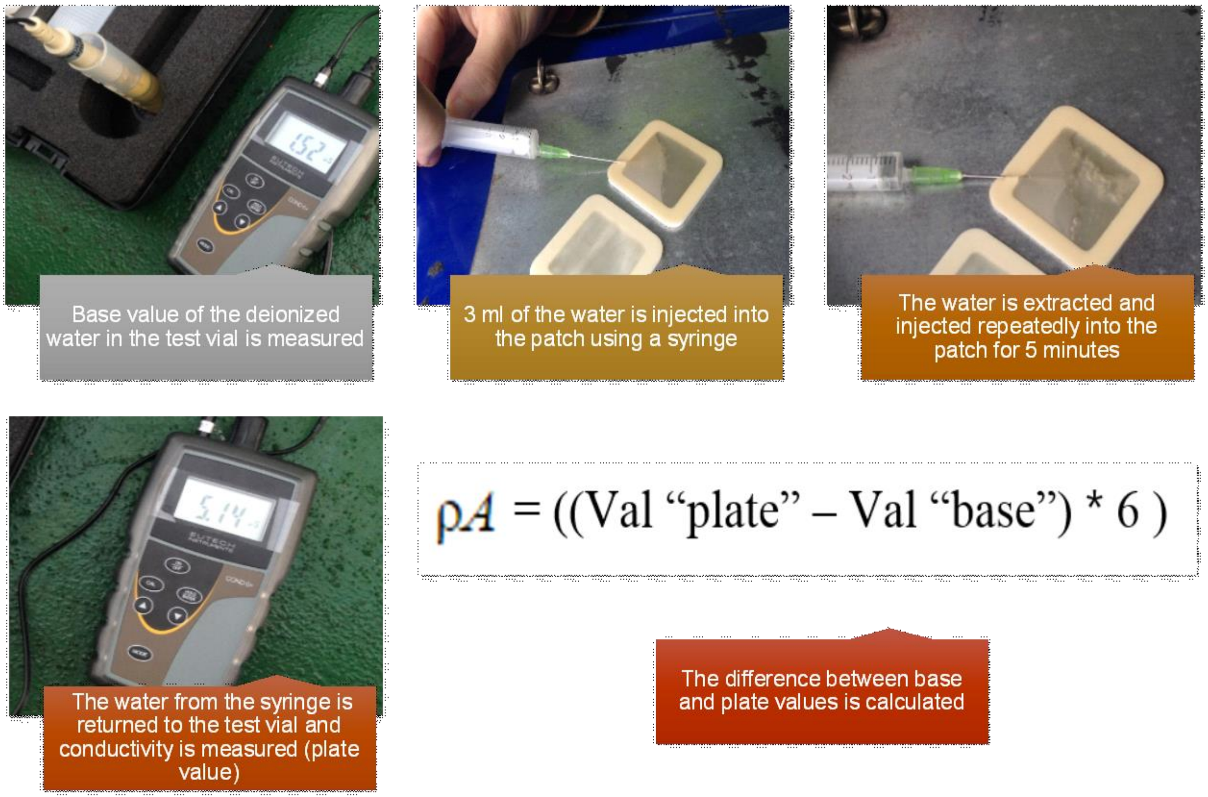

Figure 3.2 Flow diagram of the procedure used in the Bresle test (Edvard Suarez Karlsson, 2015). Private photo collection.

3.6 Weather observations on board during the voyage

In order to appreciate if the weather state during the voyage had any impact on the surface salinity on the test plates, a series of weather observations were performed. Systematic weather observations were taken and data was collected from the ship's log book in order to record the weather state during the voyages. The weather observations were conducted in eight-hour intervals. The observed values of RH, air temperature, atmospheric pressure, true wind direction/strength, precipitation and wave height were subsequently noted. Information about wind, waves and atmospheric pressure was taken from the ship's log book, which is kept at an hourly basis. The weather observations were performed at two locations on board. Measurements of temperature, RH and air pressure were taken aft of the accommodation on 1:st accommodation deck. Observations of true wind direction and strength were conducted on the bridge using the wind indicator incorporated in the navigation system.

Observations of relative humidity, temperature and air pressure were collected by a multi-function air measuring instrument (Testo 480). The vessel's on-board equipment's readings were used for wind direction and strength. Precipitation was measured by placing a rain collector aft on weather deck and wave height was assessed visually. The air temperature was measured in degrees Celsius, air pressure in hPa, precipitation in mm and wave height in metres. Wind strength was measured in Beaufort (see appendix I for a Beaufort scale) because it is the unit used in the ships' logbook and it is a more accurate way of describing the wind state since the wind strength of a time period seldom is constant in the unit metres per second (m/s).

3.7 Data collection and categorization

The raw data was structured in tables for each voyage. The first column contained a brief description of the location and was followed by columns containing a specific position ID, time for measurement, measured base value and plate value for both departure and arrival. Before final calculations were made positions on locations that were similar in appearance and close in range were simplified and grouped together for a better understanding of the results. Positions 4113, 4124 and 4116 were thus named *Weather deck aft*, positions 3034 and 3037 named *Garage deck forward* and so on. A deck plan with the positions and areas used for measurements during this study is provided in Figure 3.3.

