7. Vessel Maneuvrability

Approximately 70% of incidents of damage to harbour facilities involve damage to piers and fenders, however most are due to **mistakes in operation of the vessel**. Such mistakes in confined harbours with limited area available for maneuvering are due to the following.

① Inability to accurately determine the effects of external forces such as wind and tides.

② Mistakes in speed control and turning of the vessel while using engines and tugs.

Most harbours have pier protection, shallow areas, and other vessels in the immediate area, and overrunning the scheduled stop point while approaching the pier may result in an incident. The ship navigator gradually reduces speed in accordance with the distance remaining, and is required to adjust speed and turn the vessel while considering **its type, size, loading condition, inertia, maneuvrability, and the effects of external forces.**

7-1 Effects of External Forces (wind)

7-1-1 Transverse Movement and Turning Under Wind Pressure While Underway

How is the vessel affected by wind while underway?

① Straight ahead **if no external forces are acting** in windless conditions.

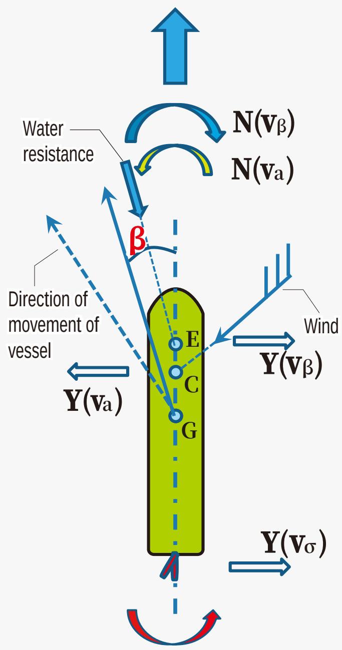
② When the wind is at 45° to starboard, the vessel is pressed to leeward. The point at which the wind acts (C) is ahead of the vessel's center of gravity (G), **and a turning moment (N (Vα)) acts to turn the vessel in the leeward direction.**

③ When the vessel begins drifting (diagonally) leeward, **water resistance is generated** on the leeside of the bow. The point (E) at which this force acts is ahead of the point at which the wind pressure acts (C), and **a turning moment (N (Vβ)) acts to turn the vessel in the windward direction**.

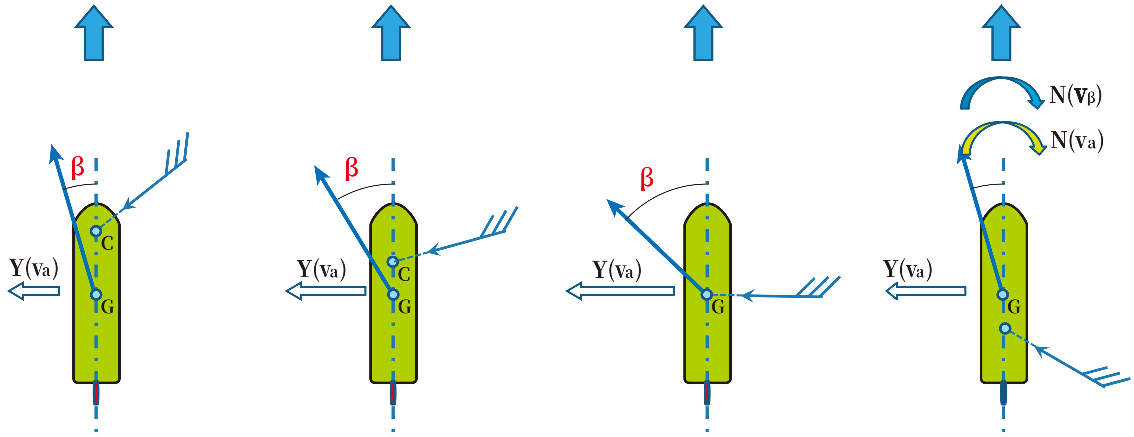
④ The vessel turns under the turning moment of the wind or water resistance, whichever is the greater. Since water resistance is normally much greater than air resistance, **the vessel begins to turn windward. (N (Vβ) > N (Vα))**

⑤ The rudder acts against the turning moment, i.e. **the vessel is controlled with the moment N (Vσ) generated by the rudder angle (σ).**

