Cellular Automata Model on AIS-based for Variable Two-way Waterway

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Abstract:

Purpose: We aim at "heavy traffic direction" and "light traffic direction" in two-way waterway traffic and attempt to promote the transit capacity of two-way waterway system.

Design/methodology/approach: We propose overtaking rules, head-on rules and a cellular automaton model for variable two-way waterway on AIS-based on the basis of NaSch (Nagel-Schreckenberg) model.

Findings: By numerical simulation to the two situations which allow changing lane and prohibit changing lane, we obtain fundamental functions between traffic flux (speed) and density and find that changing lane can promote traffic flux and average speed of two-way waterway system under the premise of no impact to the traffic order, and when waterway ship traffic is dense, flux of waterway system has a visible promotion, and when traffic is sparse, average speed of waterway system adds significantly.

Practical implications: As an implication, we can reach a compromise between traffic efficiency and safety. When no collision risk incurred, the marine administrations should allow involved ships to change lane for overtaking.

Social implications: As a suggestion, Rule 9 and Rule 10 of *COLREGs* should make some adjustments correspondingly.

Originality/value: The paper presents a method to analyze and promote transit capacity of two-way waterway.

Keywords: cellular automata, vessel traffic flow, variable two-way waterway, changing lane, numerical simulation

1. Introduction

In general, two-way waterway is usually composed by inbound lane, outbound lane and separation zone (or separation line). For the safety of navigation, *Rules 9* and *Rules 10* of *Convention on the International Regulations for the Preventing Collisions at sea, 1972 (COLREGs)*, in fact divides the two-way waterway into two isolated and independent navigable lanes. However ship traffic is always in disequilibrium, and there exist "heavy traffic direction" and "light traffic direction" (Tingting, Qin & Chaojian, 2013) in the waterway. The performance of "traffic disequilibrium" is that, ship traffic is dense in one lane (or some sections of the lane), but sparse in the other (or the others of the lane). As a result, traffic jam incurs in one lane (or some sections of the lane), but in the other lane ship traffic is disengaged. Therefore, we can make full use of the disengaged lane (or some sections of the lane) to promote the capacity of overall waterway.

In marine traffic field, the original research of two-way waterway focused on calculating the transit capacity and waterway width by empirical formulas (Fenghua & Xuefeng, 2007; Zhibang & Xin, 2011). During the process of calculation, the two-way waterway is usually treated as two independent waterways, which are hardly to embody the effect of human, machine, environmental and management factors to the waterway capacity.

For its virtues which effectively reflect the ship's response to human and environmental factors in the trajectory (waterway width), ship handing simulator is widely used in waterway research fields shortly after its birth (Inoue, 2000; Kobylinski, 2011; Seong, Jeong & Park, 2012; Yuezong & Hongbo, 2014). However, single-ship handling simulator fails to carry out large-scale, real-time and parallel simulation in hardware and software. So empirical formulas and single-ship handling simulator are helpless in the aspect of complex systems problems. Considering the integrity and systematicness of two-way waterway, Tingting et al. (2013) put

forward the concept of "Tidal Reversible Channel", but the effect of changing lane hasn't been solved and discussed in their works.

For the virtues of discretization in space, time and state, and easy implementation in algorithm on a computer, cellular automata (CA) model has been widely developed and used in traffic flow study. Feng (2013) presented a ship traffic CA model which took marine characteristics into account. In order to simulate ship traffic from the micro view and reveal the effect of lane-changing to waterway transit capacity, the paper establishes a variable two-way waterway CA model on the basis of Feng (2013). The work can be applied to the optimization, organization and management of ship traffic.

2. Cellular Automata Model on AIS-Based for Variable Two-way Waterway

The model is formed by an inbound lane and an outbound lane. Each lane is divided into n equal cells. Each cell is either occupied by a ship or empty. The velocity of ship i takes V_i, and $V_i \in \{0,1,2,…, V_{max}\}$, where V_{max} is the maximum speed of some type of ships. In the discrete lane, ship i occupies L_i cells from i to $i + L_i − 1$ (when inbound) or to $i − L_i + 1$ (when outbound), and $L_i \in \{1,2,…, L_{max}\}$, where L_{max} is length of the largest ship in waterway.

2.1. Navigational Rules

Under normal conditions, ships navigate in their lanes in compliance with "*COLREGs 1972*" and other related traffic regulations, and no ships shall normally enter a separation zone or cross a separation line. At this time, ships evolve in accordance with the *NS ship traffic CA model* in Feng (2013).

2.2. Overtaking Rules

Figure 1 is the sketch-map for overtaking. Suppose at time t, there is ship $f1$ locating in front of ship i, and

$$d1(t) - d_{safe1} < V_i(t+1) \tag{1}$$

Where $d1(t)$ denote the distance from ship i to ship $f1$, d_{safe1} denote the safety distance from ship i to ship $f1$.

For the purpose of collision avoidance, ship *i* has to slow down or stop engine. At this time, if there are enough navigable waters in front of ship *f*1 and neighbor lane is disengaged, ship *i* can change to her neighbor lane and overtake ship *f*1, then goes back to her original lane. Obviously the overtaking action would not impact the safety and traffic order of her neighbor lane, and the transit capacity of overall waterway system promotes.
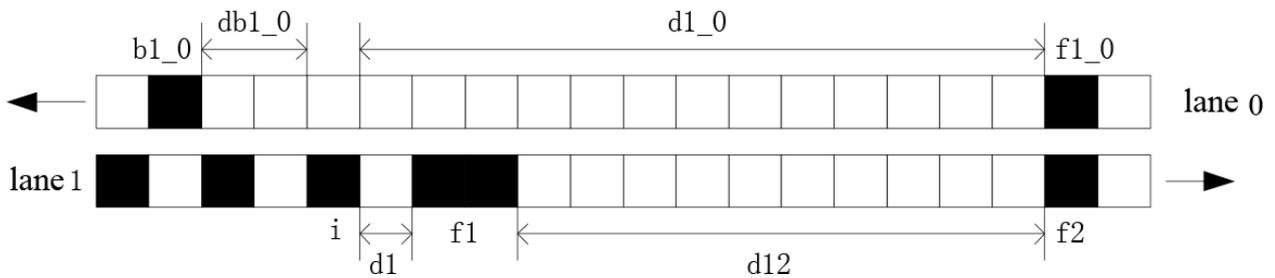

