Study of Vessel Travel Behavior at Hot Spots in Sabine-Neches Waterways

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ABSTRACT: This paper studied the travel behavior of vessels at two hot spots identified through the analysis of vessel conflicts along the whole Sabine-Neches Waterway (SNWW) using the automatic identification system (AIS) data. According to the AIS data in 2012, more than 10% of total vessel conflicts occurred within these two hot spots. Using the AIS data collected in the whole year of 2012, this paper summarized the information of trips that passed through these two spots inbound (toward the Port of Beaumont) or outbound (toward the Gulf of Mexico). The features of inbound and outbound trips at two spots were investigated, respectively. Especially, their distributions were studied. On the other hand, the density of vessels in the spot when a vessel went through was also examined. Moreover, the trips made by tankers were particularly studied at these two spots. The findings revealed the travel patterns of inbound and outbound trips passing these two spots. Meanwhile, these patterns also help examine the risk of vessel collisions at these two spots, respectively.

Keywords: travel behavior, hot spot, AIS data, Sabine-Neches Waterway

1. INTRODUCTION

The Sabine-Neces Waterway (SNWW) is the major waterway in Southeast Texas (see Figure 1 (a)), which is known as the energy gateway to the U.S. SNWW connects the Port of Beaumont, as well as the Ports of Port Arthur and Orange, with the Gulf of Mexico. The SNWW serves four refineries and many chemical plants located along the waterway. From 2002-2006, the import of crude oil through this waterway comprises 12% of the U.S and 18% of Western Gulf Coast imports (USACE, 2010). As shown in Figure 1(b), the major route of the SNWW goes from the Port of Beaumont to the Gulf via Neches River and jettied entrance channel. The channel is 40 ft (12.2 m) deep and 400 ft (122 m) wide in the section of Neches River and 42 ft (13 m) deep and 500-800 ft (152-244 m) wide in the jettied entrance channel, having the capacity for oil tankers and other big vessels. The second route goes to the Port of Orange in the northeast via Sabine River, which is 30 ft (9 m) deep and 200 ft (61 m) wide (USACE, 2010). To the southwest, the channel extends to Galveston via the Gulf Intracoastal Waterway (GIWW). There are two intersections in the SNWW, as shown in Figure 1(b).

(a) Map of Southeast Texas (b) Map of Sabine-Neches Waterway

Figure 1 Inland waterways in Southeast Texas

The vessel traffic in the SNWW steadily increases with the significant economic increase in the Southeast Texas in the recent decades. To accommodate to this continuously increasing demand, recently, a project with $1.16 billion budget will be implemented to improve the capacity of the SNWW. The plan includes seven phases, including deepening the channel, extending the length of channel and widening some parts of the channel (USACE, 2010).

The SNWW is a narrow but busy waterway. Safe navigation in the narrow waterway is one of the most important concerns to maritime authorities and researchers. According to the historical data, there is an average of 2-3 vessel collisions and 1 grounding per month (SETWAC, 2013). Collisions in the SNWW are more dangerous than groundings because the groundings in the SNWW are primarily soft (Wu et al., 2014). Our previous research studied the risk of vessel collisions in the SNWW based on the collected automatic identification system (AIS) data in the SNWW (Wu et al, 2016). In this research, the frequency of conflicts of big vessels, which is defined as the case that one vessel (at least 20 meters) enters the domain of another (at least 50 meters), was studied along the SNWW based on two months' AIS data. Two types of domains were used, respectively: circular or elliptical domains. A vessel conflict represents a kind of potential risk of vessel collision. Three types of vessel conflicts were considered: head-on, overtaken and crossing. Therefore, the higher the frequency at one location, the higher the risk of vessel collision at this location. Along the SNWW, this study identifies six hot spots, where at least 4% of total vessel conflicts in the SNWW took place. It was found that based on either circular or ellipitical domains, the locations of hot spots were almost the same for different types of vessel conflicts in different months. Figure 2 shows the locations of six hot spots based on the AIS data in March, 2012. Readers are referred to Wu et al. (2016) for the details of the theories and procedure of identifying hot spots, as well as more results of the hot spot identification.

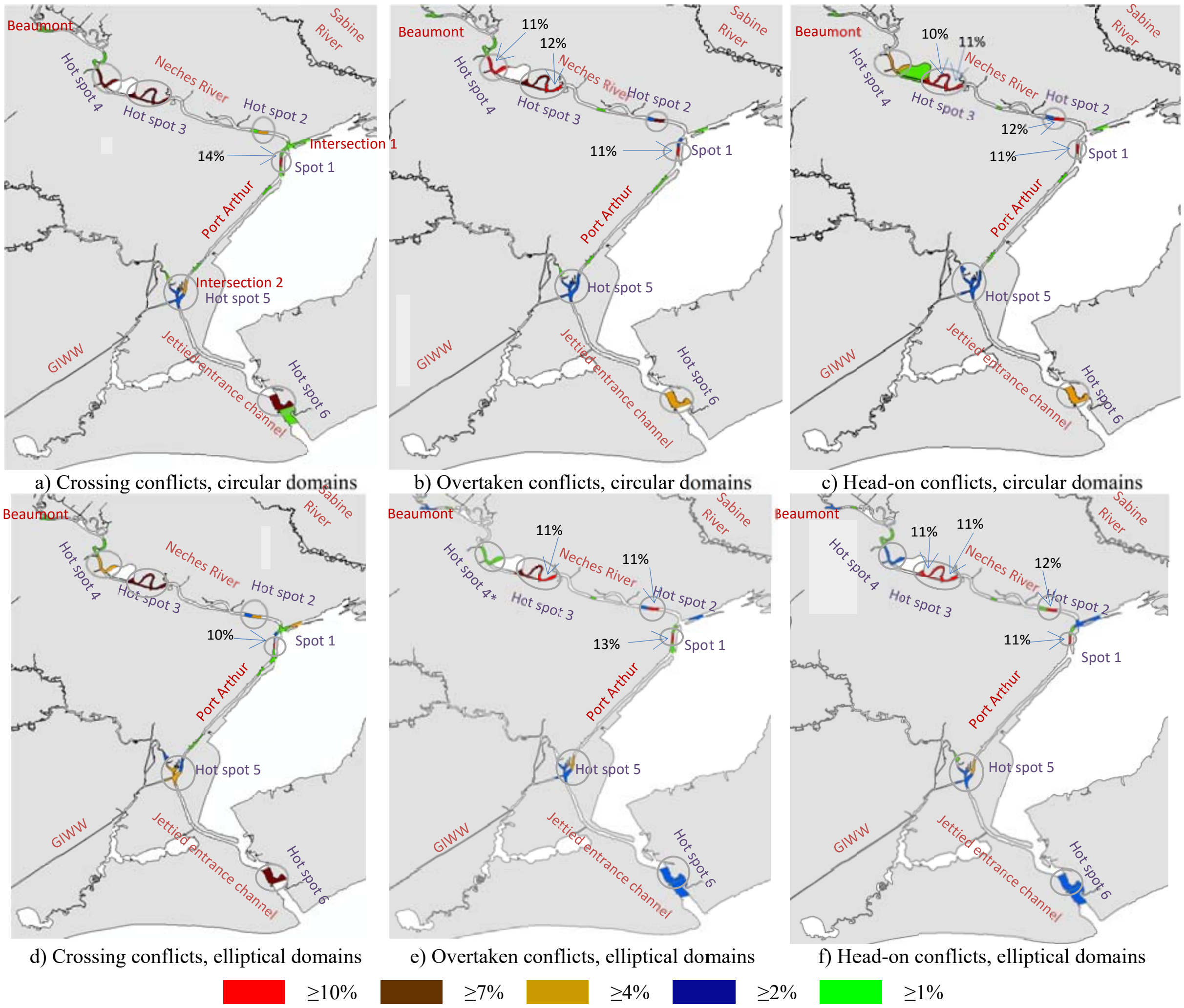


Figure 2 Hotspots with occurrence of at least 1% of each type of vessel conflicts in March, 2012 (Wu et al, 2016) Note*: the percentage of all conflicts is less than 2%, and thus strictly speaking, it may not be a "hot spot"