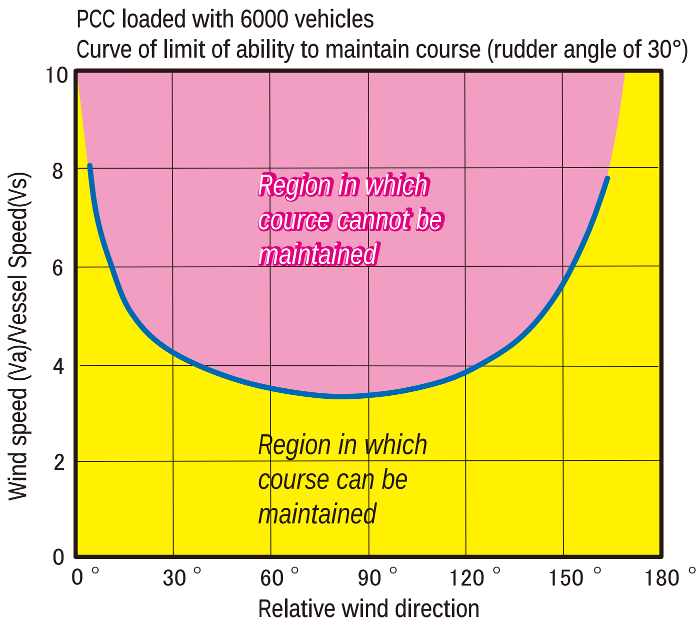
⑥ Finally, with turning moment of the wind, water resistance, and rudder in equilibrium, the vessel **maintains a course at the angle β (leeway) to the right ahead, and proceeds with drifting leeward.**



The point (C) at which the wind acts approaches the vessel's center of gravity (G) the closer the relative wind is to the transverse axis of the vessel. At 90° (abeam) it acts almost entirely on the vessel's center of gravity. As a result, the turning moment **N (Vα)** acting in the leeward direction is reduced (turn), and the force **Y (Vα)** acting on the vessel in the leeward direction increases (drift), and the diagonal angle increases, increasing the turning moment **N (Vβ)** due to water resistance.

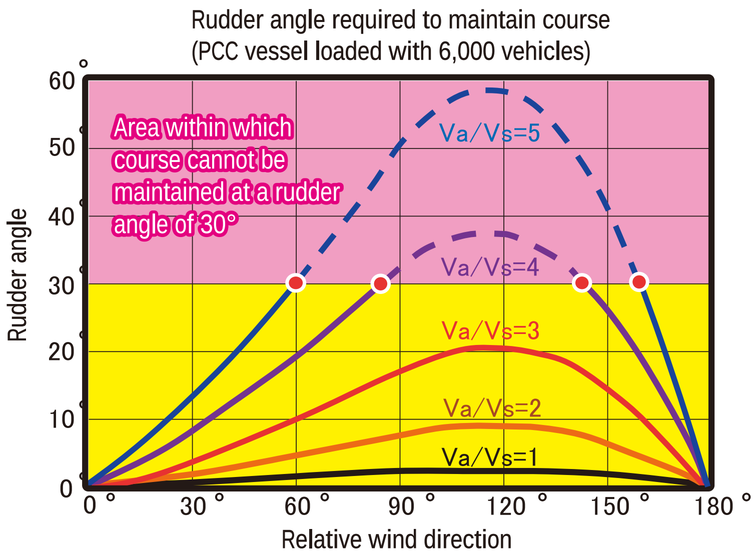


Furthermore, when the relative wind moves from the transverse to the rearward direction, the point (C) at which the wind acts moves from the vessel's of gravity towards the stern, the turning moment **N (Vα)** rounds up the bow, and acts in the same direction as the water resistance.



The course can be maintained if the moment derived from the wind and water resistance can be controlled with the rudder. **If such control is not possible, an increase in the turning moment due to water resistance increases, and the course can no longer be maintained.**

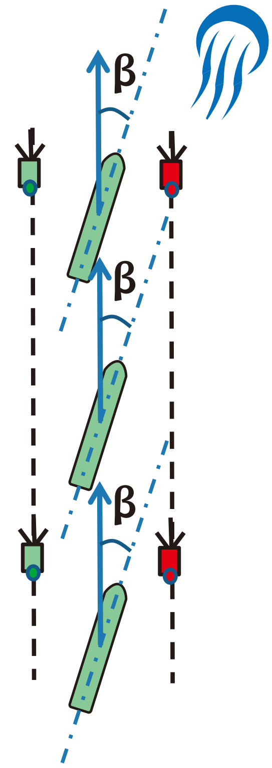
The graph above shows the ratio of wind speed (Va) to speed of the vessel (Vs) on the vertical axis, and the relative wind angle on the horizontal axis, and indicates the regions in which the course can and cannot be maintained with a rudder angle of 30°. **If the ratio of wind speed to vessel speed exceeds 3.7, a region occurs in which the course cannot be maintained due to the relative wind angle.**