Figure 1. Sketch-map for overtaking

In the practice of mariner, overtaking vessel should adopt good seamanship. Specifically, overtaking vessel would maintain communication with the overtaken vessel through VHF, make clear her intention of overtaking, and require the overtaken vessel to decelerate or keep speed. Once the overtaken ship agrees to be overtaken, overtaking ship should apply to VTS, and inform her safety measures. With the approval from VTS, overtaking ship may implement her overtaking on the premise of ensuring safety and no impact to the traffic order of her neighbor lane. According to good seamanship, only one ship shall be overtaken each time. Safety conditions to implement overtaking are as follows:

$$d_{safe2} + d_{safe3} < d_{12} \tag{2}$$

$$d1\_0 > d_{safe4} \tag{3}$$

$$db1\_0 > d_{asfe5} \tag{4}$$

$$t_{overtake} < t_{headon} \tag{5}$$

Where d_{safe2} and d_{safe3} respectively denote the safety distances between ship *i* and her fore ship *f*2 and aft ship *f*1 when overtaking is finished; d_{safe4} and d_{safe5} respectively denote the safety distance between ship *i* and her fore ship *f*1_0 and aft ship *b*1_0 which locate in her neighbor lane; d_{12} denote the distance between the two nearest ships in front of ship *i*; $d1\_0$ and $db1\_0$ respectively denote the distances between ship *i* and her fore ship and aft ship which locate in her neighbor lane; $t_{overtake}$ denote the time to overtake ship *i*'s fore ship *f*1; t_{headon} denote the time to head on ship *i*'s fore ship *f*1_0 in her neighbor lane.

2.3. Reverse Navigational Rules for Overtaking

In mariner's practice and in order to reduce the overtaking time, overtaking ship usually accelerates and the overtaken ship decelerates. Therefore, we make the reverse navigational rules for overtaking.

Overtaking ship accelerates at each time step, and then navigates at the maximum speed when reaches the maximum. For the overtaken ship, she shall maintain her speed and navigate with caution, so there is no random slowing-down during overtaking.

$$V_i\left(t+1\right) = \min\left(V_i\left(t\right)+1, V_{\max}\right) \tag{6}$$

$$V_{f1}\left(t+1\right) = V_{f1}\left(t\right) \tag{7}$$

$$p_i = 0 \tag{8}$$

$$p_{f1} = 0 \tag{9}$$

Where p_i and p_{f1}, respectively, denote random slow probabilities of overtaking ship i and overtaken ship $f1$.

2.4. Sailing-Back Rules for Overtaking Ship

Figure 2 is the schematic diagram of overtaking vessel sailing back to her original traffic lane. When overtaking ship i passes and keeps clear the overtaken ship $f1$, she shall sail back to her original lane. At this time, the precaution and obligations of overtaking ship and overtaken ship dismiss. Safety conditions to sailing back are as follows:

$$d_{safe2} < db_1 \tag{10}$$

$$d_{safe3} < df_1 \tag{11}$$

$$\begin{cases} p_i = p \\ p_{f1} = p \end{cases} \tag{12}$$

Where $d1\_0$ and $db1\_0$ respectively denote the distances between ship i and the overtaken ship and the ship in front of the overtaken ship before sailing back.
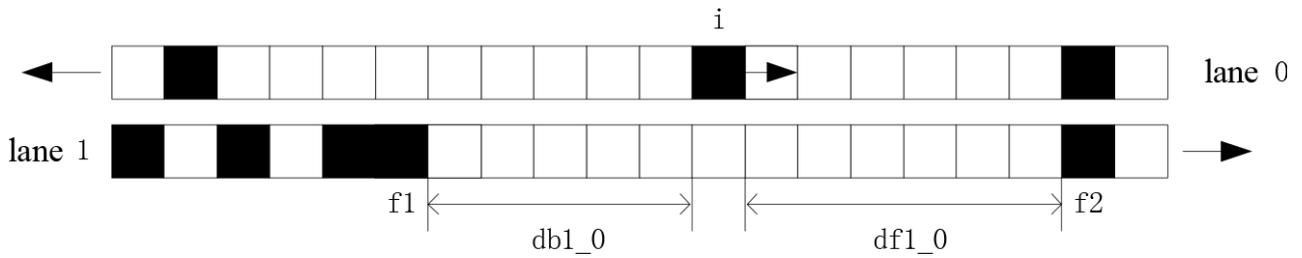
Figure 2. Sketch-map for sailing back

3. Algorithm and Simulation

3.1. Algorithm

The algorithm of above-mentioned cellular automata model on AIS-based for variable two-way waterway can describe as in Figure 3.