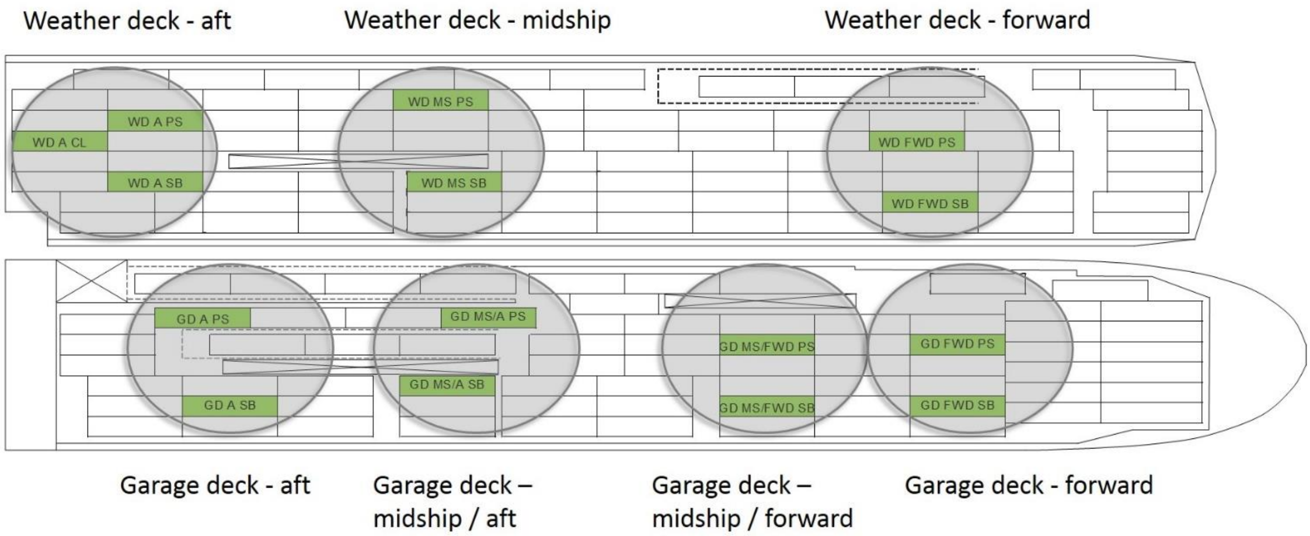

Figure 3.3 Deck plan with the positions and areas used for measurements

Mean and maximum values of weather data, such as wave height and wind strength for each voyage were calculated and synthesised together with the surface salinity data for comparison.

This was done with the purpose of linking the different weather conditions during the voyages to eventual differences in measured surface salinity.

3.7.1 Deduction of mathematical formula used to calculate surface salinity difference

The two conductivity values on the test plates obtained using the method described in section 3.5.1 were used to calculate a theoretical amount of NaCl in mg/m^2 . The formula used was provided with the Bresle kit and is derived from a formula for determining the surface density of NaCl on a surface described in ISO 8502-9 (SIS, 1998a).

In the ISO standard the formula stated is:

$$\rho A = \frac{m}{A}$$

where ρA = the surface density of NaCl

m = the mass of dissolved salts extracted from the Bresle patch in mg

A = the area of the Bresle patch in cm^2

The value *"m"* is calculated using the formula: $m = c \cdot V \cdot \Delta\gamma$ where

c = an empirical constant of ionic conductivity. The value of *c* is set as 5 $kg \cdot m^{-2} \cdot S^{-1}$

V = the volume of liquid in the beaker used during the Bresle test in ml.

$\Delta\gamma$ = the difference in conductivity between base value and plate value in µS.

The resulting formula is:

$$\rho A = \frac{c \cdot V \cdot \Delta\gamma}{A}$$

Since the volume of water in the beaker during the test procedure is 15 ml (15 cm^3), and the area of the test patches are 12,5 cm^2 the value of ρA can be derscribed as:

$$\rho A = \frac{5 \cdot 15 \cdot \Delta\gamma}{12{,}5}$$

$\frac{5 \cdot 15}{12{,}5} = 6$ which gives that $\rho A = 6 \cdot \Delta\gamma$

ρA = ((Val "plate" – Val "base") * 6)

In the formula " ρA " = the density of NaCl in mg/m^2, "Val base" and "Val plate" are the conductivity values described in section 3.5.1.

For example if the base value = 3µS and the plate value = 15µS the amount of salt is

$$\rho A = ((15 - 3) * 6)$$
$$\rho A = (12 * 6)$$
$$\rho A = 72 \text{ mg/m}^2$$

The difference in surface salinity on the plates is given simply by subtracting the value obtained at arrival from the value at departure. The difference was concluded as the amount of soluble salts that ended up on the test plates during the voyage.

4 Results

The relationships between the onboard surface salinity values and the weather data will be presented in the last part this chapter. Additionally, this will be compared with the surface salinity values obtained in the field studies at the port and at the production site in Gothenburg. It will be preceded in the first section by a detailed table presentation of the lowest, highest and average surface salinity values measured on the voyages. The salinity values are followed in section 4.2 by the results from the weather observations in a listing of weather parameters. The third part of this chapter will present the surface salinity results given by the field studies ashore.

4.1 Surface salinity values

In Table 4.1 the results of the salinity measurements are displayed. The voyages during which the pilot study was performed are excluded. Figure 4.1 is a presentation of the average values for all positions from the performed surface salinity measurements for all voyages combined. The average values for the areas defined in section 3.1 are presented together with the results from the weather measurements in section 4.4.

Table 4.1 The highest / lowest / average surface salinity difference of the different positions and during which voyage the highest / lowest values were obtained, sorted by highest average value.

	Highest voy	Lowest voy	Highest	Lowest	Average
WD A PS	3	4	1998	152	851
WD A CL	3	7	1760	53	526
WD A SB	4	6	1000	75	408
GD A PS	8	6	794	13	181
GD MS/FWD PS	5	6	446	-1	107
WD FWD PS	3	7	560	0	104
GD MS/A SB	8	6	478	1	98
GD FWD PS	8	6	378	2	72
GD MS/FWD SB	8	7	305	6	71
GD FWD SB	8	4	267	2	56
WD MS SB	8	6	153	3	40
WD MS PS	8	6	170	-1	35
GD A SB	3	6	65	4	34
GD MS/A PS	8	4	50	5	25
WD FWD SB	5	8	87	-3	22
MD	4	8	34	-8	7

