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1 Use of AIS data for performance evaluation of ship traffic with speed control

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12 **Highlights**

13 1. Rational speed control to strike an effective balance between navigation efficiency and system safety.

14 2. AIS data mining and innovative use for evaluating the performance of shipping traffic.

15 3. A new framework to explain the process of data acquisition, error elimination and combination of

16 AIS and geocoded data.

17 4. Analysis of shipping traffic performance from a new perspective with respect to the characteristics

18 of different navigational segments.

19 5. Real case study to justify the rational ship speed limit in the Shanghai section of the Yangtze River.

20

21 **Abstract**

22 Speed control in inland water systems needs to strike an effective balance between ship operational

23 efficiency and transport safety. However, speed limit regulations are largely formulated by expert

24 judgment rather than objective evidence-based evaluation, which sometimes leads to their inefficiency

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25 due to subjective bias. In this study, a new method is proposed to evaluate the performance of shipping
26 traffic under the current speed limits using automatic identification system (AIS) big data of 4923 ships
27 in the Shanghai section of the Yangtze River, China. Key elements of this method include data acquisition,
28 error elimination, combination of ship AIS and waterway geocoded data to model traffic flow
29 characteristics, and estimation of the correlation between ship speed and congestion level. This study
30 separates the peak and off-peak periods of the investigated waterways, which provides a baseline for
31 future speed control schemes with respect to different timeframes. Shipping traffic performance in
32 different segments is analyzed, and the results reveal that the overall compliance rate of the speed limit
33 is high and only a few over-speed cases are noted in certain segments. Furthermore, we use a normal
34 distribution to model the correlation between ship spot speeds and maximum traffic volumes and
35 between mean speed and aggregated traffic volume of each 0.2-knot bin. The findings support via
36 experimental evidence that the current speed limit in the Shanghai section of the Yangtze River is rational,
37 while providing useful insights for testing the rationality of speed limits in other waterways or shipping
38 channels.

39

40 Key words: Yangtze River (Shanghai section) Strait; Speed limit Regulation; Normal distribution fitting;

41 AIS data, Maritime safety

42

43 **1. Introduction**

44 The Yangtze River in China is the longest and busiest inland waterway in the world. The Shanghai
45 section of the River is 65 nautical miles (nm) long and is located at the downstream of the River towards
46 the East China Sea. Its average annual daily vessel traffic volume was 942.3 ships in 2017, which
47 increased by 13% in comparison with 833.9 ships in 2013 according to Statistical Bulletin of
48 Transportation Industry Development[1]. Given such a ship volume increase, the associated traffic safety
49 attracts growing attention, particularly in the busy segments of the Shanghai section such as Baoshan
50 North channel, Baoshan channel, and Waigaoqiao channel. The Maritime Safety Administration has
51 regulated the speed limit of 12 knots for all the vessels passing through deep-water channels greater than
52 12.5 m of the Shanghai section since 2011. However, the speed limit was determined by experts based
53 on their experience and it has not been scientifically approved given the difficulty of obtaining vessel
54 speed data in old days. In a broad sense, it raises a critical research issue for ship traffic safety by speed
55 limits in narrow waters from a theoretical perspective. This paper aims to fill this gap by introducing a
56 new paradigm shift regime in setting and justifying the ship speed limit using experimental tests based
57 on automatic identification system (AIS) data.

58 The Safety of Life at Sea convention stipulates that vessels above 300 gross tonnages on
59 international voyages should be equipped with AIS transceivers [2]. Using AIS, significant time-
60 dependent data such as ship dynamic location and ship speed can be obtained and often used to support
61 research in the marine-related field [3]. In this work, the features of real-time ship speed and ship traffic
62 volumes are analyzed to test the rationality of the speed limit in shipping traffic intensive waters in
63 general and 12-knot limit in the Shanghai section of the Yangtze River in specific.

64 The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section

65 3 discusses the research methodology, including the selection of key channels, error elimination method
66 in the use of AIS data, and calculation of traffic flow parameters. Section 4 discusses the results and
67 analyzes the correlation between speed limit and ship traffic flow. Finally, conclusions are presented in
68 Section 5.

69

70 **2. Literature Review**

71 It is crucial to investigate ship speed characteristics to ensure maritime safety. There is no shortage
72 on ship speed studies in the literature. Based on the 135 investigations conducted by the Marine Accident
73 Investigation Branch in the United Kingdom, Tirunagari et al. identified that the traffic density, ship
74 speed, confusion, equipment, bad weather, fatigue, and health were the most frequent causes of maritime
75 accidents [4]. Mazaheri et al. reported that a minor relation existed between traffic distribution and
76 groundings, whereas no relation appeared between groundings and traffic density [5].

77 Scientific research driven speed limit policies and regulations are more frequently seen from other
78 transport modes (e.g. road) than shipping. Speed limits are successfully imposed on road traffic to
79 enhance safety and reduce fuel consumption [6]. Hosseinlou et al. modeled the relation between the
80 emission of pollutants, fuel consumption, travel time, number of accidents, and vehicle speed [7]. Results
81 showed that the optimal speeds were 73 and 82 km/h from societal and road user perspectives,
82 respectively. Using large-scale data relating to the speed limit increase in western United States, Van
83 Benthem found that a 10 mph speed limit increase on highways led to an increase of 3–4 mph in travel
84 speed, 9%–15% in accidents, 34%–60% in fatal accidents, and 14%–24% in elevated pollutant
85 concentrations (carbon monoxide) around the affected freeways [8]. However, the actual mean speed
86 could be lower or higher than the speed limit. Vadeby and Forsman discovered that the mean speeds on

87 motorways were 119.9 and 115.3 km/h with speed limits of 110 and 120 km/h, respectively, whereas on
88 rural roads they were 84.6 and 84.8 km/h with speed limits of 70 and 80 km/h, respectively [9].

