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Survey of Ship Tracks in Fehmarn Belt

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ABSTRACT: A survey of the ship traffic passing Fehmarn Belt has been carried out to clarify the present ship traffic pattern in the vicinity of a proposed bridge connecting Denmark and Germany. Digitally recorded radar tracks linked with information about the ship type and size have been registered. The link between tracks and size information permits investigation of correlations between the navigational pattern and the ship sizes. A brief description of the survey is initially given. Then focus is turned to the statistical analysis of the survey data with emphasis on the lateral distribution of the position of the ships at the proposed bridge location. It is found that the traditional utilization of a normal distribution is not compatible with the survey data and an explanation for this is suggested. Finally, some considerations as to the implication to the risk of collisions to a planned fixed link across Fehmarn Belt are presented.

1 INTRODUCTION

Fehmarn Belt is a 20km wide strait between the island Fehmarn in Germany and the island Lolland of Denmark - see Figure 1. The strait is used by ship traffic between the Baltic Sea in the east and the Kiel Canal and the Great Belt in the west. About 40,000-45,000 ships pass the belt annually and the ship size may reach up to 250,000 DWT.

A fixed connection between Denmark and Germany across Fehmarn Belt is currently in consideration. On behalf of Trafikministeriet in Denmark and Bundesministerium für Verkehr, Bau- und Wohnungswesen in Germany, COWI and Lahmeyer International have performed a feasibility study of different technical concepts for a fixed connection. In the feasibility study it was initially realized that the risk of ship collisions would be one of the key issues for the suitability of a bridge solution. To develop a realistic assessment of the extent and the character of the problem an observation program was started to provide detailed information about the present navigational pattern in Fehmarn Belt. The program should collect information about the volume and types of passing ship traffic and whenever possible make digital records of the tracks of these ships.

The passage statistics (volume, type, size) would provide the necessary basis for estimation of the annual ship traffic passing the bridge. The more detailed information (cargo type, origin and destination) enables correlation

of the observations with traffic models based on trade patterns, and by appropriate calibration this would improve predictions on the future traffic that are based on these models.

Concerning the navigational pattern as described by the observed radar tracks it was realized that the information obtained would not be directly applicable to the situation after construction of a bridge. When compared to neighboring waters the area provides ample of water depth over a large part of the intended bridge alignment. A bridge will therefore represent a significant change in the navigational freedom in Fehmarn Belt. Passing ships – in particular the larger ones - would be restricted to the navigational spans provided in the bridge. Adaptation to those new conditions will take time and will require a significant effort. The navigational pattern described by the radar tracks will provide basis for planning and initiating proper adaptation of the ship traffic to the situation after a bridge has been constructed.

Initially a brief description is given of the observation program itself, the facilities used and the data collected. A more detailed account is then given of the statistical analysis of the recorded radar tracks leading to distributions of the location at which the ships pass the future alignment. Direct comparison of these distributions with the distributions typically assumed in calculation of the risk of ship collisions to the bridge illustrates how far apart the two situations are. Those differences are dis-

discussed and appropriate ways of ensuring that the change in the navigational pattern will occur are given.

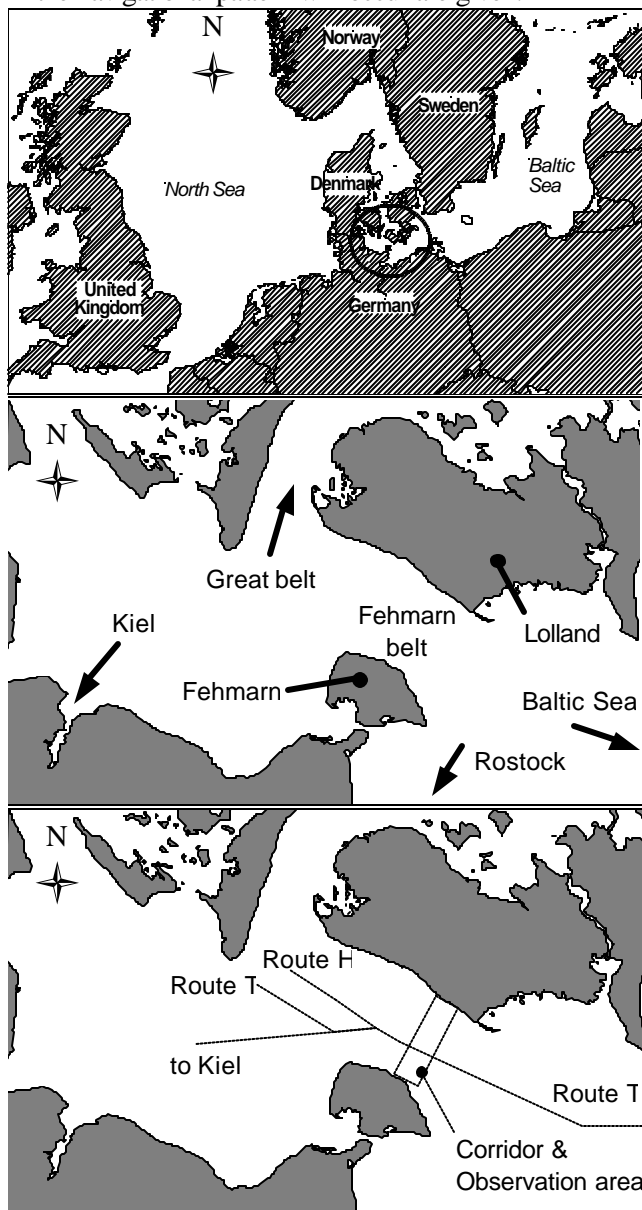


Figure 1 Fehmarn Belt: location in Northern Europe (top), destinations (middle), routes and the corridor in consideration for a fixed link (bottom).