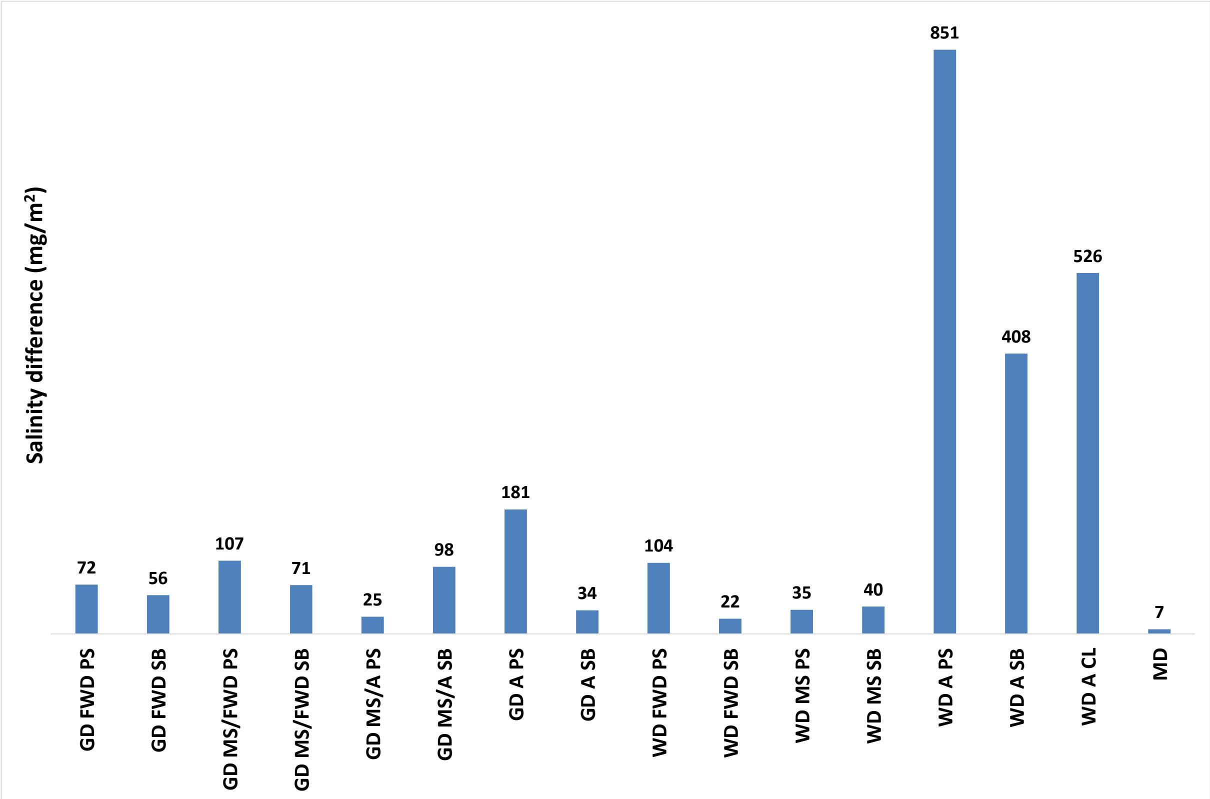

Figure 4.1 Average salinity difference for all positions and all voyages combined

As seen in Figure 4.1 and Figure 4.2, the positions located aft on weather deck clearly showed a higher surface salinity difference in general than all other locations on board. The location "WD A PS" has the highest mean value of +851 mg NaCl/m^2, followed by WD A CL with +526 mg/m^2 and WD A SB with a value of +408 mg/m^2. The position GD A PS has the highest mean surface salinity difference of the positions on garage deck. The mean value obtained for this position was +181 mg/m^2. On main deck the average surface salinity difference was +7 mg/m^2. This is a value lower than that of all other tested positions on board.

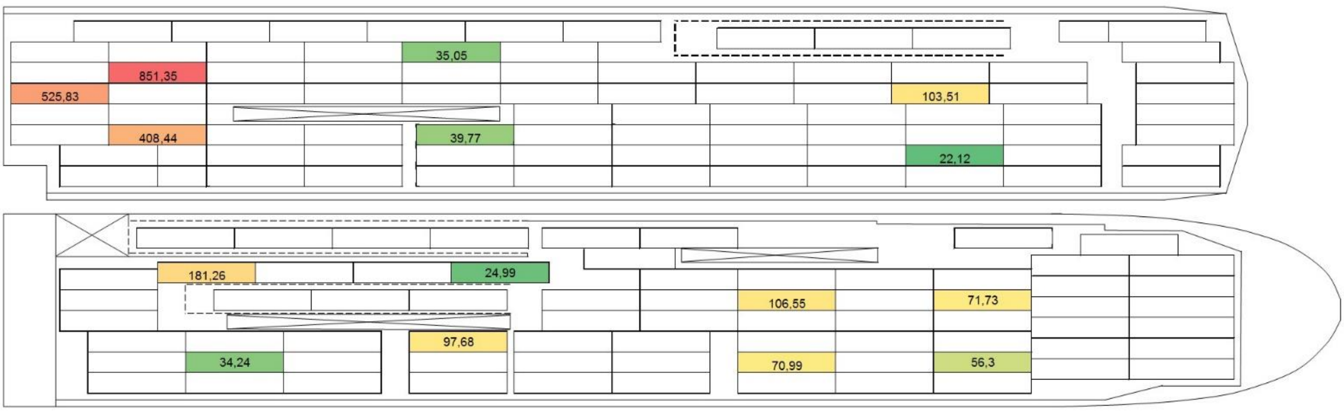

Figure 4.2 Deck plan with average surface salinity difference in mg/m^2 for all voyages combined

4.2 Results from collected weather data

As seen in table 4.2, Voyages 3, 4, and 6 were similar in their overall weather conditions. The RH on these voyages ranged between 67-75% and the max. (maximum) wind strength was 6 Beaufort. Voyage 7 and 8 were similar in that the RH was above 90%. The average temperature was similar during all of the voyages with voyage 6 having the lowest average temperature of 11℃. The precipitation during the voyages in general was limited to occasional showers. Voyage 8 had the highest amount of precipitation with 12,4 mm and voyage 4 had no precipitation at all. Voyage 8, with a maximum wind force of 11 Beaufort is the voyage with the strongest winds during this study. Voyage 8 also had the highest maximum wave height of 5 meters, while voyage 4 with a maximum wave height of 1 meter had the lowest wave heights of the voyages. The prevailing winds during each voyage are presented in Figure 4.3 using wind roses where the shaded areas in the figure show the major wind direction.