Vessel conflict ranking operator (VCRO) model developed by Zhang et al. (2015) was also employed to identify the hot spot of vessel collisions in the SNWW (Wu et al., 2016). Interestingly, it was also found that hot spots are almost the same, especially for Hot spots 1 and 2 shown in Figure 2. These two hot spots were found to have the highest frequency of all kinds of vessel conflicts (head-on, overtaken, and crossing), no matter under either circular or elliptical domains. Moreover, they are neither at the intersection of two channels (as Hot spot 5), nor close to the ports (as Hot spot 3 and 4). Usually the risk of vessel collisions is high at the intersection and the channel near the ports. Therefore, this paper particularly studies the travel behavior of vessels that pass these two hot spots using the AIS data.

The reminder of this paper is organized as follows. Section 2 reviews the existing studies of travel behavior and risk analysis based on AIS data; Section 3 studies the travel behavior of general trips at two hot spots, respectively; Section 4 specifically investigates the travel behavior of tankers at these two spots, as tankers are major vessels running in the SNWW and accidents associated with tankers would be disastrous; and Section 5 concludes this paper.

2. LITERATURE REVIEW

Since 2002, new ships and all sea-going vessels that have 300 gross tons or more, as well as all passengers vessels are required to equip an automatic identification system (AIS) on board. The AIS transmits the sailing status information between vessels, and from vessels to shore or vice versa. Therefore, AIS helps vessels "see" each other in the channel, and the waterway management agency can also monitor the status of vessels. The AIS data contains the detailed and consecutive temporal and spatial information of a vessel, as well as real maneuvering behavior of a vessel (such as speed, course, etc.). For this reason, recently, AIS data are widely used in the waterway transportation research, including the risk analysis of vessel collisions, vessel travel bahevior, etc.

Mou et al. (2010) developed linear regression models based on AIS data to evaluate the risk of vessel collisions in the North Sea off the Port of Rotterdam, based on two indicators: closest point of approach (CPA) and time to closest point of approach (TCPA) between two vessels. These two factors well reflect how veseel collisions are avoided in a given waterway. For example, if the CPA between two vessels are small, then the risk level is high for these two vessels to collide each other. Using AIS data, Weng et al. (2014a, 2014b) investigated the frequency of vessel conflicts in Singapore Straits, which occurs when one vessel enters the domain of another. They assumed a short time (30 seconds), and assume that a vessel conflict happens if one vessel will enter the doamain of another within this short time period. They defined a vessel's domain as a circle with three times of this vessel's length. Actually, the definition of a vessel's domain varies in the literature. Fujii and Tanaka (1971) defined an elliptical domain, where the major and minor radii are 4 and 1.6 times of the length of the vessel, respectively; and Qu et al. (2011) proposed the fuzzy quaternion ship domain.

In many exisiting models, it is important to know the interactions between vessels. Since AIS data provides the navigation details of vessels, the relative speed, angle and distance can be revealed between two vessels. Such information about vessel interaction serves as input to many models. For example, Zhang et al. (2015) proposed a vessel conflict ranking operator (VCRO) model which is based on a survey among maritime experts to rank the risk of various situations about the interaction between two vessels: relative speed, angle, and distance; Kujala et al. (2009) developed a collision model to study the risk of vessel collisions and groundings in the Gulf of Finland, requiring the information of relative speeds between vessels; and Montewka et al. (2010) developed models to calculate the probability of three types of vessel collisions: overtaken, head-on and crossing, where information of vessel interaction is required.

The AIS data can be also used in building simulation models. Goerlandt and Kujala (2008) developed a ship collision probability model where a Monte Carlo simulation was used. The AIS data provide the input to this model: traffic routes, the number of vessels on each route, the departure times of vessels, speeds and the dimensions of vessels. On the other hand, AIS data were used to investiage the travel behavior of vessels at some busy channels. For example, Xiao et al. (2015) investigated the travel behavior of vessels at two spots (one is near the Port of Rotterdam, and another is near Shanghai) based on AIS data. They studied the distribution of vessel speeds, courses, and arrival time intervals.

3. GENERAL TRAVEL BEHAVIOR ANALYSIS

The AIS data used in this paper are from the website of marinecadastre.gov (http://marinecadastre.gov). This paper employed the AIS data collected in the SNWW in each month of 2012. Each record represents a vessel's status: the location (longitude and latitude), timestamp (as accurate as second), speed over ground (SOG), course over ground (COG), heading, rate one turn (ROT), voyage id, vessel id (Maritime Mobile Service Identity, i.e., MMSI), etc. Also, the information of vessels and voyages, such as vessel length, type, voyage destination and starting time, is also available.

As mentioned in the first section, this paper aims to investigate travel behavior of vessels in two hot spots (see Figure 3), which were found to have the highest vessel conflict frequencies, even using different methods. The length of each hot spot is about 1500 meters. The AIS data of the entire year of 2012 were used to investigate the travel behavior of vessels in these two hot spots. After filtering data using ArcGIS, 1864 and 1376 vessels were found passing these two hot spots, respectively in 2012, and there were 1,757,815 and 1,172,331 AIS records, respectively. The following analysis is based on these records.

3.1 Analysis of trips

For each vessel, at first, the time of entering and leaving each hot spot was studied, respectively, so that the trip information can be extracted when a vessel went through this spot. However, since the time interval between two records is around 1 minute, the exact entering and leaving time may not be available. For this reason, we use the first record when a vessel enters the spot as the starting point, and last record when it leaves the spot as the ending point, so that a trip that passes through this hot spot can be revealed.

These trips were divided into three groups: inbound, outbound and moored. Traffic is regarded as outbound if it moves closer to the Gulf of Mexico; on the other hand, it is regarded as inbound if it moves closer to the Port of Beaumont. Therefore, at spot 1, northbound traffic is inbound; while at spot 2, westbound traffic is inbound. Meanwhile, vessels may also be moored at these two locations for a while. Such behavior is very different from directly running through the spots because if a vessel is moored, its speed and course may change significantly. Therefore, such status is treated separately in this paper.

