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Analysis of TSS as a potential risk- reducing measure for ship allision for a proposed floating bridge across the Nordfjord on the west coast of Norway

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This paper will focus on the potential ship allision risk for a proposed fixed crossing of the Nordfjord on the West Coast of Norway, and the effects of various riskreducing measures. The proposed project consists of a floating bridge with a relatively low clearance above the sea and a separate bascule bridge to allow for the passage of larger vessels with a height of more than 18 m. The fjord has a relatively low amount of ship traffic, but during the summer season, the fjord is frequented by some of the largest cruise ships in the world, with the potential to cause the full collapse of the floating bridge. A list of potential risk-reducing measures are discussed to find the measures with the potentially best benefits. An alternative solution with a traffic separation scheme to reduce the risk to the bridge is also investigated in this paper.

Keywords: Ship allision, Risk reducing measures, Risk analysis

1. Introduction

With the momentum of the Coastal Highway E39 Route Project, many proposals for new bridges or tunnels across fjords in western Norway as replacements for existing ferry connections have been suggested. This is also the case for the Nordfjord, where the E39 route today crosses the fjord with a ferry connection between Anda and Lote. (Dr.Techn.Olav Olsen 2021).

A previous decision to build a suspension bridge across the fjord further east will carry the future E39 route. While this was considered the best solution overall, it will give local commuters using the ferry today a much longer commute between the two towns of Sandane and Nordfjordeid. Due to this, local politicians have also proposed to build a bridge across the fjord between Anda and Lote, in addition to the planned suspension bridge further east.

Since a bridge between Anda and Lote will be part of the county road network, it will not receive government funding, and hence will be on a much stricter budget compared to other proposed crossings carrying the E39 route. A bridge here must for that reason be very cost effective. Also, the bridge cannot have any tall towers due to height restrictions in the vicinity of the local airport and must allow some of the largest cruise ships in the world to pass.

For these reasons, the proposed solution is a floating bridge to cross the width of the fjord, as seen in Fig. 1, and a separate bascule bridge across a canal to allow passage for larger vessels. (Dr.Techn.Olav Olsen 2021)

Fig. 1: Illustration of a floating bridge across the Nordfjord between Anda and Lote (Ill. Nordwest3D).

A floating bridge across the fjord would be extremely exposed to ship allisions from ship traffic on the fjord, and with many large cruise ships passing every week, the risk for the bridge related to ship allisions is significant and will seemingly be the leading design parameter for the ship traffic.

For this reason, it is important to look into the different options available to reduce the impact load the bridge needs to be designed for as much as possible. One options which is discussed is a traffic separation scheme for the sole purpose of attempting to reduce the risk to the bridge. While TSS previously have been implemented in areas with bridges, it has mainly been to reduce the risk to the ship traffic in general and particularly to reduce ship-ship collisions, TSS has never been implemented with the sole purpose to reduce the risk to the bridge.

The purpose of this study is firstly to estimate a design ship without any riskreducing measures, then to discuss the effects of risk-reducing measures which may be applied to the ship traffic on the fjord, and lastly to investigate if a Traffic Separation Scheme (TSS) may be applied to reduce the risk to the bridge. Finally, the results are discussed and a conclusion is drawn.

2. The Bridge

The main crossing of the fjord is planned as a 2 km long floating bridge roughly between the ferry quays at Anda to the south and Lote to the north. This is combined with a bascule bridge over a blasted and dredged channel in the Anda-promontory, as shown in Fig. 2, to allow a navigational passage past the bridge for larger vessels. A plan view outlining the crossing route is shown in Fig. 3.

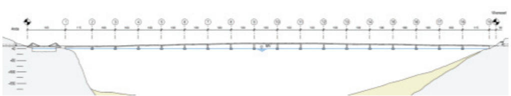

Fig. 2: Longitudinal section of floating bridge with bascule bridge and ship channel on the left (Ill. Dr.Techn. Olav Olsen).