Table 4.2 Weather data from all voyages performed during the study

	Temp ℃	RH %	Air pressure hPa	Precipitation (mm)	Wave height avg. / max (m)	Wind avg. / max (Bf)
Voy 3	14,6	67,23	1018	1	2 / 3	4 / 6
Voy 4	14,8	72,88	1033	0	0,5 / 1	3 / 6
Voy 5	14,3	75,96	1020	0,3	3 / 4	4 / 8
Voy 6	12,0	75,10	1025	1	2 / 3	3 / 6
Voy 7	11,0	95,76	1017	1,1	3 / 4	5 / 6
Voy 8	13,2	91,12	1010	12,4	4 / 5	6 / 11

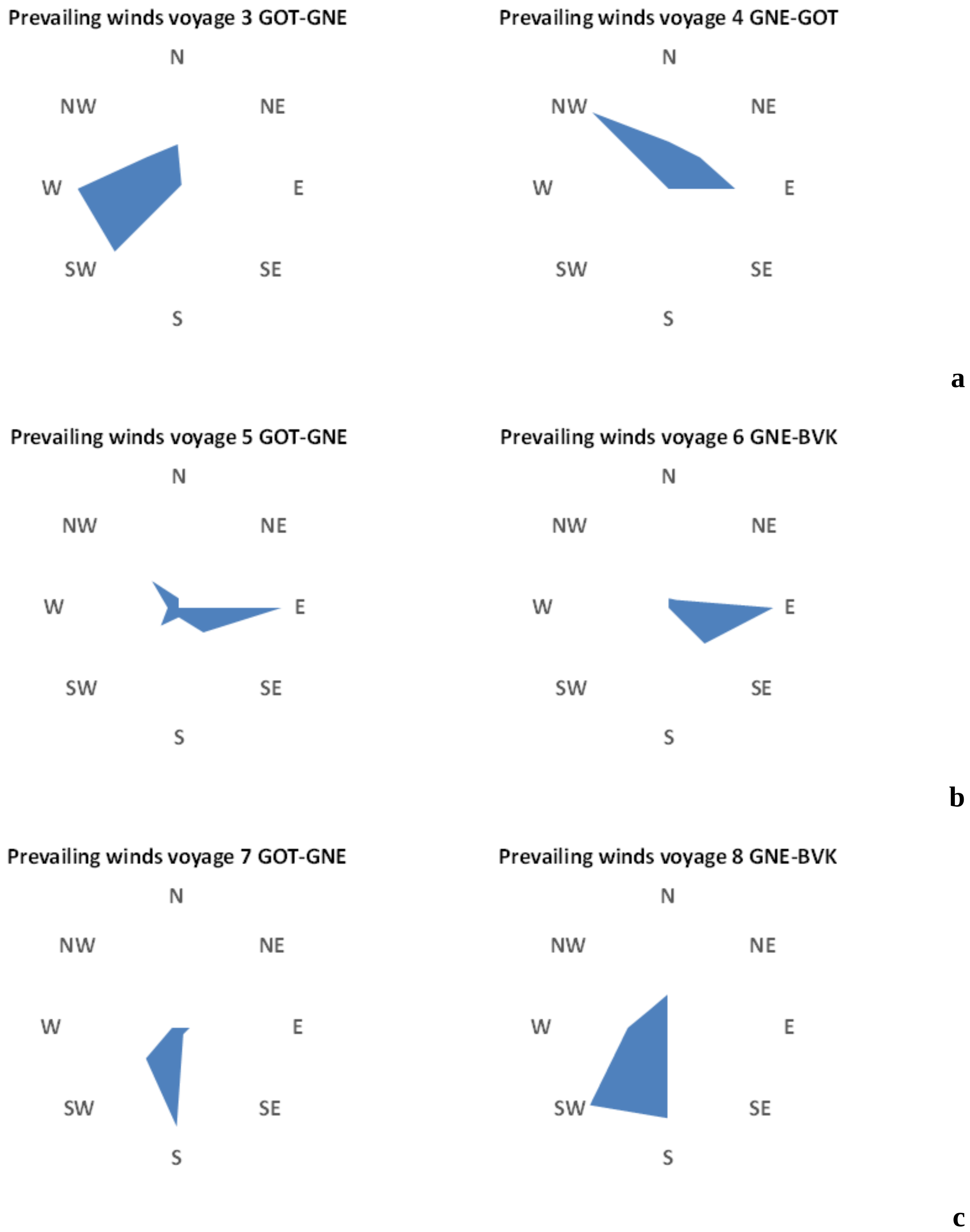

Figure 4.3 Prevailing winds during voyage 3+4 (a), 5+6 (b) and 7+8 (c)

As seen in Figure 4.3, the prevailing winds during voyage 3 and 4 came from the west, while voyage 5 and 6 had easterly winds dominating. Voyage 7 and 8 had predominantly southern winds.

4.3 Results from the field studies ashore

The field studies ashore provided reference values comparable to the results from the voyages. The results from the measurements in port are presented in table Table 4.3, and the average values from the measurements on the vehicles at the production site is shown in Figure 4.4. The table of the results from the production site also show how many days the vehicles had been outdoors at the time of measurement.

Table 4.3 Results from measurements taken in port

Measurement no.	Surface salinity difference (mg/m^2)
1	-3,4
2	-1,0
3	-0,6
4	16,4
5	0,5

The negative results shown in Table 4.3 are the values obtained from the measurements at the location where vehicles are parked before being loaded onto the vessels. The two positive values were obtained closer to the waterfront. The weather conditions during the two 30-hour periods that the plates were in the harbour were similar with a RH over 80%, occasional rain showers and a low atmospheric pressure ranging from 988 - 1012 hPa. Westerly winds were predominant during both testing periods with varying forces ranging from 1 - 6 Beaufort.

The surface salinity of the vehicles parked at the production site was similar regardless of how long they had been positioned outside. As Figure 4.4 shows, the lowest surface salinity (20 mg/m^2) was obtained from a vehicle that had been at the location for a period of 182 days, while the highest value (31 mg/m^2) was obtained from a vehicle that had been outside for about two weeks. An average surface salinity value of 25 mg/m^2 could be obtained from these measurements.