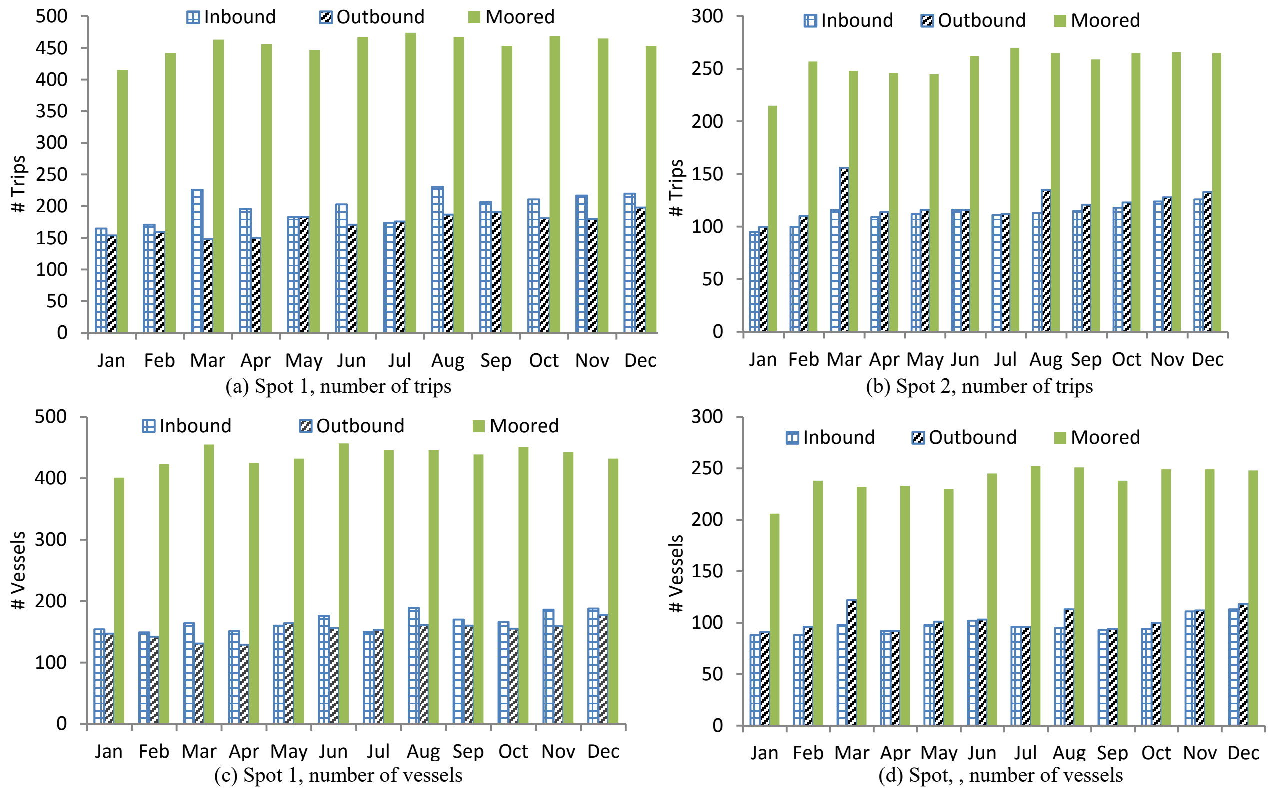
(a) (b)

Figure 3 Locations of two hot spots (view in different scale)

Figure 4 (a-b) reports the monthly number of trips in each direction (inbound, outbound as well as moored) at two spots, respectively, and Figure 4 (c-d) reports the monthly number of vessels in each diretion at two spots. There were more trips and more vessels passing spot 1 than spot 2, because the channel at spot 1 also serves the traffic along the Gulf Intracoastal Waterway (GIWW), which extends to Port of Orange to the east (and further east to Florida), and to Galveston to the west (and further west). Moreover, it is seen that the change from month to month is small, well indicating that the traffic in the SNWW is quite stable over time.

At both spots, the number of moored trips (i.e., a vessel has been moored when it passed this spot) was much more than the number of trips that directly went through the spot without stopping. Meanwhile, the number of vessels that have been moored is also much larger than those directly passed through, as shown in Figure 4 (c-d). On the other hand, the numbers of inbound and outbound trips (excluding moored trips), as well as the number of vessels in two directions at both spots are almost the same.

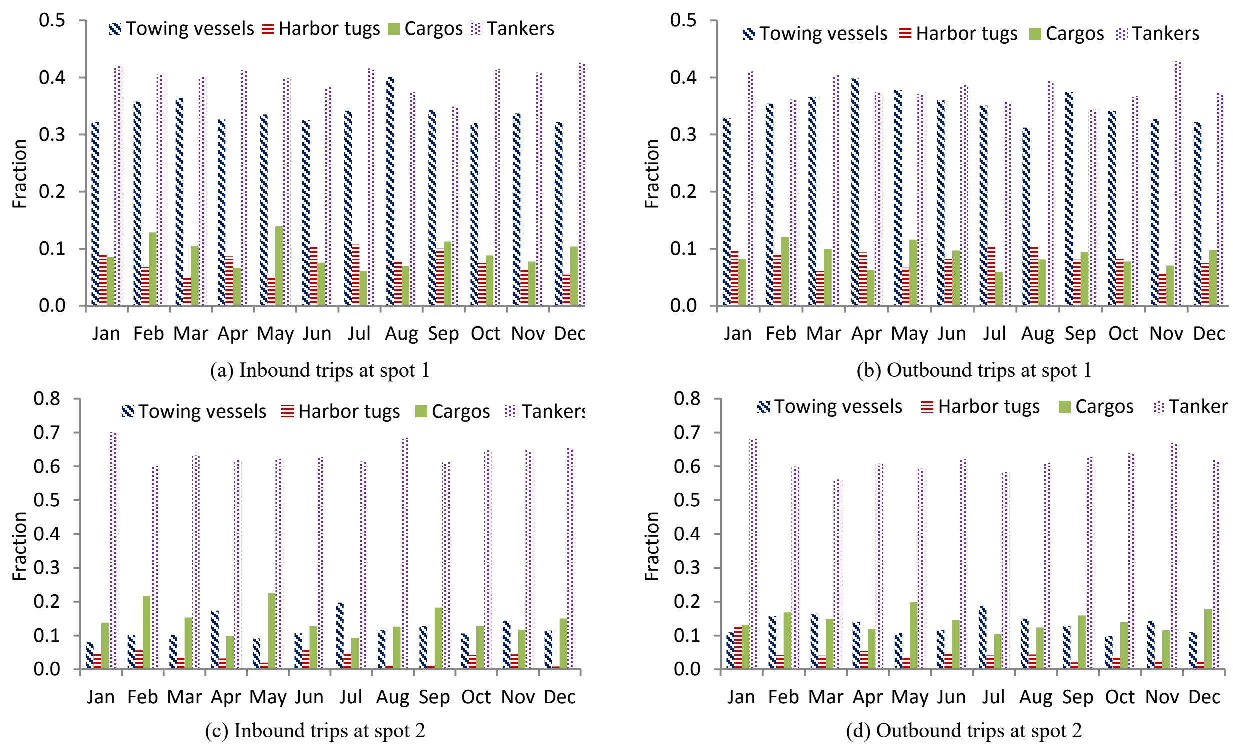
Further, the distribution of vessel types in inbound and outbound traffic at both spots were investigated, respectively. The results were reported in Figure 5. At spot 1, it is seen that towing vessels and tankers were two major type of vessels (about 35% and 40% of the total, respectively) in each month of 2012; while at spot 2, there were much less number of towing vessels, and consequently, making tankers the major type of vessels passing there (60-70% of the total). The reason is that spot 1 is in the channel shared by GIWW and SNWW (see Section 1 for details), and the former is primary for towing vessels.