89 Compared to the road transport speed limit research, studies on shipping speed control and its guide
90 to policy making are scanty in the current literature. This study aims to propose an approach for studying
91 the relation between actual mean speed and speed limit in the maritime field. Recently, the use of AIS
92 data has gained considerable attention in the maritime research area. The used approaches are at large
93 classified into two categories in terms of their applications, namely traffic characteristics of ships and
94 navigation safety. In the case of ship traffic, considerable research has been conducted based on AIS
95 data. Wen et al. established a marine traffic complexity model to evaluate traffic situation [10]. Zhang et
96 al. presented an effective analysis method to analyze ship traffic demand and ship traffic spatiotemporal
97 dynamics in port waters [11]. Christian and Kang processed AIS using a Hough Transform algorithm to
98 estimate possible intersections between the shipment route and marine traffic [12]. Furthermore, Kang
99 et al. estimated the speed-density relation based on the Greenshields model, Greenberg model,
100 Underwood model, and Pipes generalized model for analyzing the vessel traffic flow of Singapore Strait
101 [13]. In the case of ship collisions, Kujala et al. used AIS data to calculate the geometric probability of
102 ship collision in the Gulf of Finland [14]. Results revealed that the highest risks were caused by high
103 traffic intensity. Moreover, Mou et al. developed a linear regression model to determine the correlation
104 between the closest point of approach and size, speed, and ship headings; then, they analyzed ship
105 collision using the AIS data of Rotterdam Port [15]. Zhang et al. proposed a method that detected possible
106 near miss ship–ship collisions using AIS data [16]. Furthermore, a good number of studies had
107 undertaken a correlation analysis between ship accidents and traffic data obtained from AIS. Mazaheri
108 et al. conducted a correlation analysis regarding the relation between traffic conditions, complexity of

109 the waterway, and grounding accidents [17]. Goerlandt et al. found that ship collisions occurred when
110 the ship's speed was lower than the average speed of the vessel fleet [3]. Bye and Aalberg used a
111 multivariate logistic regression model to identify the conditions associated with navigation accidents and
112 regarded these conditions as risk indicators based on the Norwegian Maritime Directorate (NMA) data
113 and AIS data [18]. In light of the above, to our best knowledge, no previous studies have investigated
114 the relation between ship actual mean speed and speed limit using AIS big data, despite its important
115 influence on transport safety as indicated in road transport.

116 The above literature review reveals that 1) ship speed is among the most important attributes
117 influencing marine navigational safety; 2) actual vehicle speeds are not always perfectly in line with the
118 speed limit accordingly to the lesson learnt from other transport modes (e.g. road); 3) research on ship
119 speed limits is scarce in the current literature; 4) AIS data are often used to obtain the traffic
120 characteristics of ships and analyze their navigation safety, however, rarely on the solution to ship speed
121 limit. This study therefore proposes a methodology to quantify the characteristics of actual ship speed
122 and traffic volume based on AIS data and demonstrate it using the speed limit of the Shanghai section of
123 the Yangtze River. The results will aid to develop rational speed limit regulations to optimize ship traffic
124 flow while minimizing the associated maritime risks.

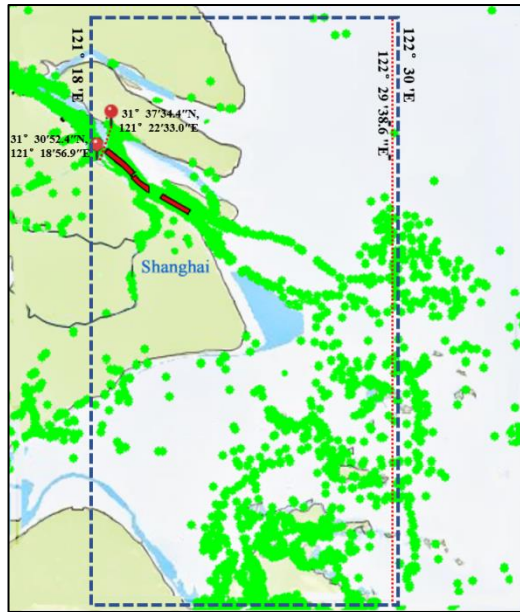
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126 **3. Observations from AIS data**

127 **3.1 AIS data acquisition**

128 In total, 83140629 AIS records (from June 1, 2014, 8:00:00 to June 30, 2014, 8:00:00) involving
129 4923 ships are obtained from the Shanghai section of the Yangtze River. The geographic scope used for
130 the AIS data collection is shown by the blue dotted line in Fig. 1. The corresponding longitudes and

131 latitudes of the four vertices are (121°18'E, 30°N), (121°18'E, 31°N), (122°30'E, 30°N), and (122°30'E,
132 31°N), respectively. The border of the Shanghai section of the Yangtze River is a line between point
133 (31°30' 52.4"N, 121°18'56.9"E), point (31°37'34.4"N, 121°22'33.0"E), and line of longitude
134 122°29'38.6"E, as depicted by red dotted line in Fig. 1.



135

136

Fig. 1 Geographic scope of the AIS data.

137

Note: The green dots represent the ships.

138

139 3.2 AIS data error elimination

140 The cleaning of big data is recommended by detecting and removing errors and inconsistencies
141 from the data to improve the data quality [19]. In the case of AIS big data, data cleaning methods include
142 deleting duplicate data, handling abnormal MMSI number, location, speed data, and disposing out-of-
143 range data [13, 20]. For missing data, interpolation processing will be employed [11]. There are four
144 steps to clean the AIS data:

145 **Step 1:** Delete duplicate AIS records.

146 If records are repetitive, only one record is kept. Duplicate data refer to two or more AIS data that

147 have the same field values, such as MMSI number, receiving time stamp of field data, ship dynamic
148 location, and ship speed.

149 **Step 2:** Delete abnormal AIS data records.

150 Abnormal AIS data refer to the records where the associated MMSI numbers are outside the
151 permissible range [100000000, 999999999] [13], or the speed over ground (SOG) is outside the range
152 of the AIS receiver (e.g. $SOG < 0$ and $SOG > 102.2$), or the record where absolute longitude is $|X| > 180^\circ$,
153 or the absolute latitude is $|Y| > 90^\circ$ [20], or the geographic coordinates exceed the expected AIS
154 receiving range [13, 20].

155 Herein, all the abnormal AIS records are deleted.

156 **Step 3:** Delete unreasonable ship speed and unreasonable ship acceleration/deceleration.

157 Based on the traffic restrictions in the Singapore straits, Kang et al. set the minimum ship speeds as
158 4 knots [13]. Meanwhile, Qu et al. found that 25% of the ship speed was greater than the maximum
159 speed limit (15 knots) for traffic restrictions in the Singapore straits [21]. Therefore, they expanded the
160 reasonable maximum speed to 20 knots, and the reasonable ship speeds are defined in the range from 4
161 to 20 knots. Moreover, Qu et al. and Zhang et al. calculated the average speed by the ratio of distance to
162 the time interval based on Newton's laws of motion to determine whether the ship speed is reasonable
163 with the ship's position and acceleration/deceleration [11, 21].

164 The ship speed regulation in the Yangtze River sets up the speed limit at 12 knots excluding high
165 speed vessels. From the AIS data records of the Yangtze River, Fig. 2 reveals that only 0.06% of speeds
166 are greater than 30 knots. It is difficult to decide whether the corresponding data is from high speed ships
167 or speed errors. Hence, the reasonable speed range is defined from 0 to 30 knots and the out-of-scope
168 data are deleted.

