THE IMPACT OF EU SULPHUR DIRECTIVE ON THE EMISSIONS OF SHIPS

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Abstract: The recent changes in marine fuel sulphur content requirements set by the directive 2005/33/EC have reduced the SO_x and fine particle ($PM_{2.5}$) emissions from ships in European sea regions. There are significant reductions of SO_x emissions from shipping in the Emission Control Areas of the Baltic Sea and the North Sea, especially in port areas throughout the EU. The requirement to use 0.1%S fuel in ships' engines while at berth has decreased emissions from ships in areas which are close to significant human populations. From IMO-registered vessels, the predicted annual emissions of SO_x (2009-2011) have decreased by 105 200 metric tons (32.6%) while CO_2 emissions increased approximately 2.9%. For $PM_{2.5}$, the reduction of 14 600 tons (19.7 %) was predicted, respectively. This work is based on the Automatic Identification System data and STEAM ship emission modelling work (Jalkanen et al, 2009; 2012), which reflect the true traffic image of shipping and technical details of each vessel. There is no need for mathematical construction of route networks over large distances.

In this paper we will demonstrate significant emissions reductions in four port cities (Helsinki, Tallinn, Rotterdam and Gdansk). We will show that SO_x and $PM_{2.5}$ emission from IMO-registered traffic has decreased significantly more than the presented overall ECA reductions. In addition to the emission inventories, fleet characteristics of each port are reported. The temporal variation of emissions is retained facilitating an hourly update of ship emissions in port areas. These results can be used as input material for dispersion modelling work to estimate the ship contribution to the overall air quality in port cities. This study will contribute to TRANSPHORM and BSR InnoShip projects.

Key words*: Shipping emissions, SECA, STEAM, AIS, SOx, Sulphur, NOx, PM*

METHODS

The shipping emissions of the northern Emission Control Area (ECA) region which includes the North Sea, the English Channel and the Baltic Sea, were evaluated using an emission modelling program Ship Traffic Emission Assessment Model, (STEAM); for a more detailed description of this model, the reader is referred to Jalkanen et al. (2009, 2012 and 2013). The model allows for the influences of travel routes and ship speed, engine load, fuel sulphur content, multiengine setups, abatement methods and waves (Jalkanen et al, 2012). This modelling approach uses the position reports generated by the Automatic Identification System (AIS); this system is on-board every vessel that weighs more than 300 tons globally. The AIS system provides for automatic updates of the positions and instantaneous speeds of ships at intervals of a few seconds. The model requires as input the detailed technical specifications of all fuel consuming systems on-board and other relevant technical details of the ships for all the ships considered. Such technical specifications were therefore collected and archived for over 50000 ships from various sources of information; the data from IHS Fairplay (IHS Fairplay, 2011) was the most significant source. A large portion of AIS-messages comes from non-IMO registered ships however, and for these ships generic small vessel attributes (500 gross tons with a 1000kW 4-stroke engine) are used. The STEAM model is then used to combine the AIS-based information with the detailed technical knowledge of the ships evaluating instantaneous fuel consumption and emissions of selected pollutants. The fuel consumption and emissions are computed separately for all the vessels; by using archived regional AIS data this results in a regional emission inventory. In the following, we refer to the Northern European Emission Control Area simply as 'ECA'. For this paper, archived AIS-messages provided by the North Sea and the Baltic Sea riparian states in 2009 were combined, covering the entire ECA region. The combined dataset contains more than 552 million archived AIS-messages. For ECA in 2011, AIS-messages were extracted from a dataset provided by the European Maritime Safety Agency (EMSA). This extracted dataset contains 607 million archived AIS messages. The harbour emission estimations presented in this paper are based on the ECA 2011 dataset.

