# Inland Waterway Traffic Simulator

**Shimpei Watanabe**, Osaka University, Osaka/Japan, Shinpei_Watanabe@naoe.eng.osaka-u.ac.jp
**Kazuhiko Hasegawa**, Osaka University, Osaka/Japan, hase@naoe.eng.osaka-u.ac.jp
**Philippe Rigo**, University of Liege, Liege/Belgium

**Abstract**

*A tracking simulation model based on ship motion theory is applied to evaluate safety of waterways. Results show that the simulator is useful for assessing safety and efficiency.*

## 1. Introduction

At European inland waterways, technologies such as ECDIS, AIS, etc. are developed for safety, intermodality and speed-up of traffic flow. Fleet management and lock management can be optimized utilizing these technologies. As a result, traffic density of inland waterways will increase and safety evaluation for these congested waterways has become important. Tracking simulation based on ship motion theory is effective to evaluate safety of waterways. We developed and applied such a simulation model, possibly for the first time ever. We can evaluate not only safety and security of the area, but also the efficiency of the transport using the tracking simulation. Such simulations can be useful for strategic planning of waterway infrastructure (like dimensions of waterways, etc) and operational planning during phases of high traffic density.

The base of the simulation was the software "Marine traffic simulator" developed at Osaka University. "Marine Traffic Simulator" simulates marine traffic flow realistically based on the "Ship Auto Navigation Fuzzy Expert System" (SAFES). On this system, each ship has its own characteristics (principal particulars, speed, maneuvering parameters, OD (origin and destination) and waypoints). The physics of its maneuvering follow ship motion theory. In congested areas, the ship avoids collisions with other ships or obstacles by a computerized pilot/captain based on fuzzy-set theory.

The software was extended to create the "Inland Waterway Traffic Simulator", using the calculation part and normal sailing part of "Marine Traffic Simulator". But for inland navigation, vessels are subject to shore effects and must obey navigations rule for inland waterways. For example, vessels should not change direction to avoid collision, but wait for vessels entering an intersection earlier. This part of the simulator was then developed newly.

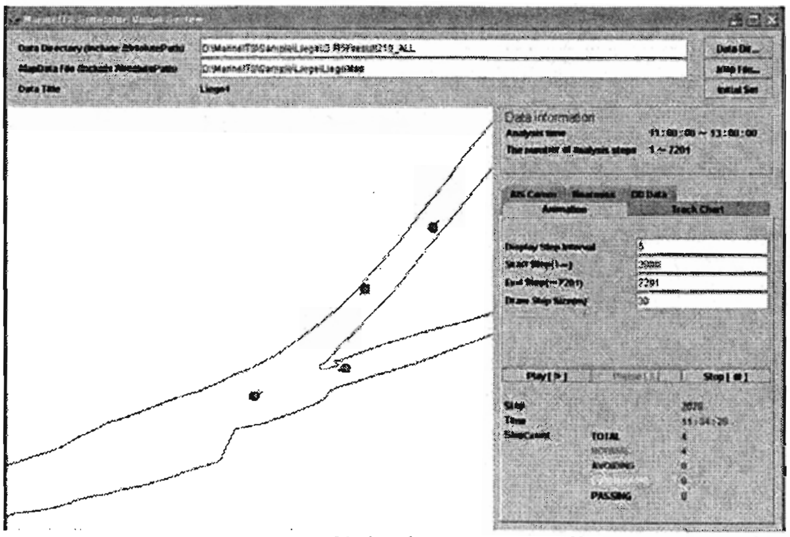

Fig.1: Sample output of inland waterway traffic simulator

The "Inland Waterway Traffic Simulator" was applied on an inland waterway intersection. This case features aspects not found in open-water maritime traffic, such as sharp corners, narrow waterway (canal) and cross section. Thus, the simulator should evaluate a larger area of inland waterway for a correct simulation.

## 2. Automatic Navigation System for maritime

### 2.1 Ship Auto-navigation Fuzzy Expert System (SAFES)

The Ship Auto-navigation Fuzzy Expert System (SAFES) is the base system of the Intelligent Marine Traffic Simulator, re-used for the "Inland Waterway Traffic Simulator". It can be applied for any configuration of waterways and any number of ships. As the system includes a captain's model, it will instruct each ship to follow her mission including collision/ grounding avoidance manoeuvres. In this system, multi-agent problem and conflict decision-making are solved by an expert system and instruction was done by fuzzy reasoning/control. To realize the traffic simulation, the following procedure is used:

(1) Set destination and departure gates/ports of each ship according to the statistics
(2) Determine the creation or deletion of each ship according to the arrival time or completion of the task
(3) Set route including waypoints for each ship
(4) Set parameters of each ship
(5) Determine the steering instruction according to the each ship task as well as target ship's positions and behaviors
(6) Calculate ship velocity and position according to the instruction

### 2.2 Decision-making of navigation

The simulated captain makes navigation status "Normal" or "Avoiding" according to the traffic situation. Two parameters are needed: DCPA (Distance to Closest Point Approach) and TCPA (Time to Closest Point Approach). DCPA is the shortest distance between own ship and target ship assuming their speed and direction are kept. TCPA is the time to reach DCPA. To consider differences in ship size, DCPA is made to dimensionless by ship length (DCPA'). DCPA, DCPA' and TCPA are obtained as shown in Fig.2. Using TCPA and DCPA, the judgment parameter for avoiding called collision risk (CR) is determined using fuzzy-set theory.