At vessel speeds of 6 – 8 knots (3.1 – 4.1m/sec) inside the harbour, a wind speed of 11 – 15m/sec results in a ratio of wind speed to vessel speed of 3.7, and the course may not be able to be maintained in these conditions depending on the direction of the relative wind.

In the graph below, rudder angle is shown on the vertical axis, and the regions in which the course can and cannot be maintained for each ratio of wind speed to vessel speed. When the ratio of wind speed to vessel speed (Va/Vs) reaches 4, depending on the angle of the relative wind, a region in which the course cannot be maintained occurs, despite a rudder angle of 30°.

It is important to maneuver the vessel while **considering the rounding up angle leeway (β)** when navigating in a channel without the assistance of tugs under wind pressure. In such cases, wind direction and speed, and vessel speed, must be considered, and an investigation conducted to determine whether or not maneuvering is possible in the region in which the course can be maintained.

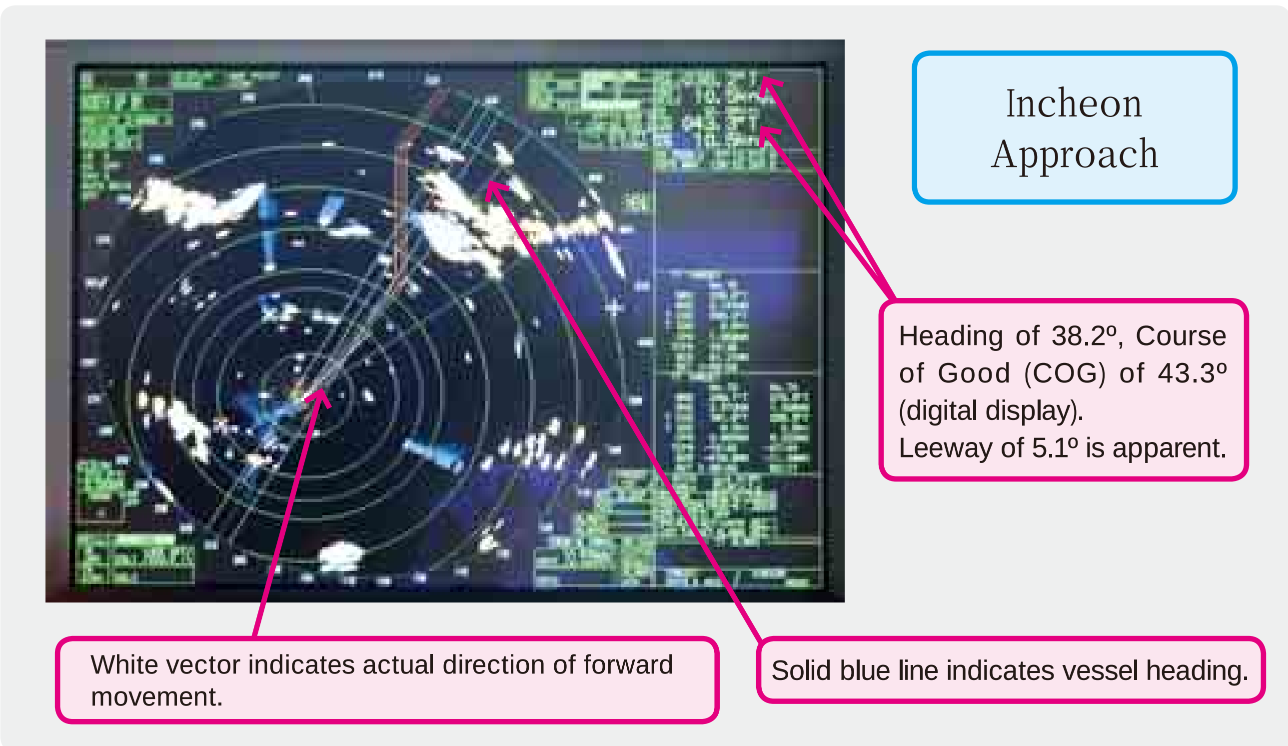


The maximum allowable wind speed for entering and leaving the harbour is very often set, however hull shape etc. should be considered together with the criteria established for the harbour in question.

