The effect of reducing cruise ship speed in the World Heritage fjords

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Objective:
This study has been carried out on behalf of the Norwegian Maritime Authority (NMA) and examines the effects of speed limitation on cruise ships operating in Norwegian World Heritage fjords. The study quantifies the anticipated reduction in emissions, especially for nitrogen oxide (NOx), sulfur dioxide (SO_2) and particulate matter (PM_{10} and $PM_{2,5}$).

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1 INTRODUCTION

1.1 General

This study has been carried out on behalf of the Norwegian Maritime Authority (NMA) and examines the effects of speed limitation on cruise ships operating in Norwegian World Heritage fjords. Speed limitation is one of several concrete measures that the NMA is considering in order to limit pollution from ships in these areas. The assessments are based on present sailing speeds and traffic situation in the Geirangerfjord and Nærøyfjord. The study consists of the following parts:

• Assess the effect of speed reduction in the World Heritage fjords.

• Recommend an ideal sailing speed for cruise ships in the fjords, with the aim of minimising emissions.

• Quantify the anticipated reduction in emissions, especially for nitrogen oxide (NOx), sulfur dioxide (SO_2) and particulate matter (PM_{10} and $PM_{2,5}$).

Ship traffic covered in the analysis includes cruise ships and vessels serving the Bergen-Kirkenes coastal route (Hurtigruten). AIS-based analyses have been used to identify current sailing speeds and operating patterns for the assessed fleet, and to calculate fuel consumption and associated emissions. The analyses are based on the methods used in havbase.no, with corrections for use of emission reduction measures.

Calculations are based on actual ship activity from January 2016 through October 2017, and form a reference base for the current situation (baseline). Speed analyses were then performed for the same traffic load, and the effect of different speed limits was modelled for the fleet considered.

The first part of the report describes approaches and assumptions, and estimates are presented for potential reductions in fuel consumption and emissions. The report concludes with a recommendation of an ideal sailing speed for cruise ships in the fjords, with the aim of reducing emissions.

The study does not address other potential consequences of speed limitation for operators (e.g. of a practical/economic nature).

1.2 Area delineation

Figure 1-1 shows a section of the World Heritage sites, Geirangerfjord and Nærøyfjord. The red borderline shows the delineation of the World Heritage sites, where the effect of speed limits on cruise ships and Hurtigruten traffic has been assessed. The area for analysis of speed reduction is:

• South of 62,252 degrees north in Sunnylvsfjord, encompassing the entire fjord in to Geiranger. The fjord inlet to Hellesylt is also included in the analysis, although it lies outside the World Heritage area. This has little significance for the results of the analysis.

• South of 61,057 degrees north in Aurlandfjord and encompassing the entire fjord in to Aurland, as well as Nærøyfjord to Gudvangen.

Geirangerfjord

Aurland and Nærøyfjord

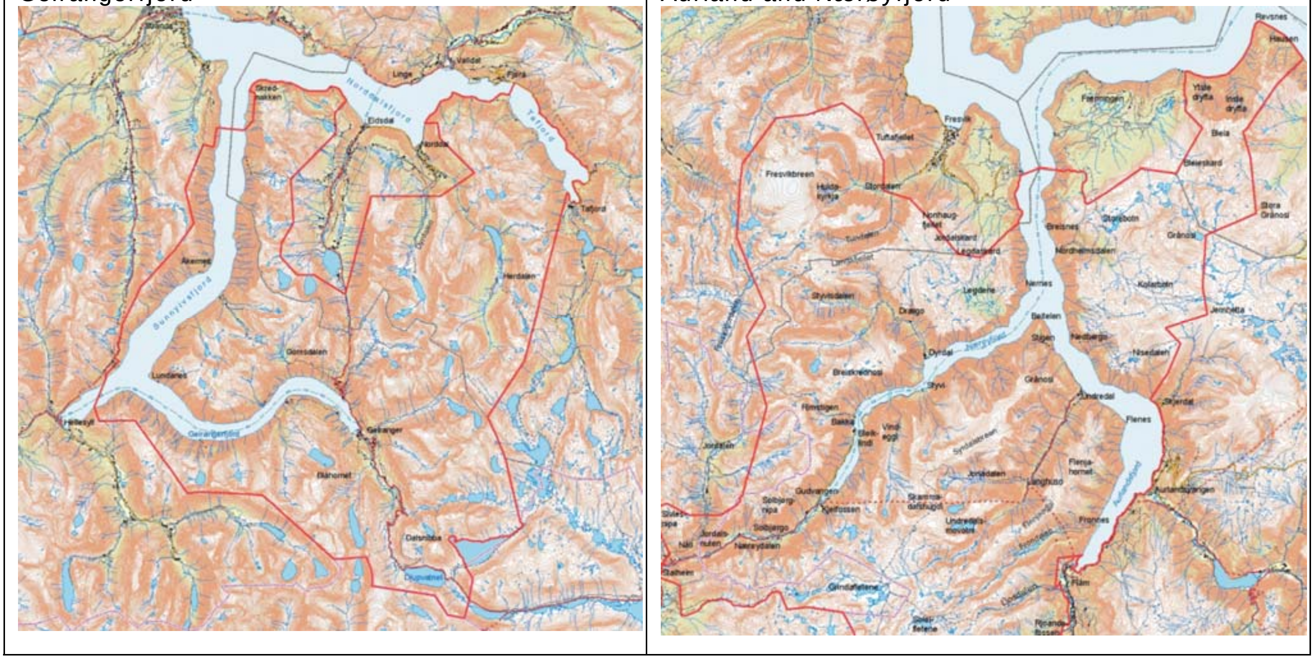

Figure 1-1 Definition of the World Heritage areas, Geirangerfjord and Nærøyfjord

2 METHODOLOGY

2.1 General

Speed reduction (slow steaming) can be an effective way of reducing the fuel consumption and emissions from a ship. The amount of fuel a ship uses for propulsion is proportional to the energy required to overcome the resistance the ship meets as it travels through the water at a given speed. The relationship between fuel consumption and the speed of the ship is usually exponential. As a rule of thumb, it can be assumed that the fuel consumption follows the third power of the speed ("Cubic Rule" method). That is, a 10% speed reduction reduces fuel consumption by 27%. In order to evaluate the total fuel savings based on an entire voyage, one has to take into account the extra time it takes to sail a given distance due to lower speed. By taking this into consideration, roughly simplified, one may assume that a 10% speed reduction gives a total fuel saving of approximately 19% for a given voyage (DNV GL, 2017).