The simulated captain makes decision on avoidance by CR, ACR, VCR and closing type between own ship and target ship. ACR is the CR when assuming that the own ship changes course to avoid collision. VCR is the CR when assuming that the own ship changes course parallel to its former route. The closing type is defined by $\theta$ and $\phi$, Fig.2. For CR > 0.7 and ACR < CR, the captain decides how to avoid collision referring to the closing type. For CR < ACR, he reduces the ship speed. When the ship avoids collision against other ships or obstacles, the captain refers to VCR for the timing to go back to the initial setting route, Fig.3. When the closing type is 'taking-over', another way to avoid the target ship is needed as described in a later section.

$$DCPA = \frac{D|V_0 \sin\alpha + V_t \sin\beta|}{\sqrt{V_0^2 + V_t^2 + 2V_0V_t\cos(\alpha-\beta)}} \quad [m] \qquad (1)$$

$$TCPA = \frac{D(V_0 \cos\alpha + V_t \cos\beta)}{V_0^2 + V_t^2 + 2V_0V_t\cos(\alpha-\beta)} \quad [\text{sec}] \qquad (2)$$

$$DCPA' = \frac{DCPA}{L} \qquad (3)$$

$V_o$ is the own ship's speed, $V_t$ the target ship's speed, $\alpha$ the direction from own ship to target ship, $\beta$ the direction from target ship to own ship, and D the distance between own ship and target ship.