(a) Spot 1, number of trips (b) Spot 2, number of trips

(c) Spot 1, number of vessels (d) Spot, , number of vessels

Figure 4 Number of trips and vessels in each direction in each month of 2012 at two hotspots



(a) Inbound trips at spot 1 (b) Outbound trips at spot 1

(c) Inbound trips at spot 2 (d) Outbound trips at spot 2

Figure 5 Distribution of vessel types in each direction in each month of 2012 at two hotspots

3.2 Analysis of travel speed

To study the behavior of vessels that pass through these two hot spots, it is necessary to investigate their speed distribution. Fortunately, the AIS data provides the detailed information of navigation, including the speed, course, and route. After summarizing the information of trips, each trip's average speed can be obtained by simply considering the time intervel and distance between the starting and ending points of this trip when passing through each spot. Therefore, it is actually a space mean speed of each trip. In the following, we simply call it as the speed of a trip. By analysing the AIS data, the speed of each inbound or outbound trip at each spot was calculated. Note that to better describe the speed distribution of all trips in each direction, the moored trips were not considered here given their average speed were almost 0.

At first, the statistical summary of the inbound or outbound trip speeds at two spots were investigated, respectively, as reported in Table 1. It is seen that generally, the speed is low. Even 99th percentiles of speed are less than 12 knot at spot 1, and less than 10 knots at spot 2. It seems that at spot 1, even though the mean speeds of two directions were almost the same, inbound trips experienced large variances. That is why inbound trips had a smaller median, but a slightly larger 90th-percentile and a much larger 99th-percentile. That is, the speed of inbound trips varies in a larger range. On the other hand, at spot 2, inbound trips had smaller speeds than outbound trips in general. For example, even inbound trips' speed suffered from larger variance, its 99th-percentile is still less than that of outbound trips.

Table 1 Data summary and normality test of each trip's speeds at two spots (Note: 1 knot = 30.867 m/min)

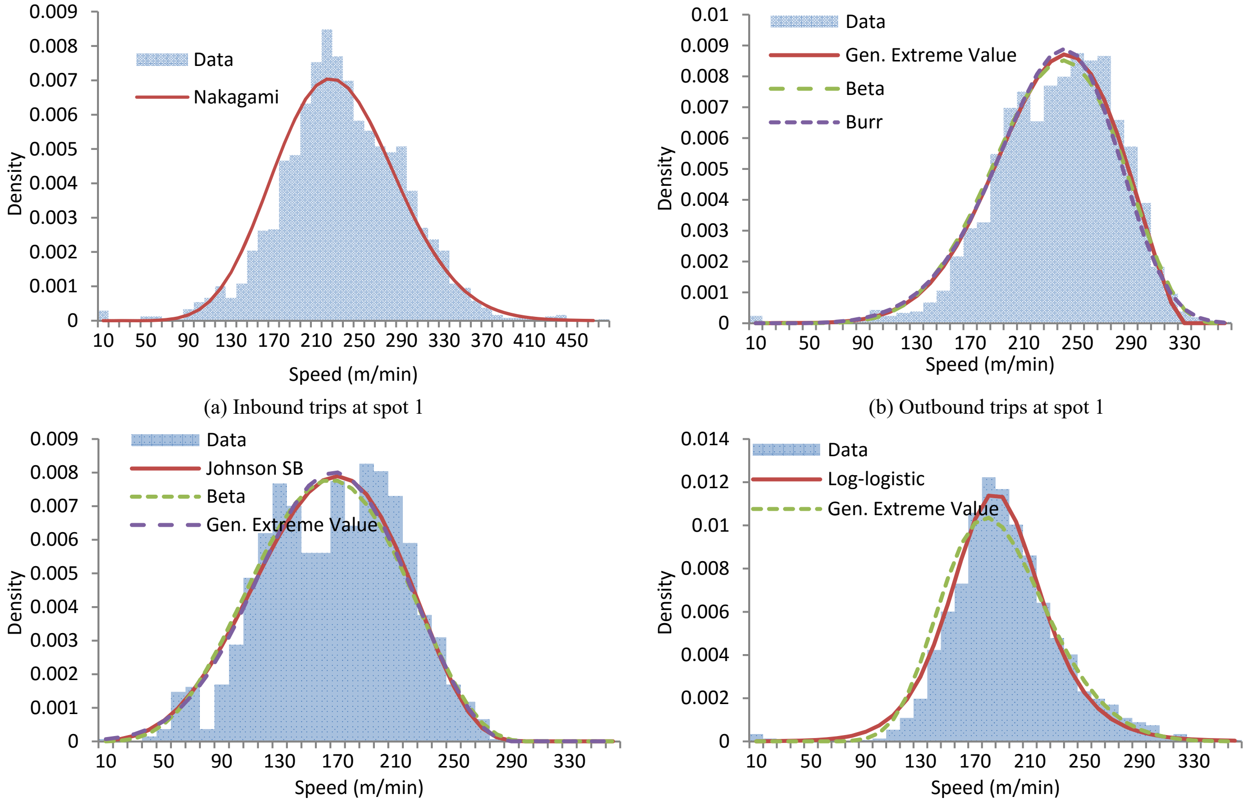
	Spot 1		Spot 2	
	Inbound	Outbound	Inbound	Outbound
Data Summary (unit: knots)				
Mean	7.47	7.48	5.27	6.09
Standard deviation	1.88	1.46	1.54	1.32
Median	7.38	7.59	5.37	5.97
70th-percentile	8.41	8.36	6.21	6.61
90th-percentile	9.82	9.23	7.16	7.74
99th-percentile	11.78	10.31	8.42	9.64
Skewness	-0.0685	-0.6345	-0.1889	0.1208
Kolmogorov-Smirnov test (normality test)				
P-value	0.0197	0.0022	0.0040	0.0004

The skewness check of four trip speed distributions shows that only the speed distrubtion of outbound trips at spot 2 are positively skewed, and other three are negatively skewed, especially for the outbound trips at spot 1. Note that the speeds of inbound trips at spot 1 are close to be symmetrically distributed, so it is necessary to check its normality. Using the Kolmogorov-Smirnov test, it was found that none of four were normally distributed, given a significant level of 0.05, because all P-values are less than 0.05 (see Table 1), leading to reject the hypothesis of normality. This paper uses 0.05 as the significant level, which is most commonly used in statistical analysis.

To better investigate the speed distributions of inbound and outbound trips at two spots, we plot these distributions in Figure 6, and we further attempted to fit these speeds using various distributions (totally 61 distributions were checked, conducted by EasyFitXL). Still based on the Kolmogorov-Smirnov test, the distributions with a P-value greater than 0.05 (as the pre-defined significant level) were kept. For each direction, up-to three best fitted distributions (based on P-values) were reported in Figure 6. Table 2 reports the P-values of each fitted distributions. Though there is no common distribution that fits all of four speed distributions, it seems that *generalized extreme value distribution* fits three (at least P-values are larger enough): outbound trips at Spot 1 and both in- and out-bound trips at Spot 2. Equation (1) gives the probability density function (PDF) of generalized extreme value distribution, which has three parameters: shape parameter k, scale parameter σ and location parameter μ. Table 3 reports the parameters of generalized extreme value distributions that fit the speed distributions of three trips.

$$f(x) = \frac{1}{\sigma} exp\left[-(1+kz)^{-1/k}\right](1+kz)^{-1-1/k} \tag{1}$$

where $z = \frac{x-\mu}{\sigma}$.