Fuel savings from reduced speed have been documented in practice (e.g. Zanne et al 2013) and through theoretical studies (e.g. Eide et al 2017; Lindstad et al., 2015; Corbett et al 2009; Yin et al, 2017; Traut et al 2013). Legal, technical and environmental aspects of introducing speed limits at sea have also been considered (e.g.CE Delft, 2012). An overview of various studies and calculation methodologies can be found e.g. in Linstad et al. (2015). Yin et al (2017) have undertaken 32 studies, 15 of which used the "Cubic Rule" method.

2.2 AIS based environmental accounting (havbase.no)

DNV GL has access to historical Automatic Identification System (AIS) data for the entire Norwegian waters from 2013 to the present. These data provide a detailed and high-resolution overview of current sailing speeds, operating patterns, sailed distances (nautical miles) and time spent by each vessel. The information from AIS is compiled with technical databases for detailed information on the individual ships, such as installed power on main and auxiliary engines, machine configuration (diesel-electric versus diesel-mechanical / direct-driven), ship design speed, tonnage, etc. These data form the basis of an AIS-based environmental accounting, which is used to calculate fuel consumption, emissions and operational characteristics for voyages and when in port. Separate calculations for main engines, auxiliary engines and boilers are made for each individual ship. The method has been established in cooperation with the Norwegian Coastal Administration (NMA), and aggregated results for a number of ship types and size categories are presented in havbase.no.

AIS-based fuel consumption modelling for propulsion machinery performed according to the "Cubic Rule" method utilizes knowledge of the ship's design speed and observed speed from the AIS system. This means that we can calculate relatively accurately the load on the main engine, and hence the ship's fuel consumption. For cruise ships, this is typically done with a 5-10% margin of error compared to reported consumption. For port calls, the uncertainty in total fuel consumption will be linked to fuel consumption for auxiliary engines and boilers, where AIS cannot be used for other than indicating operating hours. In an evaluation of the World Heritage fjords, conducted by Marintek in 2017, fuel consumption data was obtained for cruise ships in port. DNV GL has gained access to the data for 22 ships, with reported fuel consumption / hours in port (presented in Rambøll, 2017). Using these data, a statistical relationship (formula) between fuel consumption / hours and DWT was prepared to validate the results in this analysis. The results correlate for ships up to about 60,000 DWT, but underestimate fuel consumption in port for larger vessels. This means that the share of consumption / emissions in port is likely to be somewhat underestimated in this study. Consumption in port does not affect estimated reduction potential due to speed limitation.

The following factors form the basis for the emissions calculations:

• Specific fuel consumption for main and auxiliary engines for different types and size categories of ships is based on the 2009 IMO GHG study, and so used in havbase.no.

• Calculation of CO_2 is based on standard factors for Marine Distillate Fuel, as used in havbase.no.

• Calculation of NOx emissions is based on standard factors for different types and size categories of ships based on EIAPP values (weighted values) for relevant machinery, as used in havbase.no.

• SOx and particulate matter are based on emission factors for marine distillate fuel. This is in line with data from the survey conducted by Rambøll (2017), where most ships reported either use of marine distillate fuel or scrubbing technology to meet the requirement of maximum 0.1% sulphur content in fuel (equivalent to requirements in port or when vessels sailing from or to the ECA area for SOx in the North Sea).

2.3 AIS-modelling of speed reduction

The AIS-based traffic analysis carried out identifies all unique cruise ships and Hurtigruten vessels in the analysis areas, and is based on actual ship activity in 2016 and 2017 (through October). The AIS analyses are used to establish the baseline for current fuel consumption and emissions to air.

For analysis of emission reduction as a result of to speed limitation in the area, speed analyses have been performed for all vessels, where various maximum allowed speeds are entered into the model. All observed speeds of a single ship exceeding the specified limit within the analysis area adjusted down to the specified limit. The model then calculates the amount of fuel savings, as well as the associated emission reductions, using the “Cubic Rule” method. Change in specific fuel consumption at modified engine load is also considered (see below). Figure 2-1 shows the calculation principle used, where each ship sailing above the speed limit is assigned a speed within the assigned speed limit.

The method is based on unchanged total sailing distance (entry and exit), but where fuel consumption (per nautical mile) at sailing speeds above the speed limit is adjusted down to consumption (per nautical mile) at the set speed limit. Additional fuel use resulting from additional sailing time at reduced speed is accounted for. Reduction in fuel consumption will only apply to the propulsion engine, while the auxiliary engine and boiler consumption will essentially remain constant. By performing the same exercise for all ships in the analysis area, reduction potential with different speed limits may be estimated. The model assumes that the extra time involved in the entry and exit phase when speed is reduced is compensated for outside the analysis area.

In summary, somewhat longer entry and exit times with the same berthing time in the harbours / fjords gives more total time spent in the analysis areas. Alternatively, operators may reduce time spent in the protected fjords, but this alternative is not considered in this study.