Reference photo : Leeway of 3 °to starboard to ensure passage under center of bridge.

Modern radar with advanced technology displays generally incorporates GPS information. If this function is used skillfully **the leeway angle and direction of drift can be understood in numerical terms. This information is effective in maneuvering the vessel.**

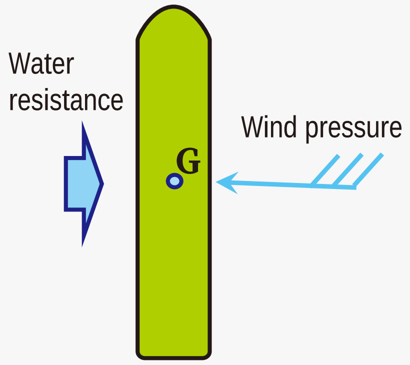
An example is shown below.



7-1-2 Drifting While Stopped

Extreme care is required with drifting of the vessel due to wind pressure when stopped in front of the pier with an onshore wind directly abeam, or when the turning.

When drifting with the wind pressure above the water line balanced against the water resistance below the water line, the drift speed can be calculated with the following equation.



Wind pressure = Water resistance

$$\frac{1}{2}\rho a \times Ca \times Ba \times Va^2 = \frac{1}{2}\rho w \times Cw \times Bw \times Vw^2$$

ρ a : Air density (0.125kg・sec^2/m^4)
ρ w : Density of seawater (104.5kg・sec^2/m^4)
C a : Wind pressure lateral force coefficient
C w : Drift pressure lateral force coefficient
B a : Lateral area of vessel above waterline (m^2)
B w : Lateral area of vessel below waterline (m^2)
V a : Relative wind speed (m/sec)
V w : Relative current speed (m/sec)

Drift speed (Vw)is calculated with the above equation as follows.

$$Vw = \sqrt{\frac{\rho a}{\rho w} \cdot \frac{Ca}{Cw} \cdot \frac{Ba}{Bw}} \times Va$$

With Pure Car Carriers (PCCs), the coefficients Ca and Cw, the lateral area of the vessel above the waterline (Ba), and the lateral area of the vessel below the waterline (Bw), are approximately as follows. Substituting these values in the equation above allows for a simplified calculation of drift speed.

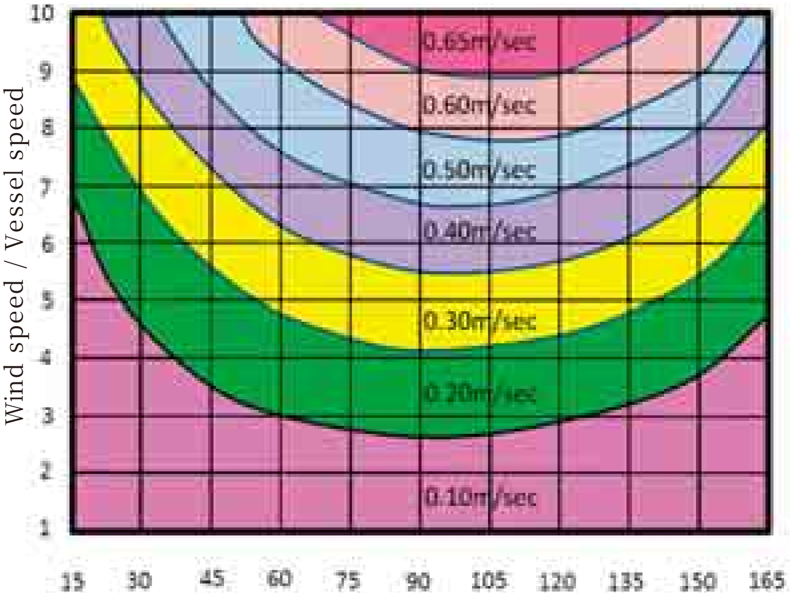
$\frac{Ca}{Cw}$ 1.3 (approximate, differs with vessel)

$\frac{Ba}{Bw}$ 3.0 (PCCs)

$$\mathbf{Vw = 0.068Va}$$

A PCC with 4,500 vehicles on board, speed has decreased, wind abeam, drift speed gradually increasing, **reaching a steady state in 2 – 3 minutes.**
For example, reducing speed to 2 knots (1.0m/sec) to approach the pier, with a wind of 10m/sec abeam. The ratio of wind speed to vessel speed in this situation is approximately 10, and drift speed horizontally will be **approximately 0.65m/sec 120 seconds later.** This is shown in the graph below.