(a) Inbound trips at spot 1

(b) Outbound trips at spot 1

(c) Inbound trips at spot 2

(d) Outbound trips at spot 2

Figure 6 Speed distributions of in- and out-bound trips at two hotspots (histograms of the data and the fitted distributions)

Table 2 P-values of the fitted distributions, given a significant level of 0.05

Spot 1		Spot 2	
Inbound	Outbound	Inbound	Outbound
0.07447 (Nakagami)	0.54789 (Gen. Extreme Value) 0.40244 (Beta) 0.33718 (Burr) 0.08329 (Kumaraswamy) 0.07182 (Weibull)	0.12904 (Johnson SB) 0.10212 (Beta) 0.08095(Gen. Extreme Value) 0.06434 (Error)	0.39893 (Log-logistic) 0.06206 (Gen. Extreme Value)

Table 3 Estimates of three parameters of the fitted generalized extreme value distributions

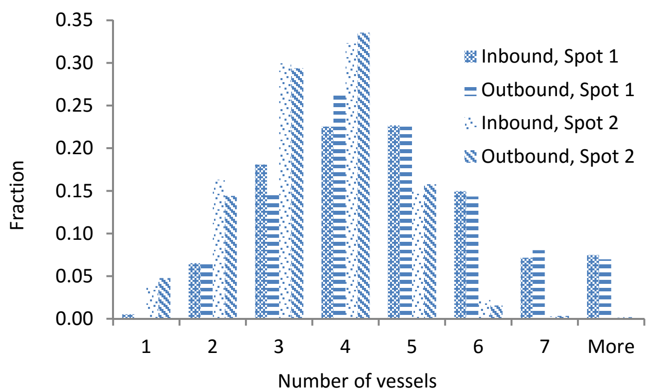
	k	σ	μ
Outbound trips at spot 1	-0.4271	47.034	218.31
Inbound trips at spot 2	-0.3513	49.261	147.31
Outbound trips at spot 2	-0.1582	35.957	172.21

For the estimates of parameters of other fitted distribution, please refer to Appendix at the end of this paper. Generally speaking, the trip speed distributions varies in different directions at two spots, though generalized extreme value distributions can be used to roughly describe some of these distributions. In the following, we will specifically analyze the speed distributions of trips made by tankers.

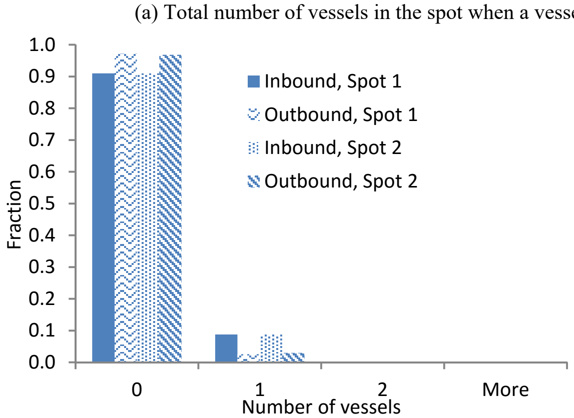
3.3 Analysis of vessel density

Based on the revealed trip information, which includes both temporal and spatial information, this paper further analyzed the number of vessels in one spot when there was a vessel passing through this spot. This information is important because it is related to the risk of collisions. Note that the identification of hot spots depends on the frequency of vessel conflicts, which occur when one vessel enters the domain of another (Wu et al., 2016). When it went through a spot, a vessel may encounter other vessels in three types of status: moored, running through in the opposite direction, or in the same direction.

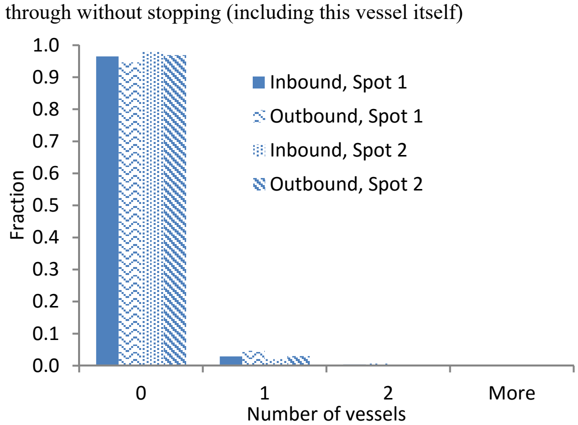
First, during the time when a vessel passed through a spot (without stopping), i.e., an in- or out-bound trip, the total number of all vessels (including this vessel itself) in this spot were recorded. This number of vessels can be regarded as "*vessel density*" if taking a spot as a unit. Then for all in- or out-bound trips, the distribution of the vessel density were investigated, as reported in Figure 7 (a). For example, it shows that 6.5% of all inbound trips at spot 1 in the whole year of 2012 saw another vessel in the spot (i.e., 2 vessels in total); while 22.6% or 22.7% of them saw 3 or 4 other vessels in the spot, respectively (i.e., 4 or 5 in total). It is seen that for trips in both directions at two spots, it is most likely to encounter 2-4 other vessels. Moreover, generally spot 1 was more congested than spot 2. For example, around 15% of all trips (both in- and out-bound) at spot 1 saw more than 5 other vessels (i.e., 7 or more in total); while at spot 2, such trips were less than 0.5% of the total. It is because spot 1 is located in the channel shared by both SNWW and GIWW, so that there are lots of barges at spot 1, as discussed in Section 3.1.



(a) Total number of vessels in the spot when a vessel went through without stopping (including this vessel itself)



(b) Number of vessels moving in the opposing direction



(c) Number of vessels moving in the same direction

Figure 7 Distribution of the number of vessels encoutered by a vessel that went through a hotspot without stopping

When a vessel travels through a spot, we are particularly interested in the number of vessels that were also in motion, especially those moving in the opposing direction, because apparently such numbers are more related with the risk of vessel collisions. For each trip, the numbers of vessels that moved in the opposing direction, as well as in the same direction, were investigated, respectively. Figure 8(b-c) reports the distrubtions of these two types of numbers. Interestingly, it was seen from these two figures that over 90% of in- or out-bound trips at each spot did not see another in- or out-bound trip at the same time at the same spot. That is, even if a vessel may see some other vessels in this spot when it moves through, ,most of them were moored. This findings reveal that actually the risk of vessel collisions could be not as high as expected based on Figure 7(a).

It is seen that at both spots, an inbound trip had more chances to encounter an outbound trip. For example, at both spots, around 3% of total outbound trips encountered an inbound trip; while around as high as 9% of total inbound trips encountered one outbound trip. Therefore, it seems that inbound trips may suffer the higher risk than outbound trips at both spots, considering head-on collision risk. . On the other hand, at both spots, only 2-3% trips had a chance to see another trip in the same direction at the same time.