The floating bridge, as shown in Fig. 2, is proposed with a maximum sailing height of 18 m in the middle of the fjord to allow smaller vessels to pass the bridge without the bascule bridge being opened and car traffic being stopped. The bridge is planned with spans of around 100 meters between the pontoons.

Fig. 3: Plan view outline of the floating bridge between Anda and Lote, with an outline of the navigation channel in the south (Ill. Dr.Techn. Olav Olsen).

The dimensions of the channel will physically need to allow even the largest cruise ships in the world to pass on their way to the cruise quay in Olden in the innermost part of the fjord. For this reason, the ship channel is planned with a width of 80 meter with the front edges of the abutments parallel to the sides of the dredged and blasted ship channel. An illustration of this can be seen in Fig. 4.

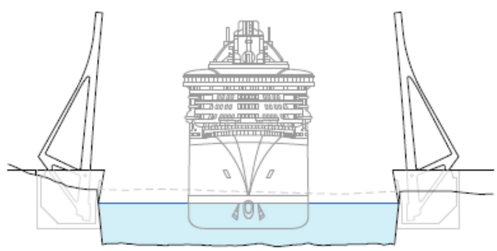

Fig. 4: Cross-section of ship channel with 80 meters sailing width and 12.5 meters sailing depth (Ill. Dr.Techn. Olav Olsen).

The construction of a low floating bridge across the entire fjord will disrupt ship traffic as it is today, and the fjord will have a completely different traffic pattern when all ships higher than 18 meters must be threaded through a narrow ship passage in the Anda-promontory.

As with other bascule bridges in Norway, it is assumed that the Road Traffic Control Center of the Norwegian Public Roads Administration will control the bascule bridge and stop road traffic crossing the bridge when the bridge needs to be opened in order for ships to pass. In the work carried out by Dr.Techn.Olav Olsen (2021), a maximum speed of 5 knots is assumed when a vessel passes the bascule bridge. For the largest ships, an average speed of 2 knots is assumed. In the concept sketch, 8 m/s has been set as the upper limit for passage, but they also state conclude that ships are expected to be able to pass with wind speeds of up to 12 m/s, referring to simulator runs.

The safe passage of vessels through the canal and the bascule bridge has its own set of risks that need to be addressed, both for the ships as well as for the bascule bridge, but as it is not related to the risk of the floating bridge, it will not be addressed in this paper.

3. Ship traffic on the Nordfjord

In addition to the ferry traffic between Anda and Lote, ship traffic on the fjord is characterized by local goods transport and industry, including aquaculture. During the summer, there is also a significant amount of cruise traffic on the fjord. The heatmap in Fig. 5 showing ship traffic from October 2019 - October 2024, shows a relatively complex sailing pattern west of the proposed bridge location, with ship traffic going in and out of Gloppefjorden and Hyenfjorden, vessels servicing fish farms in several locations, as well as through traffic, mainly cruise ships, back and forth from the cruise location in inner Nordfjord.

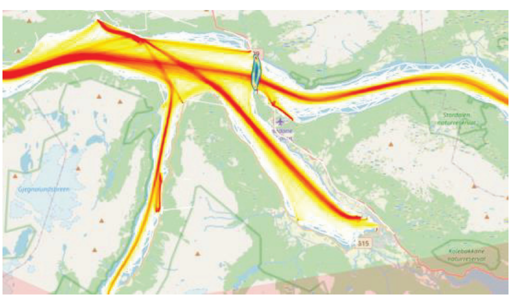

Fig. 5: "Heatmap" of ship traffic on Nordfjorden in the area around the proposed crossing. The location is proposed to be in the area currently trafficked by the Anda-Lote ferry, visible as the area with the most intense ship traffic marked in blue and yellow.

The ferry traffic between Anda-Lote will no longer be present if the proposed bridge is built between Anda and Lote. This traffic is therefore not included in the modeling.

It must also be remarked that there is great variation in the ship traffic in different areas of the fjord, with a clear trend that ship traffic decreases further east into the fjord. While there are about 200 vessels passing annually each way west of the Hyenfjord, this number is reduced to slightly over 100 passages annually each way east of the crossing point at Anda-Lote. East of the line between Anda and Lote, the majority of the ship traffic consist of cruise ships heading for or leaving the cruise quay in Olden.