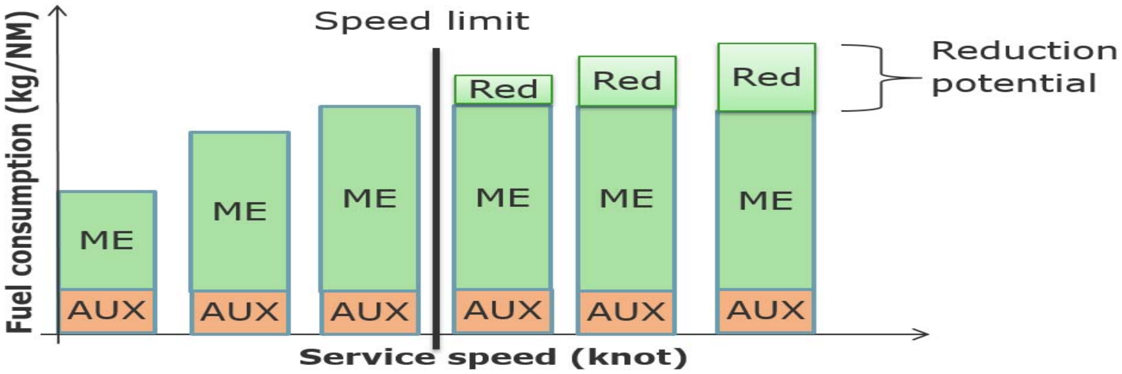

Figure 2-1 Principle for estimating emission reduction potentials introducing speed limits

Specific fuel consumption for marine engines (grams of fuel / kWh) is optimal at around 70% - 80% engine load, which is typical load areas for the propulsion engines when a ship maintains design speed (service speed). A correlation between the engine load factor and deviations in specific fuel consumption from optimal load is shown in Figure 2-2. The curves are based on an analysis of EIAPP engine certificates for approximately 800 engines of different sizes of diesel-electric and diesel-mechanical / direct-driven propulsion systems. Both engine configurations show a similar trend in specific consumption in load ranges above 50%, while with lower engine loads, specific fuel consumption (g / kWh) increases more for diesel-electric compared to direct drive. This is taken into account in calculations when ships are sailing at reduced speed.

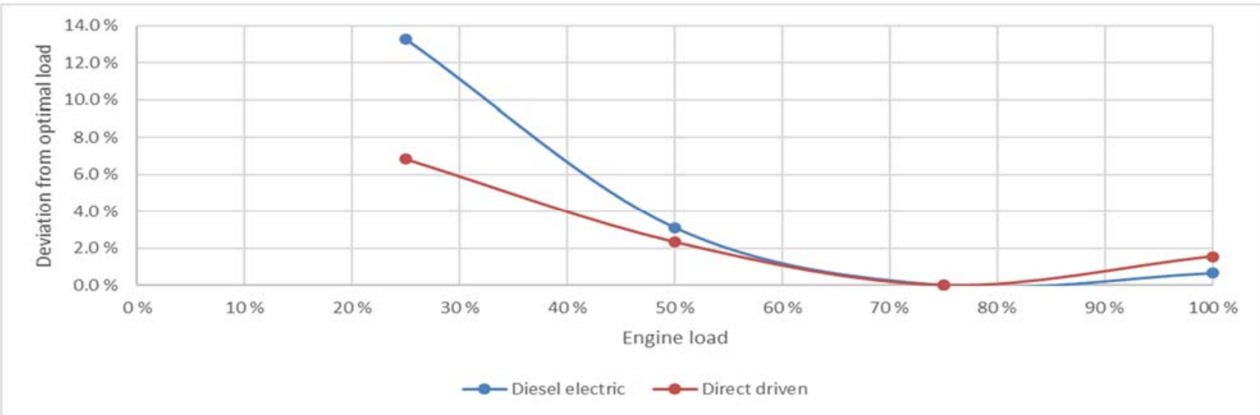

Figure 2-2 Deviation in specific fuel oil consumption from optimal load. Source: DNV GL

If the vessel's entry and exit sailing speed is restricted, propulsion engines will have to operate in a lower load range and thus will be less energy efficient. To what extent this increased consumption compensates for reduced energy required to propel the vessel at a lower speed through the water, depends on the actual change in speed and engine load. However, for ships with multiple engines, diesel-electric propulsion systems or a shaft generator in combination with auxiliary motors, it may be possible to shut down one or more engines, thus optimising engine efficiency (efficiency level) also at lower speeds. This effect is not taken into account in the calculations, as it requires detailed knowledge of the operation of each individual ship. Regardless, the effect of this is assumed to have minimal impact on the analysis.

3 ANALYSIS OF CRUISE AND HURTIGRUTEN SHIPS

3.1 Geirangerfjord

This study encompasses all cruise and Hurtigruten ships operating within the analysis area from January 2016 through to October 2017. This period was selected as it offers the timeframe with the best AIS coverage for the area, thus providing a solid foundation of data for analysis. Through AIS analysis of the area, 89 individual cruise and Hurtigruten vessels were identified during the period. In 2016 and 2017 there were 69 and 73 unique vessels respectively. Many of the vessels have several sailings in the fjord with calls in Geiranger, and all voyages are included in the speed analysis.

Figure 3-1 shows the speed profile for all vessels divided into different size categories of ships. From the entry to Sunnylvsfjord through to Geiranger, the vessels have a typical sailing speed of approximately 14-16 knots. During entry, several vessels maintain this speed for up to 45% of the time. Based on AIS analysis, we can see that only three vessels do not operate over 10-11 knots. This means that a speed limit of 12 knots or less will affect almost all cruise and Hurtigruten vessels operating in the Geirangerfjord.