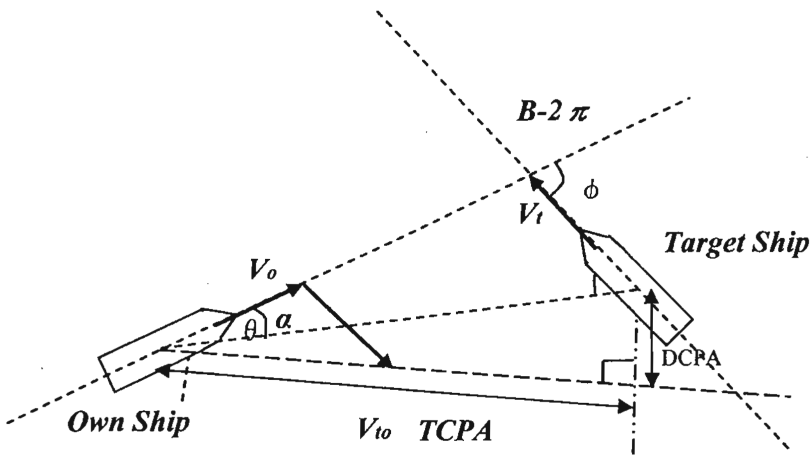


Fig.2: TCPA and DCPA

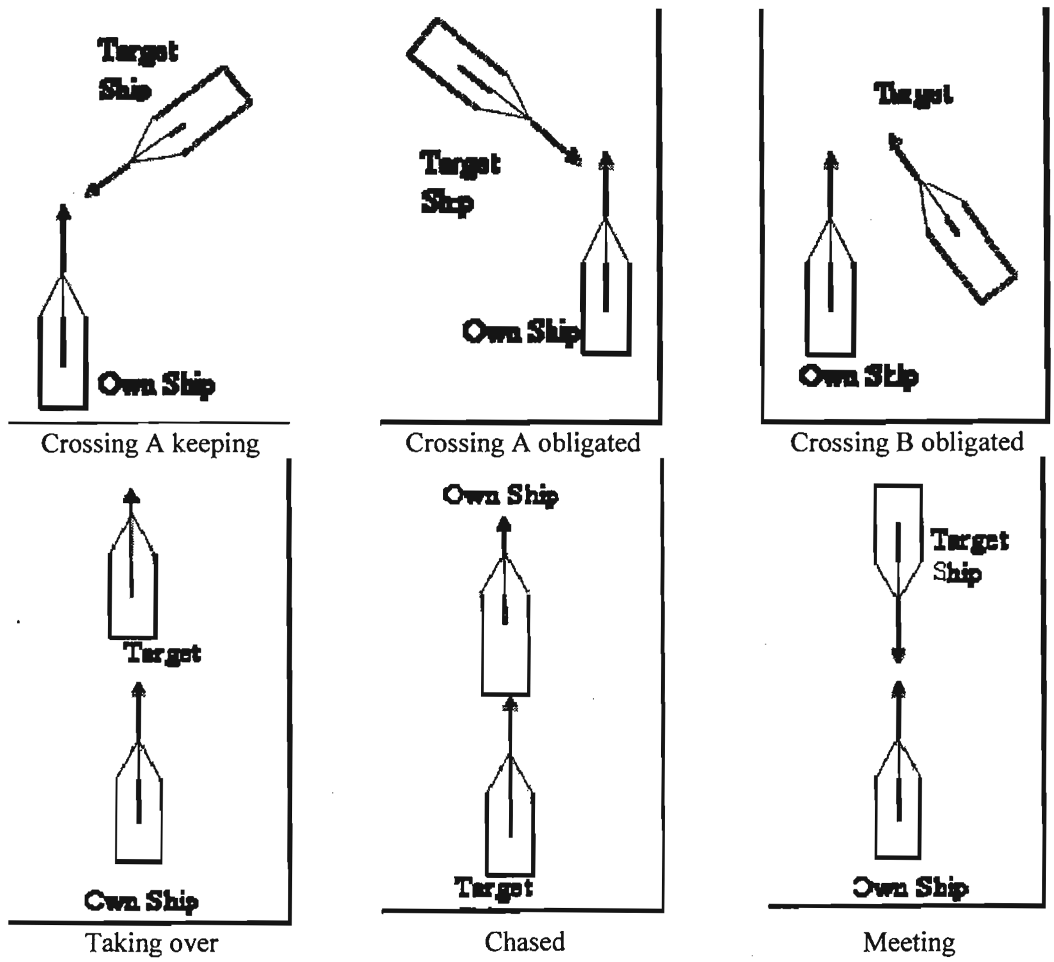


Fig.3: Crossing Types

In maritime traffic, the ship coming from the right-hand side has right of way. Therefore the closing type 'crossing' is subdivided into 'obligated' and 'keeping'. For CR > 0.7 and closing type 'Crossing keeping', the own ship should keep course. For CR > 0.85, the ship changes course to avoid collision.

### 3. Automatic Navigation System for Inland Waterway

#### 3.1. Differences between open-water (maritime) and inland navigation

The Marine Traffic Simulator was initially constructed for bay traffic simulation. For inland navigation, domain restrictions due to the shore are more severe. In open-water navigation, the ship coming from the right-hand side has right way, in inland navigation the ship arriving first at a cross point. This requires modifications to the navigation system.

#### 3.2. Calculation of Collision Risk

In the simulation loop, we assume one vessel to be Own Ship and calculate "collision risk" for all other vessels. "Own Ship" chooses the best navigation state by "collision risk (CR)" and the other parameters. On 'maritime', it is enough to calculate CR, ACR, VCR and Closing Type for decision-making. For inland navigation, we need to consider grounding and collision. To model the shore, we put virtual ships on the shore as shown in Fig.4 calculate "collision risk" as for other vessels.

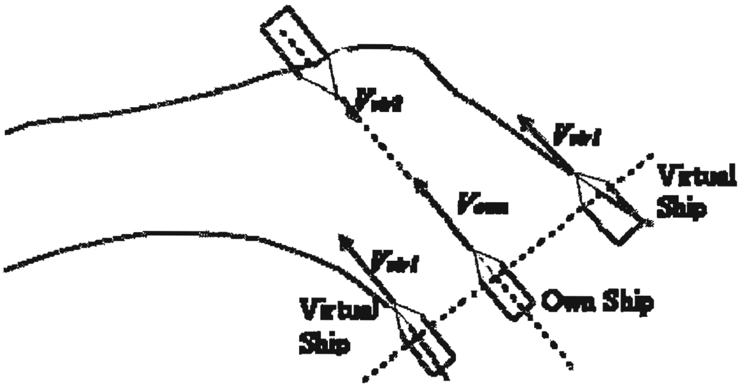


Fig.4: Virtual ship modeling the shore; $V_{own}$ is the speed of the own ship, $V_{vir1} = V_{own}$ the speed of the virtual ships put on the shore normal to the direction of advance of Own Ship, $V_{vir2} = -0.01\ V_{own}$ the speed of the virtual ship put on opposite course to Own Ship.

Then we calculate VCR (direction 2 on Fig.5) and "Original direction CR (OCR)", the CR for own ship going back to initial setting route (direction 3 on Fig.6) and ACR (direction 2 on Fig.7). TCPA and DCPA for ACR, VCR and OCR are defined as:

$$DCPA_{ACR} = \frac{D\left|V_0 \sin(\alpha+\varphi) + V_t \sin\beta\right|}{\sqrt{V_0^{\,2} + V_t^2 + 2V_0V_t\cos(\alpha+\varphi-\beta)}} \quad [m] \qquad (4)$$

$$TCPA_{ACR} = \frac{D(V_0\cos(\alpha+\varphi) + V_t\cos\beta)}{V_0^2 + V_t^2 + 2V_0V_t\cos(\alpha+\varphi-\beta)} \quad [\text{sec}] \qquad (5)$$

$$DCPA_{VCR} = \frac{D\left|V_0 \sin\alpha_{old} + V_t \sin\beta\right|}{\sqrt{V_0^{\,2} + V_t^2 + 2V_0V_t\cos(\alpha_{old}-\beta)}} \quad [m] \qquad (6)$$

$$TCPA_{VCR} = \frac{D(V_0\cos\alpha_{old} + V_t\cos\beta)}{V_0^2 + V_t^2 + 2V_0V_t\cos(\alpha_{old}-\beta)} \quad [\text{sec}] \qquad (7)$$

$$DCPA_{OCR} = \frac{D\left|V_0 \sin(\alpha+\varepsilon) + V_t \sin\beta\right|}{\sqrt{V_0^{\,2} + V_t^2 + 2V_0V_t\cos(\alpha+\varepsilon-\beta)}} \quad [m] \qquad (8)$$