All the largest vessels sailing on the fjord are cruise ships visiting inner Nordfjord. For this reason, this ship traffic is crucial in determining the design ship and impact load for the bridge. While there has been some variations in cruise calls to Olden/Loen in recent years, not least due to Covid 19, there has for the last few years been on average about 100 cruise ships a year visiting the fjord. This means that relatively large cruise ships have passed the bridge location about 200 times each year. Although the trend is rising, this is used as a base case as the main purpose here is to investigate the effect of a traffic separation scheme, while establishing a new design ship is second order in this case. With basis in an average of 100 cruise ships visiting the inner Nordfjord every year, and the size of the visiting cruise ships the past few years, a distribution of ships based on length overall (LOA) with steps of 25 meters is chosen as shown in Table 1.

Table 1. Overview of number of passenger ships per length category used in the simulation.

LOA (m)	Number of ships
100-125	5
125-150	15
150-175	5
175-200	5
200-225	5
225-250	5
250-275	5
275-300	10
300-325	15
325-350	30

This gives a fair representation of the distribution of todays cruise ship traffic. It gives a clear indication of a preference of either very large cruise ships between 275-350 meters in length, or smaller more customised cruise ships with a length of around 125-150 meters.

4. Modelling of future ship traffic and estimation of allision probability with the floating bridge

The ship traffic is modelled in the software IWRAP MKII. The software is developed in collaboration with, and adopted by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) and is used by many public agencies around the world to estimate maritime risk. IWRAP MKII is based on theory developed in connection with the Great Belt construction in Denmark in the 1980s and 1990s, and has later been further developed for more general use (Friis-Hansen 2008).

Automatic identification system (AIS) data from vessels in the area is provided by the Norwegian Coastal Authorities is uploaded to the software and all ship journeys are plotted in a heatmap as shown earlier in Fig. 5. Based on the heatmap, today's ship traffic is modeled based on so-called "legs" that the user defines. A "leg" is part of a journey, and by entering multiple "legs", the goal is to represent all ship traffic in the relevant part of the fjord. The program converts AIS tracks into a probability distribution for ship traffic across a "leg", this distribution consists of one or more elements that are either normally distributed or evenly distributed across the entire width. It is then possible to move a leg to new positions as well as to manipulate the probability distribution of ship traffic, in order to analyze a new possible traffic pattern. Fig. 6 illustrates how the future ship traffic is modeled and how the "legs" nearest the future bridge route are moved southward to model a future sailing route through a dredged ship channel in the Anda-promontory.

While it is often common to use a "Heinrich factor" or severity reduction factor when estimating the risk of ship impact on this type of extreme fjord crossings (Johansen et.al. 2019) (Askeland et. al. 2021), this has not been applied in this study, since it is not the absolute value which is the most important here, but rather the effect of the measures introduced.

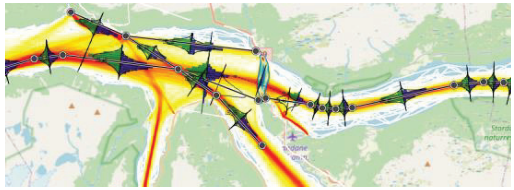

Fig. 6: This figure shows the modeling of ship traffic using "legs", as well as the moving of "legs" near the crossing at Anda-Lote to lead future ship traffic through the planned ship channel.

The requirements related to accident loads in the Norwegian Public Roads Administration's (NPRA) manual "N400 Design of Bridges" require the bridges to be designed for all events with an annual probability exceeding 10^-4. For the accident load ship impact, this means, that the annual probability of ship impact for each length category is added together, starting with the largest ships, including categories for smaller and smaller ships until the annual probability of the summed-up categories exceeds 10^-4. The category that causes the total annual probability of ship impact to exceed this limit will determine the design ship.

