Human-like Decision-making Approach Based on Bayesian Belief Network for Ship Crossing in the Inland Waterway

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Abstract— **Ship-crossing is a common behavior within inland waterways, which will influence the navigation safety for both own crossing-ship and ships using channels. This paper proposes a human-like decision-making approach based on Bayesian belief network (BBN) for ship-crossing by considering ship behaviors and maneuverability. The input variables consider the motion information of ships and the predicted information in future moment, while the evaluation variables are used for determining the intention of crossing-ship. The proposed model is validated in the real crossing scenario in the midstream of Yangtze River. From the results of scenario of ship-crossing, the proposed approach can be used for navigation assistance of ship crossing in busy waterways.**

Keywords-ship behavior; crossing strategy; intelligent decision-making; bayesian belief network

I. INTRODUCTION

The Yangtze River has been the largest inland waterways in the world in term of cargo transportation volume since 2005. Statistics indicate that there are over 147,000 of ships navigating along the Yangtze River [1]. Ships encounter with others often must take different behaviors to guarantee safety and efficiency of navigating.

The midstream and downstream of Yangtze River are both typical waterways and have introduced the traffic separation scheme [2]. According to statistics, the crossing ship in the downstream of Yangtze river will encounter with ships around 15,000 times a day. In the midstream and downstream of the Yangtze river, as there are many ferries and docks, accidents occur frequently in the process of vessels crossing and converging. The majority of such accidents were caused by unreasonable recognition for current situation and prediction for future of situation [3].

On the Anhui section of the Yangtze river, 15 lives lost in the capsized accident of a crossing-ship called “Mahedu 104” on August 16th 2012. It was mainly contributed to the operator's insufficient recognition of the encounter situations and failure to predict the next situation. Moreover, accidents have occurred due to similar failure in many inland waterways. Moreover, it is analyzed how crossing behavior of ships effect navigable capability of lanes [4]. It is illustrated that how ship-crossing intervenes evolution of traffic density [5]. These studies have been used to improve safety of navigation in the inland waterways. However, few attentions have been drawn on the safety of process of ship-crossing. Setting sail, crossing and converging of ships are mainly faced with the characteristics of crossing the channel, water flow, traffic density, complex factors affecting manipulation, and difficulty in avoiding collision [6].

Therefore, to address these inadequacies of decision support for ship-crossing behavior, the main objective of this paper is to carry out a human-like decision-making approach to assist operators to propose reasonable strategies of ship behavior considering influencing multiple factors. The remainder of this paper is organized as follows. Section 2 analyzes the ship-crossing process and presents the Bayesian network method for decision-making. Section 3 develops the intelligent decision-making model and describes the input and output varia-

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bles in detail. Section 4 uses an illustrative example to verify the proposed model. Conclusions are drawn in Section 5.

II. PRELIMINARIES ON CROSSING STRATEGY SELECTION

A. Fundamentals of BBN

Bayesian Belief network (BBN) is one of the most common applied methods for decision-making in maritime transportation, due to its four distinguishing characteristics. First, BBN can illustrate the relationships among multiple variables intuitively [7][8]. And then, it can quantify these relationships from the perspective of probabilistic approach [9]. Third, BBN provides a learning and updating mechanism using historical data and expert judgments [10][11]. Lastly, BBN can cope with uncertain information characterized by incompleteness and vagueness [12].

A BBN is a graphical representation of a set of random variables (the nodes) together with directed interconnecting links (arcs). The arrow forming an arc sets the direction of a causal relationship between parent and child. For the BBN discussed here, each node has a set of discrete states, either numeric or as ordered descriptions. For each node, a conditional probability table (CPT) captures the relationships between the states of the parent nodes and those of each child node. It is shown as Fig. 1.