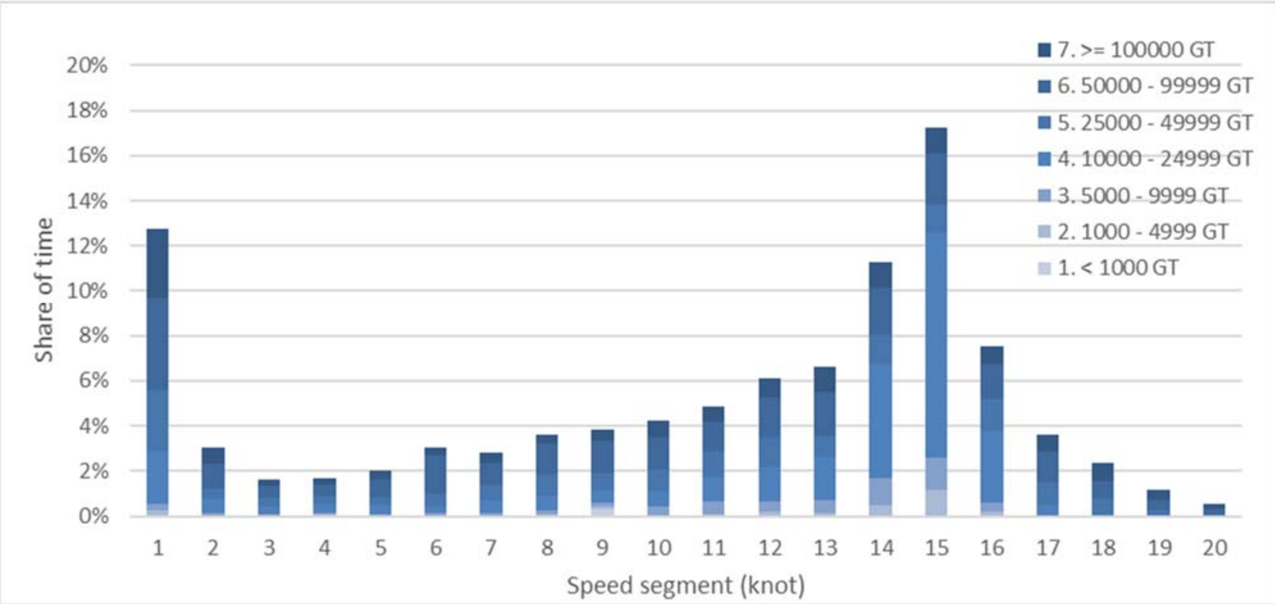

Figure 3-1 Speed profile for different vessel size categories operating in Geirangerfjord (2016-2017)

To assess the speed limits that can be set for the vessels in the study area, an analysis of fuel consumption (tonnes / nm) has been performed at different sailing speeds, i.e. tonnes of fuel per nautical mile. The effect of speed reduction must be calculated for each individual vessel, as there are large operating variations between the ships. As an illustration of this, Figure 3-2 shows the average fuel consumption / nautical miles for different size of ships. The figure shows that there is typically a lower threshold of 6-8 knots where reduced speed no longer gives reduced fuel consumption / nautical miles. If the speed is reduced too much, consumption and emissions will actually increase.

Based on these results, the decision was made to analyse the effects of speed limitation equal to 8, 10 and 12 knots. The speed limits include both entry and departure to and from the analysis area.

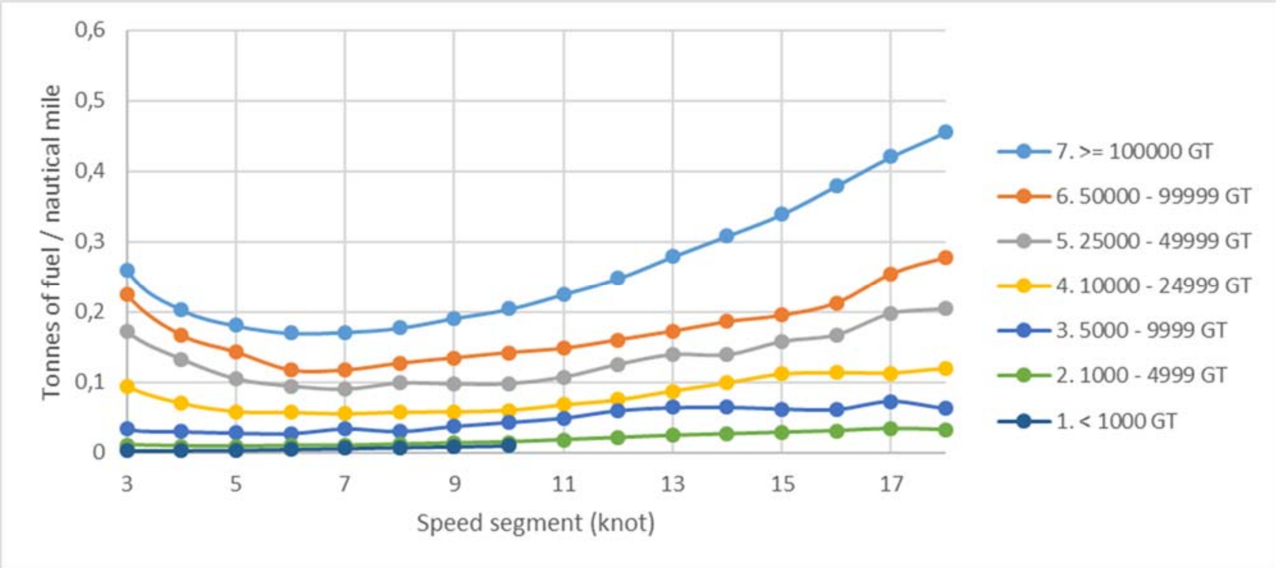

Figure 3-2 Fuel consumption for different speeds and size categories of ship. Source DNV GL

Table 3-1 shows a potential reduction in fuel consumption and emissions to air for sailing through the area, in both directions, in the range of 19% - 21% for 12 knots, 28% - 31% for 10 knots and between 34% - 37% for 8 knots. If fuel consumption in port is included, the reduction for the entire analysis area will be 10-11%, 14-17% and 17-20%, respectively, at the same speed limits. Fuel consumption in port accounts for about half of the total fuel consumption in the analysis area.