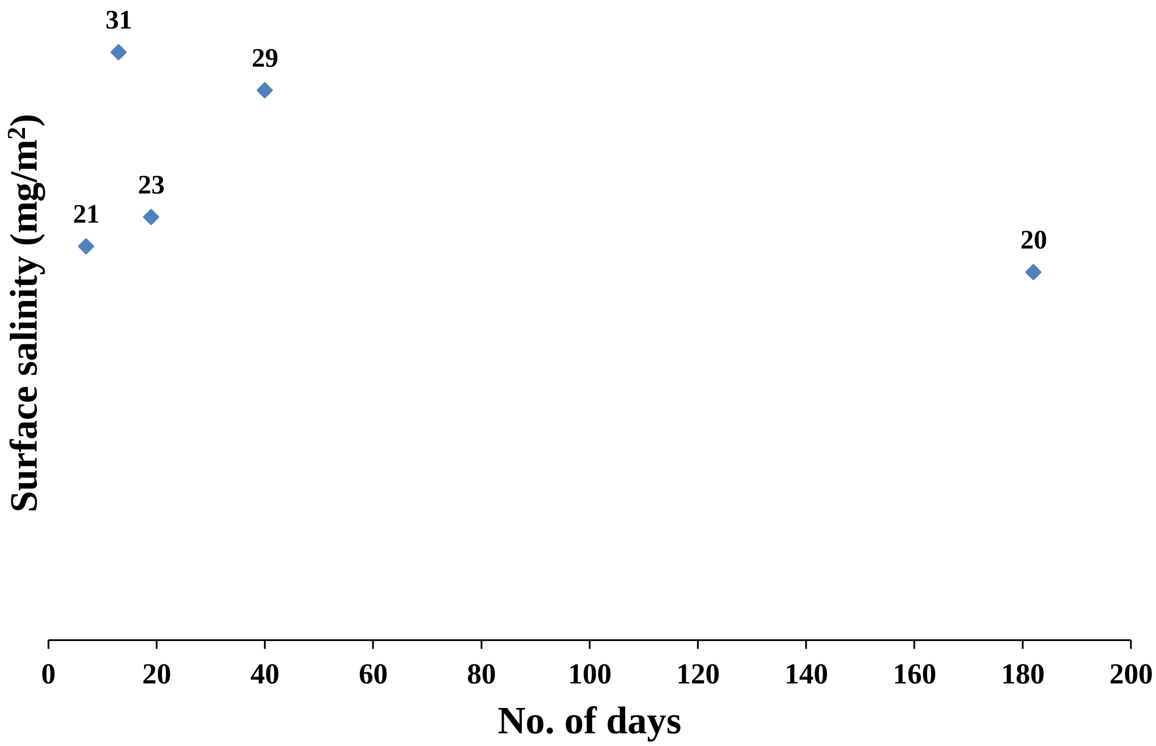

Figure 4.4 Results from the measurements at the production site in Tuve, Gothenburg

4.4 Combination of data from salinity and weather measurements

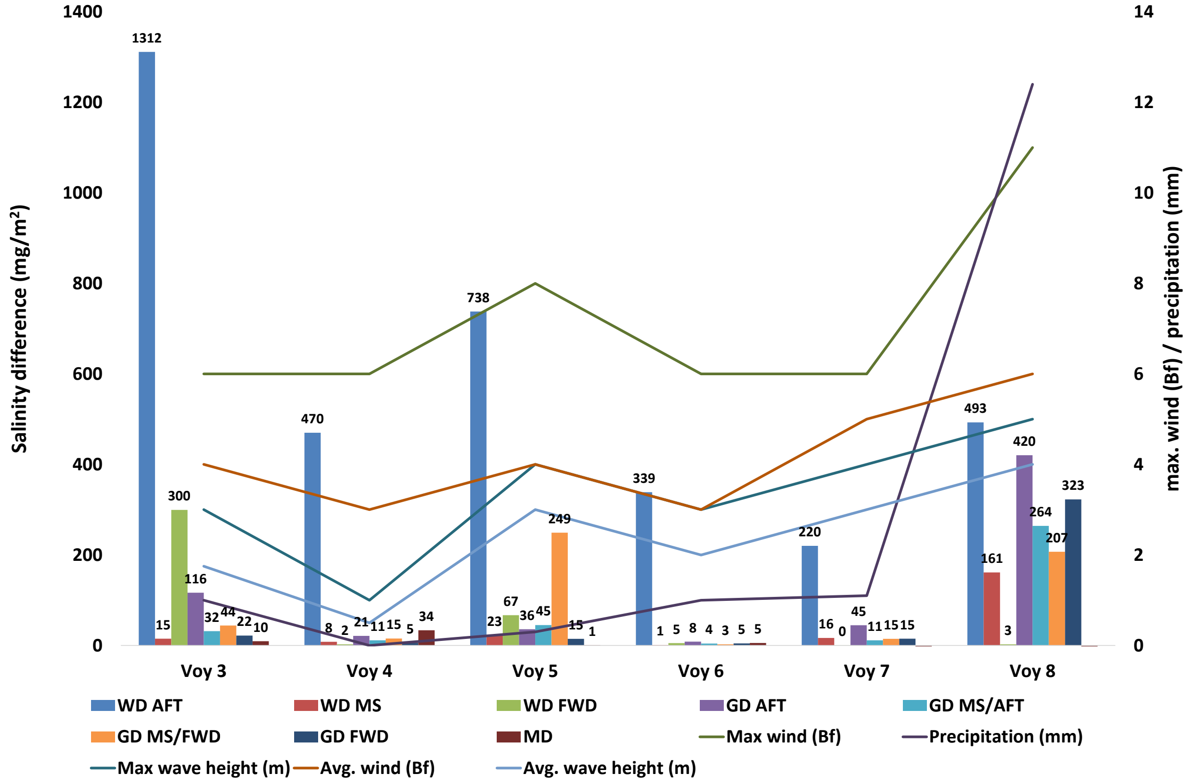

Figure 4.5 Average surface salinity difference for each voyage and area in combination with weather data

The area aft on weather deck consistently showed higher surface salinity difference than all other locations on board while the midship position on the same deck showed low values. This with the exception of voyage 8. In general, voyage 8 resulted in high surface salinity differences in areas where the values had been relatively low during previous voyages. These results are illustrated in Figure 4.5.