A simulation using the ship traffic pattern as shown in Fig. 6 estimates that the return period for powered allisions, i.e. not including drifting ships, with the bridge is 462 years, and that a design ship will be a cruise ship with a length overall (LOA) of 250-275 meters. This is a great deal higher than the estimates performed by the NPRA (Eidem 2025), but this is mainly due to the lack of severity reduction factor in the simulations done for this paper.

5. Proposals for risk reducing measures

To reduce the probability and/or consequences of a potential ship impact with the bridge, several risk reducing measures can be considered. In the following, four different measures are discussed.

5.1. *Pilotage*

In Norway, there is a general pilotage requirement for all ships over 70 meters in length and passenger boats over 50 meters within the baseline. However, the pilotage requirement can be waived if one has a Pilot Exemption Certificate

(PEC) for the ship and the sea lane for ships up to 150 meters. Local restrictions can be introduced to negate the possibility of PEC here. However, PEC is most likely only used by vessels from the Norwegian company "Hurtigruten", and not by any other companies. This means, that in reality, most ships passing the proposed bridge site today, and all cruise ships above 150 metres in length already use pilots. Introducing restrictions on PEC will for this reason not give a significant contribution in reducing the risk, as it will only affect "Hurtigruten" with their relatively small cruise ships. At the same time, it will place a large additional burden on the smaller vessels that frequently sail on the fjord, and which in any case pose a lesser threat to the bridge.

5.2. *Vessel Traffic Service (VTS)*

The Norwegian Coastal Administration (NCA) can introduce VTS monitoring of the area. The NCA already operates a VTS, "Kinn VTS", for the Florø-Måløy area right at the mouth of the Nordfjord. It is a possibility to extend the responsibility for this VTS to cover the entire length of the Nordfjord, including the area around the bridge site. A study on the Great Belt Bridge in Denmarkestimates a 60-90% reduction of the frequency of allisions, collisions and groundings with the introduction of VTS. (T. Lehn-Schiøler et. al. 2013). However, if a ship already has a pilot on board the voyage, the risk-reducing effect of VTS is very limited.

5.3. *Closing of the bridge in cases of ships astray*

This is a risk reducing measure that reduces the consequence of a potential ship allision with the bridge. In the case of ships astray, or in cases where ships do not respond to calls from the VTS operator, road traffic is stopped on land on both sides of the bridge. The bridge would be cleared of cars in a matter of minutes, and the consequence is reduced to financial loss. By limiting the loss to material damage, it might be possible to accept a higher probability of bridge collapse due to ship allisions. The owner organisation of The Great Belt Bridge accepts a lower return period for the design ship for ship impact, reducing it from 10 000 years to 5 000 years, and also introduced VTS monitoring of ship traffic to stop road traffic entering the bridge during incidents where there are ships astray heading towards any vulnerable parts of the bridge (Gimsing N.J. 1998). This may have a significant contribution to reducing the size of the design ship, but it will also require the introduction of VTS monitoring of the area. However, pedestrians will still be at risk, as they are not able to evacuate the bridge at the same speed as road traffic. This will most likely limit the possibility of this option.

5.4. *Traffic Separation Scheme (TSS)*

TSS can be introduced to provide clearly defined routes for ships sailing in and out of the fjord, in contrast with today, where ships are theoretically free to use the entire width of the fjord as long as the vessel does not violate any navigation rules. Originally, TSS is a system designed to separate traffic moving in different directions in areas with high ship traffic but can also be used in narrower waters to guide ship traffic along designated routes. By introducing this on the Nordfjord, the time and distance during which a ship has a course pointing towards the bridge can be reduced, thereby lowering the probability of a ship failing to change course and colliding with the bridge. For TSS to function effectively, it is dependent on the area being monitored by VTS. As the effect the introduction of TSS may have on ship allision with bridges has not been studied before, this effect will be investigated in the next section of the paper.

6. Modelling of ship traffic with traffic separation scheme

To analyse the effect a Traffic Separation Scheme (TSS) might have on the probability of ship allisions with the proposed bridge, the model is again modified to simulate one possible TSS for ship traffic sailing in and out of the fjord.