2 THE OBSERVATION PROGRAM

The purpose of the observation program was to clarify the volume, composition and navigational pattern of the ship traffic within the corridor of the investigated fixed link (Figure 1, bottom).

Classification – or preferably identification - of the passing ships is an important part of the survey. However, Fehmarn Belt is an international strait and there are no legal means of enforcing radio contact with the passing traffic. Identification and classification of the passing ships therefore had to rely on visual means only. Monocular, a long-range TV camera and an infrared TV

camera were used to provide visual basis for classification and identification if possible.

A dedicated computer was used to store the information established for each passing ship:

- Identification (call sign, hull number, picture)
- Type and size (DWT, length, height)
- Direction of passage (origin, destination)
- Radar track for the passage

The information was entered into a database that provided easy access to information on previously registered passages. Combined with a database from Lloyds Register and a database with passage information from the Kiel Canal, the system provided a prompt and extensive support for classification of passing ships. The two TV cameras were linked to the computer allowing approximate determination of the length and height of the ship on basis of the onscreen TV image. These data collecting and data processing features were provided by a custom made computer program.

The observation program was initiated in the summer of 1998 and provided the first bulk of data in February 1999. The basis of the results presented in this paper covers observations made from August 1998 to January 1999. About 12,000 passages were registered during this period. Unintentionally, some of these passages represented movements by the ferry connection operating within the corridor. Also not all of the passages were tracked. By eliminating of those the population of tracked passages is reduced to about 5,000.

The observation program continued beyond the period included in the present analysis, and a large amount of data is thus available for more detailed analysis at a later stage in the planning process.

3 SHIP TRACK ANALYSES

The analysis of the ship tracks focuses on the part of the track that is inside the corridor – in the following denoted the observation area. The area is 5km wide and extends from the German coast in south to the Danish coast in North. The crossing point of the Eastern and Western boundaries of the observation area are used as basis for the statistical analysis of the tracks.

To make sure that a track is relevant to consider in relation to the planned bridge alignment it was required that the track shall cross the boundaries of the observation area. Hence, East-West passages shall have points on both sides of the eastern boundary and West-East passages shall have points on both sides of the West boundary – see Figure 3. This limitation brings the population down to about 3,500 tracks: 1,900 westbound tracks and 1,600 eastbound tracks. The tracks are shown in Figure 2.