Route and activity deduction

In the STEAM model the travel routes are evaluated in a stepwise manner, by a linear interpolation for each consecutive AIS-message pair. However, AIS-transmitter calibration and use is susceptible to human error and especially with smaller ships without an IMO number may seem to behave somewhat erratically based on the AIS-messages they send. Furthermore, using sparse AIS data with harbor emissions estimation facilitates a risk that route intervals are interpreted incorrectly even if the message information is accurate. For instance, it is not uncommon that the last message from a ship indicates maneuvering activities with non-zero speed while soon after the ship is actually berthing and stationary. Due to this discrete nature of determining routes and the possibility of erroneous messages, it is necessary to analyze the validity of each route segment, before emissions will be assessed. Furthermore, at open sea operations large spatial and temporal gaps must be allowed while at harbor operations the possible down-time of ships (i.e. interval between an end point of a berthing activity and the start point of another) needs to be identified with a smaller temporal separation tolerance. Thus, before emission estimation the validity of each linear route segment is evaluated based on several key indicators, such as the temporal and spatial separation of message points, the average speed included in messages, the actual average speed determined by the spatial/temporal change and finally the ship's listed design speed; only if all of the selected indicators show no significant contradictions, emissions are calculated and distributed to emission grid cells.

Evaluation of fuel sulphur content

Fuel sulfur content affects significantly to the produced $PM_{2.5}$ and SO_x emissions per fuel amount burned. In ECA since the beginning of 2010, the maximum allowed FSC in inland waterway vessels and for ships at berth has been restricted to 0.1%; the latter regulation applies only to vessels which are berthing for more than 2 hours. Otherwise, the maximum FSC has been limited to 1.0% since July 2010. In STEAM model, FSC is determined separately for main and auxiliary engines, by taking into account engine specifications and region specific limitations. All vessels are assumed to use the cheapest accepted fuel (commonly this is also the heaviest fuel). The fuel sulphur content is therefore assumed to be

$$FSC = \min\{FSC_C, FSC_A\} \quad \text{(Eq.1)}$$

where the maximum FSC the engine can use, FSC_C, is estimated by using the engine's power output rating, stroke type and RPM (Hulskotte, 2010), (Kuiken, 2008). The maximum allowed FSC, FSC_A is determined based on region, date and speed; vessels with a speed lower than 1 knot are assumed to be berthing, resulting in FSC of 0.1% in ECA region after the beginning of 2010, given that the vessel speed will not exceed the selected threshold value before 2 hours has passed.

Model evaluation

The model has been able to predict aggregate annual fuel consumption of a collection of large marine ships with a mean prediction error of 9% (Jalkanen et al, 2012). Large-scale comparisons to ship owner fuel reports are constrained by the availability of vessel fuel reports, but have so far been done for a limited dataset of 20 vessels. The capability of the model for estimating instantaneous power consumption has been evaluated to be moderately less accurate, with a mean prediction error of 15 % in a thorough case-study (Jalkanen et al., 2012). The evaluated emissions also agree fairly well with the results of several measurement campaigns presented in literature, for various engines, engine loads and pollutants. A more detailed description of the model evaluation studies are presented by Jalkanen et al. (2009 and 2012).

RESULTS

In Figure 1, the weekly time profile of CO_2 emissions for different ship categories is presented. It can be seen from the figure that CO_2 emission output is mainly dominated by the combination of tankers, container and cargo ships. The most notable seasonal variation can be associated with passenger ships, which operate more actively during the summer season.

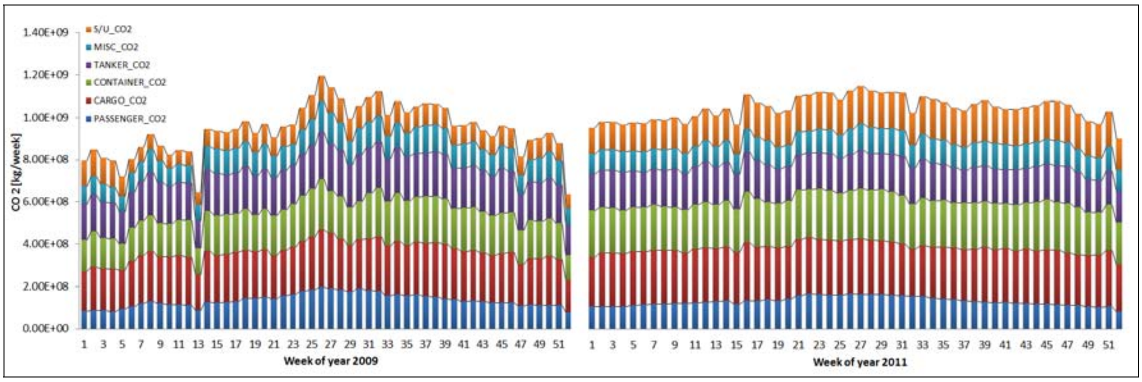

Figure 1: Weekly time profile of CO_2 emissions for different ship types in ECA 2009 and 2011. Cargo ships include Bulk carriers, general cargo vessels and vehicle carriers. Passenger ships include ROPAX ships, ferries and passenger cruisers.