$$TCPA_{OCR} = \frac{D(V_0\cos(\alpha+\varepsilon) + V_t\cos\beta)}{V_0^2 + V_t^2 + 2V_0V_t\cos(\alpha+\varepsilon-\beta)} \quad [\text{sec}] \qquad (9)$$

$$\alpha_{old} = \alpha + \phi_0 - \phi_{old} \qquad (10)$$

$$(\varepsilon = \Psi_I - \phi_0) \qquad (11)$$

$\phi_O$ is the direct angle of Own Ship, $\phi_{old}$ the direct angle of Own Ship before avoiding, and φ the avoiding angle, Fig.5. The ship decides its course by these 4 CR on the new simulator. When a ship faces a danger situation, the ship calculates CR and ACR. For ACR > CR, the ship keeps course and slows down if necessary. For ACR < CR, the ships starts avoiding action. When avoiding another ship, CR, ACR and VCR are calculated. For VCR smaller than a threshold value, the ship gets its course parallel against former route. Else for CR < ACR, the ship's course is kept. For CR > ACR, the ship increases the avoiding angle. As next step, when the ship goes on the parallel course, CR, ACR and OCR are calculated. If OCR is smaller than a threshold value, the ship sails normally.

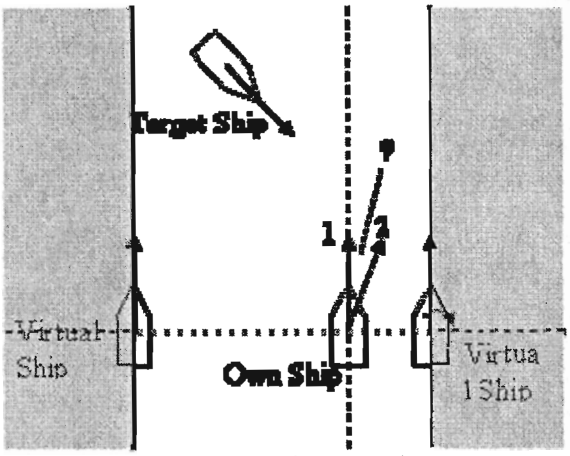


Fig.5: Time history of avoiding motion 1

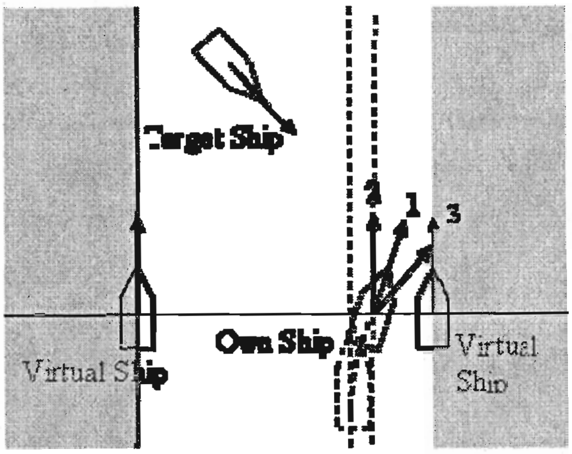


Fig.6: Time history of avoiding motion 2

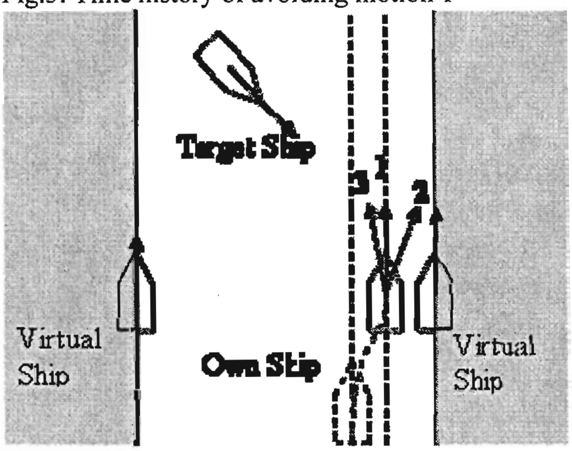


Fig.7: Time history of avoiding motion 3

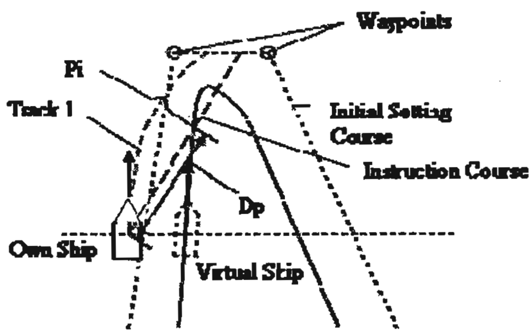


Fig.8: Starting point of rudder action at sharp corner

### 3.3. Instruction Course and Avoiding Action at Sharp Corners

It is difficult to navigate ships sailing around sharp corners by the above criteria. This is because the calculation of OCR does not consider that the ship's action has a certain delay against rudder action. On Fig.8, the own ship should sail according to the instruction course and will trace Track 1, but the OCR is larger than the value for normal sailing. Thus, another criterion is needed for this situation. First, the distance Dp between own ship and point $P_i$ (the intersection between instruction course and shore line) is calculated. We define a virtual TCPA against point $P_i$ as:

$$TCPA_{Pi} = \frac{Dp}{Vo} \qquad (12)$$

If $TCPA_{Pi}$ is larger than a threshold value, ships at sharp corners sail normally according to the instruction course.