This illustrates that there is a significant potential for reduced fuel consumption and emissions introducing speeds restrictions in the World Heritage area. Of the total reduction potential, more than 70% is from ships larger than 25,000 BT.

Table 3-1 The effect of reduced vessel speed in Geirangerfjord

Parameter	**2016**			**Up to October 2017**		
	Entry and departure	**In port ***	**Total**	**Entry and departure**	**In port ***	**Total**
Distance sailed	10243	~ 0	10243	9886	~ 0	9886
Number of hours	935	1743	2678	919	1682	2601
Fuel consumption (tonnes)	1538	1441	2979	1704	1465	3168
Change in consumption at max 12 knots (%)	-19%	-	-10%	-21%	-	-11%
Change in consumption at max 10 knots (%)	-28%	-	-14%	-31%	-	-17%
Change in consumption at max 8 knots (%)	-34%	-	-17%	-37%	-	-20%

* Vessel speed is under 1 knot

For the analysis area, total CO_2, NOx, SOx, PM_{10} and $PM_{2.5}$ emissions were calculated for entry and departure without limitations on speed and port-based emissions, i.e. the baseline for cruise and Hurtigruten vessels. There are small differences in fuel consumption and emissions between the two years, with average emissions from the vessels in the range of 9800 tonnes CO_2/year, 165 tonnes NOx/year, 6.1 tonnes SOx/year, and 4.6 tonnes PM_{10}/year or 4.3 tonnes $PM_{2.5}$/year.

The reduction in emissions resulting from reduced speed for the individual components is assumed to be proportional to the reduction in fuel consumption for the main engines. Lower engine loads can result in a higher degree of soot formation in the engines, thus affecting the emission of particles. However, there is little data available describing these conditions, therefore it is assumed that PM_{10} and $PM_{2.5}$ are also reduced in accordance with the main engine's fuel consumption. NOx emissions (g/kwh) will also vary with engine load, but this is not taken into account in the study. Table 3-2 shows the calculated reduction in emissions to air as a result of establishing speed limits in the analysis area.

Table 3-2 Reduction in emissions to air as a result of speed limitation

Reduction per emission component	Max 12 knots	Max 10 knots	Max 8 knots
CO_2 emissions (tonne/year)	1000	1500	1800
NOx emissions (tonne/year)	17	26	30
SOx emissions (tonne/year)	0.7	1.0	1.1
PM10 emissions (tonne/year)	0.5	0.7	0.9
PM2.5 emissions (tonne/year)	0.5	0.7	0.8

Figure 3-3 indicates the areas that will obtain reduced emissions as a result of establishing speed limits for all cruise and Hurtigruten vessels. The figure shows the impact areas for speed limits of 12 and 8 knots. The red areas indicate where the highest emission cuts are achieved, while the dark blue areas indicate the areas with the lowest reductions. Reduced speed will result in reduced emissions throughout the fjord area, from the inlet in Sunnylvsfjord to the harbour area in Geiranger. The reduction is at least in the inner parts of the fjords (where speeds are already low). Note that the colour scales varies between the two figures.

12 knots speed limit | 8 knots speed limit

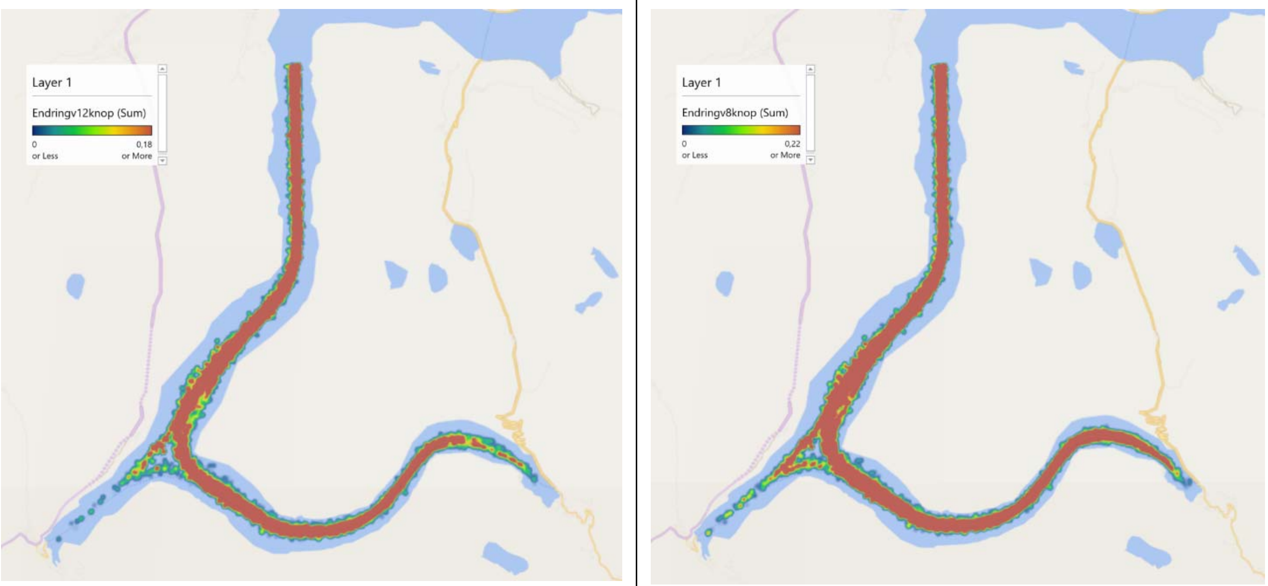

Figure 3-3 Emission reduction areas based on speed limits of 12 knots (left) and 8 knots (right). Source DNV GL

Cruise and Hurtigruten vessels do not operate year-round in Geirangerfjord. Calculated fuel consumption, emissions and reduction potential as a result of measures to reduce speed will therefore apply only at certain times of the year. Figure 3-4 shows the overall reduction in fuel consumption and emissions, with a speed limit of 8 knots, for the months that the vessels operate in the area. As illustrated, there is a slight difference in vessel operations between 2016 and 2017, and hence a variation in the reduction potential. Activity and potential for reducing emissions and fuel consumption are mainly related to the three summer months of June, July and August, with lower activity levels on both sides of the summer.