According to the modelling results for 2009, approximately 49.4 million tons of CO_2 were produced by shipping in ECA. In 2011, 53.9 million tons were produced respectively. The increase in CO_2 output is mainly due to the increase in non-IMO registered ships that steadily continue to increase their contribution in shipping emissions, although it is more likely that existing small vessels have installed AIS-transmitter rather than the actual number of small vessels has increased with such observed rate. The highest $PM_{2.5}$ emissions were situated near the coast of Netherlands and South-Eastern parts of UK (Figure 2). The same observation can be made from the geographical distribution of other modelled pollutants (results not shown).

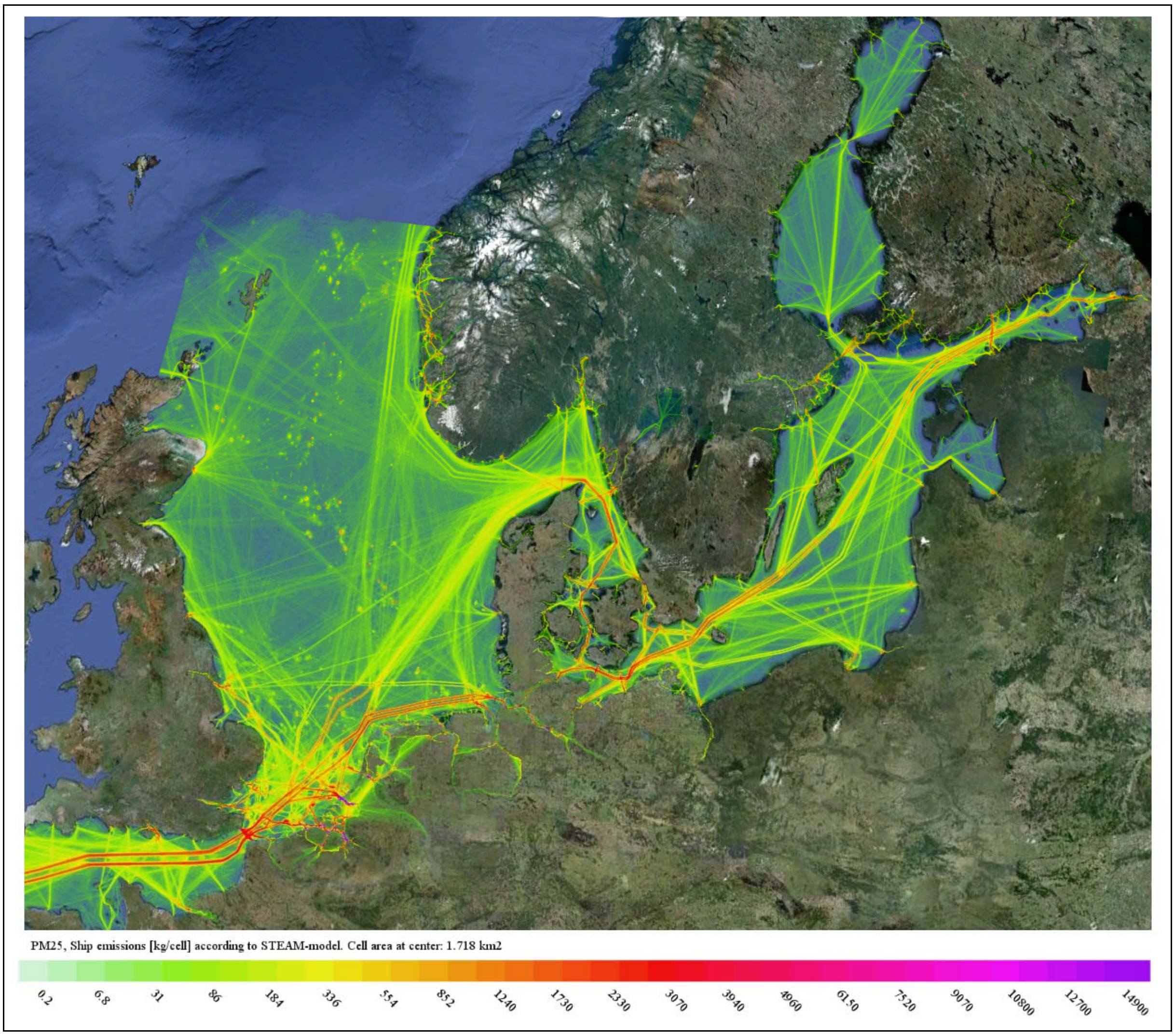

Figure 2: Geographic shipping emissions distribution in ECA 2011 for $PM_{2.5}$ which consists of organic and elemental carbon, ash and wet sulfate particles.

The evolution of emissions from IMO-registered ships, which have been presented in Table 1b, does not suffer from the uncertainties arising from the number of operational unidentified small vessels. It can be seen from the table that in 2009, when the maximum allowed FSC was 1.5%, resulted in a total of 322 ktons of SO_x and 74 ktons of $PM_{2.5}$ emissions from IMO-registered shipping. In 2011, the estimated amount of SO_x emissions have decreased to 217 ktons (-32.6%) and $PM_{2.5}$ emissions decreased to 59.4 ktons (-19.7%). A closer inspection reveals that the highest relative reductions in SO_x and $PM_{2.5}$ can be associated with container and tanker ships. These large reductions goes to show how large a portion of fuel consumption occurs at berthing operation, which in 2011 was to be done with low sulfur fuels; we estimate that approximately 25% of fuel burned in ECA in 2011 occurred near harbors.

The reductions in SO_x and $PM_{2.5}$ emissions from IMO-registered ships in the selected harbors however, have decreased even more; In Rotterdam, Tallinn and Gdansk we predict a decrease of approximately 59% in SO_x emissions. These results indicate that the requirement to switch to low-sulfur distillates while berthing has decreased SO_x and $PM_{2.5}$ emissions significantly