Drift speed 120 seconds after subject to effects of wind pressure
(PCC loaded with 4500 vehicles, h/d = 1.3)



Relative Wind Direction

ECDIS image

The photo image shows the actual drift track of a PCC on an electronic chart. It may be interesting to record tracks if the opportunity to drift under strong winds presents itself.

7-2 Turning the Vessel

7-2-1 Turning With One Tug and Free of Effects of External Forces

When turning with one tug pushing at the stern (or bow), the center of the turn is the pivot point (P), rather than the center of gravity (G). **Turning the vessel on the spot in a circle of radius 1/2L (L being the vessel length) is therefore not possible.**

The radius of area required for turning can be found with the following equation.

$$\text{Turning radius (R)} = GP + \frac{1}{2}L$$

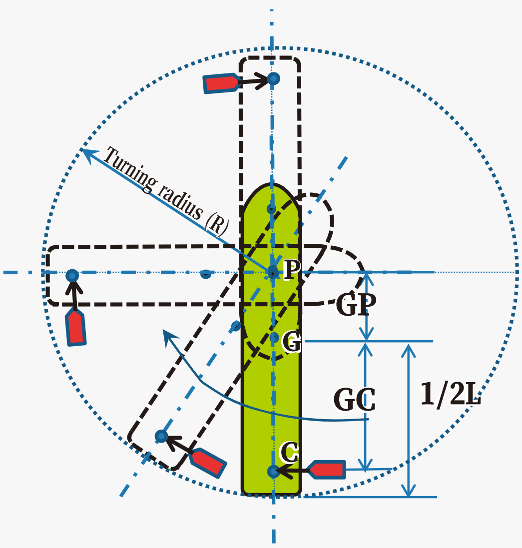
$$\underline{GP} = k^2 / \underline{GC}$$

k : Turning radius of moment of inertia around vertical axis through center of gravity (G) 0.35L

P : Pivot point, center of rotation when turning vessel

G : Center of gravity

C : Point at which tug acts on vessel



As is apparent from the above equation, the position of P (turning center: pivot point) is not related to the pushing (or pulling) force applied by the tug, but to the point on the vessel at which the tug pushes, and this position is on the side opposite the center of gravity. In other words, as the point at which the tug acts on the vessel approaches the center of gravity, GC becomes smaller. GP therefore increases, as does the turning radius.

Understand the turning radius at each point at which the tug acts.

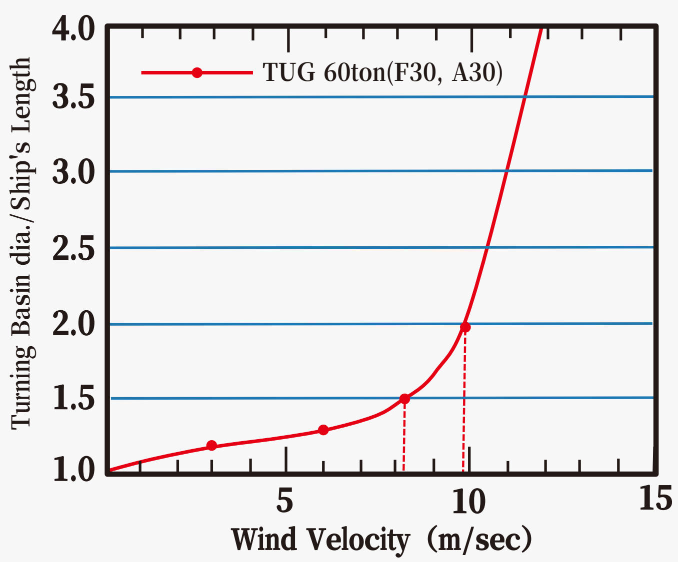
7-2-2 Turning With Two Tugs or Bow Thrusters and One Stern Tug, and With Effects of External Forces (wind)