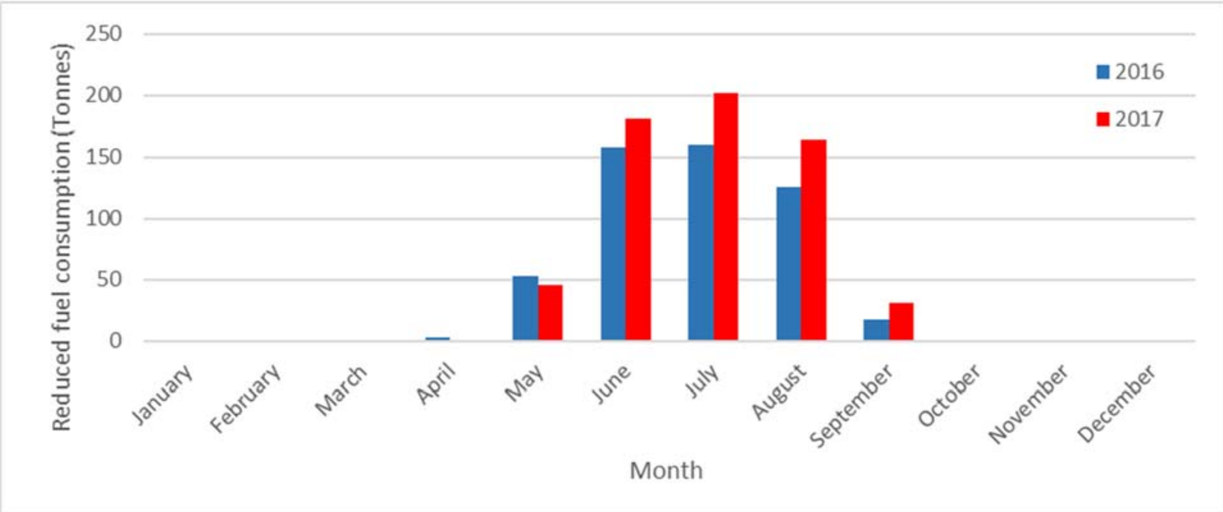

Figure 3-4 Distribution of monthly fuel consumption reduction potentials, with a speed limit of 8 knots, based on 2016 and 2017 data. Source DNV GL

3.2 Aurlandsfjord and Nærøyfjord

As with the analysis for Geirangerfjord, the study in Aurlandsfjord and Nærøyfjord includes all cruise and Hurtigruten vessels operating within the designated area of analysis from 2016 through October 2017. AIS analysis identifies 76 unique cruise and Hurtigruten vessels throughout the period, with 58 in 2016 and 54 in 2017, respectively. Many of the vessels have multiple sailings in the fjords, mainly calling in Aurland, but there are also some trips into Nærøyfjord. All voyages are included in the speed analysis.

The speed profile of all cruise and Hurtigruten vessels operating within the Aurlandfjord and Nærøyfjord study area is shown in Figure 3-5. There is a wide range of sailing speeds for the vessels, and they maintain speeds over 12 knots about 30% of the time. Based on the AIS analysis, we can see that there is only one vessel that does not operate at over 10 knots. This means that a speed limit will affect almost all cruise and Hurtigruten vessels operating in the area.

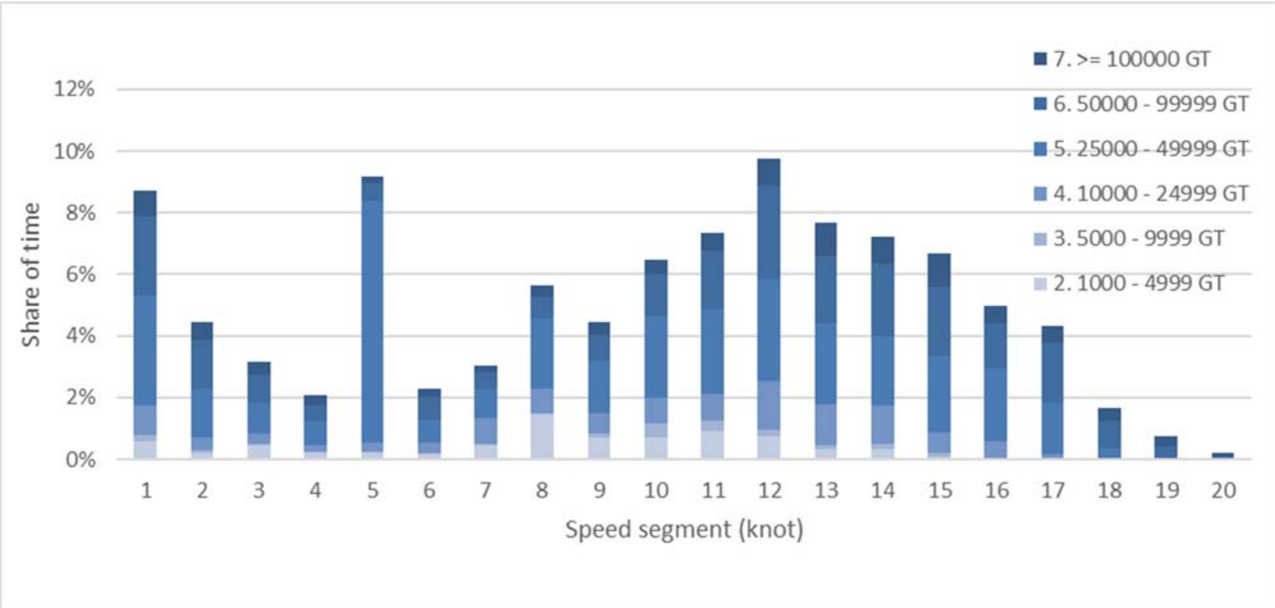

Figure 3-5 Speed profile for different vessel size categories operating in Aurlandsfjord and Nærøyfjord. Source DNV GL