## 4. Tracking Simulation by Inland Waterway Traffic Simulator

To verify Traffic Simulator modified for inland waterway, simulation at Intersection (Fig.4.1) has been done. This area is located nearby Albert Canal. On this simulation, a cross point of routes, a sharp corner and narrow canal is found. Thus, it would be appropriate to simulate on larger area if ships were navigated realistically on this minimum simulation.

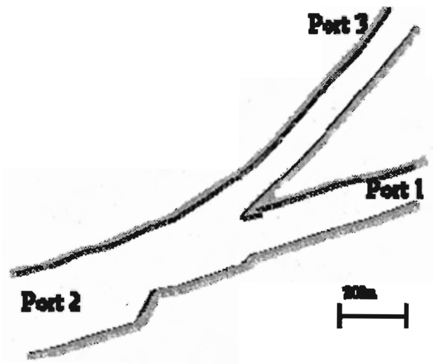


Fig.9: Intersection of inland waterway

### 4.1. Tracking Simulation at Intersection

For this simulation, we defined 8 types of vessels. Principal particulars, manoeuvring parameters and OD data are shown at following Table I and II. Instruction Velocity of ship is set 10 km/h (3.0 m/s).

Table I: Principal particulars

| | | Tonnage(t) | Length(m) | Breadth(m) | Depth(m) |
|---|---|---|---|---|---|
| Self Propeller Ship | Ship A | 150 | 20 | 4.5 | 1.6 |
| | Ship B | 350 | 26 | 5.05 | 2.3 |
| | Ship C | 550 | 38.5 | 6.6 | 2.5 |
| | Ship D | 950 | 67 | 8.2 | 2.5 |
| | Ship E | 1350 | 80 | 9.5 | 2.6 |
| Barge Ship | Ship F | 1600 | 50 | 11.4 | 2.5 |
| | Ship G | 3200 | 90 | 11.4 | 2.5 |
| | Ship H | 3200 | 50 | 22.8 | 2.6 |

Table II: Maneuvering parameters

| | | K' | T' | T_V' | T_E | K_P | T_D |
|---|---|---|---|---|---|---|---|
| Self Propeller Ship | Ship A | 2.3 | 2.06 | 5 | 1.8 | 1.5 | 0.9 |
| | Ship B | 2.25 | 2.06 | 6 | 1.8 | 1.5 | 0.9 |
| | Ship C | 2.07 | 2.06 | 7 | 1.8 | 1.5 | 0.9 |
| | Ship D | 2.07 | 2.06 | 8 | 1.8 | 1.5 | 0.9 |
| | Ship E | 2.07 | 2.06 | 10 | 1.8 | 1.5 | 0.9 |
| Barge Ship | Ship F | 2.07 | 1.57 | 10 | 2 | 1.5 | 0.9 |
| | Ship G | 2.07 | 1.57 | 10 | 2 | 1.5 | 0.9 |
| | Ship H | 2.07 | 1.57 | 10 | 2 | 1.5 | 0.9 |

K', T' are maneuvering constants; T_V' a time constant of velocity; T_E time constant of steering; K_P, T_D constants of PD controller.

Table III Distribution of Ship Type

| | Distribution (%) | |
|---|---|---|
| Self Propeller Ship | Ship A | 9.5 |
| | Ship B | 20.5 |
| | Ship C | 54 |
| | Ship D | 9.5 |
| | Ship E | 2 |
| Barge Ship | Ship F | 2 |
| | Ship G | 1.5 |
| | Ship H | 1 |

Table IV: O-D table

| | | Destination | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Origin | 1 | 0 | 60 | 40 |
| | 2 | 50 | 0 | 50 |
| | 3 | 40 | 60 | 0 |

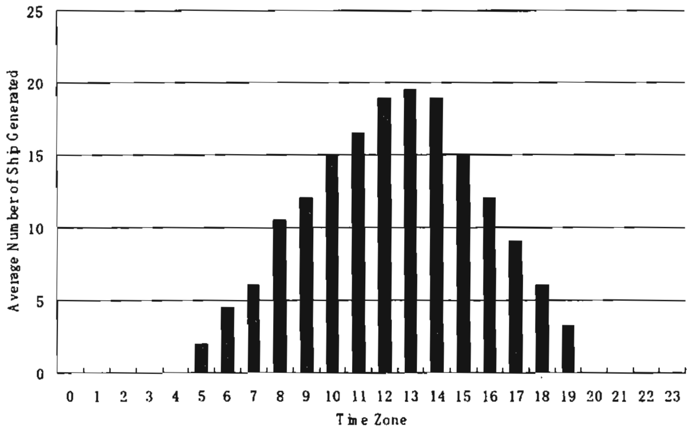


Fig.10: Time zone ship count

### 4.2. Simulations at Intersection on Different Traffic Density

We simulated different conditions for safety assessment. First, we simulated for three different densities: Simulation 1 with 157 ships/day, Simulation 2 with 169 ships/day, and Simulation 3 with 214 ships/day). The other data were kept as in the previous section. The simulation time is one day. We calculated the average time of travel (ATT) to evaluate efficiency of traffic at each case. Fig.11 shows the values of each simulation. We can see the influence of increasing of density. Especially, ATT of Simulation 3 is large compared to others. Thus the capacity of this area is more or less this density (about 210 ships / day).