5 Discussion

It is difficult to determine what should be regarded as a "low" surface salinity. The corrosion process is affected by many synergetic factors and surface salinity alone does not cause the surface to corrode without the impact of high RH and other factors. The results of the surface salinity measurements are discussed in the next subchapter, followed by a discussion of the chosen method in subchapter 5.2

5.1 Discussion of surface salinity results

In general, the results obtained contained few surprises. After exclusion of the results from the voyage with the highest wind forces and wave heights (voyage 8), the average results from all areas on board except GD MD/FWD confirmed the expectations of suitability. Tables 5.1 and 5.2 show the suitability of each area, the first with the results from all voyages included and the next with exclusion of voyage 8. The weather characteristics during voyages 3 - 7 constitutes what can be deemed reasonable for transporting cargo sensitive to surface salts. The conditions during voyage 8 with maximum wind forces of 11 Beaufort together with a maximum wave height of 5 meters has proved to lead to higher surface salinity increases during this study, making these weather conditions unsuitable for the transportation of cargo sensitive to surface salts on most of the areas.

Table 5.1 Suitability of areas according to IMO (2006) standard: all voyages

	WD AFT	WD MS	WD FWD	GD AFT	GD MS/AFT	GD MS/FWD	GD FWD	MD
Average surface salinity difference in mg/m^2	595	37	63	108	61	89	64	7
Deviation from the IMO (2006) limit of surface salt in mg/m^2	545	-13	13	58	11	39	14	-43
Deviation from the IMO (2006) limit of surface salt in %	1090%	-25%	26%	116%	23%	78%	28%	-87%
Expected to be a suitable area for transportation	NO	**YES**	NO	**YES**	**YES**	**YES**	**YES**	**YES**
Suitable compared to salinity limit in IMO (2006) $50mg/m^2$	NO	**YES**	NO	NO	NO	NO	NO	**YES**

Table 5.2 Suitability of areas according to IMO (2006) standard: voyages 3 – 7

	WD AFT	WD MS	WD FWD	GD AFT	GD MS/AFT	GD MS/FWD	GD FWD	MD
Average surface salinity difference in mg/m^2	616	13	75	45	21	65	12	9
Deviation from the IMO (2006) limit of surface salt in mg/m^2	566	-37	25	-5	-29	15	-38	-41
Deviation from the IMO (2006) limit of surface salt in %	1132%	-74%	50%	-10%	-58%	30%	-76%	-82%
Expected to be a suitable area for transportation	NO	**YES**	NO	**YES**	**YES**	**YES**	**YES**	**YES**
Suitable according to salinity limit in IMO (2006) $50mg/m^2$	NO	**YES**	NO	**YES**	**YES**	NO	**YES**	**YES**

The differences in surface salinity in the exposed locations were more varied than expected. The values differed greatly between the forward and aft position on weather deck, as shown in section 4.1 Figure 4.2. The noticeably higher values obtained on aft weather deck leads to the question of why the same high values does not appear in the forward section of the ship. The areas have similar general environmental properties which one would assume would lead to similar surface salinity values. However, one environmental factor differs between forward and aft - the location relative to the funnel and its fumes. All DFDS vessels are fitted with a scrubber in order to clean the exhausts from the main engine as described in section 2.4. The scrubbers use seawater to clean the fumes from the main engine. One theory about why the surface salinity value of the locations aft on weather deck are so high is that the fallout from the funnel ends up on deck, thus increasing the presence of pollutants and soluble salts on the cargo located there.

One might assume that the side (port or starboard) facing the wind would absorb more air transported salts than the opposing side. The results from comparing the predominant winds to the surface salinity values obtained on the different sides of the vessel has however not led to anything conclusive. Only on three out of six voyages could a possible relationship be seen between which side that had the higher value of surface salinity difference and from which side the prevailing winds were coming. The reason for this could be explained by wind turbulence caused by the structure of the vessel and the cargo surrounding the test plates.