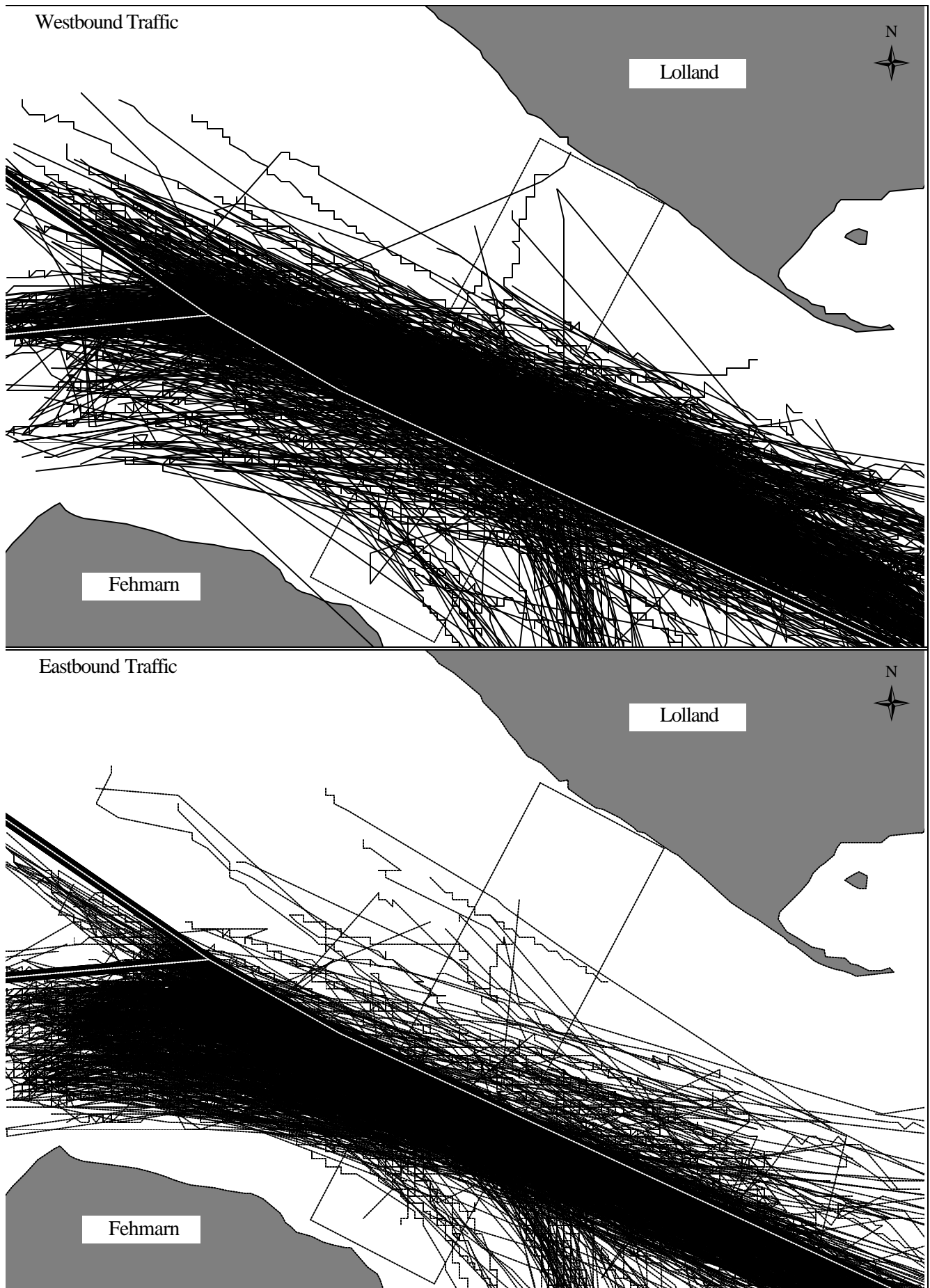


Figure 2 Plot of the track included in each direction. Top: Westbound passages, Bottom: Eastbound passages

3.1 Idealization of Track Passages

To eliminate noise on the track points originating from radar uncertainties and the limited refresh rate of the tracker, each track is replaced by a linear regression. This regression is based on last track point before entering the observation area and all subsequent points within the observation area – see Figure 3.

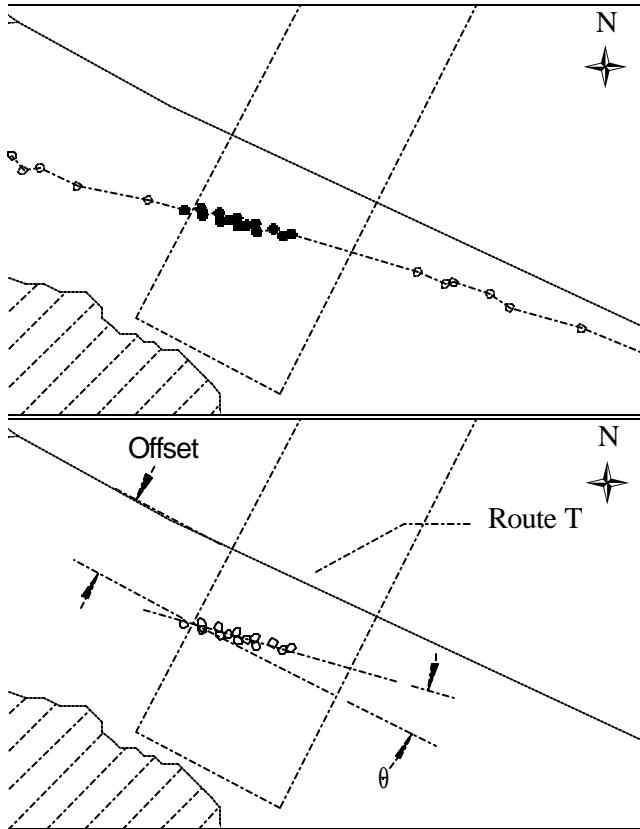


Figure 3 Qualifying track (top, east-going track) and linear approximation the track within observation area (bottom).

The distance from the marked Route T to the intersection point between the linear regression and the boundary is used to define the *Offset* from the route. The angle of intersection is also defined but this variable has not been subjected to statistical analysis.

3.2 Statistics of Offset

The population of passing ships is divided into westbound (W) and eastbound (E) passages and is further grouped into the ship length ranges as follows:

Class	Length range
75	$50\text{m} < L \leq 75\text{m}$
100	$75\text{m} < L \leq 100\text{m}$
150	$100\text{m} < L \leq 150\text{m}$
200	$150\text{m} < L \leq 200\text{m}$
250	$200\text{m} < L \leq 250\text{m}$
300	$250\text{m} < L \leq 300\text{m}$

Those subpopulations are referred to by the direction (E or W) followed by the length class. Hence, *E150*

comprises eastbound ships with a length between 100m and 150m.

The basic statistics of the *Offset* for the defined populations are given in Table 1.