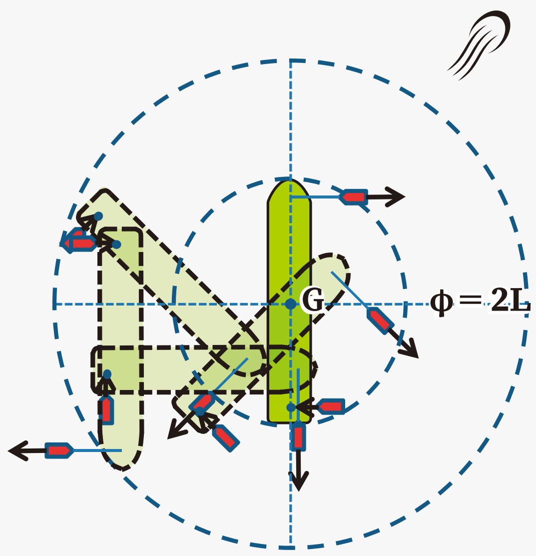
Tugs fore and aft, or bow thrusters and a stern tug, must be used when turning on the spot (turning within a circle of diameter 1L). When turning under the effects of external forces (wind), the relative wind varies while turning, so that turning occurs on the spot while controlling drift, resulting in considerable difficulties in maneuvering.

A simulation was run of turning a container vessel of 246m in length subject to winds of 10m/sec at 45° to starboard at the beginning of the turn, using two tugs. The tugs were used solely for turning, and no adjustment was made for drift.

Hull shape (Container vessel) using simulator

Loa(m)		246.27
Lpp(m)		230.00
Bredth(m)		32.24
Depth(m)		21.20
Draft(m)		11.50
Disp.(KT)		53,875
Trim(m)		0.00
G position		-5.5
Wind Project.	Front(m^2)	850
	Side (m^2)	6,090

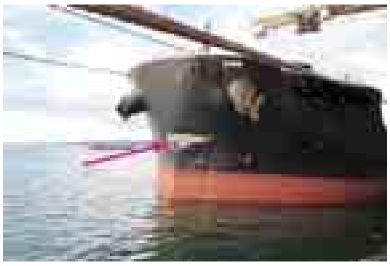




A 180° turn requires a circle of diameter 2L around the center of gravity at the beginning of the turn.

Japanese harbour design criteria guidelines specify a 2L circle for turning with tugs. While dependent on hull shape and vessel type, a wind speed of 10m/sec is the limit, even if a 2L circle is available for turning this vessel. A larger area is required for turning at wind speeds in excess of 10m/sec.

7-3 Speed Control



Incidents of failing to control a ship's speed while entering harbour, with the vessel consequently colliding with the pier causing major damage to the pier, shore cranes, and the vessel itself, never cease.

Ships differ from motor vehicles in that they are not fitted with a braking mechanism to reduce speed. Control of speed must therefore rely on controlling the speed of the main engine, reversing the main engine, or the assistance of a tug.

In order to ensure that the vessel stops precisely at the scheduled point, the ship navigator is required to consider its type, size, loading condition, inertia, and manoeuvrability, and the effects of external forces etc. when adjusting speed.

These factors are obviously not formally calculated while the vessel is approaching the pier, and lack of communication between the pilot and captain is a cause of incidents, as is insufficient advice from the captain.

Both the captain and pilot are required to have a quantitative, rather than an intuitive exchange of information, based on experience, understanding of the stopping distance and the time required to stop.

7-3-1 Assessing the Dangers of Overrun (safety margin)

A safety margin on the approach allows an evaluation of the distance the vessel will travel while braking with engine reversed or with a tug on the stern, and the distance toward the scheduled stop point at which the vessel will stop. This is expressed with the following equation.

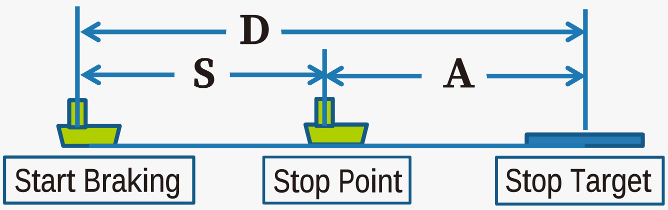
A questionaire given to pilots showed that a safety margin (R) of 0.3 – 0.6 when dead slow astern is initiated allows operation to ensure that control of the vessel is not lost.