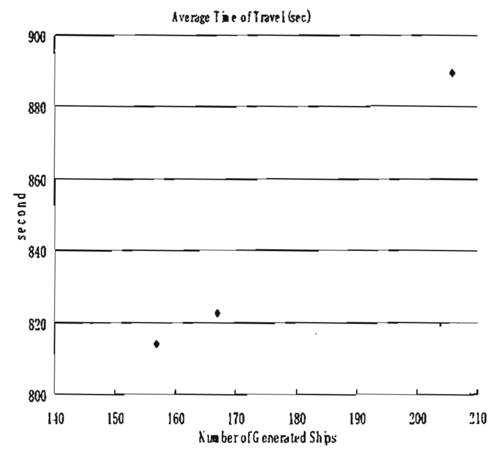


Fig.11: ATT

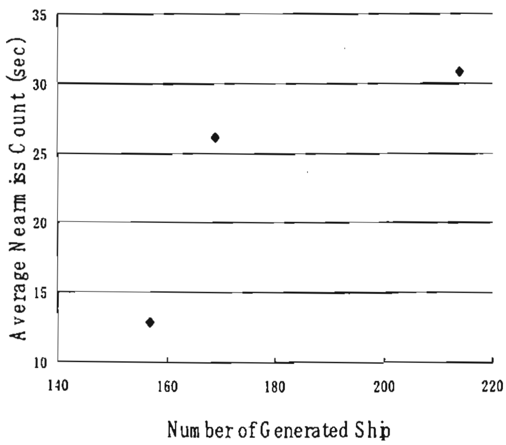


Fig.12: Average near-miss Count

The near misses were counted to evaluate the safety of each case, Fig.12. To compare each ship's safety, all near-miss counts in each simulation were divided by the number of generated ships. The value is called 'Average Near-miss Count', representing the proportion of near misses in one ship's travel. The influence of ship increasing is obvious. Comparing with ATT, at a simulation over 170 ships / day, the near-miss count does not increase but ATT increases. That means the capacity of this area is more or less 170 ships / day.

### 4.3. Simulations at Intersection on different operational velocity

We simulated different operational velocity as next step of our safety assessment. Optimized operational velocity resulted from comparing the simulation results. We considered operational velocity 12 km/h (for simulations 4, 5, 6), 14 km/h (for simulations 7, 8, 9). Again, these simulations considered different traffic density: 155 ships/day for simulation 4, 189 ships/day for simulation 5, 223 ships/day for simulation 6, 169 ships/day for simulation 7, 179 ships/day for simulation 8, and 231 ships/day for simulation 9. The simulation time was one day.

Fig.13 shows ATT for simulations 1 to 6. For efficiency, the operational velocity should be 12 km/h rather than 10 km/h. The number of erased ships is much larger for simulation 6 than the others. Thus the traffic density of simulation 6 is insecure, because the erased ship slows down its velocity to avoid collision. The results of simulation 7, 8, 9 show that an operational velocity 14 km/h is efficient but insecure.

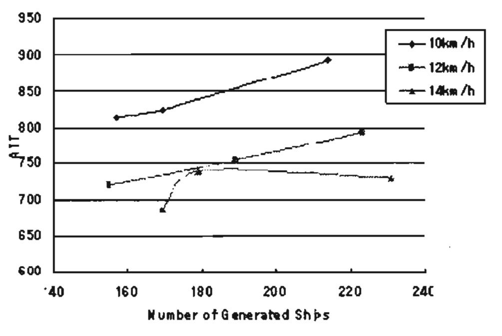


Fig.13: ATT at different instruction velocity

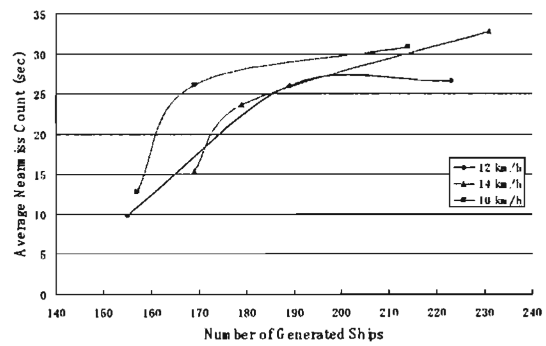


Fig.14: Average near-miss count at different instruction velocity

Fig.14 compares the 'Average near-miss count' between simulation 1,2,3 and simulation 4,5,6. The operational velocity should be 12 km/h rather than 10 km/h, both for safety and efficiency. The capacity of this sample area for smooth and safe traffic is between 155 and 189 (ships / day), because because the near-miss count does not increase and RATT increases even if more ships sail at this area (simulation 6). Also, the autopilot slows down the vessel to avoid collision. As a result, the value of near-miss count has a certain limit.