near harbors while the decrease of maximum allowed fuel sulfur content to 1.0% after June 2010 has decreased SO_x and $PM_{2.5}$ emissions to a great extent in all ECA. In Figure 3a-d the geographical distribution of $PM_{2.5}$ emissions in the selected harbors in 2011, bundled with area satellite images, are shown. It should be noted that the size of figures represent the size of area, as the "eye-altitude" for the satellite images is the same. It can be seen that the $PM_{2.5}$ emissions are clearly the largest in Rotterdam and are more evenly distributed within the harbor area, while in Tallinn, Gdansk and Helsinki a small number of emission "hot-spots" can be identified. In Rotterdam we predict $PM_{2.5}$ emissions which are approximately 4-5 times the respective emissions in any of the other three modelled harbor areas (Table 1). In Helsinki and Tallinn the estimated $PM_{2.5}$ emissions are almost equal but in Gdansk approximately 25% larger.

Table 1: Estimated shipping emissions in ECA and selected harbours within ECA. Emissions have presented for 2009 and 2011, separately for all ships (All) and IMO-registered ships (IMO).

		CO2 [ton]	NOx [ton]	Sox [ton]	PM2.5 [ton]	CO [ton]	Ships
ECA (All)	**2011**	53 951 000	1 085 100	238 300	66 900	108 500	30 167
	2009	49 362 000	1 032 900	350 370	80 710	96 300	23 599
Rotterdam (All)	**2011**	1 452 877	25 186	3 003	1 238	3 499	10 985
	2009	1 165 133	20 508	5 472	1 448	2 840	7 021
Helsinki (All)	**2011**	236 013	3 626	570	212	556	560
	2009	193 163	3 049	1 122	271	554	426
Gdansk (All)	**2011**	367 432	6 428	472	270	672	2 152
	2009	270 591	4 764	1 100	305	476	1 933
Tallinn (All)	**2011**	277 694	4 523	462	215	539	1 450
	2009	231 164	3 799	1 114	286	475	1 324
ECA (IMO)	**2011**	45 635 000	944 100	217 000	59 400	89 100	16 030
	2009	44 344 000	948 700	322 180	73 970	84 400	15 438
Rotterdam (IMO)	**2011**	1 033 304	18 245	1 980	869	2 533	6 637
	2009	1 044 483	18 489	4 795	1 286	2 529	6 191
Helsinki (IMO)	**2011**	184 274	2 772	477	172	424	359
	2009	168 075	2 630	981	238	484	359
Gdansk (IMO)	**2011**	323 826	5 706	396	237	574	1 969
	2009	246 894	4 369	967	273	421	1 853
Tallinn (IMO)	**2011**	255 716	4 161	436	200	489	1 352
	2009	223 174	3 666	1 069	275	454	1 276