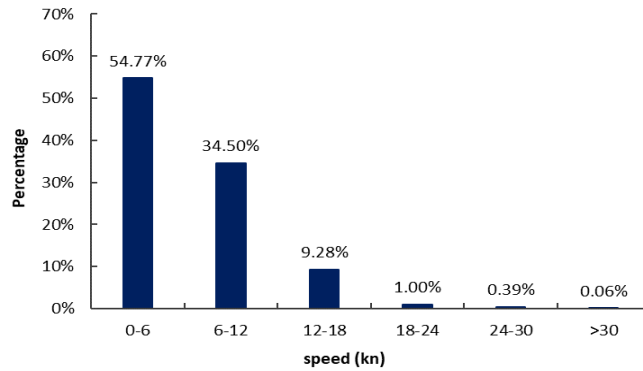


Fig. 2 Ship speed distribution.

Step 4: Correction of missing data.

Salama filled missing data by statistical analysis and dynamic similarity matching [22]. However, Zhang et al. set an interval of 30s for AIS data linear interpolation [11]. Moreover, Shelmerdine interpolated ship speed, length, draft, and tonnage using a natural neighbor function [23].

In this work, the AIS data are aggregated into 20-min bins to obtain the average ship speed and ship traffic volume. The AIS records are then sorted over time from small to large for each vessel, when the time between two AIS records of a specific vessel is larger than 20 min. Meanwhile, the interpolated method is used to cope with the supplementary data. Given that the proportion of time interval greater than 20 min is only 0.021%, the interpolation is not taken into account in the investigated case of the Shanghai section.

Table 1 lists the AIS data cleaning steps of the Yangtze River from June 1, 2014 to June 30, 2014.

Table 1 Summary of data cleaning results.

Steps	Type of data	Records before cleaning	Records of cleaned	% of deleted records
1	Duplicate data	83,140,629	1,622,296	1.95
2	Abnormal MMSI	81,518,333	274,388	0.33
	Abnormal SOG	81,243,945	152,838	0.18
	Abnormal latitude and longitude	81,091,107	0	—
3	Speed out-of-scope data	81,091,107	48,164	0.06
4	Missing data	81,042,943	0	—

187

188 3.3 Geocoding AIS data to deep-water channels

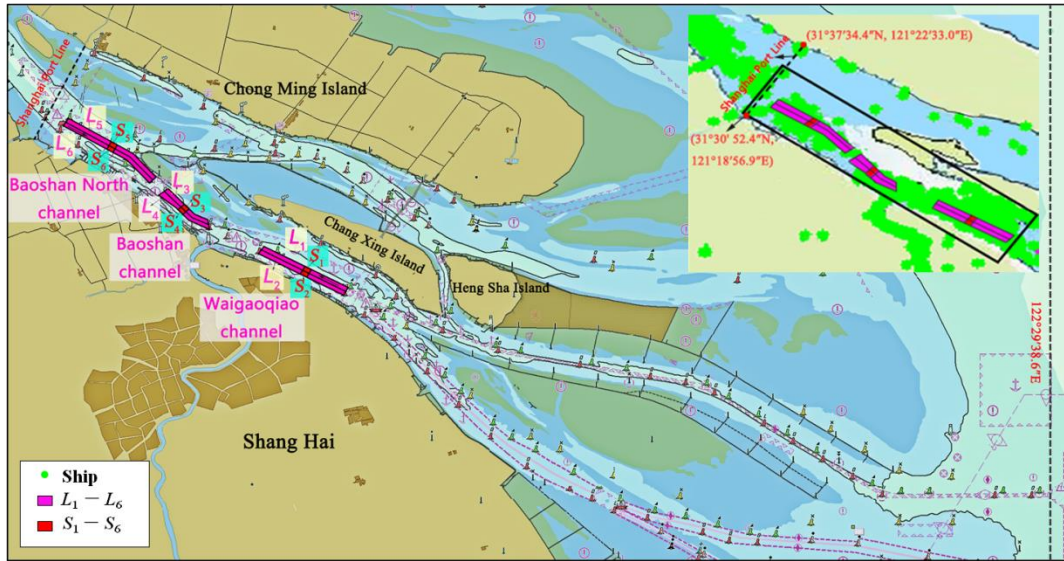
189 (1) Selection of key deep-water channels (lanes)

190 There are five deep-water channels in the Shanghai section, namely Waigaoqiao channel, Baoshan
 191 channel, Baoshan North channel, South channel, and Yangtze estuary deep-water channel. Based on their
 192 geographical distribution, this study considers, based on the trajectory intensity, three main channels,
 193 namely Waigaoqiao channel, Baoshan channel, and Baoshan North channel. The three key dual-lane
 194 channels are numbered as lane 1, lane 2, ..., lane 6, and coded as L_1, \dots, L_6 . Herein, L_1, L_3 , and L_5 are
 195 the lanes of traffic towards the upstream of the River (e.g. river direction), whereas L_2, L_4 , and L_6 are the
 196 lanes of traffic towards the downstream of the River (i.e. sea direction), as shown in Fig. 3.

197 (2) Selection of small segments in the middle of waterway lanes

198 Six small segments were selected from the middle of the six lanes $\{L_1, \dots, L_6\}$ and recorded as S_k
 199 ($k \in \{1, 2, \dots, 6\}$) correspondingly (Fig. 3). S_k^+ and S_k^- represent the upstream and downstream areas
 200 of S_k , respectively, as shown in Fig. 4. The length of the observed middle area was set as 0.25 nm. Based
 201 on the hypothesis that a ship can travel 0.33 nm within 20 min if its minimum speed is 1 knot, this study
 202 selects 0.25 nm as the length of observation sections to ensure that the ship can travel through it within

203 20 min.



204

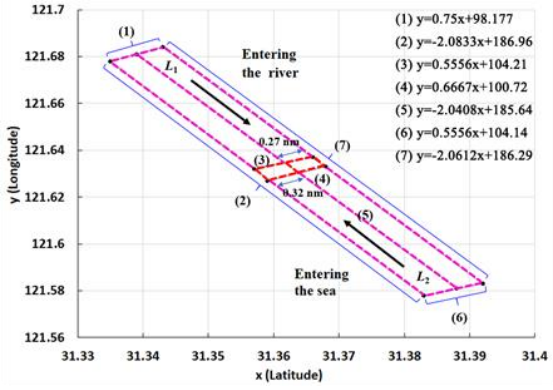
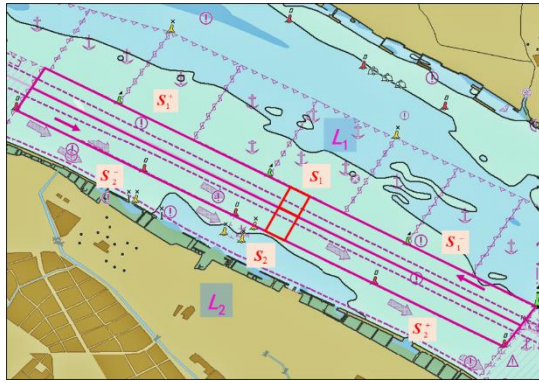
205 Fig. 3 Key lanes in the Yangtze River (Shanghai section)

206 Notes: In the rectangular area in the small window, the green point represents the ship, and the higher density
207 of the green points represents a higher density of ship trajectory.