	Number	Min [km]	Max [km]	Mean [km]	Std [km]
W	1 896	-6.1	5.5	1.4	1.2
W75	271	-6.0	5.5	1.5	1.9
W100	543	-5.8	5.5	1.6	1.3
W150	669	-5.0	4.4	1.5	0.9
W200	321	-3.3	5.1	1.2	0.8
W250	73	-6.1	2.8	0.9	0.9
W300	19	0.4	3.0	1.2	0.7
E	1 593	-11.7	5.7	1.0	1.0
E75	265	-6.6	5.7	1.2	1.4
E100	512	-11.7	4.3	1.2	1.1
E150	543	-6.0	3.7	0.9	0.8
E200	200	-2.1	2.8	0.7	0.6
E250	67	-0.4	3.5	0.5	0.6
E300	6	0.1	0.5	0.4	0.1

Table 1 Basic statistics of Offset

The statistics indicate that the mean and standard deviation of the *Offset* reduces with increasing ship size. However, because of smaller sample size of the larger ship size groups, the uncertainty on those statistical estimates will also increase. To investigate whether the trends observed are significant compared to the statistical uncertainty the 90% confidence range of the mean value estimate is plotted in Figure 4 and Figure 5 as a function of the ship length. With exception of *E250* and *E300* the statistical uncertainty is generally small compared to the dependency on the ship length.

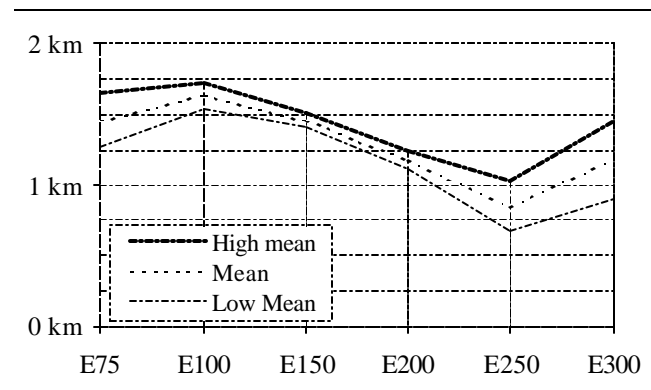


Figure 4 Mean value estimates and 90% confidence range for Offset as function of the ship size category. Eastbound passages.

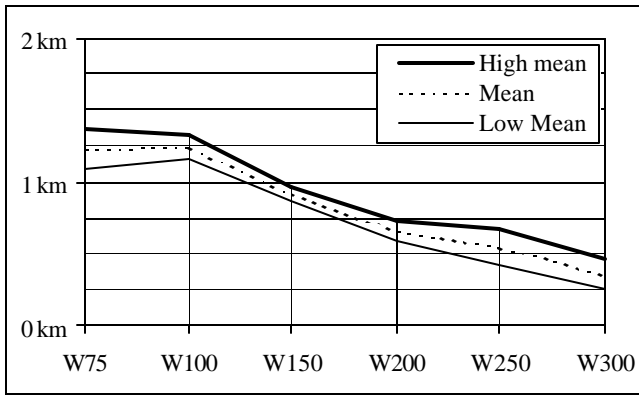


Figure 5 Mean value estimates and 90% confidence range for Offset as function of the ship size category. Westbound passages.

Consequently, the decreasing trend is not a result of statistical uncertainty but represents a true correlation.

3.3 Distribution of Offset

The density functions of the *Offset* for the populations *W* and *E* are shown in Figure 6 and Figure 7.

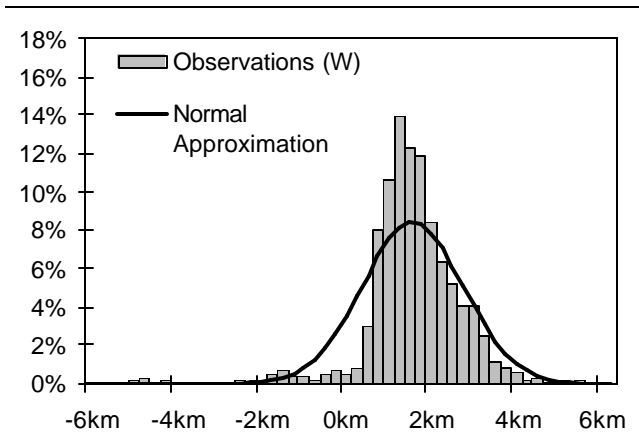


Figure 6 Histogram of the Offset for East-to-West passages and the Normal approximation.

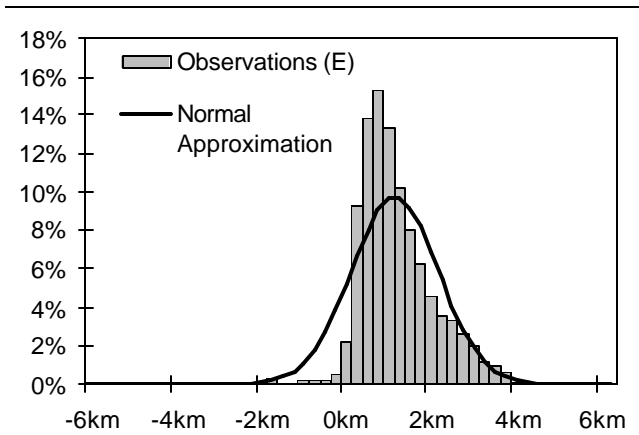


Figure 7 Histogram of the Offset for West-to-East passages and the Normal approximation.