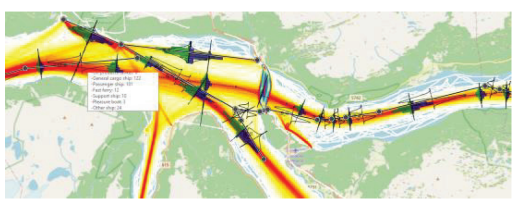

Fig. 7: Illustration of how the ship traffic was modelled with TSS in IWRAP MK2.

In the model shown in Fig. 7, the distance between the mean of the ship traffic in the eastbound direction and westbound direction is chosen to be 350 meters. The standard deviation for traffic in one direction is chosen to be 60 meters. Other ship traffic on the fjord is modelled to sail as it does today, unless it overlaps the area of the TSS. As an example, the resulting ship traffic distribution model for Leg 43 is shown in Fig. 8.

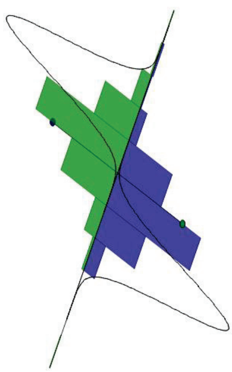

Fig. 8: Distribution of ship traffic in the modelled TSS for Leg 43, also showing relative to todays ship traffic.

A simulation using the new ship traffic pattern with TSS as shown in Fig. 7 estimates that the return period for powered allisions, i.e. not including drifting ships, with the bridge is 834 years, and that the design ship will be a cruise ship with a length overall (LOA) of 200-225 meters.

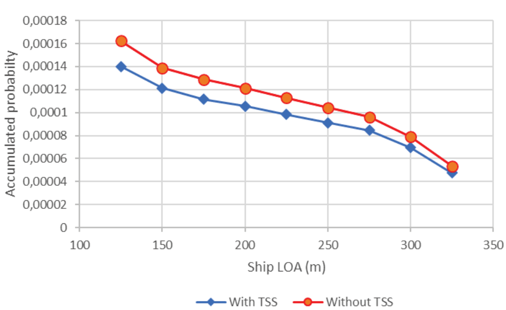

Fig. 9: Graph showing the risk reducing effect of introducing TSS on the probability of ship impact to the bridge.

A comparison between the results from the two models is shown in Fig. 9. It shows a reduction of about 13 % in annual probability in the range where the size of the design ship is determined.

7. Discussion and Conclusion

A model of the ship traffic in the event of the construction of a floating bridge across the Nordfjord between Anda and Lote is established, and a frequency for ship allisions is estimated. From this, a design ship with the length of 250-275 meters is determined.

Four risk reducing measures are discussed, Pilotage, Vessel Traffic Service (VTS), Traffic Separation Scheme (TSS) and closing of the bridge in cases with stray ships. None of the measures stand out as an easy solution to greatly reduce the size of the design ship, but since TSS shows promise and has not been studied for this purpose only before, it is investigated further.

A model of the ship traffic in the area with one possible TSS is established. It reduces the estimates for the frequencies of ship impact with 13%, which is enough to reduce the design ship two length categories to a length of 200-225 meters. While the reduction in the size of the design ship is considerable, the reduction in allison frequency is not. However, it shows that there is a potential to use TSS as a risk reducing measure for a bridge exposed to ship impacts. In this paper, only one route and one set of values were investigated for the TSS on this fjord, which opens the possibility for optimalization in order to further reduce the risk to the bridge. It is important to keep in mind that this paper only focused the effects a TSS might have on the bridge and did not investigate the effects, positive or negative, to the ship traffic in general. In any case, this warrants further investigation to determine whether this is a unique case or not.

The estimated design ship in Section 4 clearly shows that the risk to the bridge related to ship impact is considerable, and even if the design ship in this case probably is to large due to the lack of severity reduction factor, accidental load due to ship impact will most likely be a showstopper for this bridge.

Acknowledgement

Perplexity AI has been used to some extent in translation and rephrasing of sentences.

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