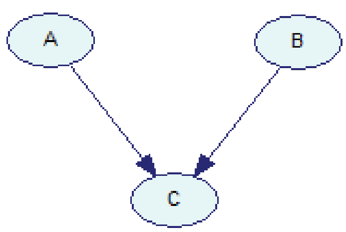


Figure 1. Illustrative example of BBN

Node A and B are the parents of C. The probability distribution of C can be obtained by the combination of prior distributions of A and B and the CPT with the following equation:

$$P(C=c_K)=\sum_{i,j=1}^{2}P(A=a_i)P(B=b_j)$$
$$P(C_K \mid A=a_i,\ B=b_j),\quad k=1,2. \tag{1}$$

These conditional probabilities are assigned by experts, based on their knowledge of the interactions between the factors described by the parent nodes and how they affect the child nodes [13]. A BBN model is typically composed of target, intermediate and observable nodes. Target nodes are nodes that represent variables for which will be computed through a probability distribution. Observable nodes represent variables that are measurable or directly observable. Intermediate nodes are mainly defined to reduce the size of the conditional probability tables, adding transparency by representing hidden variables or highlighting hidden interactions between variables. The following sections the relations among observable, intermediate and target nodes. A probabilistic model is this established to define and predict ship-crossing risk.

B. Description of ship-crossing process

One common behavior of ships is crossing, which means ships set sail from shores, then, cross the main lanes to reach opposite lanes or to converge the main traffic flow. According to Rules of the People's Republic of China for preventing collisions in inland waters, crossing ships have to conform that the crossing ship should pay attention to the situation of the channel and the surrounding environment, and confirm that neither the crossing process nor the completion of crossing behavior can affect the navigation of other ships in the main lanes and the stability of traffic flow. Specifically, the process of ship-crossing is required that: (1) Before crossing, crossing ship (CS) should keep the safe distance with preceding ship (PS) and with following ship (FS) respectively, and process of crossing will not influence the traffic flow of main lane. (2) After converging, CS should also keep the safe distance with PS and FS respectively and cannot influence ship navigating in the opposite lane. As shown in Fig. 2, this paper focus on waterways which considering two lanes separated by red dotted line. A and B represent ships navigating in opposite lanes. CS is crossing ship. PS is crossed preceding ship and FS is crossed following ship. The process of CS crossing is described from t_0 moment to t_e moment. The t_0 represents the moment before crossing. At that time, CS_0 should keep safe distance with FS_0 as well as PS_0 and should not cause FS_0 or PS_0 to increase or decrease speed passively. Besides, FS and PS adjust their speed for guaranteeing their own safety of navigation according to traffic flow condition. CS need to keep certain safe distances with FS and PS until CS finishes converging, which aims to ensure to not affect A and B navigating in opposite lane.

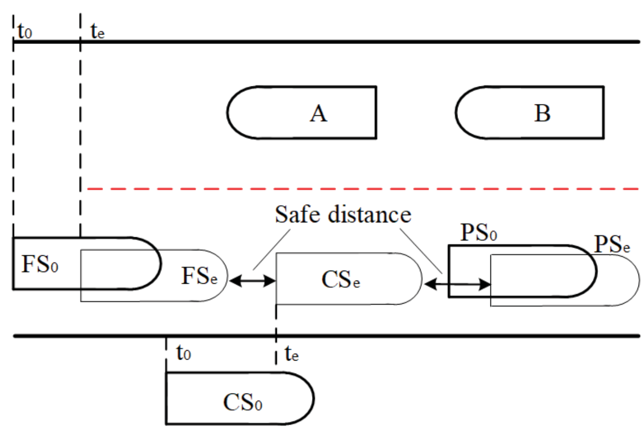


Figure 2. Ship-crossing scenario within inland waterways

III. DEVELOPMENT OF INTELLIGENT DECISION-MAKING MODEL FOR SHIP CROSSING STRATEGY

A. Determining influencing factors of ship-crossing

Similar with the human-like decision-making, this paper establishes a model according to operating experience and navigation rules, and construct the coupling relations among various information. Input variables of this model are motion information from CS, PS and FS in the crossing scenario.

Input nodes are selected according to experience of crews. The invited captain and seafarers are from Maritime Management of Yangtze River and Navigation Simulation Center of Wuhan University of Technology. States and meanings of input nodes are shown as follow in details.