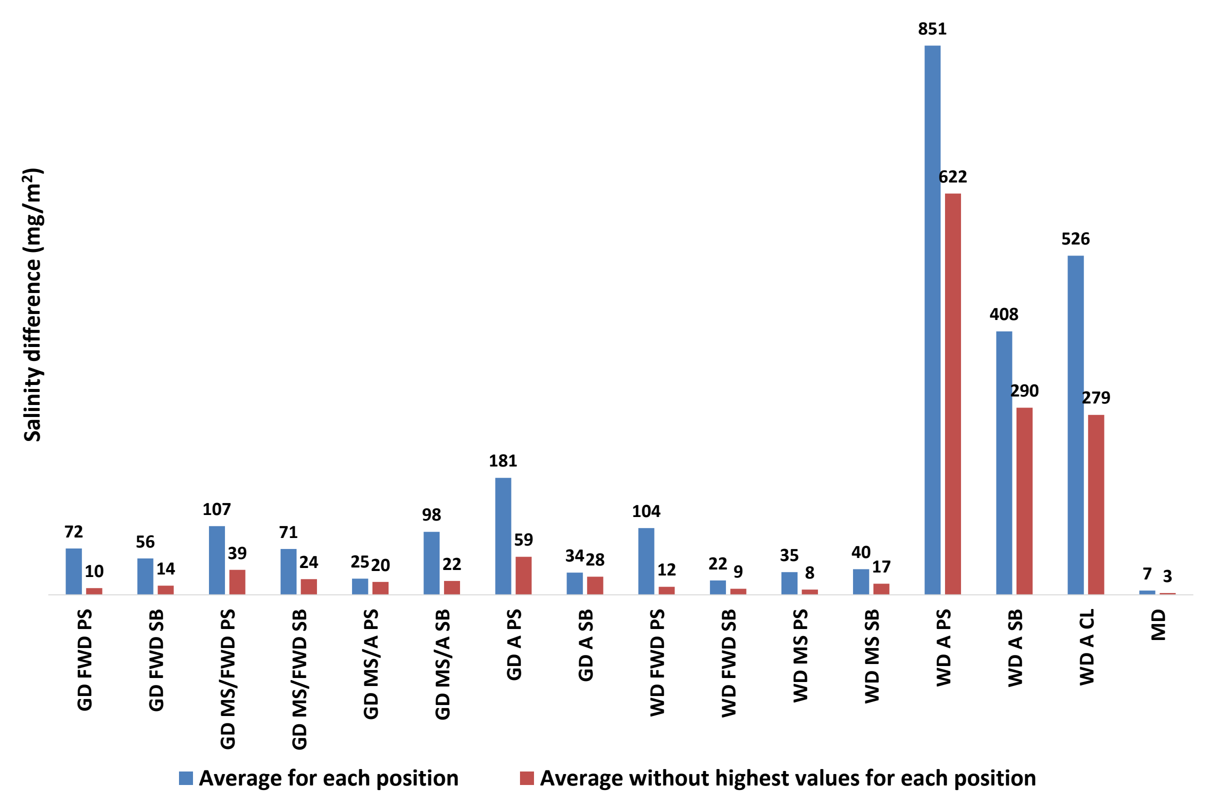

Figure 5.1 The effect of occasional extreme values on average surface salinity difference

Due to the limited number of voyages, each voyage had a considerable impact on the average value. Occasional high values increased the average value significantly of positions in the same general area. In order to show the impact of these extreme values, Figure 5.1 shows a comparison between the average values of all the positions, and the average values with the top value for each position deducted.

As is stated in chapter 3.4 the results from the measurements in port and at the production site were meant to be compared to the results from the on board measurements. The results in chapter 4.3 could be interpreted as if the units of this particular time period are exposed to less surface salts in port than when being transported. These results are not included in the conclusions of this study because the comparison would be based on unequal grounds. A greater amount of data during a longer period of time would have made a comparison more valid. Also, the validity of a comparison with units parked at the production site would be greater if more measurements had been taken on separate occasions.

5.2 The chosen method

In terms of validity of the chosen method, the Bresle method is a standardized and reliable way of determining surface salinity. IMO recommends this method to measure the surface salinity prior to coating of ballast tanks in their performance standard (IMO, 2006). Nevertheless, some minor aspects of the field study could be a cause of data uncertainty. The identified sources are presented below, covering the lack of variety in the weather factors, a deviation from the ISO standard, wind instrument reliability and a difference between the material in the plates used in the study and the material of the corrosion sensitive parts of the actual vehicles.

The small range of weather data in an area where the weather conditions can vary greatly over the year makes this study unrepresentative for the other yearly seasons. Since the results show a connection between weather (particularly wind strength) and surface salinity difference conducting a similar study during a different season might have given other results. However, the fact that the weather parameters did not fluctuate too much also increases the integrity of the results under the given conditions. One source of data uncertainty regarding the weather is that the anemometers (wind speed measurement instrument) on board the vessels are located in the forward part of the ship and can, depending on the vessel's heading and the prevailing winds, be disturbed by the superstructure located midships.

The Bresle test kit was delivered with a guarantee that all equipment needed to conduct the Bresle test according to the ISO standard 8502-9: 1998 was provided. The standard demands a beaker made of glass in order to prevent static electricity from building when the probe is inserted in the deionized water. After the first voyage it was noted that the beaker provided in the test kit was made of plastic instead of glass, nevertheless a decision was made to keep using the plastic beaker in order to get the most unitary results as possible. It is not known how much the plastic beaker might have affected the conductivity values. However, since the purpose of this study is to determine the difference between values and since the same equipment was used consistently, the reliability of the results should not be affected.

The materials of which the test plates and the gearboxes on vehicles differ as is described in section 2.5. It is uncertain if the same salinity differences observed in this study would appear on the actual cargo, and if it would be more or less. The surfaces of the gearboxes on the chassis are more porous than the test plates used during this study and might attract/repel more salts.

6 Conclusions

This report was based on the following questions:

- How does the difference in surface salinity on cargo units vary depending on what position they have on board during transportation?
- Which positions on the garage- and weather decks appear more suitable than other positions on board for transportation of cargo sensitive to surface salts?

The answers to both questions are illustrated in figure 6.1. In the figure, green color represents the areas which are regarded as suitable, yellow areas are less suitable and red areas are not considered as suitable. The classification is based on the maximum salinity limit recommended by IMO (2006).

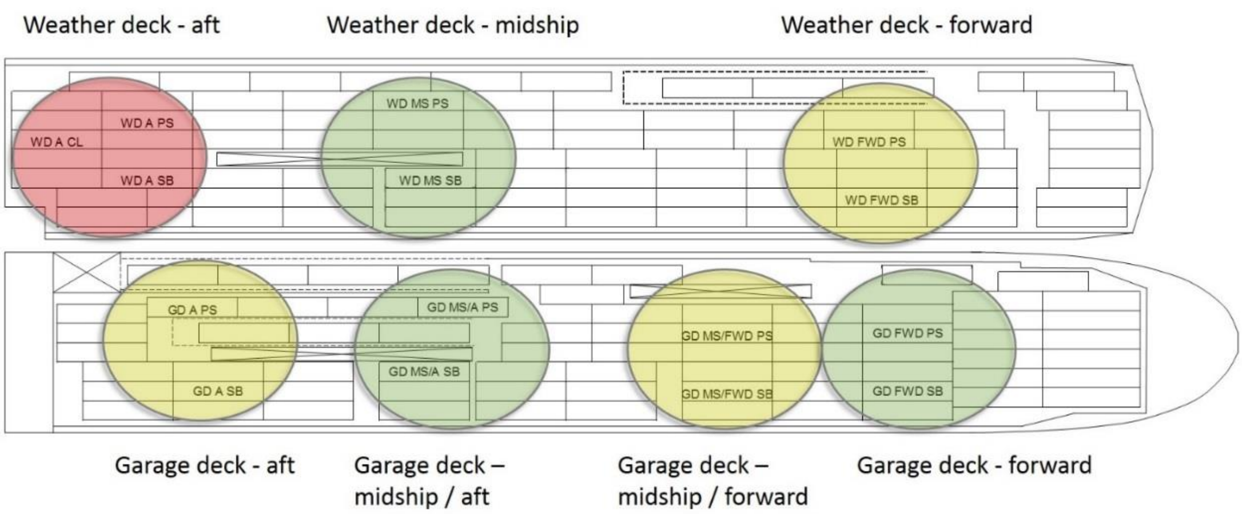

Figure 6.1 Deck plan with areas on board, showing their suitability for the transportation of cargo sensitive to corrosion.