### 4.4. Sample Case of Waterway Design

As an exercise of waterway design by Inland Waterway Traffic Simulator, simulations on the area shown in Fig.15 were performed. For evaluating efficiency and safety, we simulated four simulations (11, 12, 13, and 14) on different traffic density. Operational velocity was always kept at 12 km/h. Traffic density on Simulation 10, 11, 12, 13 is 170, 188, 217, 236 ships / day, respectively. Fig.16 shows ATT of Simulation 10, 11, 12, 13 and Simulation 4, 5, 6. Concerning efficiency, there is no difference between temporary and planned waterway. This is expected, because the planned waterway does not seem to have an efficiency advantage over the present (temporary) one. Fig.17 shows the average near-miss counts. The planned waterway plan has a good influence on safety. Its capacity is 220~240 ships / day because Average Near-miss Count does not increase but RATT increases.

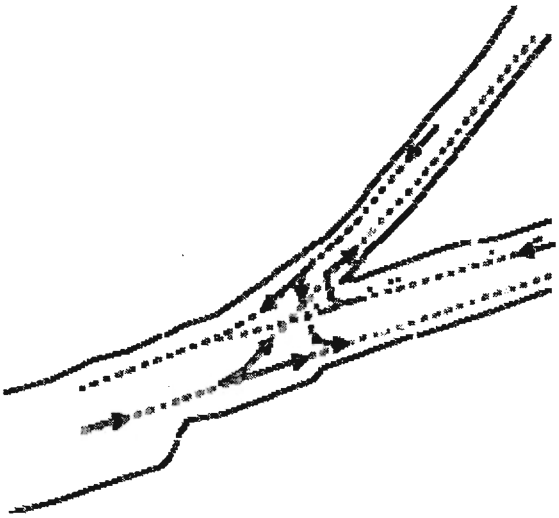

Fig.15: Sample waterway design and setting route

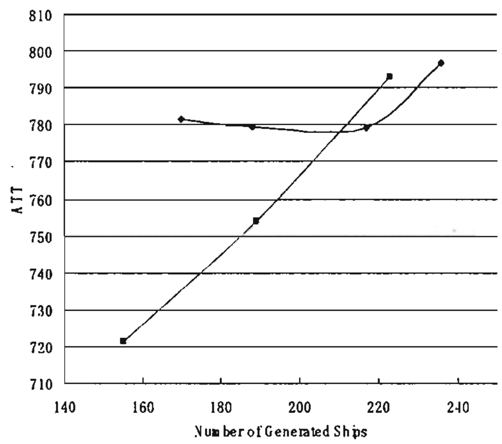


Fig.16: ATT on planned waterway and temporary waterway

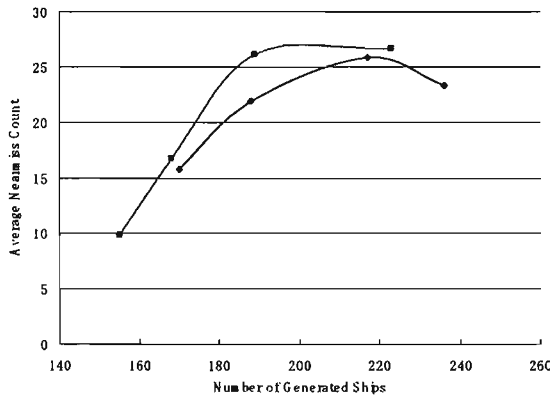


Fig.17: Average Near-miss Count on Simulation 11, 12, 13 and 4, 5, 6, 7

### 4.5. Tracking Simulation including Locks

To simulate larger area traffic, an algorithm for locks was included in "Inland Waterway Simulator". In addition, AIS systems are simulated in large area tracking simulations.

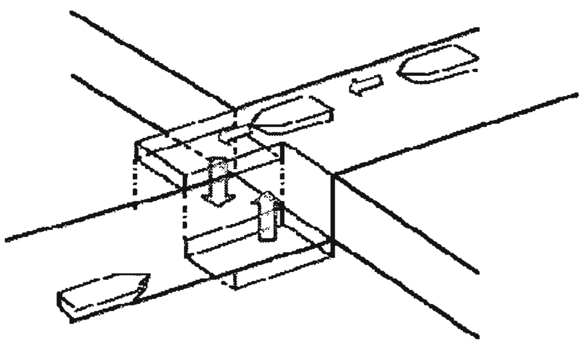

Fig.18: Sketch of lock

For simplification, the lock algorithm was provided as follows:

1. Deciding parameter of locks (capacity of a lift, time for up down): For simplification, the number is fixed to two lifts in our simulation. A lock is considered as a special waypoint and the parameters are included in the input data.
2. When no ship comes to the lock, lifts wait at up and down.
3. When a ship (subject ship) comes to the lock, ETA (Established Time on Arrival) of the ship for the lock is calculated.
4. When there is a lift at the same side as the ship (Lift 1), the lift waits for the subject ship. When capacity of Lift 2 is over and ETA of the subject ship to Lift 1 is larger than the time for up-down, Lift 1 goes to opposite side.
5. As soon as the subject ship arrives at the lock, Lift 1 goes to the opposite side. If there is a ship coming from the same side, the ETA of the ship for Lift 1 is calculated. However, if the ETA is less than 30 s, Lift 1 waits for the ship.