(1) Traffic density in the lane

T_{raf} is denoted as traffic density, which can influence ship behavior in main lanes with its different states. And it is set as three states which are light, stable and heavy.

(2) Distance between CS and PS (or FS)

D_p and D_f represent safe distances between CS and PS and CS and FS respectively, which mean safe distance for CS to take collision avoidance actions considering ship maneuverability. They were defined as three levels of “5-7 kn”, “3-4.9 kn” and “0-3 kn”.

(3) Speed of CS (or PS, FS)

V_C, V_p and V_F are defined as speed of CS, PS and FS respectively. They are all divided into four level of “higher than 9kn”, “7-8.9 kn”, “5-6.9 kn” and “2-4.9 kn”. Speed of ships navigating in inland waterways should not be more than the required maximum speed (i.e. 9 kn).

(4) Planning time of deviation for CS

According to work experience of captains and expert judgement, when CS starting to cross two ships and converge to the main lane, CS put the bow direct to PS’s stern constantly before it arriving at the area where the distance between CS and PS is about 3 times of its length. This kind of scenario is shown as at t0 and t1 moments in Fig. 3. Until CS arrives the area at t2 moment, captain will keep the current direction instead of previous operation. It is shown as t2 moment in Fig. 3. In other words, if CS changes intention of deviation earlier than t2 moment, the risk of CS colliding with FS will increase. And if CS change later than t2 moment, the risk of CS colliding with FS would decrease, which can be deduced from Fig. 3. Therefore, time selection of changing deviation is a key issue to safety of crossing behavior of ships due to its uncertainty.

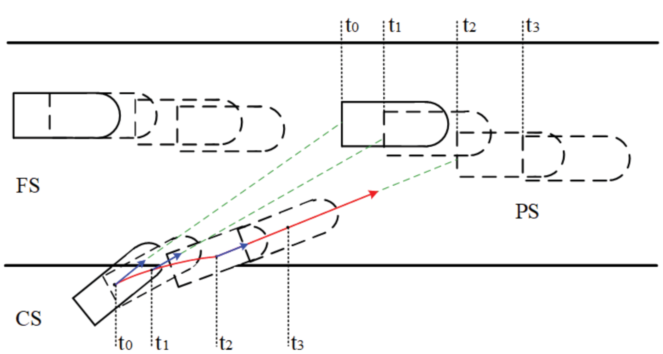


Figure 3. Microscopic process of deviation for CS

B. Designing evaluation variables for ship-crossing

States of the evaluation variables and their explanations are shown as follow. Note that if PS is far from its front ship and speed of this ship is low, PS is assumed to accelerate. However, if the distance between PS and its front ship is small and speed of this ship is high, PS is assumed to decelerate. According to traffic density and current speed of FS, predicted speed is obtained. It can be seen that if the ship intends to accelerate with a low speed, the predicted speed is still low because of the heavy traffic flow.

(1) Speed difference between CS and PS (or FS)

According to experience of captain operating, the distinguishing characteristics occur in three stages that are 0-3 kn/h, 3.1-5 kn/h and 5.1-7 kn/h. Other situations are rare.

(2) Predicted speed of PS(FS)

It is a factor for CS to select intention of deviation time. According to current speed of PS(FS) and traffic density, predicted speed of PS(FS) can be estimated as high, moderate or low.

(3) Risk level of PS(FS)

Distance and difference speed between CS and FS determine risk level of FS, which is a factor for CS to determine crossing or not.

(4) Intention of deviation for CS

It represents the current intention of deviation rather than final crossing strategy. This intention includes three states for deviation: in advance, maintain and delay.

(5) Crossing

It depends on current intention of deviation for CS and risk of FS and PS and takes crossing or not.

C. Applying nodes to obtain the graphical structure

By introducing the method described in Section 2.1, the decision-making model for ship-crossing is designed based on BBN. Its graphical structure was obtained by GeNIe software and shown in Fig. 4.