208 (3) Geocoding of selected lanes and segments

209 Based on the landmarks along the boundary of each lane, such as geographical marking points,
210 buoys, and lighthouses, the range of the lanes $\{L_1, \dots, L_6\}$ (Fig. 3) is shown in the nautical map (Figs. 4
211 a–c). A linear function is then adopted to express each edge of the polygon boundary of the key lanes, as
212 shown in Figs. 4(d–f).

213 To obtain the red lined segments $\{S_1, \dots, S_6\}$, we randomly selected some points near the middle
214 part of each lane as the boundary points. The width of each section is defined as 0.25 nm, and length of
215 each segment is shown in Figs. 4(d–f). Each edge of the middle segment is also geocoded using linear
216 functions.

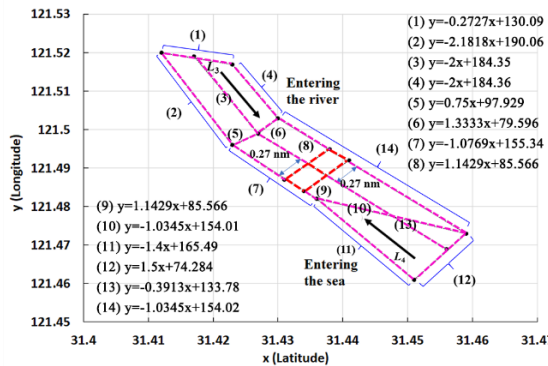
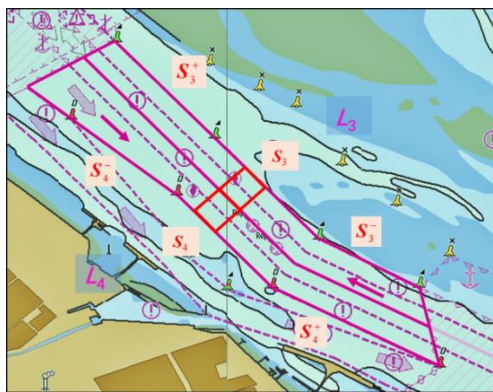


217

(a) Boundary of Waigaoqiao channel

(d) Polygon of Waigaoqiao channel and function expressions

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219

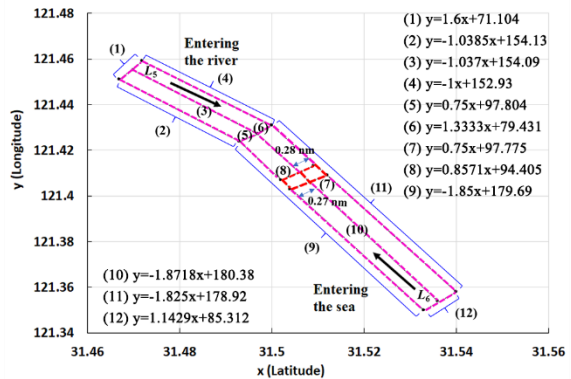
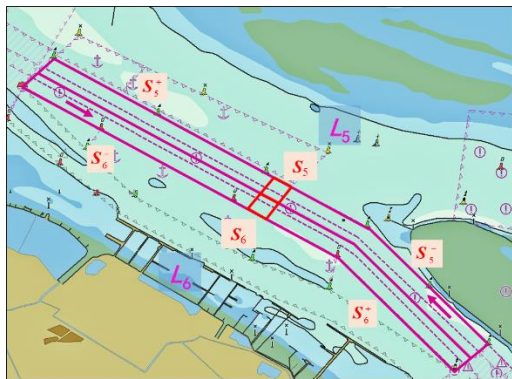


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(b) Boundary of Baoshan channel

(e) Polygon of Baoshan channel and function expressions

221



222

(c) Boundary of Baoshan North channel

(f) polygon of Baoshan North channel and function expressions

223
224

225

Fig. 4 Location and function expressions of each channel.

226

(4) Geocoding AIS data of the selected lanes and segments

227

Using the functions in Fig. 4, we extract the AIS data involving the selected lanes and segments. A

228 total of 4923 ships and 5217849 AIS records are obtained. The detailed data are listed in Table 2.

229 Table 2 AIS data of the key channels.

Channel/Middle section of channel	Symbol	Inland river direction	Symbol	Sea direction
Waigaoqiao channel	L_1	1,200,405	L_2	1,416,215
Baoshan channel	L_3	728,077	L_4	360,956
Baoshan North channel	L_5	1,015,448	L_6	496,748
Middle segment of Waigaoqiao channel	S_1	47438	S_2	55779
Middle segment of Baoshan channel	S_3	51102	S_4	16389
Middle segment of Baoshan North channel	S_5	30387	S_6	9326

230

231 4. Calculation steps of ship traffic flow parameters

232 The AIS data are aggregated into 20-min bins for each channel to obtain the traffic volume and ship
 233 speed. The total time is divided into intervals, such as $[t_0, t_1)$, \dots , $[t_i, t_{i+1})$, \dots , $[t_{n-1}, t_n)$, where $t_0 =$
 234 08:00:00, June 1, 2014, $t_n = 08:00:00$, June 30, 2014, and $t_{i+1} = t_i + 20$ min.

235 The traffic volume is calculated as the number of the ships passing through S_k . The ship speed is a
 236 spot speed, calculated as the average value of the real time speeds of all ships passing through S_k . The
 237 traffic volume and ship speed of each channel L_1, L_2, \dots, L_6 are calculated using the following three steps:

238 **Step 1:** Calculation of the traffic volume $Q^{S_k, [t_i, t_{i+1})}$.

239 For each lane L_k ($k = 1, 2, \dots, 6$), the ship passes the middle of the lane in the sequence of S_k^- , S_k ,
 240 and S_k^+ . The set $Q^{S_k, [t_i, t_{i+1})}$ (ship/20 min) represents the traffic volume of S_k during $[t_i, t_{i+1})$. Herein,
 241 we define a new parameter $Z_{d_j}^{S_k, [t_i, t_{i+1})}$ as an evaluation indicator to examine whether the ship d_j appears
 242 in the segment S_k during time $[t_i, t_{i+1})$.

243 a. If the trajectory of ship d_j during time $[t_i, t_{i+1})$ appear only in segment S_k^- or S_k^+ , ship d_j
 244 does not pass through segment S_k . Therefore, $Z_{d_j}^{S_k, [t_i, t_{i+1})} = 0$.

245 b. If the trajectory of ship d_j during time $[t_i, t_{i+1})$ appear in any of the following sets of S_k , (S_k^- &
 246 S_k), (S_k^- & S_k & S_k^+), (S_k & S_k^+), or (S_k^- & S_k^+), ship d_j passes through S_k during $[t_i, t_{i+1})$.