3.2. Simulation

Considering the actual traffic situation, suppose there are 3 types of ships sailing along the two-way waterway, where small-size ship $L_s \in [30, 89]$ (m), $V_s \in [0, 6]$ (knot), medium-sized ships $L_m \in [90, 200]$ (m), $V_m \in [0, 16]$ (knot), and large-size ships $L_1 \in [201, 300]$ (m), $V_1 \in [0, 12]$ (knot). The three types of ships mix in the two-way waterway in length of 30 n miles.
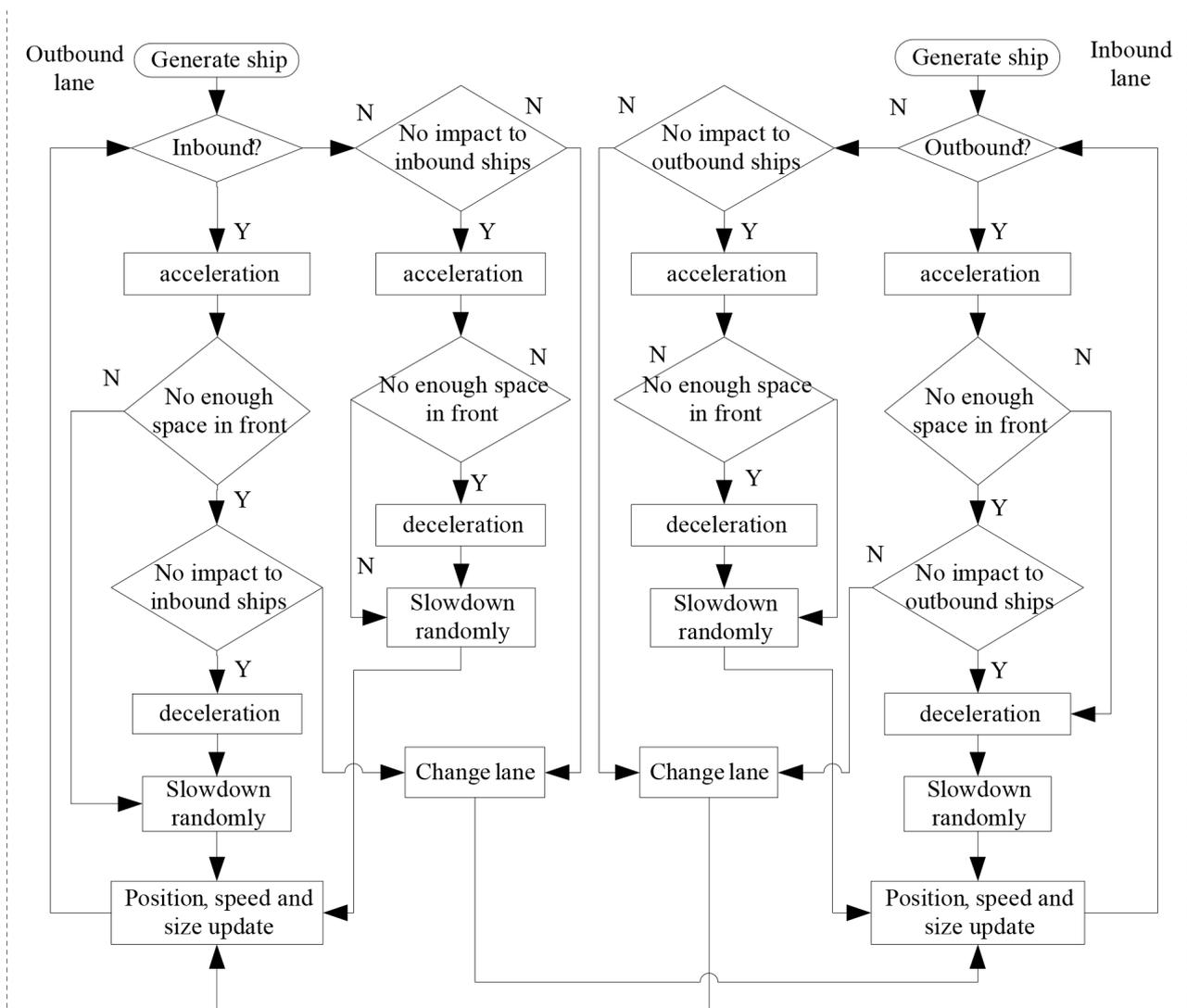
Figure 3. Cellular automata model for variable two-way waterway on AIS-based

3.2.1. Determination of Cell Size and Other Parameters

Determination of cell size is usually on the compromise consideration of calculation accuracy and computational complexity by expert judgment (Qu & Meng, 2012). This study takes each cell length of 30 m, and then waterway has 1852 cells in length; and therefore small-size ship $L_s \in \{1,2\}$ (cell) , $V_s \in \{0,1,2,…,6\}$ (cell/Δt), medium-sized ships $L_m \in \{3,4,5,6\}$ (cell), $V_m \in \{0,1,2,…,16\}$ (cell/Δt), large-size ships $L_1 \in \{7,8,9,10\}$ (cell), $V_1 \in \{0,1,2,…,12\}$ (cell/Δt).

3.2.2. Safety Distance

According to the discussion in paper (Feng, 2013), the minimum safety distances between ship i and other ships are determined by the following formulas:

$$\begin{aligned} &IF \quad k=1 \\ &\qquad d_{safe1} = \mathrm{round}\left(\max\left(3L_i, 1.8L_{f1}\right)\right) \\ &ELSE \\ &\qquad d_{safe1} = \mathrm{round}\left(3L_i + 3L_{f1}\right) \end{aligned} \tag{13}$$

$$\begin{aligned} &IF \quad k=1 \\ &\qquad d_{safe2} = \mathrm{round}\left(\max\left(3L_i, 1.8L_{f2}\right)\right) \\ &ELSE \\ &\qquad d_{safe2} = \mathrm{round}\left(3L_i + 3L_{f2}\right) \end{aligned} \tag{14}$$

$$\begin{aligned} &IF \quad k=1 \\ &\qquad d_{safe3} = \mathrm{round}\left(\max\left(3L_{f1}, 1.8L_i\right)\right) \\ &ELSE \\ &\qquad d_{safe3} = \mathrm{round}\left(\max\left(1.8L_{f1}, 1.8L_i\right)\right) \end{aligned} \tag{15}$$

$$\begin{aligned} &IF \quad k=1 \\ &\qquad d_{safe4} = \mathrm{round}\left(3L_i + 3L_{f1\_0}\right) \\ &ELSE \\ &\qquad d_{safe4} = \mathrm{round}\left(\max\left(3L_i, 1.8L_{f1\_0}\right)\right) \end{aligned} \tag{16}$$

$$\begin{aligned} &IF \quad k=1 \\ &\qquad d_{safe5} = \mathrm{round}\left(\max\left(1.8L_{b1\_0}, 1.8L_i\right)\right) \\ &ELSE \\ &\qquad d_{safe5} = \mathrm{round}\left(\max\left(3L_{b1\_0}, 1.8L_i\right)\right) \end{aligned} \tag{17}$$

Where L_{f1} and L_{f2} respectively denote the lengths of her two nearest ships in front of overtaking ship; L_{f1_0} and L_{b1_0} respectively denote the lengths of fore ship and aft ship which locate in her neighbor lane; and $K = \{0,1\}$ denote the running direction of overtaking ship relative to another ship, 0 means inbound and 1 outbound.