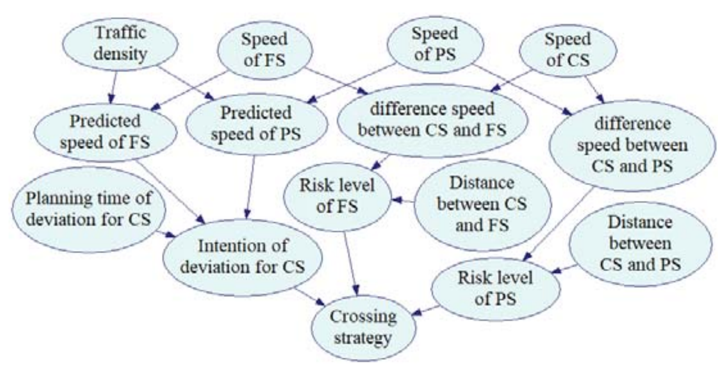


Figure 4. Decision-making model for ship-crossing

D. Establishing CPTs for nodes

Developing CPTs is an important and difficult step in the development of the decision-making model. The most widely used method for developing such rules is to use the available statistical data. To obtain the complete CPTs in the proposed decision-making model, five experts from the above-mentioned universities or companies in Section 3.2 were invited to give judgments by using the extended rules. Their average value was used for establishing CPTs. In this paper, only the CPT for the evaluation variable of the intention of deviation for CS is given as an example in Table I.

TABLE I. CPTS OF INTENTION OF DEVIATION FOR CS

Traffic density	**Heavy**				**Stable**				**Light**			
Speed of FS	≥9	7-8.9	5-6.9	2-4.9	≥9	7-8.9	5-6.9	2-4.9	≥9	7-8.9	5-6.9	2-4.9
High	0.9	0.9	0.3	0.2	0.9	0.6	0.6	0.2	0.95	0.9	0.7	0.3
Low	0.05	0.05	0.1	0.55	0.05	0.1	0.1	0.25	0.01	0.01	0.1	0.5
moderate	0.05	0.05	0.6	0.25	0.05	0.3	0.3	0.55	0.04	0.09	0.2	0.2

IV. CASE STUDY

A. Scenario description

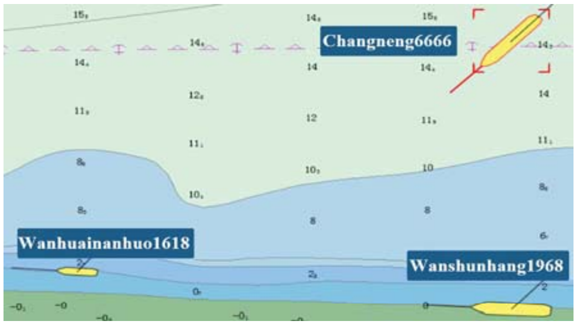
In the inland waterways, there are many ports for the ships to berth and unberth, and scenarios of ship-crossing occur frequently every day. In order to apply the proposed model for ship-crossing, the real data, which are derived from automatic identification system, are collected. Note that the real time data is used for validation in this paper. This is reasonable because this paper intends to achieve the human-like decision-making. Note that in the future, if the autonomous ships have been introduced, the criterion for the safe distance between ships may be different (e.g. shorter than human handling), and some criteria may be adjusted. However, in this paper, this factor is ignored. If the result of the proposed model is accordant with the human handing, this is believed to be reasonable, and this will be further discussed in the future.