4. TRAVEL BEHAVIOR OF TANKERS

Southeast Texas is famous for its oil industy in the U.S. Tankers in SNWW plays a critical role in supporting the oil industry in Southeast Texas. Section 3.1 shows that tankers are major vessels passing two spots, and especially, they accounted for 60-70% of total vessels in Spot 2 in 2012. This section speciafically studied travel behavior of tankers at these two spots.

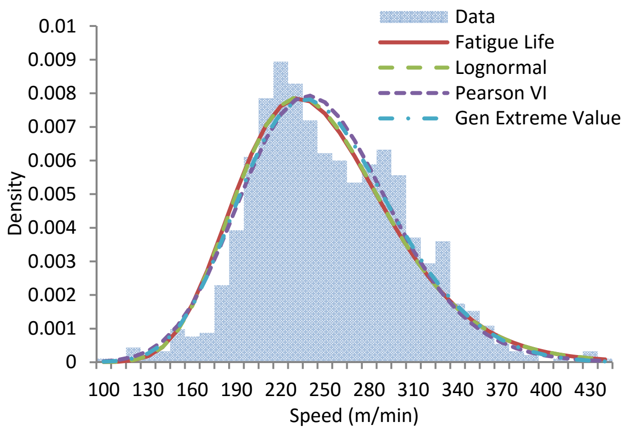
4.1 Analysis of travel speed

First, the trips made by tankers were picked out for analysis. At spots 1 and 2, there were 917 and 859 inbound, and 727 and 886 outbound tanker trips, respectively. Table 4 summarizes the statistical features of the speed of these trips. It is seen that at spot 1, similar to general trips made by all vessels, inbound truck trips suffered from a large variance in speed than outbound trips, though it had a smaller mean speed. The median of inbound trip was less, but roughtly from the 70^{th}, the percentile of inbound trip became larger than that of outbound. On the other hand, at spot 2, inbound tanker trips had generally smaller speeds than outbound trips, even if it had a larger variance. This feature is also similar to those general trips of all vessels.

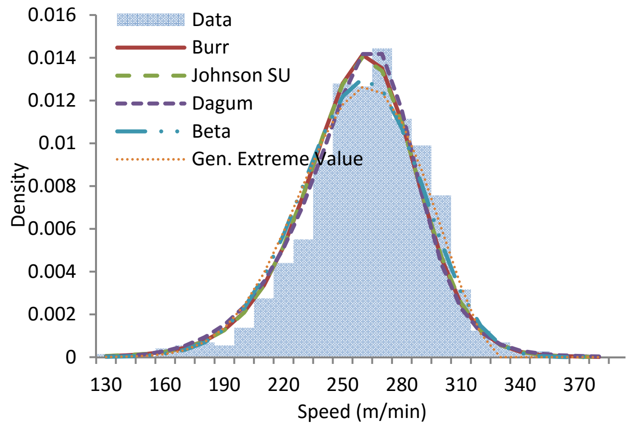
Table 4 Data summary and normality test of tanker trip speeds in each direction at two spots (Note: 1 knot = 30.867 m/min)

	Spot 1		Spot 2	
	Inbound	Outbound	Inbound	Outbound
Data Summary (knot)				
Mean	8.05	8.34	4.76	5.86
Standard deviation	1.67	1.00	1.49	1.10
Median	7.83	8.39	4.57	5.74
70^{th}-percentile	8.97	8.88	5.57	6.23
90^{th}-percentile	10.26	9.50	6.78	7.18
99^{th}-percentile	11.99	10.57	8.10	9.26
Skewness	0.3051	-0.3929	0.1443	0.6266
Kolmogorov-Smirnov test (normality test)				
P-value	0.0014	0.2341	0.0145	0.0005

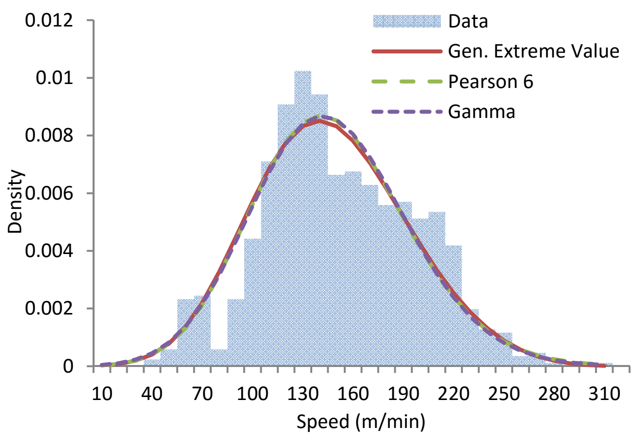
Moreover, compared with general trips, it was seen that tanker trips generally had higher speeds at spot 1, but lower at spot 2. Furhter, Kolmogorov-Smirnov tests show that none were normally distributed, except the outbound trips at spot 1. This findings were also consistents with those about general trips. The speed distributions of tanker trips in different directions were further investigated in the following.



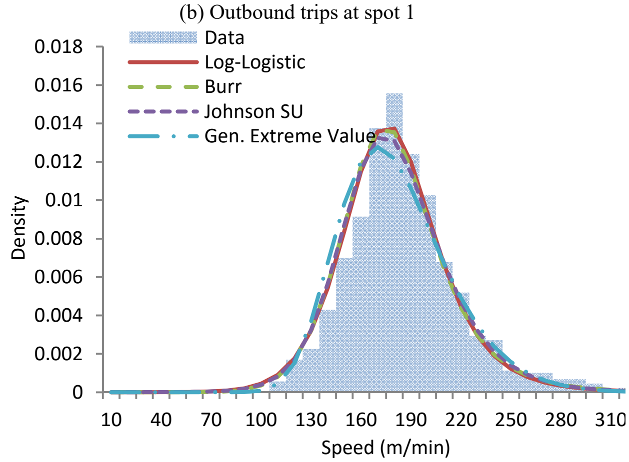
(a) Inbound trips at spot 1



(b) Outbound trips at spot 1



(c) Inbound trips at spot 2



(d) Outbound trips at spot 2

Figure 8 Speed distributions of in- and out-bound trips made by tankers at two hotspots (histograms of the data and the fitted distributions)

Table 5 P-values of the fitted distributions for trips made by tankers, given a significant level of 0.05

Spot 1		Spot 2	
Inbound	Outbound	Inbound	Outbound
0.20719 (Fatigue Life) 0.20344 (Lognormal) 0.161 (Pearson 6) 0.16034 (Gen. Extreme Value)	0.99965 (Burr) 0.99875 (Johnson SU) 0.96177 (Dagum) 0.7941 (Beta) 0.65814 (Gen. Extreme Value) 0.35735 (Weibull) 0.2341 (Normal) 0.1655 (Gamma)	0.23893 (Gen. Extreme Value) 0.17932 (Pearson VI) 0.16739 (Gamma)	0.84435(Log-logistic) 0.76088(Burr) 0.53423 (Johnson SU) 0.09366 (Gen. Extreme Value)