3.2.3. Time and Distance Parameters Between Overtaking Ship and Other Ships

$$\begin{aligned} &IF \quad k=1 \\ &\qquad d1(t) = f1 + V_{f1}(t) - i - V_i(t) - L_i \\ &ELSE \\ &\qquad d1(t) = f1 - V_{f1}(t) - L_{f1} - i - V_i(t) - L_i + 1 \end{aligned} \tag{18}$$

IF $k_{f1} = 1 \&\& k_{f2} = 1$

$$d1(t) = f2 + V_{f2}(t) - f1 - V_{f1}(t) - L_{f1}$$

ELSEIF $k_{f1} = 1 \&\& k_{f2} = 0$

$$d1(t) = f2 - V_{f2}(t) - L_{f2} - f1 - V_{f1}(t) - L_{f1} + 1$$

ELSEIF $k_{f1} = 0 \&\& k_{f2} = 1$ (19)

$$d1(t) = f2 + V_{f2}(t) - f1 + V_{f1}(t) - 1$$

ELSE

$$d1(t) = f2 - V_{f2}(t) - L_{f2} - f1 + V_{f1}(t)$$

END

IF $k = 1$

$$d1\_0(t) = f1\_0 + V_{f1\_0}(t) - f1 - V_{f1}(t) - L_{f1}$$

ELSE (20)

$$d1\_0(t) = f1\_0 + V_{f1\_0}(t) - L_{f2} - f1 - V_{f1}(t) - L_{f1} + 1$$

END

IF $k = 1$

$$db1\_0(t) = f1 + V_{f1}(t) - f1\_0 - V_{f1\_0}(t) - L_{f1\_0}$$

ELSE (21)

$$db1\_0(t) = f1 + V_{f1}(t) - f1\_0 + V_{f1\_0}(t) - 1$$

END

IF $k = 1$

$$db1(t) = i + V_i(t) - f1 - V_{f1}(t) - L_{f1}$$

ELSE (22)

$$db1(t) = i + V_i(t) - f1 + V_{f1\_0}(t) - 1$$

END

IF $k = 1$

$$df1(t) = f2 + V_{f2}(t) - i - V_i(t) - L_i$$

ELSE (23)

$$df1(t) = f2 - V_{f2}(t) - L_{f1} - i - V_i(t) - L_i + 1$$

IF $k = 1$

$$t_{overtake} = \left. \left(f1 - i + d_{safe3} \right) \middle/ \left(\left(V_i(t) + V_{max} \right) \middle/ 2 - V_{f1}(t) \right) \right.$$ (24)

ELSE

$$t_{overtake} = \infty$$

IF $k = 0$

$$t_{headon} = \left. \left(f_{1\_0} - i - L_i - L_{f1\_0} - d_{safe2} \right) \middle/ \left(\left(V_i(t) + V_{max} \right) \middle/ 2 + V_{f1\_0}(t) \right) \right.$$ (25)

ELSE

$$t_{headon} = 0$$

3.2.4. Fundamental Characteristic Parameters of Ship Traffic Flow

In order to explicit the kinetic properties of traffic flow; we define two-way channel system and its average density, speed and traffic flux (Rong-Sen, Hui-Li, Ling-jiang & Mu-ren, 2005).

$$\rho = \frac{N}{2L} = \frac{N_s + N_m + N_l}{2L} = \rho_s + \rho_m + \rho_l \tag{26}$$

$$V = \frac{1}{N}\sum_{i=1}^{N} V_i(t) = \frac{1}{2L\rho}\sum_{i=1}^{N} V_i(t) \tag{27}$$

$$Q = \rho \times V \tag{28}$$

Where N_s, N_m, N_l and ρ_s, ρ_m, ρ_l respectively denote the number and density of small-size ship, medium-size ship and large-size ships, and N is the number of all ships in system.

Ship density, speed and flux of one-way direction are determined as follows:

$$\rho_k = \frac{N_k}{2L} = \frac{N_{ks} + N_{km} + N_{kl}}{2L} = \rho_{ks} + \rho_{km} + \rho_{kl} \tag{29}$$

$$V_k = \frac{1}{N_k}\sum_{i=1}^{N_k} V_{ki}(t) = \frac{1}{2L\rho_k}\sum_{i=1}^{N_k} V_{ki}(t) \tag{30}$$

$$Q_k = \rho_k \times V_k \tag{31}$$

Here we introduce ship type mixed proportion coefficient α_s, α_m and α_l, where $0 \le \alpha_s \le 1$, $0 \le \alpha_m \le 1$ and $0 \le \alpha_l \le 1$, $\alpha_s + \alpha_m + \alpha_l = 1$. Then we can get $\rho_s = \alpha_s\rho$, $\rho_m = \alpha_m\rho$ and $\rho_l = \alpha_l\rho$, lane traffic density ratio coefficient

$$f = \frac{\rho_1}{\rho_0} \tag{32}$$

Where $0 < \rho_1 \le 1$ and $0 < \rho_0 \le 1$. So density of overall waterway system

$$\rho = \frac{(1+f)\rho_0}{2} \tag{33}$$

Where ρ_1 and ρ_0 respectively denote the original density of lane 1 and lane 0. Obviously, if $f = 1$, original density of the two lanes is equal, otherwise unequal. Because the result of $f > 1$ is accordant with that of $f < 1$, we can discuss the situation of $f \le 1$ only.

3.2.5. Ship Generation Model

According to on-the-spot observation of ship traffic flow, ship arrival rate obeys *Erlang* distribution, bow distances between ships follow negative exponential distribution, and ship lengths as well as velocity meet normal distribution.

3.2.6. Simulation Conditions

In the next section, we would carry out simulation to explore the relationship between traffic flux (speed) and ship arrival rate. In the simulation, the original status of waterway is unoccupied and random slow probability take 0.25. The input parameter is ship arrival rate, and the simulation of each parameter would repeat for 20 times in order to eliminate the random effects. During each simulation, and for the purpose of equal original simulation conditions, we proceed the situation which allow changing lane first, and at the same time record the ship arrival at entrance, then proceed the situation which prohibit changing lane with former records. *Ship arrival rate* hereon is the quantity of arrival ships in 1 minute.

4. Simulation and Discussions

4.1 Characteristic of Traffic Flux (Speed) when Inbound and Outbound Traffic is Symmetrical

4.1.1. Spatial-Temporal Spot Diagram of Two-Way Waterway

Figures 4 and 5 are respectively inbound spatial-temporal spot diagram of allowing changing and prohibiting changing when inbound and outbound ship arrival rate are both 3. Figures 6 and 7 are respectively outbound spatial-temporal spot diagram of allowing changing and prohibiting changing when inbound and outbound ship arrival rate are both 3. From Figures 4 to 7 we can find that the spatial-temporal spot diagram of allowing changing are more uniform than that of prohibiting changing. During the simulation 16 times changing occur in inbound lane and 35 times in outbound lane, and the trajectories of target lanes are both in order, so the changing actions do not impact waterway traffic order; compared with prohibiting changing, traffic flux and average speed of allow changing promote 4.4 % and 2 % respectively.