The weather state during the voyage plays a crucial role in how much salts end up on the different positions. The areas “WD MS”, “GD MS/A” and “GD FWD” have shown an average surface salinity difference below 50 mg/m^2 (the limit which is recommended by IMO (2006) for coating application) in the weather states during five of the six total voyages (maximum wind forces of 6 to 8 Beaufort and a maximum wave height of 4 meters). Said positions can be considered more suitable than others for the transportation of cargo sensitive to surface salts during similar weather conditions and are marked with green color in figure 6.1. Meanwhile, the area “WD A” is marked in red color in the figure and has shown considerably higher surface salinity differences regardless of the weather state during the voyage, making the area the least suitable of the areas in this study for the transportation of cargo sensitive to surface salts. The yellow-marked areas “WD FWD”, “GD MS/FWD” and “GD A” has shown occasional high values making them more suitable than the area aft on weather deck but less suitable than the areas located midship on garage- and weather deck and forward on garage deck.

It can be concluded that the surface salinity difference on the test plates does differ depending on what position they have onboard during the sea voyage. The test plates are chosen to represent cargo units and are assumed to be affected the same way in terms of surface salinity, although there are uncertainties because of the differences in material characteristics. During a voyage, the surface salinity increases on all positions on weather- and garage deck but in varying levels. The units transported on main deck have lower surface salinity differences in comparison with the levels observed at positions on garage deck and weather deck.

This study reveals trends regarding suitable positions onboard for sensitive cargo and further studies might verify the results of this report. A greater amount of data from more voyages over a longer time period is desirable to reduce the impact of each measurement on the average value. A further study of what amount of salt that in fact increases the risk of tarnish and corrosion on the gearboxes would bring a more definite limit to compare the measured surface salinity values with. The values obtained aft on weather deck might be connected to fallout from the seawater scrubber in the funnel. An investigation on what effect the eventual fallout actually has on the cargo and on the environment is of interest, not only to parties involved in ro-ro shipping, but to the whole shipping industry.

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Appendix I – Metoffice Beaufort scale

Force	Description	Specification for use at sea*	Equivalent speed at 10 metres above sea level				Description in forecast	State of sea	Probable height of waves* /metres
			Mean		Limits				
			/knots	/ms^{-1}	/knots	/ms^{-1}			
0	Calm	Sea like a mirror	0	0.0	<1	0.0 to 0.2	Calm	Calm	0.0
1	Light air	Ripples with the appearance of scales are formed, but without foam crests	2	0.8	1 to 3	0.3 to 1.5	Light	Calm	0.1 (0.1)
2	Light breeze	Small wavelets, still short but more pronounced. Crests have a glassy appearance and do not break	5	2.4	4 to 6	1.6 to 3.3	Light	Smooth	0.2 (0.3)
3	Gentle breeze	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered white horses	9	4.3	7 to 10	3.4 to 5.4	Light	S mooth	0.6 (1.0)
4	Moderate breeze	Small waves, becoming longer, fairly frequent white horses	13	6.7	11 to 16	5.5 to 7.9	Moderate	Slight	1.0 (1.5)
5	Fresh breeze	Moderate waves, taking a more pronounced long form; many white horses are formed. Chance of some spray	19	9.3	17 to 21	8.0 to 10.7	Fresh	Moderate	2.0 (2.5)
6	Strong breeze	Large waves begin to form; the white foam crests are more extensive everywhere. Probably some spray	24	12.3	22 to 27	10.8 to 13.8	Strong	Rough	3.0 (4.0)
7	Near gale	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind	30	15.5	28 to 33	13.9 to 17.1	Strong	Very rough	4.0 (5.5)
8	Gale	Moderate high waves of greater length; edges of crests begin to break into spindrift. The foam is blown in well-marked streaks along the direction of the wind	37	18.9	34 to 40	17.2 to 20.7	Gale	High	5.5 (7.5)

*These columns are a guide to show roughly what may be expected in the open sea, remote from land. Figures in brackets indicate the probable maximum height of waves. In enclosed waters, or when near land with an offshore wind, wave heights will be smaller and the waves steeper.

Force	Description	Specification for use at sea*	Equivalent speed at 10 metres above sea level				Description in forecast	State of sea	Probable height of waves* /metres
			Mean		Limits				
			/knots	/ms^{-1}	/knots	/ms^{-1}			
9	Strong gale	High waves. Dense streaks of foam along the direction of the wind. Crests of waves begin to topple, tumble and roll over. Spray may affect visibility	44	22.6	41 to 47	20.8 to 24.4	Severe gale	Very high	7.0 (10.0)
10	Storm	Very high waves with long over-hanging crests. The resulting foam, in great patches, is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes on a white appearance. The 'tumbling' of the sea becomes heavy and shock-like. Visibility affected	52	26.4	48 to 55	24.5 to 28.4	Storm	Very high	9.0 (12.5)
11	Violent storm	Exceptionally high waves (small and medium-sized ships might be for a time lost behind the waves). The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected	60	30.5	56 to 63	28.5 to 32.6	Violent storm	Phenomenal	11.5 (16.0)
12	Hurricane	The air is filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected	-	-	64 and over	32.7 and over	Hurricane force	Phenomenal	14.0 (-)

*These columns are a guide to show roughly what may be expected in the open sea, remote from land.

Extract from *National Meteorological Library and Archive Fact sheet 6 – The Beaufort Scale (version 01)* Published by Met Office, retrieved from library.metoffice.gov.uk