The observed distributions are characterized by

- A dominating weight of the distribution just starboard (right) of the center of the route
- An abrupt but not complete cutoff towards the center of the route
- A 'fat tail' (slow decay) of the density far right from the route

These characteristics suggest that the marking of the route using only central buoys is important. Ships will generally navigate close to the markings, but will, according to the rules, remain on the starboard (right) side of the marking to avoid encounters with opposing traffic. The width and water depth of the channel allows for large deviations starboard of the route. The 'fat tail' of the distribution suggests that this is opportunity is utilized.

4 DISTRIBUTION APPROXIMATION

Various attempts to approximate the observed density functions have been made. Inspired by the traditional use of the Normal density, different combinations of narrow and wide normal distributions was initially used for approximations. But they were not able to represent the steep drop towards the route marking.

Based on the influence that the central route marking has on the navigational pattern an approximation is sought by assuming the traffic divided into two idealized types of navigational behavior:

A: Ships that navigate close to the route marking and exclusively on the starboard side

B: Ships that navigate with little reference to the central route marking

A *Lognormal* density is used to represent *A* and a *Normal* density is used to represent *B* – see Figure 8.

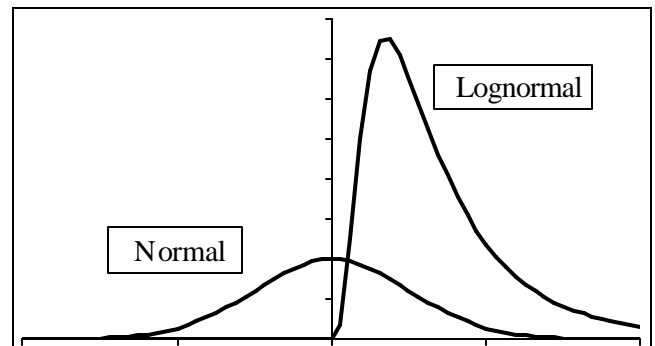


Figure 8 Typical shapes of the Normal and the Lognormal density functions.

The compound density of the two idealized densities is - in short - given by

$$p(x) = \begin{cases} \mathbf{q} g(x) & x \leq \mathbf{l} \\ \mathbf{q} g(x) + (1 - \mathbf{q}) f(x - \mathbf{l}) & x > \mathbf{l} \end{cases} \quad (1)$$

where $g(x)$ is the Normal density function

$$g(x) = \frac{1}{\sqrt{2p}} \frac{1}{s_N} \exp\left(-\frac{1}{2}\left(\frac{x - m_N}{s_N}\right)^2\right) \quad (2)$$

and $f(x)$ is the Lognormal density function:

$$f(x) = \frac{1}{\sqrt{2p}} \frac{1}{b} \exp\left(-\frac{1}{2}\left(\frac{\ln x - a}{b}\right)^2\right) \frac{1}{x} \quad (3)$$

The parameters of the compound density are

- q relative fraction of the Normal part
- m_N mean value of the Normal part
- s_N standard deviation of the Normal part
- l shift of the Lognormal part
- α, β shape parameters of the Lognormal part
- m_L mean value of the Lognormal part
- s_L standard deviation of the Lognormal part

The relationship between m_L and s_L and the shape parameters a and b are

$$a = \ln m_L - 0.5 \cdot \ln\left(\left(\frac{s_L}{m_L}\right)^2 + 1\right) \quad (4)$$

$$b^2 = \ln\left(\left(\frac{s_L}{m_L}\right)^2 + 1\right) \quad (5)$$

In total the approximation includes 6 parameters (q, m_N, s_N, l, m_L, s_L) which makes automatic numerical fitting (e.g. using least square error) of the approximation to the data difficult. Instead the parameters have been determined by visual fitting of the approximating distribution function to the observed distribution function. A typical shape of the approximating distribution is shown in Figure 9.

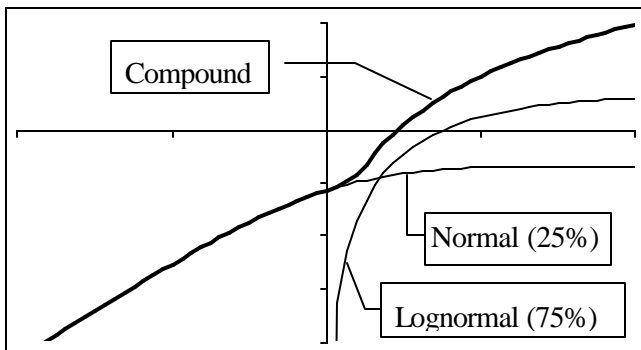


Figure 9 Example of the shape of the compound distribution function in a Normal distribution plot.