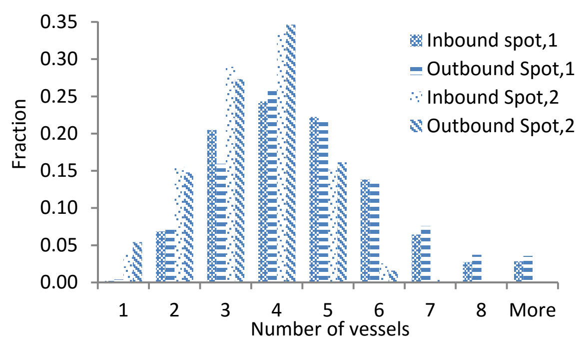
This paper studied the speed distributions of tanker trips (as reported in Figure 8), and attempted to use some specific distributions to fit these speed data using EasyFitXL. Figure 8 shows the fitted distributions. It is seen that the speed distributions of tanker trips were more regular than those of general trips made by all vessels, because much more distributions were found to be able to fit the speed data, especially for outbound trips at spot 2. Note that only the top-ranked distributions were reported in Figure 8(b). Table 5 reports the P-value of these top-ranked distributions that fit these speed distributions well. As mentioned before, P-values that are greater than 0.05 (predefined significant level) lead to not reject the hypothesis that this distribution well fits the given speed data. Interestingly, it was found that it is still the generalized extreme value distribution (see Eq. (1) for its PDF) that fits all speed data of both in- and out-bound tanker trips at two spots. Table 6 reports the estimates of the parameters of the fitted generalized extreme value distributions. Please refer to Appendix for the estimates of the parameters for other fitted distributions.

Table 6 Estimate of three parameters of the fitted generalized extreme value distributions for

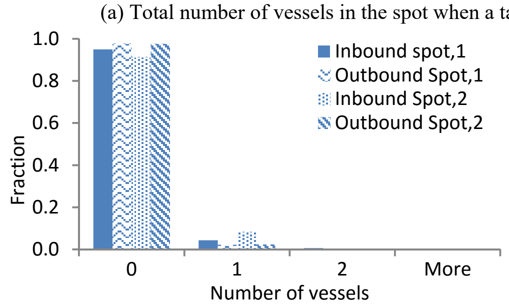
	k	σ	μ
Outbound trips at spot 1	-0.39161	31.78	248.27
Inbound trips at spot 1	-0.16677	47.65	227.97
Outbound trips at spot 2	-0.10517	28.984	166.95
Inbound trips at spot 2	-0.21437	44.298	129.36

4.2 Analysis of density

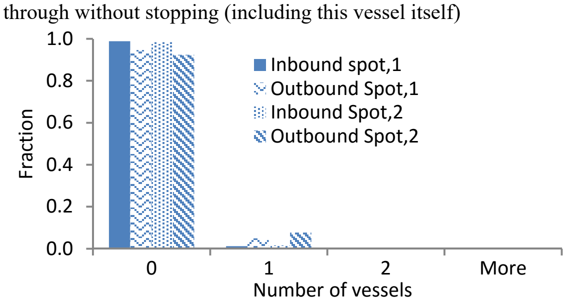
Also, when a tanker passed through a spot, the number of vessels in the spot were also recorded and its distribution was investigated. The finding is quite similar to that of general trips. At spot 2, more than 60% of tanker trips (both in- and out-bound) saw 3 – 4 other vessels at this spot when it ran through. While less than 0.5% of tanker trips saw more than 6 other vessels at this spot. Spot 1 was more congested. Around 15% of tanker trips (both in- and out-bound) saw more than 6 other vessels at this spot when it went through. However, the number of vessels that were not moored is much smaller.



(a) Total number of vessels in the spot when a tanker went through without stopping (including this vessel itself)



(b) Number of vessels moving in the opposing direction



(c) Number of vessels moving in the same direction

Figure 9 Distribution of the number of vessels encoutered by a tanker that went through a hotspot without stopping

Still, more than 90% of tanker trips (both in- and out-bound) at two spots only saw moored vessels in this spot. Only 4% and 8% of all inbound tanker trips encountered an outbound trip (by any vessel) at spots 1 and 2, respectively; whie only 2% of outbound tanker trips encountered an inbound trip at two spots, respectively. Therefore, inbound tanker trips at two spots, especially at spot 2, may suffer from higher risk of head-on collisions, compared with outbound tanker trips at these two spots. These findings are well consistent to the findings of general trips, as discussed in Section 3.3.

On the other hand, interestingly, it seems that ourbound tanker trips may suffer from higher risk of overtaken collisions at both two spots: around 5% and 8% of outbound tanker trips saw another outbound trip (by any vessel) at the same time at spots 1 and 2, repsectively; while only about 1% and 2% of inbound tanker trips saw another inbound trip at the same time at spots 1 and 2, respectively. Such features were not revealed in the analysis of general trips by all vessels.

5. CONCLUSIONS

This paper studied the travel behavior of vessels at two hot spots in SNWW, which were identified in our previous research based on the analysis of vessel conflict frequencies using AIS data (Wu et al, 2016). A vessel conflict occurs when a vessel enters the domain of another. It was found that more than 10% of total vessel conflicts along the whole SNWW occurred at these two hot spots. Moreover, these two spots are not located at the intersection, nor close to the port. Therefore, it would be easier to investigate the travel behavior of vessels.

At each spot, using the AIS data of the whole year of 2012, vessels' navigation information were organized into various trips within each spot. For each trip of a vessel, the first and last time stamps within a spot are regarded as the starting and ending time of a trip within this spot, respectively, so that the time duration of a trip within this spot can be known. With the known travel distance within this spot, the average speed of a trip can be found. This speed can be regarded as "space mean speed" of a trip. On the other hand, with known spatial and temporal information of trips, the interaction between vessels within a spot can be also examined. This paper particularly studied the distributions of these trip speeds in each direction at each spot. The findings of this paper were summarized as follows.

- At both spots, the number of moored trips (i.e., a vessel had been moored at these two spots) is much larger than that of vessels directly running through (either inbound or outbound)
- At spot 1, the major vessel types were towing vessels (30-40%) and tankers (about 40%); while tankers accounted for 60-70% of all vessels at spot 2. The traffic flow of each type of vessels were stable from month to month.
- The speed distributions of general trips are not normally distributed. Instead, the distributions varies. Roughly, a generalized extreme value distribution can discribe some of these distributions. While for tank trips, the speed distributions were more regular. Generalized extreme value distributions can fit all speed distributions of tanker trips in both direction at two spots.
- Generally, around 60% of trips saw 3-4 other vessels in spot 1, and 2-3 other vessels at spot 2 at the same time. Spot 1 was found to be more congested than spot 2. However, in more than 90% of cases, the vessels that were encounted by another vessel which was running through a spot, were moored at this spot. It is also found that inbound trips at both spots suffers higher risk of head-on collisions than outbound trips.
- As to tankers, it was found that tankers ran faster than general trips at spot 1, but relatively slower at spot 2. Most vessels that a tanker encountered when it was going through a spot were moored. It was also found that inbound tanker trips at both spots, especially at spot 2, may suffer from higher risk of head-on collisions than outbound ones, given that it is more likely for a tanker (running inbound) to entercounter another vessel running outbound. On the other hand, outbound tanker trips may suffer from higher risk of overtaken collisions at

both spots, as a tanker running in the outbound direcition has a larger chance to have another vessel also running outbound at the same time and at the same spot.

This paper investigated the travel behavior of vessels at two hot spots in SNWW based on AIS data collected during the whole year of 2012. There exists some other hot spots located at the intersection of two channels, as well as those near the spots. Meanwhile, it is also important to study the human factors associated with various types of vessel behavior. It warranties futher investigation.