Because large number of ships in waterway system, increasing quantities of traffic flux and average speed do not seem huge. However for those overtaking ships, economic benefit from the addition of speed and the saving of navigation time and social benefit from the promotion of ship traffic flux are matter-of-course.
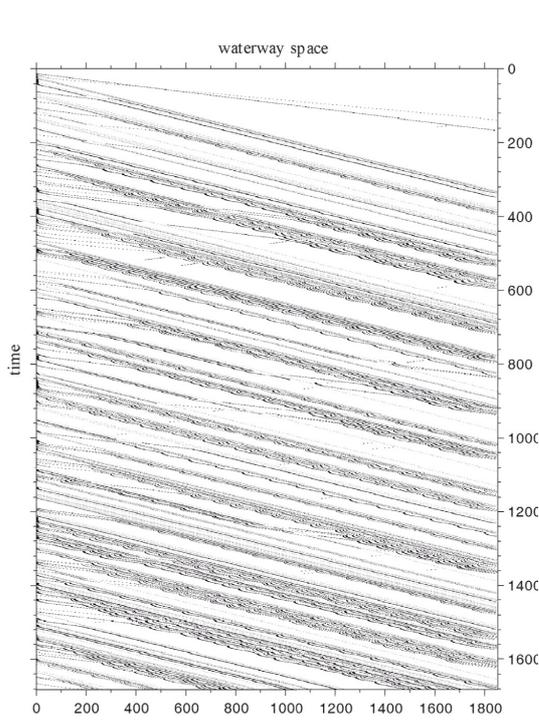
Figure 4. Inbound spatial-temporal spot diagram when allow changing
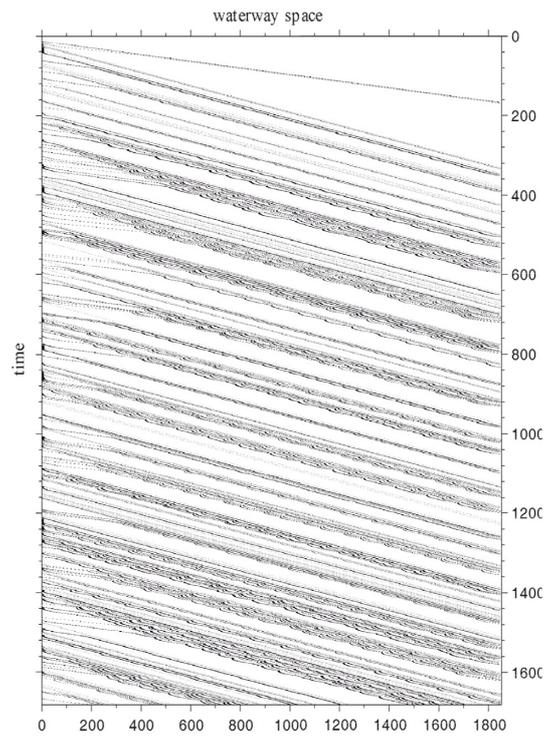

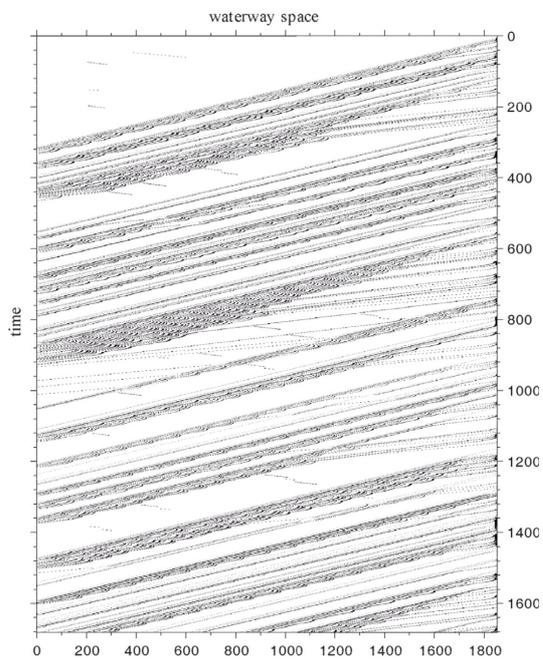Figure 5. Outbound spatial-temporal spot diagram when prohibit changing

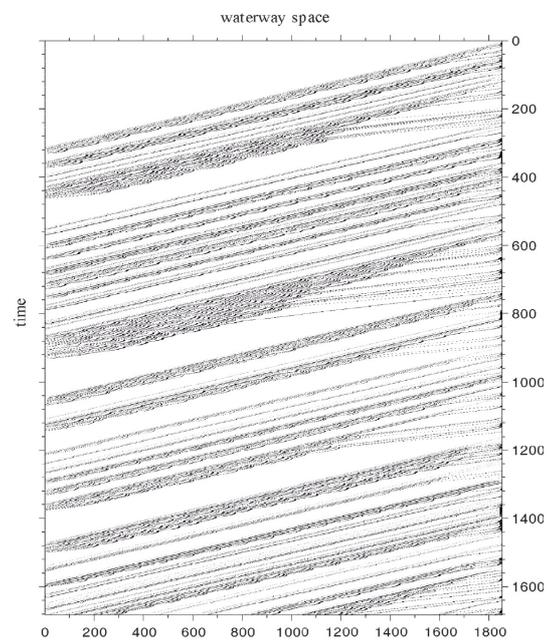Figure 6. Outbound spatial-temporal spot diagram when allow changing