Assessment of which speed limits that can be established for the vessels is based on the same approach utilised in the Geirangerfjord analysis (see section 3.1), i.e. tonnes of fuel per nautical mile. A graph corresponding to Figure 3-2 was used for vessels operating in Aurlandsfjord and Nærøyfjord (established using the same methodology but including fewer, and some different, vessels). The lowest fuel consumption per nautical mile is also in the same range for this group, i.e. around 6-8 knots.

Based on these results, it was decided to analyse the impact of reducing speed in accordance with the Geirangerfjord analysis, i.e. 8, 10 and 12 knots. The speed limits include both entry and departure to and from Aurlandsfjord and Nærøyfjord.

Table 3-3 shows a potential reduction in fuel consumption and emissions to air for sailing in both directions through the study area in the range of 15% - 19% for 12 knots, 22% - 28% for 10 knots and between 27% - 33% for 8 knots. If fuel consumption in ports is included, the reduction for the entire area of analysis will be 6%, 8% and 10%, respectively. Fuel consumption in port accounts for about 60% of total fuel consumption in the analysis area.

Compared to the Geirangerfjord, the total reduction potential is lower. Of the total reduction potential, more than 70% is from ships larger than 25,000 BT. That said, there is also for Aurlandsfjord and Nærøyfjord a considerable potential for reducing fuel consumption and emissions by reducing the sailing speed.

Table 3-3 Reduction in emissions to air as a result of speed in Aurlandsfjord and Nærøyfjord

Parameter	2016			Up to October 2017		
	Entry and departure	In port *	Total	Entry and departure	In port *	Total
Distance sailed	5343	~ 0	5343	4143	~ 0	4143
Number of hours	566	1630		403	1447	
Fuel consumption (tonne)	726	1202	1928	725	1185	1911
Change in consumption at max 12 knots (%)	-15%	-	-6%	-19%	-	-7%
Change in consumption at max 10 knots (%)	-22%	-	-8%	-28%	-	-10%
Change in consumption at max 8 knots (%)	-27%	-	-10%	-33%	-	-12%

* Vessel speed is under 1 knot

For the analysis area, total CO_2, NOx, SOx, PM_{10} and $PM_{2.5}$ emissions were calculated for entry and departure without limitations on speed and port-based emissions, i.e. the baseline for cruise and Hurtigruten vessels. There are small differences in fuel consumption and emissions between the two years, with average emissions from the vessels in the range of 6050 tonnes CO_2/year, 90 tonnes NOx/year, 3.8 tons SOx/year and 2.9 tons PM_{10}/year or 2.7 tonnes $PM_{2.5}$/per year.

The reduction in emissions for the individual components as a result of reduced speed is assumed to be proportional to the reduction in fuel consumption for the main engines. Table 3-4 shows the calculated reduction in emissions to air as a result of establishing speed limits in the analysis area.

Table 3-4 Reduction in emissions to air as a result of speed limitation

Reduction per emission component	Max 12 knots	Max 10 knots	Max 8 knots
CO_2 emissions (tonne/year)	390	570	680
NOx emissions (tonne/year)	6	8	10
SOx emissions (tonne/year)	0.2	0.4	0.4
PM10 emissions (tonne/year)	0.2	0.3	0.3
PM2.5 emissions (tonne/year)	0.2	0.3	0.3

Figure 3-6 indicates the areas that will obtain reduced emissions as a result of establishing speed limits for all cruise and Hurtigruten vessels. The figure shows the impact areas for speed limits of 12 and 8 knots. The red areas indicate where the highest emission cuts are achieved, while the dark blue areas indicate the areas with the lowest reductions. Reduced speed will result in reduced emissions throughout the entire area, from the approach to Aurlandsfjord and into the port area of Aurland. For Nærøyfjord, the reduction potential is less significant as the vessels generally maintain a lower speed. At a speed limit of 12 knots in Nærøyfjord, there will be a slight reduction in the outer half of the fjord, with no impact in the inner half. If the speed limit is set to 8 knots, there will be a slight reduction in almost the entire Nærøyfjord area.