247 Therefore, $Z_{d_j}^{S_k, [t_i, t_{i+1}]} = 1$.

248 c. $Q^{S_k, [t_i, t_{i+1}]}$ is accordingly calculated as follows:

$$249 \quad Q^{S_k, [t_i, t_{i+1}]} = \sum_{d_j=1}^n (Z_{d_j}^{S_k, [t_i, t_{i+1}]} = 1), \quad (1)$$

250 where n is the total number of ships passing through S_k during $[t_i, t_{i+1})$.

251 **Step 2:** Calculation of the ship speed $v^{S_k, [t_i, t_{i+1}]}$.

252 Since the change of ship speed is very small, the spot speed is considered as the average speed at
253 every 20-min interval, which is denoted as $v^{S_k, [t_i, t_{i+1}]}$ and calculated as the average value of all ship
254 speeds over S_k during a time slot of 20 mins, as follows:

$$255 \quad v^{S_k, [t_i, t_{i+1}]} = \frac{v_1^{S_k, [t_i, t_{i+1}]} + L + v_{d_j}^{S_k, [t_i, t_{i+1}]} + L + v_n^{S_k, [t_i, t_{i+1}]}}{n}, \quad (2)$$

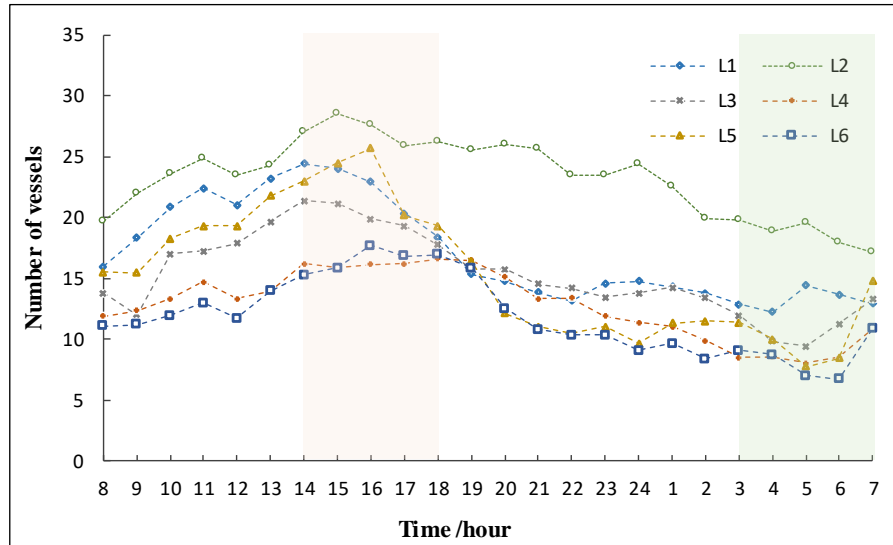
256 where $v_{d_j}^{S_k, [t_i, t_{i+1}]}$ refers to the average speed of ship d_j passing through S_k during $[t_i, t_{i+1})$.

257

258 4. Observations from AIS data

259 4.1 Observations from ship numbers in the lanes

260 **Figure 5** shows the numbers of vessels in the six channels per hour based on AIS data. The vessel
261 numbers of each channel (L_1, L_2, L_3, L_4, L_5 , and L_6) range in the intervals of [12.28, 24.41], [17.17, 28.59],
262 [9.45, 21.38], [8.07, 16.62], [7.76, 25.69], and [6.72, 17.72], respectively. Moreover, two traffic periods
263 are shown in **Fig. 5** with a peak period from 2:00 to 6:00 p.m. and an off-peak period from 3:00 to 7:00
264 a.m. Besides, the ship number between 8:00 a.m. and 6:00 p.m. is slightly larger than that of the period
265 between 6:00 p.m. and 8:00 a.m., indicating that the waterway traffic is slightly more congested during
266 the morning time. Identifying the peak and low peak periods can provide a baseline for future speed
267 control schemes under different time periods.



268

269

Fig. 5 Average numbers of vessels in the six channels per hour.

270

4.2 Characteristics of ship traveling speed in the investigated segments

271

Characteristics of real ship traveling speed in the six chosen segments are shown in Fig. 6. For the

272

Waigaoqiao channel segment (S_1 , S_2), the average ship speed passing through the segment is slightly

273

higher than 12 knots in some special periods. However, the majority of all average speeds are lower than

274

the speed limit ranging between 6 and 8 knots. For the Baoshan North channel key segment (S_5 , S_6), all

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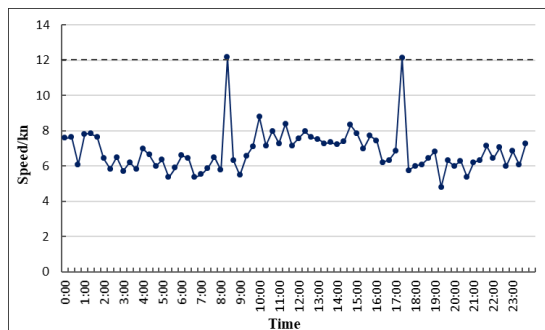
the speeds are much lower than 12 knots ranging from 4 to 8 knots, whereas approximate 25% of the

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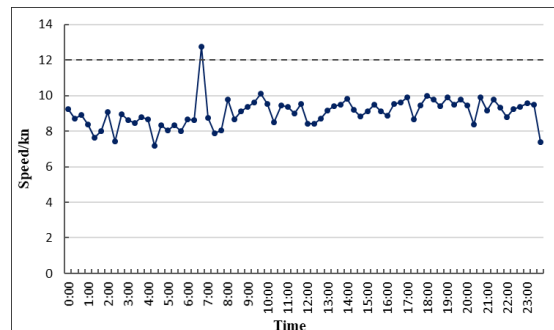
speeds in the Baoshan channel key segments (S_3 , S_4) are slightly larger than the speed limit. Most of the

277

average speeds range from 8 to 12 knots.