Figure 7. Outbound spatial-temporal spot diagram when prohibit changing

4.1.2. Characteristic of Traffic Flux (Speed) when Inbound and Outbound Traffic is Symmetrical

Figures 8 and 9 are respectively the relationship between traffic flux and ship arrival rate when inbound ship arrival rate is symmetrical. In the diagram, changing-lane would promote the traffic flux when inbound or outbound ship arrival rate is big (ship arrival rate is 3, 4, 5 or 6); in the simulation, when ship arrival rate of both lanes are low at the same time (ship arrival rate is 5 or 6), average speed of waterway system would promote 17% at most.
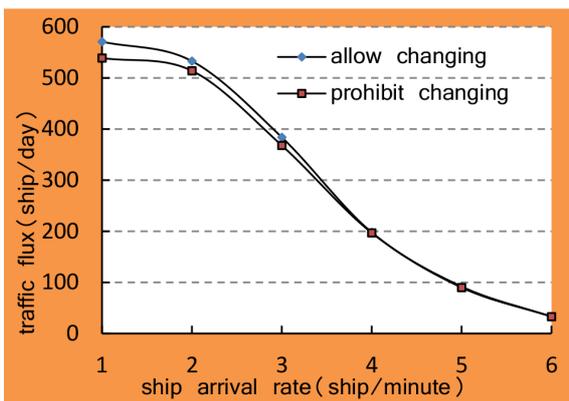
Figure 8. Traffic flux and ship arrival rate as a function when inbound and outbound ship arrival rates are symmetrical
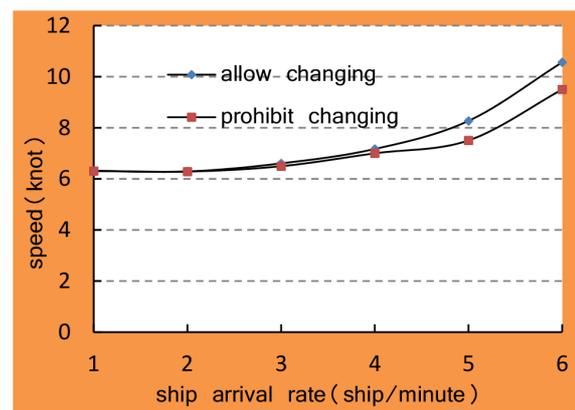
Figure 9. Average speed and ship arrival rate as a function when inbound and outbound ship arrival rates are symmetrical

4.2 Characteristic of flux (speed) when inbound traffic and outbound traffic is unsymmetrical

In the marine practice, the common traffic density in two-way waterway is dynamic and unsymmetrical. So the discussion of unsymmetrical ship density is more significant.

4.2.1. The Relationship Between Traffic Flux and Ship Arrival Rate when Inbound and Outbound Traffic is Unsymmetrical

Figures 10 and 11 are respectively the relationship between the flux of waterway system and outbound ship arrival rate at different inbound ship arrival rate when allow changing and prohibit changing. We can find that the flux of waterway system decrease as ship arrival rate increase; when ship traffic flow in waterway is in a free status (ship arrival rate is 4, 5 or 6), traffic flux decreases monotone; and when ship traffic flow is dense, a phenomenon in which ship arrival rate is low and however the traffic flux is low too, occurs in some areas of the

relational diagraphs. The phenomenon is caused by low-speed ship. When there are a large amount of low-speed ships locating in waterway, or when two or more low-speed ships sail one after the other, it's hard for fast-speed ships to overtake.
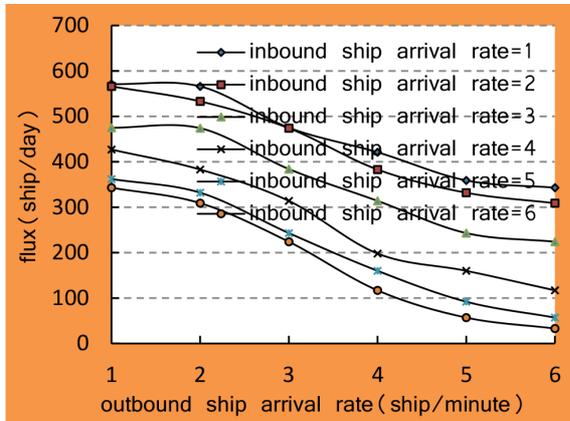

Figure 10. Traffic flux of waterway system and outbound ship arrival rate as a function at variable inbound ship arrival rate (when allow changing)
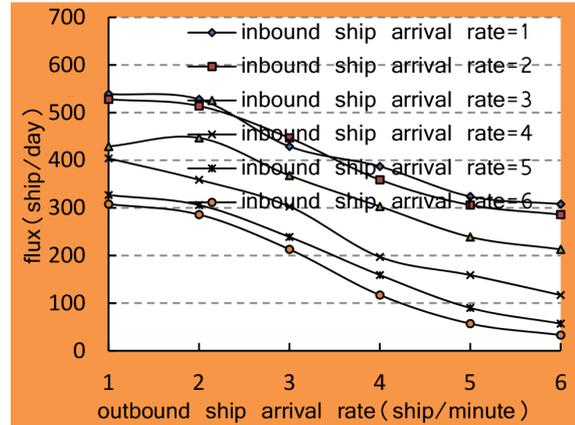
Figure 11. Traffic flux of waterway system and outbound ship arrival rate as a function at variable inbound ship arrival rate (when prohibit changing)