12 knots speed limit | 8 knots speed limit

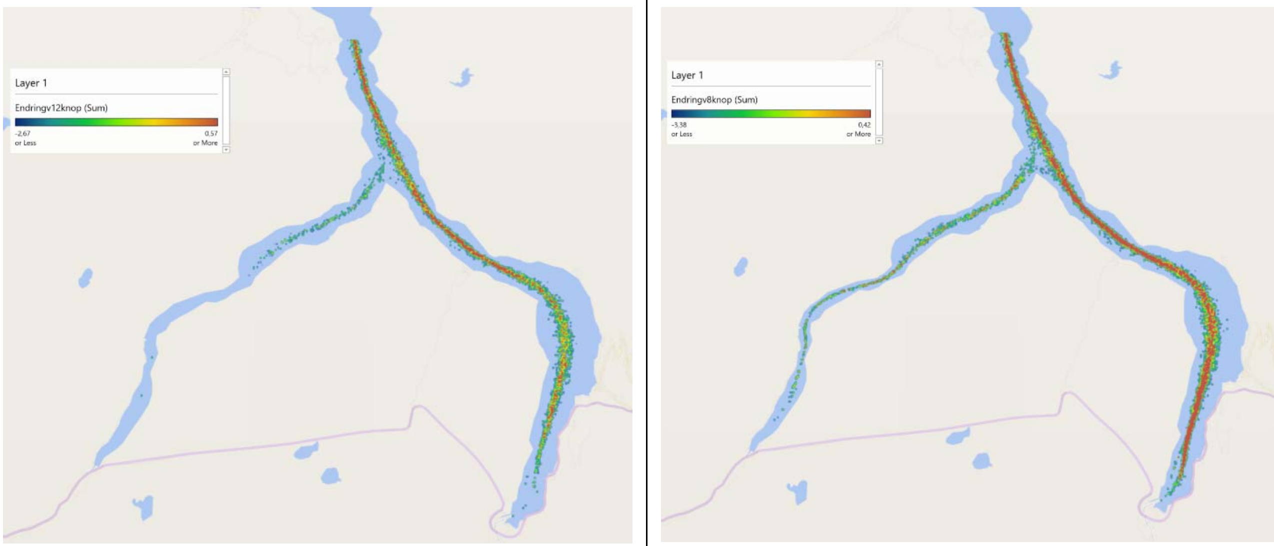

Figure 3-6 Area of influence for potential emission reduction with speed limits of 12 knots (left) and 8 knots (right). Source DNV GL

Cruise and Hurtigruten vessels do not operate year-round in Aurlandsfjord and Nærøyfjord. Estimated fuel consumption, emissions and reduction potential as a result of reduced speed will therefore only apply at certain times of the year. Figure 3-7 shows the overall reduction in fuel consumption and emissions, with a speed limit of 8 knots, for the months the vessels operate in the area. As illustrated, there is a slight difference in vessel operations between 2016 and 2017, and hence a variation in the reduction potential. The main activity and therefore the potential for reducing emissions and fuel consumption is related to the four summer months of May, June, July and August.

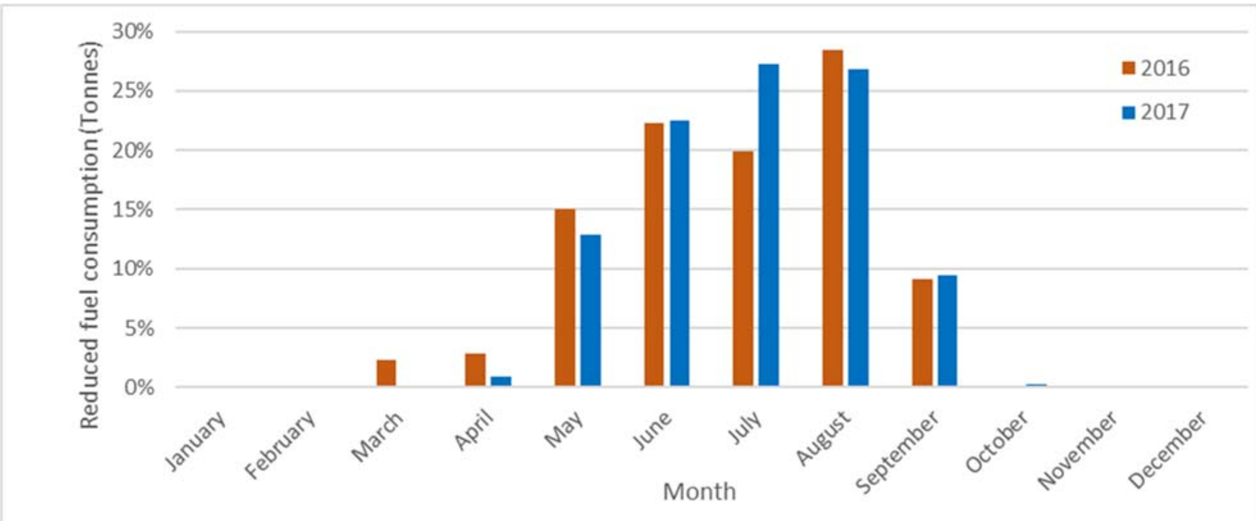

Figure 3-7 Distribution of monthly fuel consumption reduction potentials, with a speed limit of 8 knots, based on 2016 and 2017 data. Source DNV GL

4 SUMMARY AND RECOMMENDATIONS

Cruise and Hurtigruten ship traffic in Norwegian Heritage fjords accounts for a significant proportion of total emissions to air in these areas. If speed limitation is introduced in the World Heritage fjords, this will lead to reduced fuel consumption and reduced emissions to air along the entire route to the destination area in these fjords. Using a maximum speed of 12, 10 or 8 knots in the World Heritage areas would mean a reduction in total maritime emissions of 10%, 15% and 19% respectively for Geirangerfjord, and in the range of 6%, 8% and 10% for Nærøyfjord. The reduction potential is lower in the Nærøyfjord area because vessels generally maintain a lower speed, in particular those vessels entering Nærøyfjord. In both analysis areas, the largest vessels have the largest reduction potential. As expected, there is also a significant seasonal variation in reduction potential.

The analysis also shows that for the actual fleet there is a lower emission reduction threshold of 8 knots. This means that reduction in speed from today's operating practice will significantly reduce fuel consumption and emissions down to this speed limit. Further speed reduction does not provide any significant further reduction. This threshold will be individual for each ship, but for the collective fleet (the major contributors), 8 knots could be an ideal lower speed limit in order to reduce emissions. Such a speed limit is believed not to have adverse effects on the vessels' manoeuvrability and marine safety. It is noted that the Ministry has set a speed limit of 8 knots in the inner part of Geirangerfjord, cf. anchorage regulations for Geirangerfjord.

It should be noted that reduced speeds could have consequences for operators that are not investigated in this study. For example, ships operating on schedules (such as Hurtigruten) may need to increase their speed outside of the World Heritage area to recover lost time. This could lead to an increase in emissions outside the World Heritage sites.

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Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil & gas and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our professionals are dedicated to helping our customers make the world safer, smarter and greener.