The graphic approximation have emphasized on representing the following characteristics:

- The level and slope of the distribution on the left side of the route middle
- The location of the transition (kink)

- the slope and curvature of the distribution to the right of this kink

Separate approximating distributions have been estimated for each direction, one for all ship sizes (50-300m) and individual distributions for each size range. Because the number of observations of ships in the size range 250-300m is too limited to establish a reliable distribution function the individual distribution have not been estimated for this size range. But the observations are included in the distribution function of the total populations (W and E). The estimated distribution parameters are given in Table 2.

	q	m_N [km]	s_N [km]	l [km]	m_L [km]	s_L [km]
W	10.0%	0.0	2.50	-0.4	2.20	1.50
W75	25.0%	0.0	3.00	-0.4	2.70	2.00
W100	11.0%	0.0	2.60	-0.4	2.45	1.65
W150	6.5%	0.0	1.80	-0.4	2.15	1.45
W200	5.0%	0.0	1.70	-0.4	1.87	1.24
W250	3.0%	0.0	3.20	-0.4	1.47	0.83
E	4.5%	0.0	2.50	-0.4	1.72	1.50
E75	13.0%	0.3	3.40	-0.5	2.20	2.00
E100	3.5%	0.0	2.50	-0.4	1.95	1.64
E150	2.4%	0.0	1.70	-0.4	1.48	1.20
E200	5.0%	0.0	1.50	-0.4	1.25	1.01
E250	2.0%	0.0	2.50	-0.4	0.97	0.63

Table 2 Parameters of the proposed distribution approximation.

The plot of the observed and approximating distributions is shown in Figure 10 for westbound passages and in Figure 11 for eastbound passages.

The distribution approximations are generally better for the westbound passages than for the eastbound passages. For the eastbound passages discrepancies are found for offsets above 2.5-3km where the approximating distribution suggest more frequent and larger offsets than actually observed. Inspection of the track plots in Figure 2 reveals that the alignments of the eastbound tracks are influenced by the bend on Route T west of the observation area. To follow the bend the tracks comes closer to the island Fehmarn. Since the ships apparently seeks a mild curvature on their path this combination leads to a more confined pattern of the tracks at the entrance to observation area. The westbound tracks reaches the observation area more parallel and thus less restricted by land.