A typical scenario is used to illustrate the proposed model. This scenario of ship-crossing occurred in Jiujiang section of Yangtze River in Jiangxi province which belongs to midstream of Yangtze River, in May 10st 2019. At that time, the preceding ship, Wanhuainanhuo 1618 and the following ship, Wanshunhang 1968 were navigating in the main lane. The Changneng6666 crossed these two ships and converged the main traffic flow finally. In the Fig.5, small digits represent waterway depths, and they are regarded as contrasts to demonstrate trajectory changing of Changneng6666 crossing. Different colors corresponding to small digits present different waterway depths more visually. Pink triangles are anchorages, and brown stakes represent banks in waterways. Fig. 5(a-d) shows the process of Changneng6666 crossing. CS in this case was Changneng6666, PS was Wanhuainanhuo 1618 and FS was Wanshunhang 1968. These sub-figures show scenarios of processes of CS starting to cross, crossing, deviating for crossing and finishing crossing, respectively. In Fig.5(a), CS started to cross near anchorages, and PS and FS navigated in the main lane. In Fig.5(b), CS passed by border of waterway depth about 10 and 7, which is shown as small digits and different color in Fig.5(b). In Fig.5(c), CS deviated during its crossing and passed by border of waterway depth about 9 and 7. In Fig.5(d), CS finished crossing at the junction of waterway depth about 9 and 6 and navigated to somewhere between PS and FS which were navigating in the main lane. Fig.5(e) shows trajectory of Changneng6666 crossing from 13:26:22 to 13:38:07, which records four typical positions of Changneng6666 crossing in Fig.5(a-d). The green point represents the initial position of Changneng6666 crossing which is shown as Fig.5(a). Points labelled by 13:30:35 and 13:34:07 in Fig.5(e) are Changneng6666 crossing and deviating which are shown as Fig.5(b-c) respectively. The red point represents the final position of Changneng6666 finishing crossing which is shown as Fig.5(d).

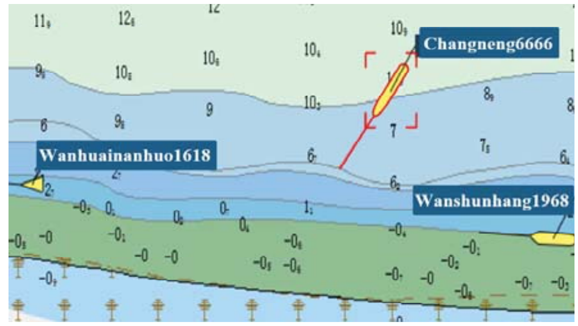
B. BBN for ship-crossing

Note that, Changneng6666 was unberthing from anchorage and intended to cross and converge the main traffic flow between Wanhuainanhuo 1618 and Wanshunhang 1968. The ship length of Changneng6666 is 96 meters, and the ship speed was 3kn when starting to cross, which are presented in Fig. 5(a). Trajectory of Changneng6666 is shown in Fig. 5(e), the green point represents the started point of crossing in Fig. 5(e) that was at 13:26:22, May 10th 2019. It can be seen that the stem of Changneng6666 approximately direct to the stern of Wanhuainanhuo 1618. Moreover, Wanhuainanhuo 1618 was PS in this scenario, the ship length is 45 meters and its speed were about 4 kn. When CS started to cross, the distance between PS and CS was nearly 564 meters, which was around 4 times of Lsum1 (i.e. 96+45=141). In addition, length of FS called Wanshunhang 1968 is 89 meters, and its speed was approximately 5 kn. The distance between FS and CS was around 462 meters, which was about 2.5 times of Lsum2 (i.e. 96+89=185). Moreover, it can be seen that the traffic density was light in Fig. 5.

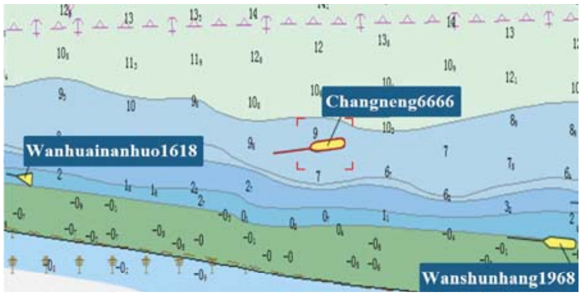
The distance between CS and PS increased stably from about 630m in Fig. 5(a) to 750m in Fig. 5(d). Moreover, the distance between CS and FS decreased from Fig. 5(a) to Fig. 5(d). However, Fig. 5(a) showed that CS had deviated in the area where the distance between CS and PS is more than 5 times of CS's length. Hence, the state of Tplan node was set as "before the experienced moment". The detailed information of scenario of ship-crossing is presented in Table II