4.2.2. Compare of Unsymmetrical Inbound and Outbound Traffic when Allow Changing and Prohibit Changing

Figures 12 to 17 are respectively the relationship between traffic flux and outbound ship arrival rate when inbound ship arrival rate is determined. In the diagram, changing-lane would promote the traffic flux significantly when inbound or outbound ship arrival rate is both low (ship arrival rate is 1 or 2); what's more, the bigger inbound and outbound lanes differ, the more ship flux promotes. In the simulation, when ship arrival rate of one lane is 1 and the other is 6, ship traffic of waterway system would promote 11.4% at most.
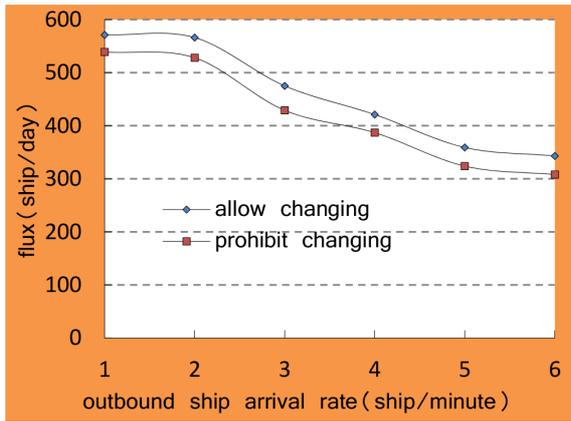
Figure 12. Traffic flux of waterway system and ship arrival rate as a function (inbound ship arrival rate = 1)
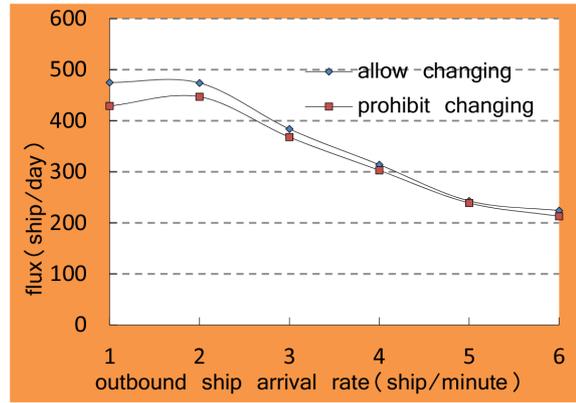
Figure 13. Traffic flux of waterway system and ship arrival rate as a function (inbound ship arrival rate = 2)
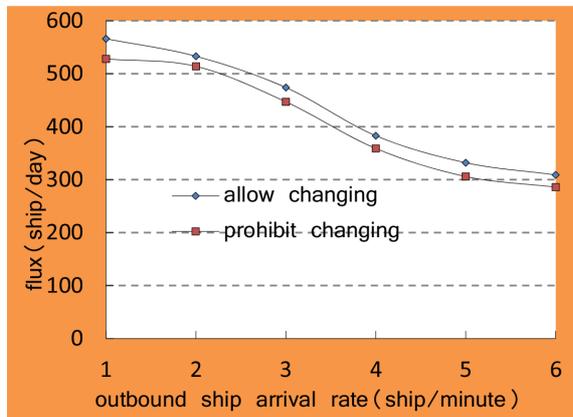
Figure 14. Traffic flux of waterway system and ship arrival rate as a function (inbound ship arrival rate = 3)
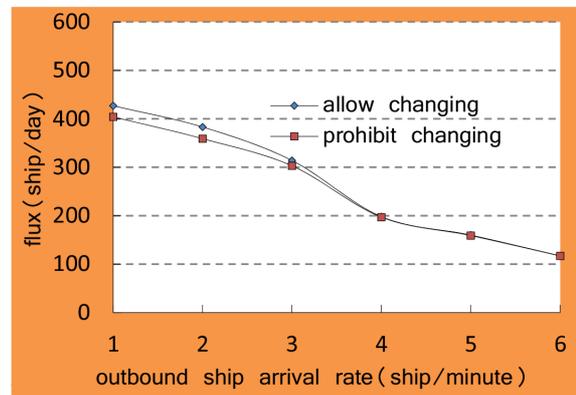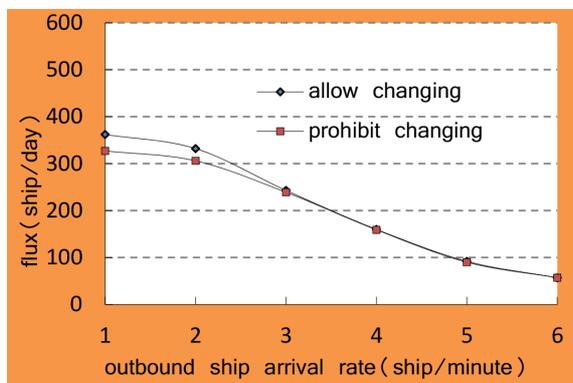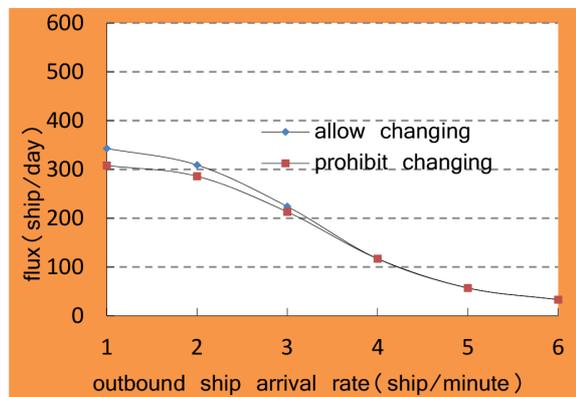
Figure 15. Traffic flux of waterway system and ship arrival rate as a function (inbound ship arrival rate = 4)

Figure 16. Traffic flux of waterway system and ship arrival rate as a function (inbound ship arrival rate = 5)

Figure 17. Traffic flux of waterway system and ship arrival rate as a function (inbound ship arrival rate = 6)

4.2.3. The Relationship Between Traffic Flux and Ship Arrival Rate when Inbound and Outbound Traffic is Unsymmetrical

Figures 18 and 19 are respectively the relationship between traffic flux and outbound ship arrival rate at different inbound ship arrival rate.

In the diagram, average speed of waterway system increase as ship arrival rate increases; when ship traffic in waterway is dense (ship arrival rate is 1, 2 or 3), average speed increases monotone; and when ship traffic is in a free status (ship arrival rate is 4, 5 or 6), the regularity of average speed and ship arrival rate is unfirm and irregular in the diagram; explanation to the phenomenon is that the interaction of ships is weak when waterway traffic is in a free status.
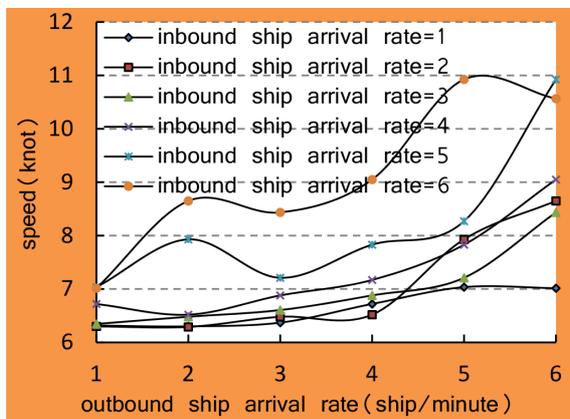
Figure 18. Average speed of waterway system and outbound ship arrival rate as a function at variable inbound ship arrival rate (when allow changing)
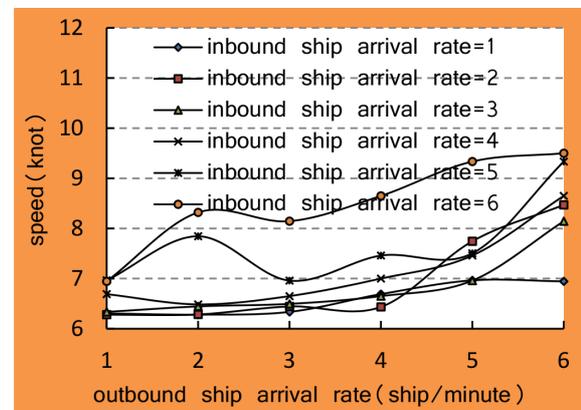
Figure 19. Average speed of waterway system and outbound ship arrival rate as a function at variable inbound ship arrival rate (when prohibit changing)