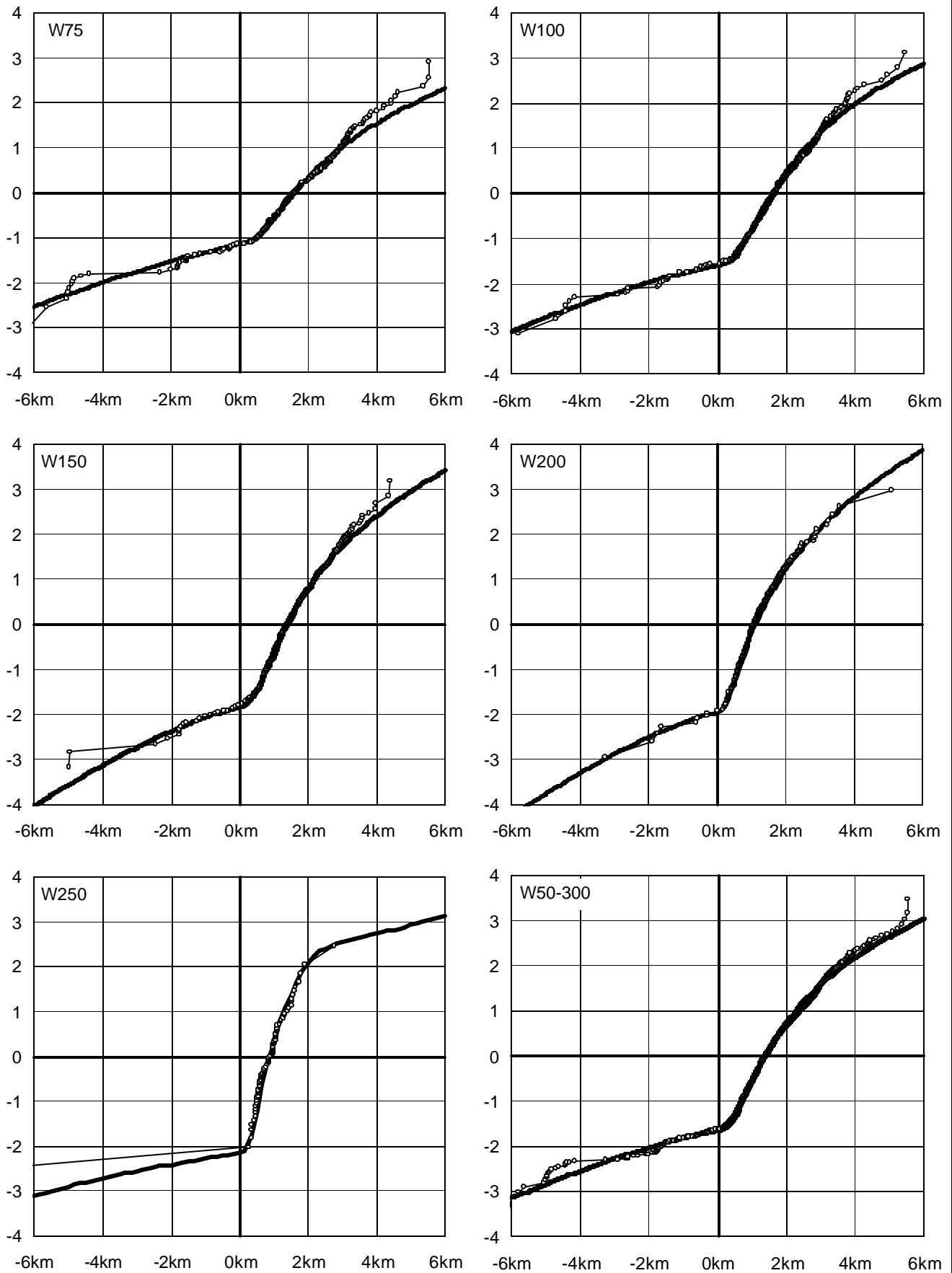


Figure 10 Distribution approximations the Offset of westbound tracks.

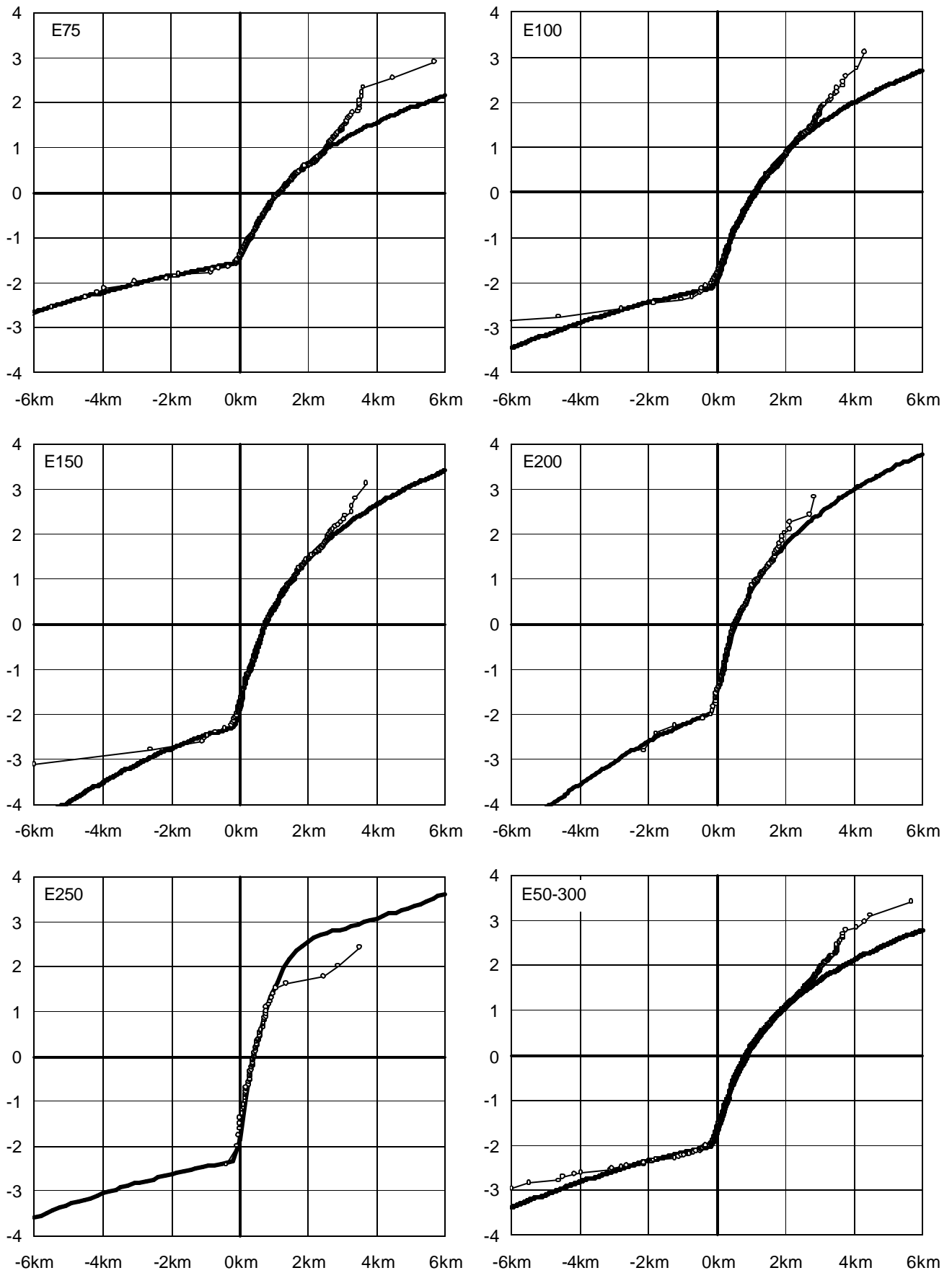


Figure 11 Distribution approximations the Offset of eastbound tracks.