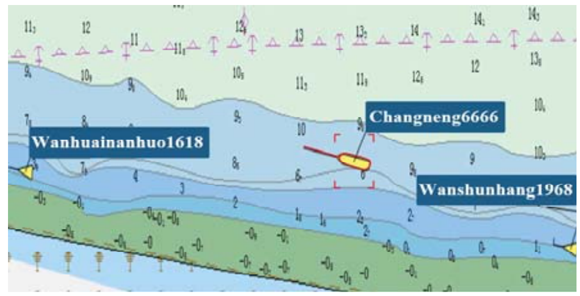
(a) Scenario of Changneng6666 preparing to cross



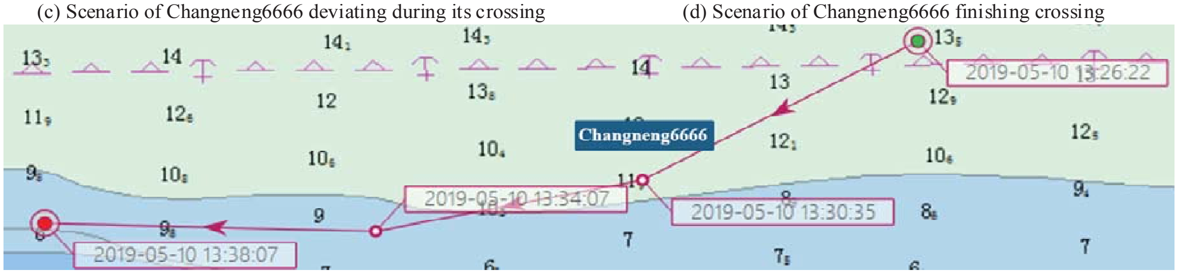
(b) Scenario of Changneng6666 crossing



(c) Scenario of Changneng6666 deviating during its crossing



(d) Scenario of Changneng6666 finishing crossing



(e) Trajectory of Changneng6666 crossing

Figure 5. Process of ship-crossing

TABLE II. PRIOR INFORMATION OF BBN BASED MODEL

Notations	Collected data	State of Nodes
T_{raf}	There was one ship navigating in the crossing scenario except CS, PS and FS.	Light
D_P	564m, which was about 4 times of L_{sum1}	Nearly 4 to 6 times of L_{sum1}
D_F	462m, which was about 2.5 times of L_{sum2}	Nearly 2 to 3.9 times of L_{sum1}
V_C	about 3 kn	Nearly 2 to 4.9 kn
V_F	about 5 kn	Nearly 5 to 6.9 kn
V_P	about 4 kn	Nearly 2 to 4.9 kn
T_{plan}	Deviating at the place where was about 3 times of length of CS from CS	Deviation before the experienced moment

C. Results and Analysis

The prior information is introduced for this model, and the probability of evaluation variables are inferred as follows. Figure 6 shows the results for the BBN example. According to model, the general likelihood of CS crossing in this scenario in Yangtze River is 71%. Besides, predicted speed of PS and FS were inferred and used to obtain the intention of deviation for CS. Finally, state of ship-crossing was determined by the intention and risk levels. Probabilities of evaluation variables are displayed in Table III, and results of model are presented in Fig. 6.

Note that the intention for CS was considered only from the perspective of deviation. However, it is necessary to concern the intention of changing speed for CS. Facing to different risk levels, CS can also cross successfully by changing speed rather than deviation, when the distance between CS and other ships is large enough. Hence, it is significant to concern in the further research.

V. CONCLUSION

An intelligent decision-making approach is proposed for determining ship-crossing in the inland waterways. This model is based on BBN. It is effective to support decision-making in time. Moreover, this proposed model is developed from the perspective of human-like decision-making. Hence, predicted speed and intention of deviation nodes were assigned as Leaf nodes. The relation among them were established based on work experience and navigation regulation, and then, reasonable crossing strategy of crossing behavior was obtained.