* Losing control of the vessel:
When the reversed engine is set to slow ahead or more for a long period, the propeller wash and water flow do not act on the hull uniformly, and it becomes difficult to maintain the heading.

$$\text{Safety Margin (R)} = \frac{A}{D}$$

A : Distance remaining between stopping point of vessel and target stop point

D : Distance between braking start point and target stop point



7-3-2 Basics of Stopping Distance, Vessel Weight, and Acceleration

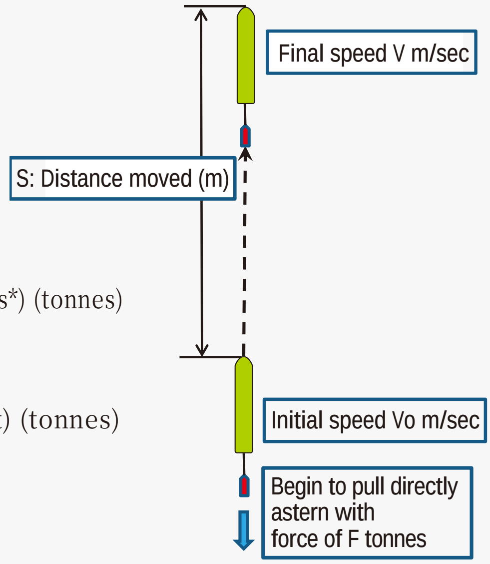
Hull shape and resistance must be considered when determining details such as stopping distance and the time required to stop, however approximate values can be derived with the following equation based on the principle of conservation of energy.

$$F = \frac{1}{2} \times \frac{W}{g \cdot S} \times (V^2 - V_0^2) = \alpha \times \frac{W}{g}$$

$$S = \frac{1}{2} \times (V + V_0) \times t = \frac{1}{2} \times \frac{W}{g \cdot F} \times (V^2 - V_0^2)$$

$$\alpha = \frac{(V - V_0)}{t} = \frac{g}{W} \times F$$

W : Apparent displacement (displacement + additional mass*) (tonnes)
Vo : Initial speed (m/sec)
V : Final speed (m/sec)
F : Forces acting (tug thrust and reverse engine thrust) (tonnes)
t : Elapsed time (seconds)
S : Forward movement (m)
α : Acceleration applied to vessel (m/sec^2)

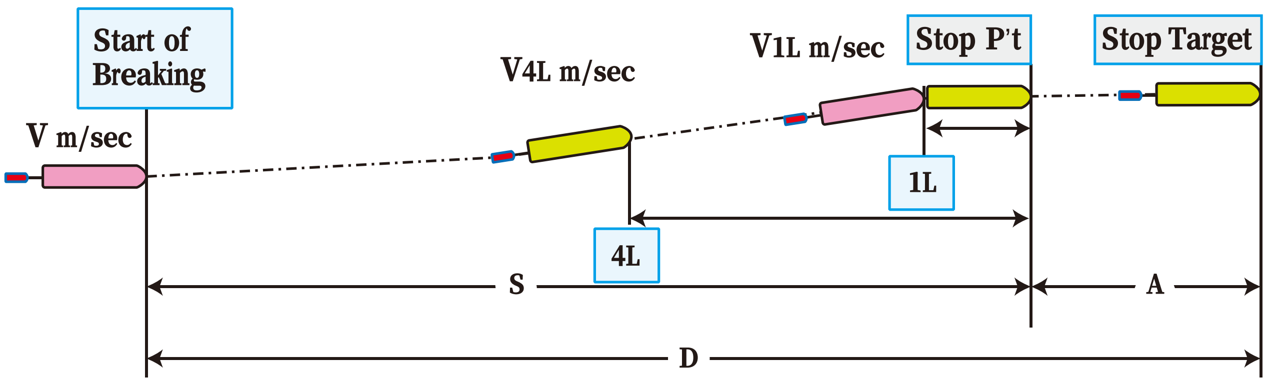


* Additional mass
When accelerating and decelerating the vessel, the vessel itself moves, while at the same time, the water in the vicinity also moves as a result of this movement. Power is therefore not only required to move the vessel, but to move a part of the water in the vicinity. This is, in effect, the same as moving a vessel of increased mass. This increased mass is referred to as 'additional mass'.

7-3-3 Speed Reduction Plan for Vessel Approaching Pier in Direction of Arrival (example)

When approaching parallel to the pier in the direction of arrival it is necessary to **determine in advance when to stop the engine, and to understand guidelines for evaluating whether or not speed through the primary waypoints is excessive while approaching the berth.**

For example, while moving forward at dead slow ahead as shown in the following image, when stopping the engine with simultaneous braking applied by a stern tug, and with a distance to the stop position of 4L and 1L, it is necessary to determine beforehand the speed at which it is possible to stop at the scheduled point. While incorporating a safety margin in the distance to the berth noted above, it is also needed to reduce speed by increasing the braking effect of the tug or by reversing the engine if the approach to the berth is at a greater speed.