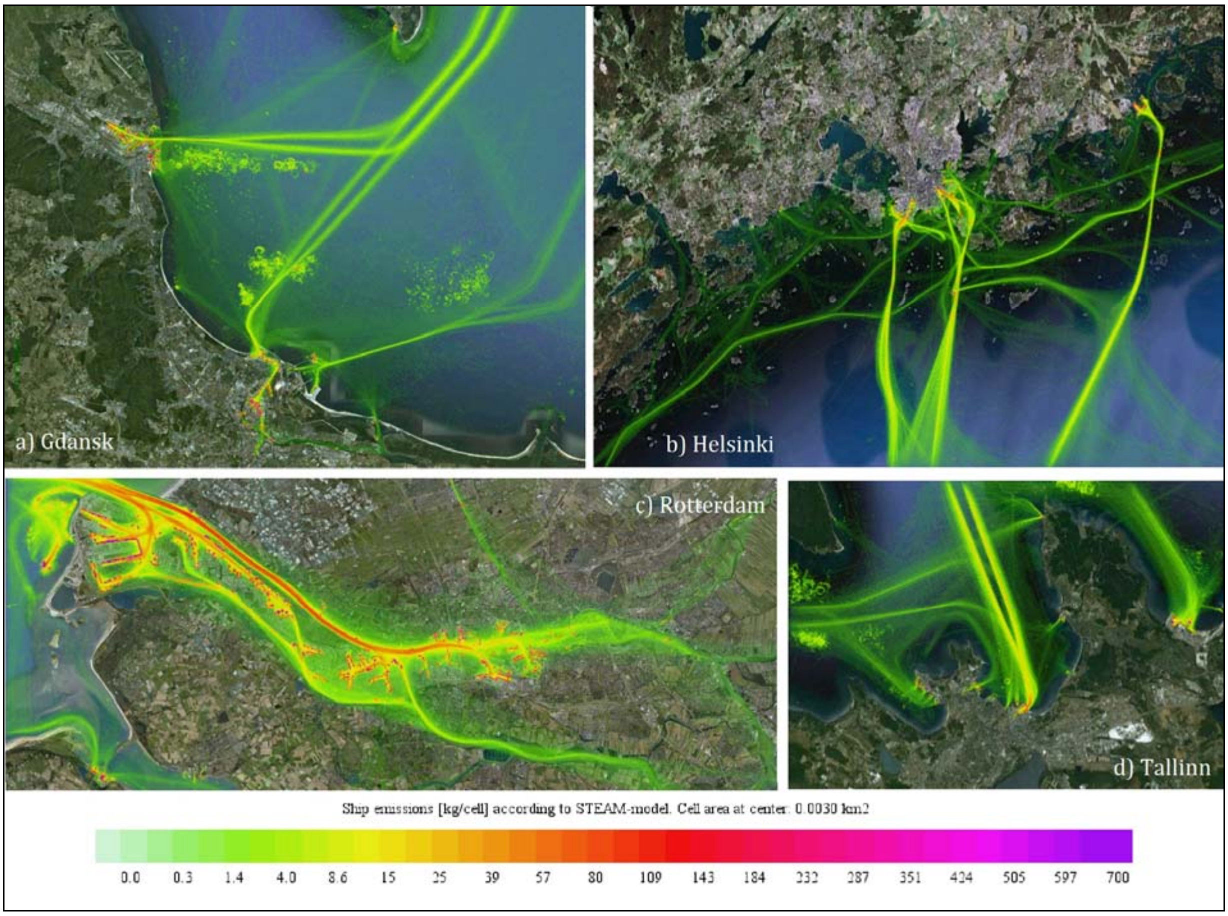

Figure 3a-d: Distribution of modelled $PM_{2.5}$ emissions in 2011 in the selected harbours. The view distance above surface (eye altitude) is the same for all figures (the size of figure represents the size of area). Satellite image layer has been provided by Google Earth 2013.