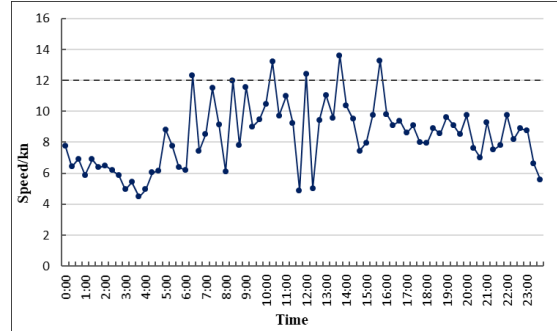
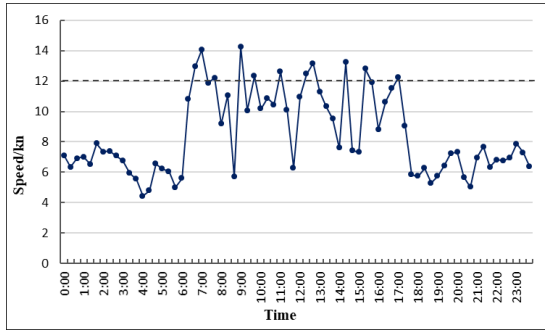
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(a) Inland river direction of Waigaoqiao channel (S_1)

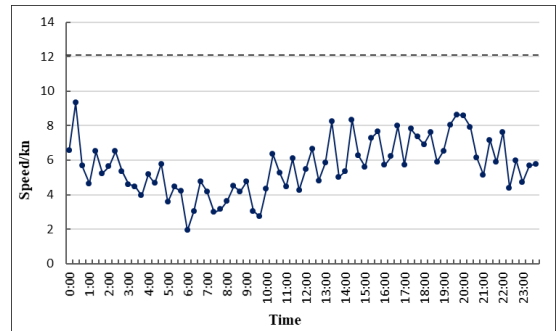
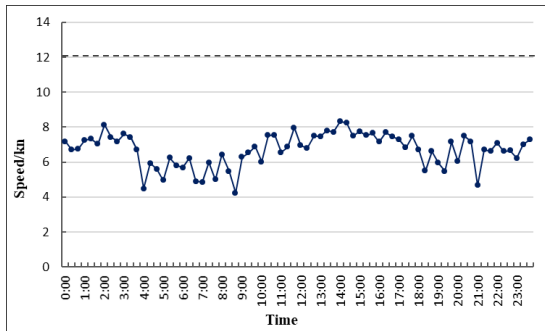
(b) Sea direction of Waigaoqiao channel (S_2)



280

281 (c) Inland river direction of Baoshan channel (S_3)

(d) Sea direction of Baoshan channel (S_4)



282

283 (e) Inland river direction of Baoshan North channel (S_5) (f) Sea direction of Baoshan North channel (S_6)

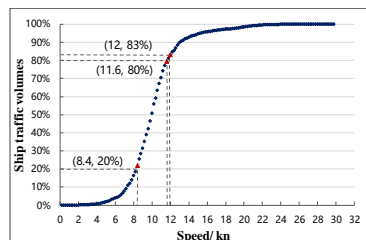
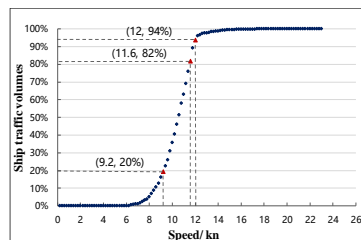
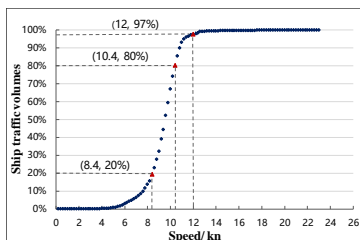
284 Fig. 6 Average speeds at every 20-min interval.

285

286 **4.3 Characteristics of ship traffic volumes in the segments**

287 From the aggregated traffic volume at different speeds (Fig. 7), approximately 20% of vessels pass
 288 through the chosen six segments at 8.4, 9.2, 8.4, 9.2, 8.4, and 9.6 knots, respectively, whereas 80% of
 289 vessels pass through the chosen six segments at 10.4, 11.6, 11.6, 12.2, 10.6, and 11.8 knots, respectively.
 290 Furthermore, the results indicate that most vessels travel below the preset speed limit of 12 knots in S_1 ,
 291 S_2 , S_5 , and S_6 , while a few over-speed cases occur in S_3 , and S_4 .

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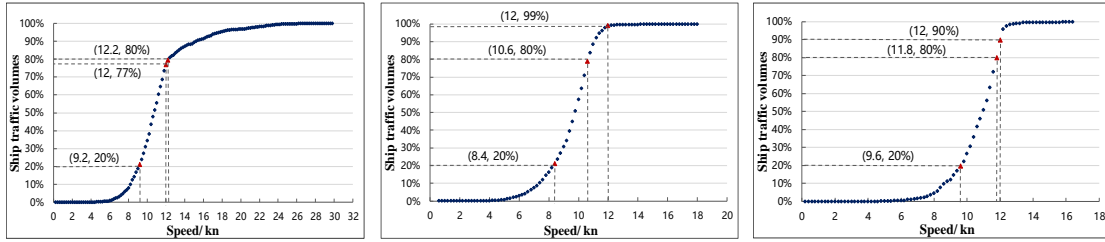
293

294

S_1

S_2

S_3



295

296

S_4

S_5

S_6

297

Fig. 7 Aggregated traffic volume vs speed.

298

299

300 4.4 Ship speed vs traffic volume curve fitting

301 (1) Ship speed vs max traffic volume

302 The kurtosis and skewness of traffic volume distributions for the chosen six segments are similar.

303 Moreover, the distributions of traffic volumes and speeds are well fitted with a normal distribution given

304 as follows:

$$305 \quad Q = f(v) = a \exp\left(-\frac{(v-b)^2}{c}\right), \quad (3)$$

306 where v is the value of $v^{S_k, [t_i, t_{i+1})}$, each $v^{S_k, [t_i, t_{i+1})}$ corresponds to several $Q^{S_k, [t_i, t_{i+1})}$, Q

307 approximates to the maximum value of $Q^{S_k, [t_i, t_{i+1})}$ (see notes in Fig. 8 for details), and a , b , and c are

308 parameters. Table 3 lists the values of the parameters and goodness of fit (R^2). The result shows that the

309 fitting degree (R^2) of S_k is 0.8624, 0.8145, 0.8672, 0.822, 0.7546, and 0.9138, respectively, indicating that

310 the fitting result is appropriate.