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APPENDIX

The following lists the probabiltiy density functions (PDFs) of a series of distributions. As to generalized extreme value distribution, please refer to Equation (1).

- Beta distribution: $f(x)=\frac{1}{B(\alpha_1,\alpha_2)}\frac{(x-a)^{\alpha_1-1}(b-x)^{\alpha_2-1}}{(b-a)^{\alpha_1+\alpha_2-1}}$
- Burr distribution: $f(x)=\alpha k\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1}\Big/\beta\left[1+\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right]^{k+1}$
- Dagum distribution: $f(x)=ak\left(\frac{x-\gamma}{\beta}\right)^{\alpha k-1}\Big/\beta\left(1+\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right)^{k+1}$
- Error distribution: $f(x)=\frac{h}{\sqrt{\pi}}\exp(-(hx)^2)$
- Fatigue life distribution: $f(x)=\frac{\sqrt{x/\beta}+\sqrt{\beta/x}}{2\alpha x}.\emptyset\left(\frac{1}{\alpha}\left(\sqrt{x/\beta}-\sqrt{\beta/x}\right)\right)$
- Gamma distribution: $f(x)=\frac{(x-\gamma)^{\alpha-1}}{\beta^{\alpha}\tau(\alpha)}exp(-(x-\gamma)/\beta)$
- Johnson SB distribution: $f(x)=\frac{\delta}{\lambda\sqrt{2\pi}z(1-z)}\exp\left(-\frac{1}{2}\left(\gamma+\delta\ln\left(\frac{z}{1-z}\right)\right)^2\right)$, where $z=\frac{x-\xi}{\lambda}$.
- Johnson SU distribution: $f(x)=\frac{\delta}{\lambda\sqrt{2\pi}\sqrt{z^2+1}}\exp\left(-\frac{1}{2}\left(\gamma+\delta\ln\left(z+\sqrt{z^2+1}\right)\right)^2\right)$, where $z=\frac{x-\xi}{\lambda}$.
- Kumaraswamy distribution: $f(x)=a_1a_2z^{a_1-1}(1-z^{a_1})^{a_2-1}/(b-a)$, where $z=\frac{x-a}{b-a}$
- Log-logistic distribution: $f(x)=\frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1}\left[1+\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right]^2$
- Lognormal distribution: $f(x)=exp\left(-\frac{1}{2}\left(\frac{lnx-\mu}{\sigma}\right)^2\right)/x\sigma\sqrt{2\pi}$
- Nakagami distribution: $f(x)=\frac{2m^m}{\Gamma(m)\Omega^m}x^{2m-1}\exp(-\frac{m}{\Omega}x^2)$
- Normal distribution: $f(x)=exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right)/\sigma\sqrt{2\pi}$
- Pearson VI distribution: $f(x)=\frac{\left((x-\gamma)/\beta\right)^{\alpha_1-1}}{\beta B(\alpha_1,\alpha_2)(1+(x-\gamma)/\beta)^{\alpha_1+\alpha_2}}$
- Weibull distribution: $f(x)=\frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1}\exp(-\left(\frac{x-\gamma}{\beta}\right)^{\alpha})$

The following list gives the estimates of the parameters of the fitted distributions.

Inbound trips at Spot 1

- Nakagami: $m=4.317, \Omega=56520$, with P-value = 0.07447

Outbound trips at Spot 1

- Generalizd extreme value: $k=-0.4271, \sigma=47.034, \mu=218.31$, P-value = 0.54789
- Beta: $\alpha_1=8.8204, \alpha_2=4.9385, a=0.00604, b=360.1$, P-value = 0.40244
- Burr: $k=117.46, \alpha=5.9296, \beta=554.58, \gamma=-0.31482$, P-value = 0.33718
- Kumaraswamy: $\alpha_1=5.7236, \alpha_2=53.361, a=0.00274, b=496.15$, P-value = 0.08329
- Weibull: $\alpha=9.4419, \beta=379.67, \gamma=-129.73$, P-value = 0.07182

Inbound trips at Spot 2

- Johnson SB: $\gamma=-0.52724, \delta=1.7346, \lambda=360.43, \xi=-42.89$, P-value = 0.12904
- Beta: $\alpha_1=4.9651, \alpha_2=4.3748, a=0.03431, b=305.82$, P-value = 0.10212

- Generalizd extreme value: $k = -0.35134, \sigma = 49.261, \mu = 147.31$, P-value = 0.08095
- Error: $k = 2.5464, \sigma = 47.451, \mu = 162.59$, P-value = 0.06434

Outbound trips at Spot 2

- Log-logistic: $\alpha = 29.37, \beta = 639.27, \gamma = -453.27$, P-value = 0.39893
- Generalizd extreme value: $k = -0.15818, \sigma = 35.957, \mu = 172.21$, P-value = 0.06206

For tanker trips:

Inbound trips at Spot 1

- Fatigue life: $\alpha = 0.21388, \beta = 243.06$, P-value =0.20719
- Lognormal: $\sigma = 0.21238, \mu = 5.494$, P-value = 0.20344
- Pearson VI: $\alpha_1 = 1050.8, \alpha_2 = 123.57, \beta = 62.447, \gamma = -287.57$, P-value = 0.161
- Generalizd extreme value: $k = -0.16677, \sigma = 47.654, \mu = 227.97$, P-value = 0.16034

Outbound trips at Spot 1

- Burr: $k = 2.2202, \alpha = 22.373, \beta = 494.54, \gamma = -213.77$, P-value = 0.99744.
- Johnson SU: $\gamma = 0.77225, \delta = 2.5755, \lambda = 70.35, \ \xi = 280.47$, P-value = 0.99875
- Dagum: $k = 0.35762, \alpha = 15.38, \beta = 186.93, \gamma = 93.303$, P-value = 0.96177
- Beta distribution: $\alpha_1 = 324.32, \alpha_2 = 46.307, a = -1310.9, b = 481.62$, P-value = 0.7941
- Generalizd extreme value: $k = -0.39161, \sigma = 31.78, \mu = 248.27$, P-value = 0.65814
- Normal: $\sigma = 30.944, \mu = 257.38$, P-value = 0.2341
- Gamma: $\alpha = 303.99, \beta = 1.8188, \gamma = -294.94$, P-value =0.1655

Inbound trips at Spot 2

- Generalizd extreme value: $k = -0.24137, \sigma = 44.298, \mu = 129.36$, P-value = 0.23893
- Pearson VI: $\alpha_1 = 110.05, \alpha_2 = 301.93, \beta = 1136.7, \gamma = -268.33$, P-value = 0.17932
- Gamma: $\alpha = 79.539, \beta = 5.1769, \gamma = -264.83$, P-value =0.16739

Outbound trips at Spot 2

- Log-logistic: $\alpha = 14.137, \beta = 254.94, \gamma = -76.74$, P-value =0.84435.
- Burr distribution: $k = 1.0218, \alpha = 9.7158, \beta = 178.44$, with P-value = 0.76088.
- Johnson SU: $\gamma = -0.8151, \delta = 2.1429, \lambda = 60.173, \ \xi = 154.78$, P-value = 0.53423
- Generalizd extreme value: $k = -0.10517, \sigma = 28.984, \mu = 166.95$, P-value = 0.09366