4.2.4. Compare of Unsymmetrical Inbound and Outbound Average Speed when Low Changing and Prohibit Changing

Figures 20 to 25 are respectively the relationship between average speed and outbound ship arrival rate when inbound ship arrival rate is determined. In the diagram, changing-lane would promote the average speed significantly when inbound or outbound ship arrival rate is big (ship arrival rate is 3, 4, 5 or 6); in the simulation, when ship arrival rates of both lanes are low at the same time (ship arrival rate is 5 or 6), average speed of waterway system would promote 17% at most.
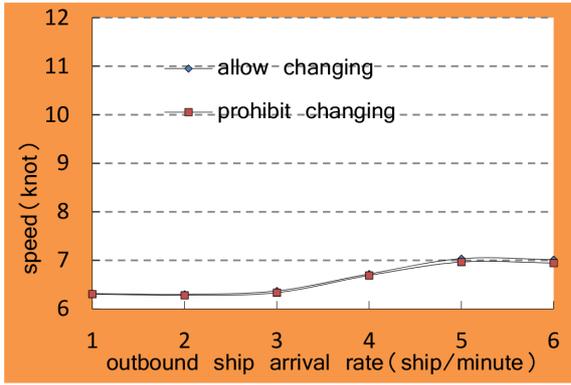
Figure 20. Average speed of waterway system and ship arrival rate as a function (inbound ship arrival rate = 1)
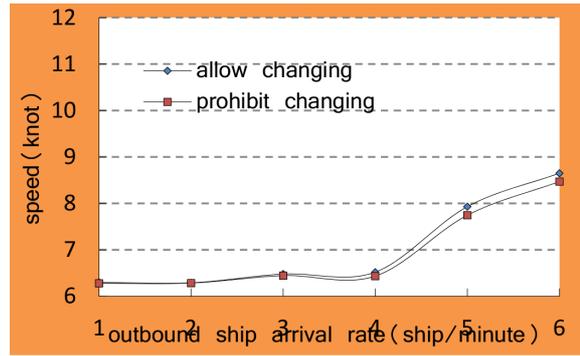

Figure 21. Average speed of waterway system and ship arrival rate as a function (inbound ship arrival rate = 2)
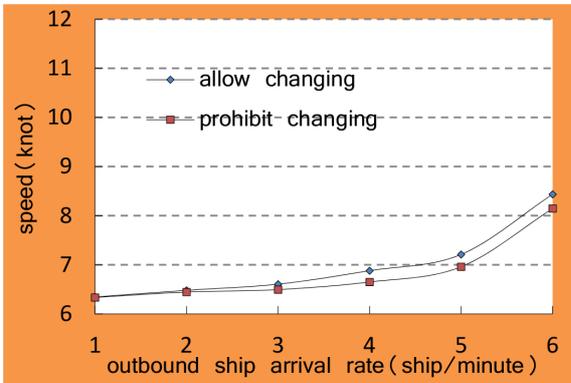

Figure 22. Average speed of waterway system and ship arrival rate as a function (inbound ship arrival rate = 3)
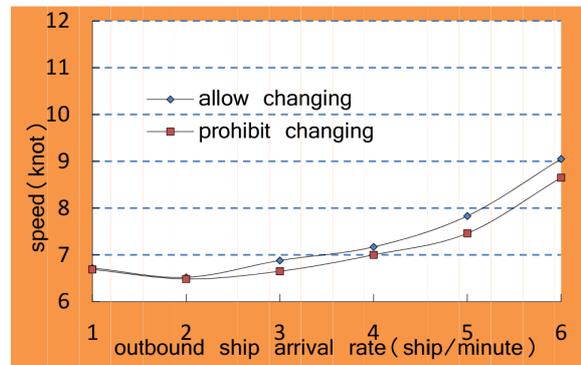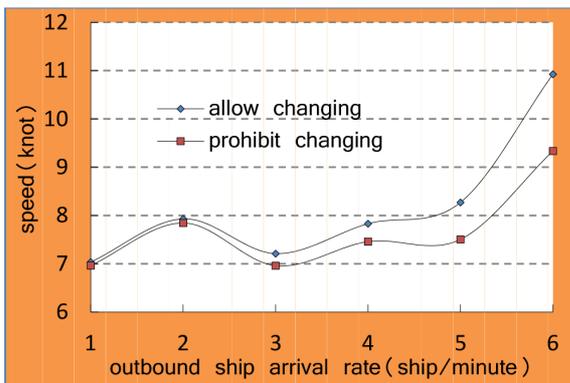

Figure 23. Average speed of waterway system and ship arrival rate as a function (inbound ship arrival rate = 4)

Figure 24. Average speed of waterway system and ship arrival rate as a function (inbound ship arrival rate = 5)
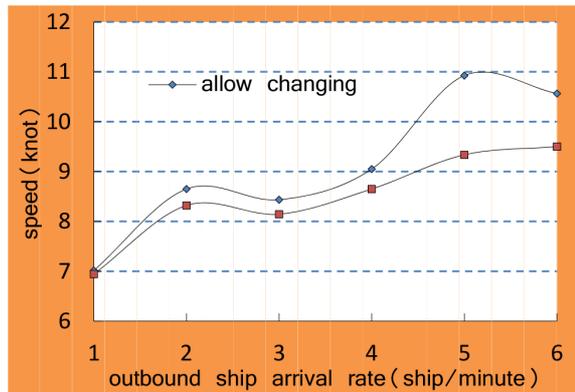

Figure 25. Average speed of waterway system and ship arrival rate as a function (inbound ship arrival rate = 6)

5. Conclusions

This paper has proposed a cellular automaton model for variable two-way waterway on AIS-based. By numerical simulation to the two situations which allow changing lane and prohibit changing lane, fundamental functions between traffic flux (speed) and density are obtained. That is, the flux of waterway system decreases and the average speed increases as ship arrival rate increases. We so find that changing lane can promote traffic flux and average speed of two-way waterway system under the premise of no impact to the traffic order. When waterway ship traffic is dense, flux of waterway system has a visible promotion, and when traffic is sparse, average speed of waterway system adds significantly.

As an implication, we can reach a compromise between traffic efficiency and safety. When no collision risk incurred, the marine administrations should allow involved ships to change lane for overtaking; and as a suggestion, Rule 9 and Rule 10 of *COLREGs* should make some adjustments correspondingly.

Acknowledgment

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