311

312 Figure 8 and Table 3 provide some insightful observations. Using the traffic volume of Waigaoqiao

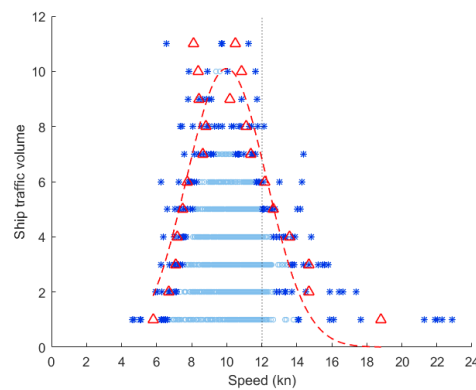
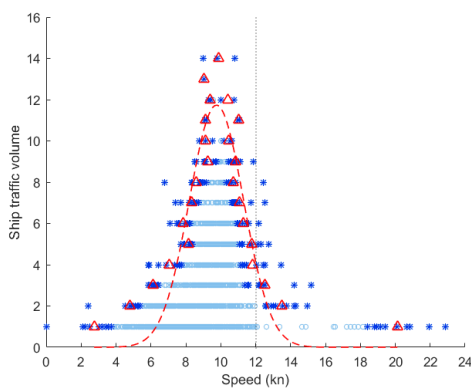
313 channel (for the direction of entering the Yangtze River) as an example, when the speed is below

314 approximately 10 knots, the traffic volume will gradually increase with an increase in speed. When the
 315 speed approaches to approximately 10 knots, the traffic volume reaches its maximum value. However,
 316 when the speed continues to increase steadily after exceeding 10 knots, the traffic volume decreases.
 317 Meanwhile, the other five sections have a similar tendency. Hence, the ship traffic volumes of the chosen
 318 six sections increase with an increase in the ship mean speed until they reach a peak stage and then they
 319 decrease. Additionally, the traffic volume of S_k ($k = 1, 2, \dots, 6$) will reach its peak value when the speed
 320 reaches 9.757, 9.995, 10.32, 11.42, 9.832, and 10.14 knots respectively, suggesting that the speed
 321 corresponding to the peak value of the traffic volume is lower than the speed limit (12 knots).

322 Table 3 Normal distribution fitting results under medium density.

Segment	a	b	c	The optimal speed	R^2
S_1	11.730	9.575	2.199	9.757	0.8624
S_2	10.100	9.995	3.223	9.995	0.8445
S_3	10.310	10.320	4.233	10.320	0.8672
S_4	6.749	11.420	5.441	11.420	0.8220
S_5	9.894	9.832	2.311	9.832	0.7546
S_6	4.935	10.140	2.954	10.14	0.9138

326

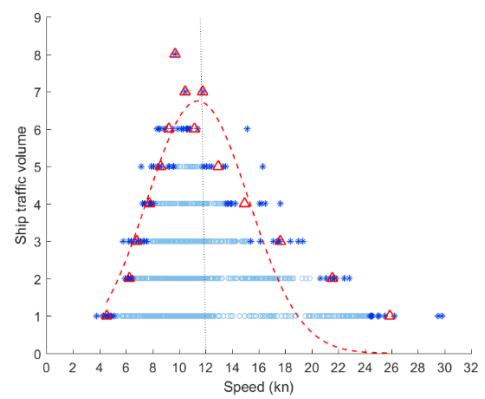
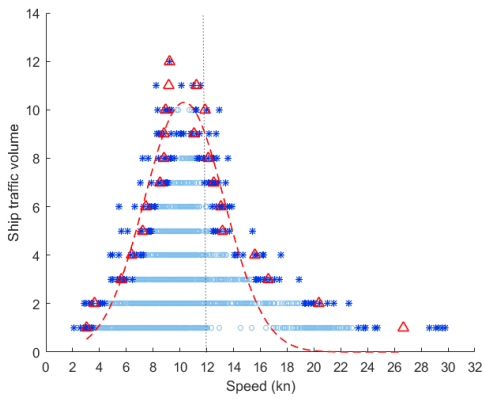


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(a) Inland river direction of Waigaoqiao channel (S_1)

(b) Sea direction of Waigaoqiao channel (S_2)

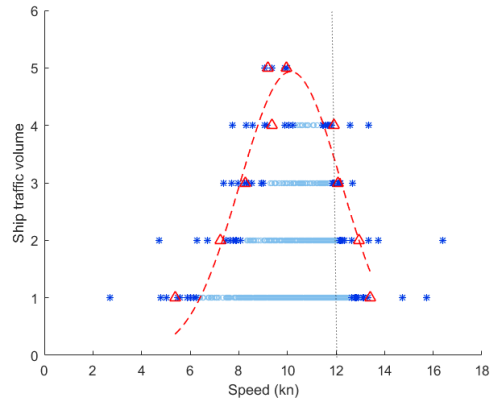
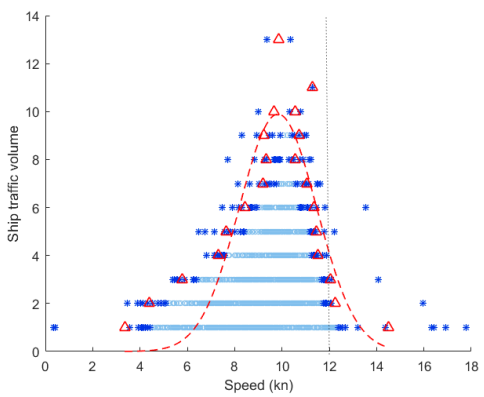


329

330

(c) Inland river direction of Baoshan channel (S_3)

(d) Sea direction of Baoshan channel (S_4)



331

332

(e) Inland river direction of Baoshan North channel (S_5)

(f) Sea direction of Baoshan North channel (S_6)

333

334

Fig. 8 Ship speed vs traffic volume fitting

335 Note:

336

The blue point (\odot) represents baseline data. The dark blue star (*) represents the value of the first 10 minimum (or

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maximum) values data of a certain ship traffic volume. The red triangle (\triangle) represents a calculated point whose value

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is equal to the average value of 10 minimum speed value for a certain ship traffic volume, or the average of the

339

corresponding 10 maximum speed value, and the red imaginary line (---) represents the normal fitted curve under

340

medium density.

341

342

(2) Ship speed vs aggregated traffic volume per 0.2-knot bin

343

The ship speeds $v^{S_k, [t_i, t_{i+1})}$ are sorted from small to large and aggregated into 0.2-knot bin, as $[0,$

344 0.2), [0.2, 0.4), ...]. For each bin, we computed the mean value of the corresponding speed $v^{S_k, [t_i, t_{i+1})}$
 345 and sum of the corresponding traffic volume $Q^{S_k, [t_i, t_{i+1})}$. Using Equation (3) to fit the relation between
 346 mean speed and aggregated traffic volume of each 0.2-knot bin, the results are indicated by $\vartheta_0^{S_k, [t_i, t_{i+1})}$
 347 and $\hat{Q}^{S_k, [t_i, t_{i+1})}$. Herein, v represents $\vartheta_0^{S_k, [t_i, t_{i+1})}$ and Q represents $\hat{Q}^{S_k, [t_i, t_{i+1})}$ in function (3).

348 Moreover, for the aggregated traffic volume at different mean speeds, the relation between ship
 349 speed and aggregated traffic volume is well fitted using a normal distribution. The R^2 values are 0.9618,
 350 0.8905, 0.95, 0.9142, 0.9104, and 0.7712 respectively, as listed in Table 4. The fitting result indicates a
 351 better performance than the fitting model of total traffic volume with mean speed, and better performance
 352 than the model proposed by Kang et al. [13], wherein average R^2 value was 0.691.