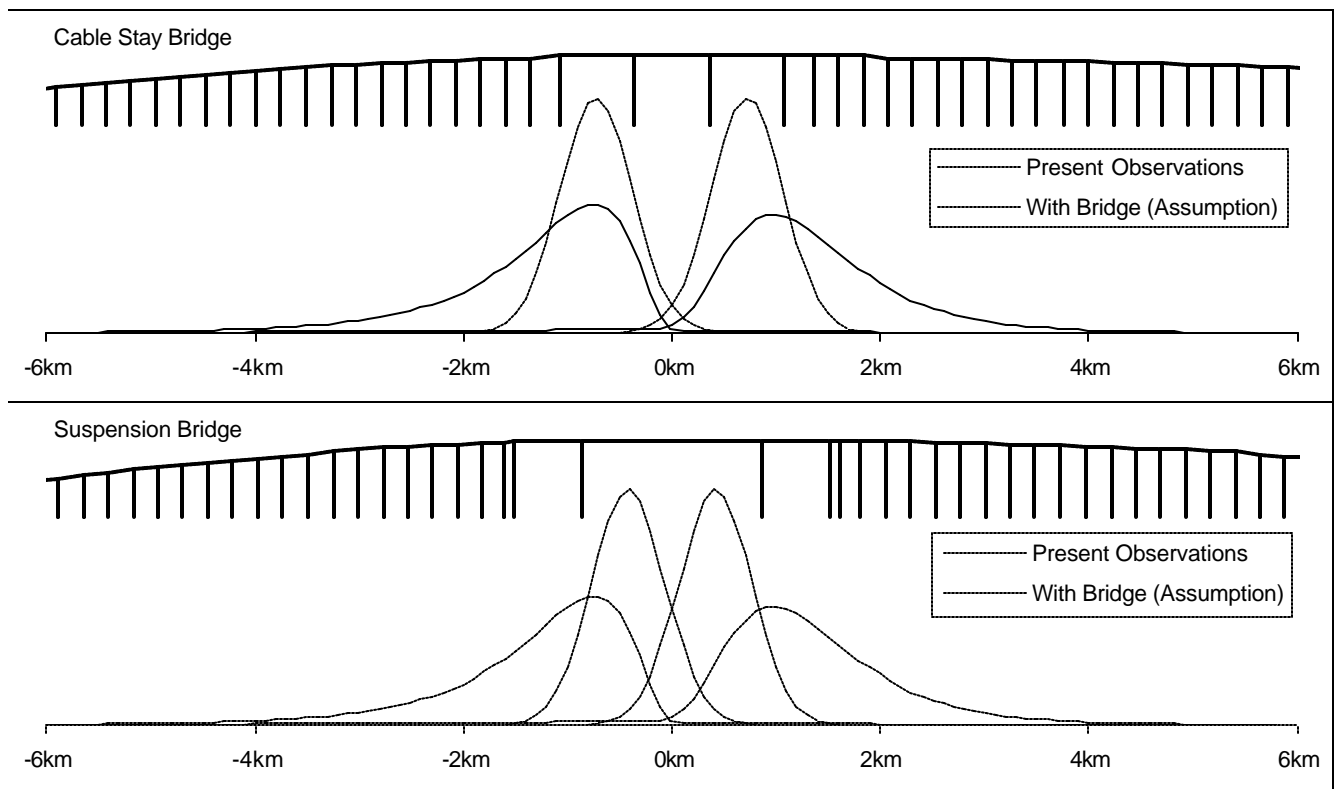


Figure 12 Distributions observed before and distribution assumed after a bridge has been established. Top: Cable stay bridge, Bottom: Suspension bridge.

Various subpopulations have been considered to investigate whether the distribution of the *Offset* depends on the origin and destination of the ships. Especially, it has been checked whether tracks that follows Route T leads to a different distribution of the *Offset*. Tracks to or from Kiel and Rostock stands out in the track plots with more curved tracks and this could lead to differences in the distributions. However, the *Offset* distributions of these subpopulations did not show significant or characteristic deviations from the total population considered above.

5 IMPLICATION OF OBSERVATIONS

The observed tracks have been made by ships navigating in accordance with the present situation – i.e. with a wide, unrestricted strait with central marking. If a bridge is constructed the traffic will navigate in accordance with those more restricted conditions. The passage of the bridge will be guided by more extensive marking of the route: individual marking of the two lanes with a separation zone to prevent close encounters of opposing ships, markings on the bridge itself and optionally a Vessel Traffic Service (VTS) system to assist the ships with information prior to and during passage of the bridge. So if a similar track observation were made after all this have been established, the distributions observed would most likely be well approximated by a normal distribution plus a distribution representing navigation errors and technical failures on board

The transition is illustrated in Figure 12 where the distributions are shown relative to a bridge. A normal distribution with a standard deviation of 350m is assumed to describe the geometric exposure to collisions after a bridge has been established.

The observed distributions would expose several of the approach span piers to collisions and a complete transition from the observed to the assumed distribution is essential for the safety of the bridge. It is therefore of high priority to ensure that the traffic is well adapted to the new navigational situation before construction is started. This implies that the final navigational arrangement should be established early (buoys, lights, separation zone etc.) and should be introduced on navigational maps. If a VTS system were planned for the final situation it would be necessary to put it into service before the construction commences. This will ensure that the system has reached a reliable operational state when the ability to prevent collisions is needed.

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