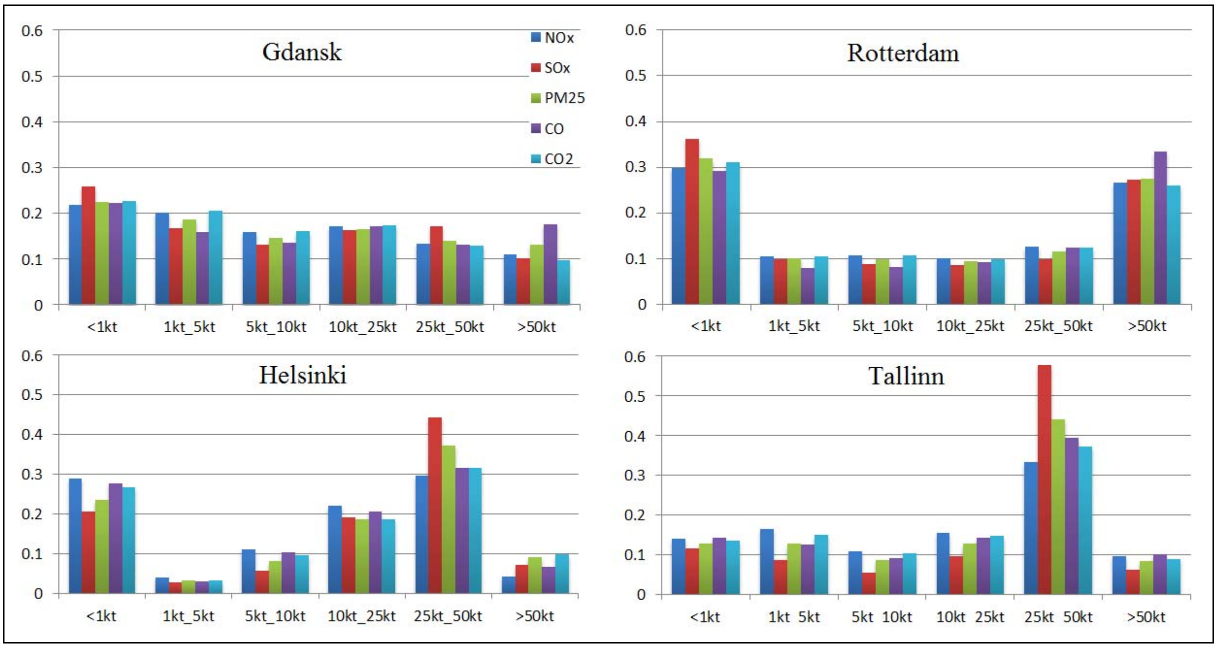

Figure 4a-d: Relative emissions distribution for the selected harbors by vessel size category (gross tonnage in ktons, horizontal axis). Vertical axis describes the relative share from total emissions.

In respect other pollutant types however, the selected harbors rank differently; for instance, modelled SO_x emissions in Helsinki are larger than in Gdansk. This can be explained by the fact that different ship types are not equally represented in the selected harbors. In Tallinn, emissions are dominated by passenger ships (especially RoPaX ships) that produce 55.5% of total $PM_{2.5}$ emissions. In Helsinki, passenger ship traffic has almost the same relative share (52.3% of $PM_{2.5}$). In Gdansk the relative contributions are more equally represented and container ships as the largest category account for 25.0% of $PM_{2.5}$ emissions and cargo ships share 21.2%. Finally in Rotterdam, container ships contribute 36.3% but also non-IMO registered ships are well represented with a 29.8% share. Consequently, emission distributions for the selected harbors by vessel size categories (Figure 4a-d) reflect these abovementioned ship type differences; in Rotterdam small and very large ships dominate while in Helsinki and Tallinn the weight class between 25 and 50 ktons, in which most of the RoPaX and passenger cruisers belong, has the highest share.

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