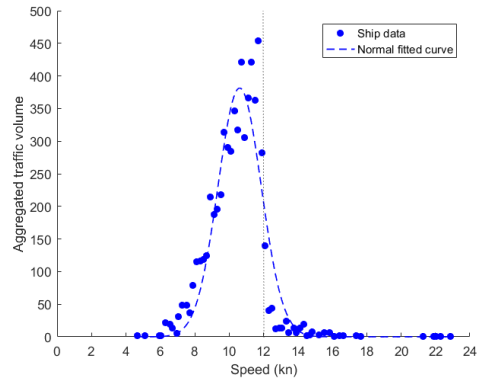
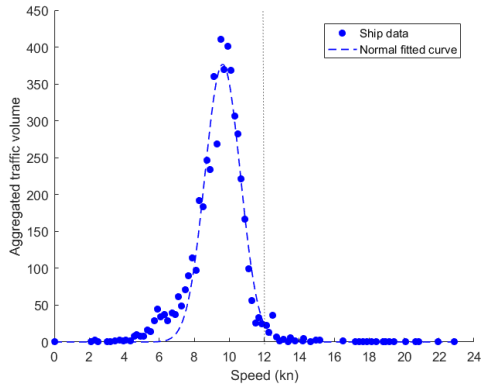
353 Figure 9 shows the same conclusion as the one derived from Figure 8. The results show the
 354 aggregated traffic volume before the speed approaches the limit level (12 knots). The optimal speed
 355 corresponding to the maximum flow of ships in different sections is slightly different, but all around 10
 356 knots, slightly below the specified speed limit of 12 knots. Furthermore, the optimal speed in the Yangtz
 357 River direction (9.63, 9.83, and 9.23 knots) is slightly lower than the optimal speed in the sea direction
 358 of the Yangtz River (e.g. 10.61, 10.51, and 11.14 knots).

359

360 Table 4 Normal distribution fitting results under medium density.

361	Segment	a	b	c	The optimal speed	R^2
362	S_1	376.5	9.628	1.427	9.63	0.9618
	S_2	381.4	10.610	1.774	10.61	0.8905
	S_3	209.0	9.834	2.559	9.83	0.9500
363	S_4	136.1	10.510	2.264	10.51	0.9126
	S_5	276.9	9.929	1.604	9.93	0.9104
364	S_6	120.1	11.14	1.483	11.14	0.7712

365

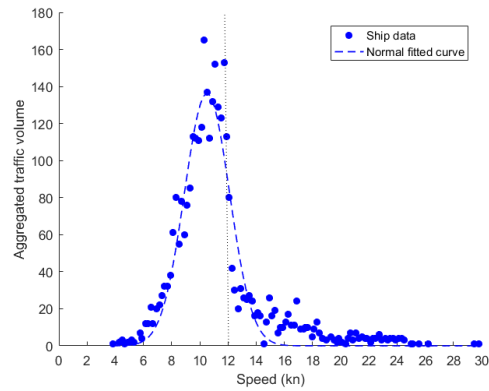
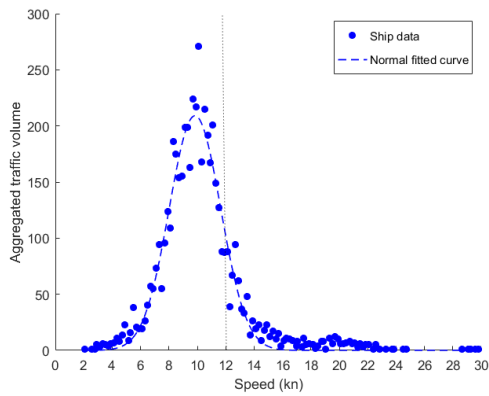


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(a) Inland river direction of Waigaoqiao channel (S_1)

(b) Sea direction of Waigaoqiao channel (S_2)

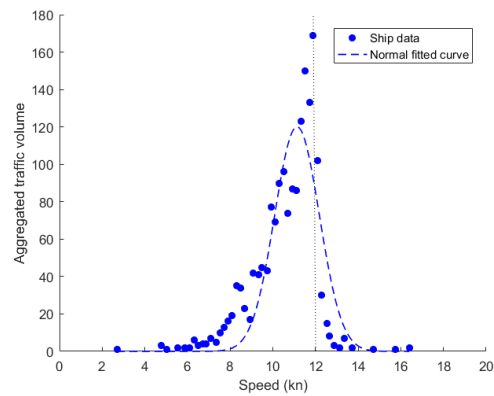
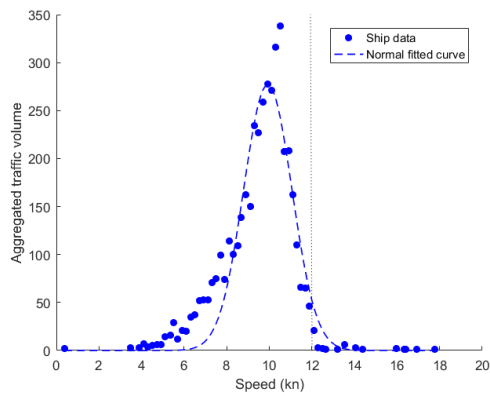


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(c) Inland river direction of Baoshan channel (S_3)

(d) Sea direction of Baoshan channel (S_4)



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371

(e) Inland river direction of Baoshan North channel (S_5)

(f) Sea direction of Baoshan North channel (S_6)

372

Note: The blue line (—) presents the normal fitted curve

373

Fig. 9 Ship mean speed vs aggregated traffic volume fitting (0.2-knot bin).

374

375 **5. Conclusion**

376 We develop an AIS data based method for evaluating the performance of shipping traffic under speed
377 limits. The Shanghai section of the Yangtze River is considered as an example. The detailed steps of the
378 proposed method include 1) cleaning the data to filter out problematic and duplicated data, 2) geocoding
379 the AIS data to waterway segments, 3) calculating the ship traffic characteristics, and 4) estimating ship
380 speed and traffic volume to analyze the rationality of the preset speed limit.

381 Our study separates the peak and off-peak periods to provide a baseline for future speed control
382 schemes within different time periods. Approximately 80% of vessels pass through the Yangtze River
383 (Shanghai section) at speeds lower than 12 knots; however, a few over-speed cases are noted in Segments
384 3 and 4. Finally, we use a normal distribution to test the fitness of the relation between spot speeds and
385 corresponding maximum traffic volumes and between mean speed and aggregated traffic volume of
386 each 0.2-knot bin. The results show that the current speed limit of 12 knots is rational.

387 This research aid maritime safety policymakers to determine rational ship speed limits based on
388 real performance data. The findings can also help both maritime safety authorities and ship owners to
389 adjust the ship speeds to avoid heavy traffic congestion in narrow waterways. The proposed methods can
390 be tailored to analyze and adjust the speed limits in other waterways in the world.

391

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399

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