TABLE III. STATE VALUES OF THE EVALUATION VARIABLES

Nodes	**State1**		**State2**		**State3**	
Predicted speed of FS	High	0.7	Moderate	0.2	Low	0.1
Predicted speed of PS	High	0.3	Moderate	0.2	Low	0.5
Difference speed between CS and FS	5-7 kn	0.1	3-4.9 kn	0.6	0-2.9 kn	0.3
Difference speed between CS and PS	5-7 kn	0.01	3-4.9 kn	0.2	0-2.9 kn	0.79
Intention of deviation for CS	In advance	0.24	Maintain	0.54	delay	0.23
Risk level of FS	dangerous	0.14	general	0.17	safe	0.69
Risk level of PS	dangerous	0.16	general	0.23	safe	0.61
Navigation strategy	Cross	0.71	Not cross	0.29	-	-

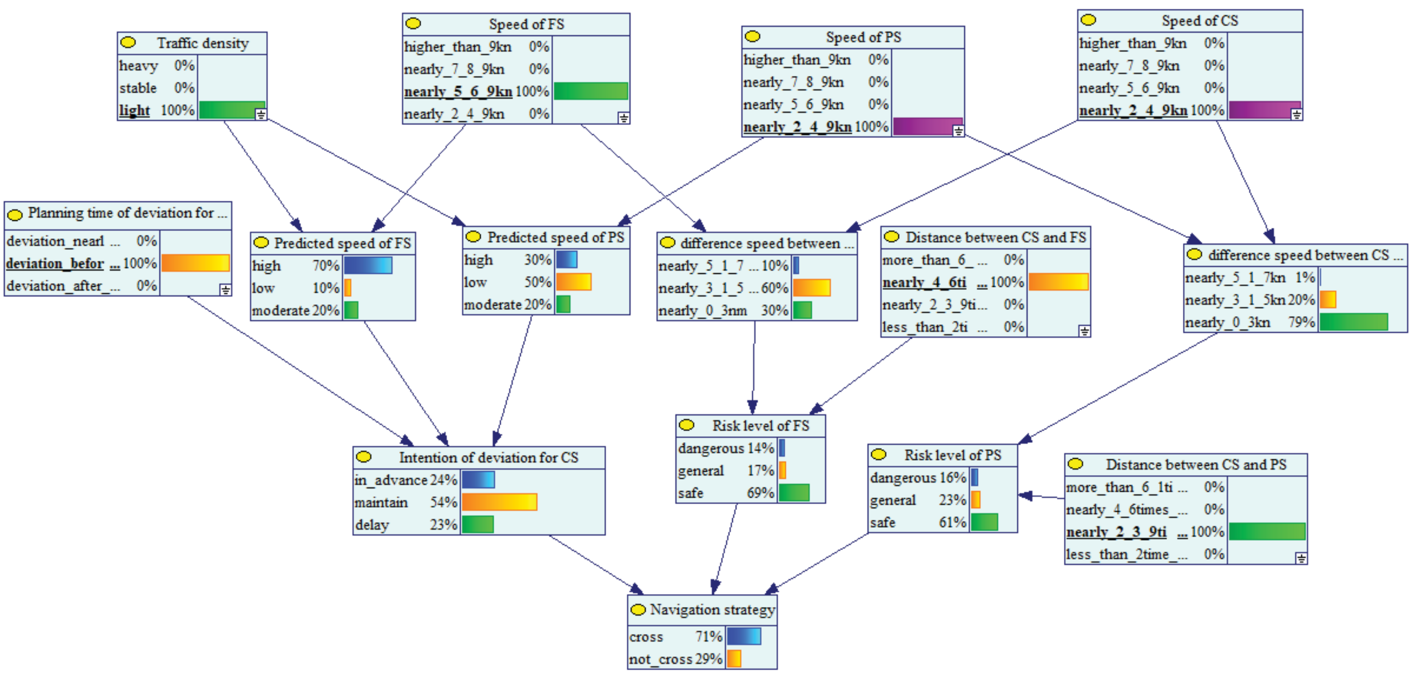


Figure 6. The results from the BBN model

In practice, the dynamic process of ship crossing and converging is common in the coasts and channels. Hence, this model is also applied on similar waterways as it has considered dynamic characteristics (e.g. ship speed, ship localization and traffic flow) of ships. However, some issues need more attention and to be addressed in the future when applied to autonomous ships and assist human to make decision.

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