For safe navigation, the CR for the ship in queue or up-down at the lock nearby cross point should be calculated in a special way. When own ship is B, Fig.19, however, a CR calculation for the ship in queue is not necessary. The way of calculation is as follows:

1. Set a virtual ship at opposite the angle and at the position of $V_t \times T_t$ ($V_t$ is the velocity of the ship in queue, $T_t$ is the remaining time until passing the lock) for the ship in queue or up-down.
2. Calculate CR for virtual ship and consider it as CR for the ship in queue or up-down.
3. When closing type by the ship in queue is "obligate" and CR > 0.9, own ship should take avoiding action.

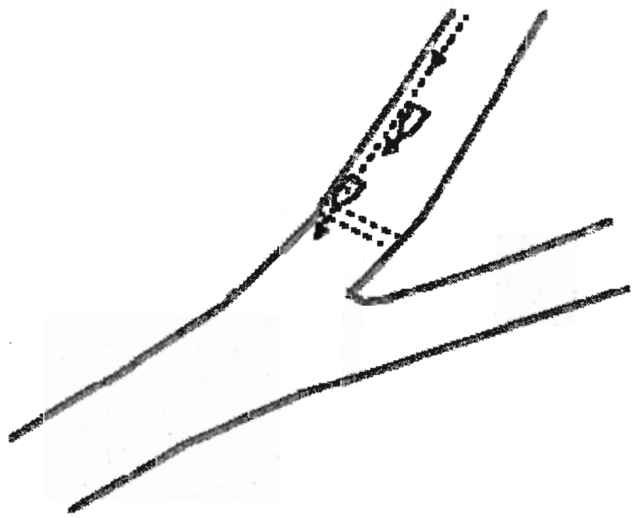

Fig.19: CR calculation for ship in queue or up-down at a lock

We simulated for an area including a lock, Fig.20. The lock was set at point A. To confirm the influence of the lock, we simulated at two variation of the time for up-down of the lifts. Comparing the simulation results, Fig.21 and Fig.22, simulations with Lock 1 (time for up-down 300 s) gave similar results to simulation without lock. Simulations with Lock 2 (time for up-down 450 s) has different tendency from simulations without lock, due to a traffic jam at the lock.

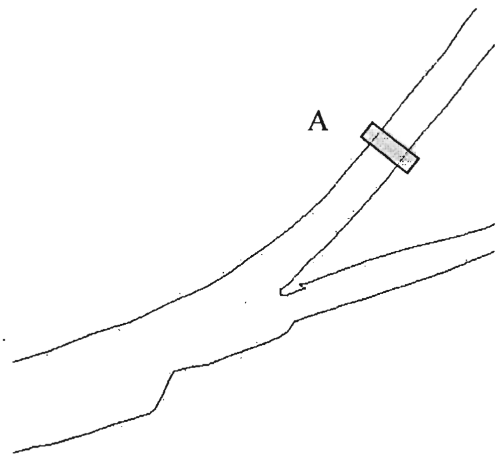


Fig.20: Simulation area and lock setting point

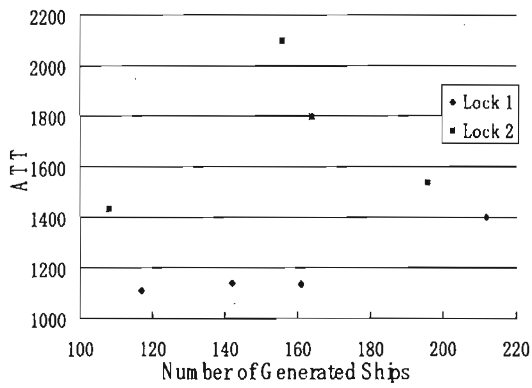


Fig.21: ATT on simulations with lock

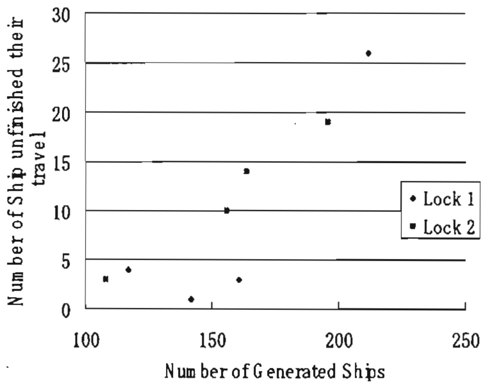


Fig.22: Number of ships unfinished travels on simulations with lock

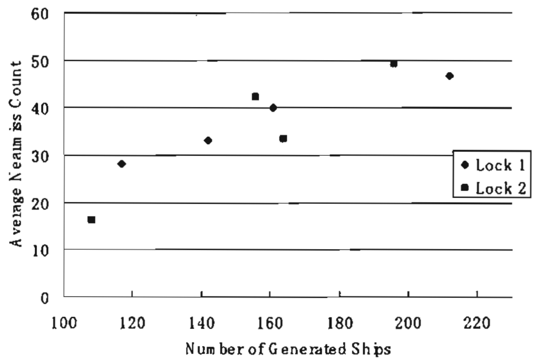


Fig.23: Average near-miss count on simulations including lock

**5. General Conclusion**

The "Inland Waterway Traffic Simulator" has been developed modifying the "Marine Traffic Simulator". Various simulations, also including locks, have shown that safety and efficiency of inland waterways can be assessed using the simulation tool.

**Acknowledgment**

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