In practice, rather than maneuvering the vessel to stop at the stop point, braking is applied while controlling speed so that the vessel stops at the target at the front of the berth without losing control.

7-3-4 Reference Values for Reducing Speed

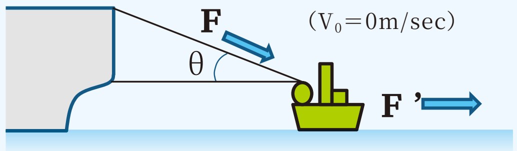
The spreadsheet below presents the equation in 7-3-2 in a format ready for data entry. Enter the necessary data to calculate approximate values for stopping distance and stopping time, and safety margin. It is important to recognise reference values for the stopping distance of the vessel using simple spreadsheets. Early braking by tug or reversing the engine is necessary if the safety margin is 0.3 or less.

Displacement	W	37,500	ton
W+ Add. Displacement	W ’	40,125	ton
Length Over All	Loa	200	m
Remaining Distance	4L	800	m
	1L	200	m
Tug Line Angle	θ	20	deg.
Braking Power	F	15.0	ton
Horizontal Braking Power	F ’	14.1	ton
Longitudal Wind Pressure for Braking Power	RL	15.5	ton
Effective Braking Force（F ’+R L）	Fb	29.6	ton
Speed at start of Braking (Speed by Dead Slow Ahead)	V	6	kts
		3.09	m/sec
Dist. Between Start of Braking and Target	D	2,000	m
Stopping Distance	S	659	m
		0.36	N.Miles
Required time to Stop	t	427	sec
		7.1	min.
Speed at 4L	V_{4L}	6.6	kts
		3.4	m/sec
Speed at 1L	V_{1L}	3.3	kts
		1.7	m/sec
Remaining Dist at Stop Point	A	1,341	m
		6.7	L
Safety Factor	R	0.67	0.3 ～ 0.6

Input
Aut.Cal.
Result

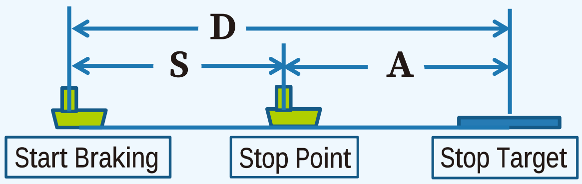
Speed Reduction Reference table

$$W' = W \times 1.07$$



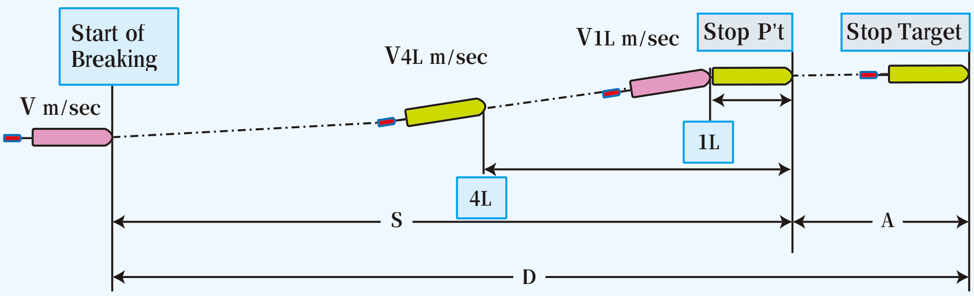
$$F' = F \times \cos\theta \qquad S = \frac{1}{2} \times \frac{W'}{g \cdot F} \times (V^2 - V_0^2)$$

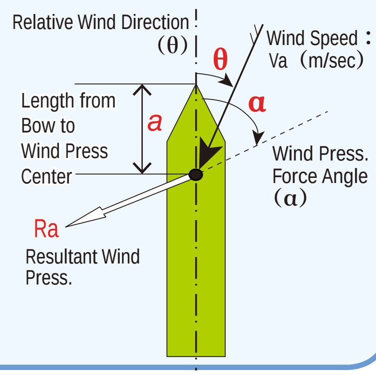
$$t = 2 \times \frac{S}{(V + V_0)} \qquad R = \frac{A}{D}$$



Wind Speed Calculation

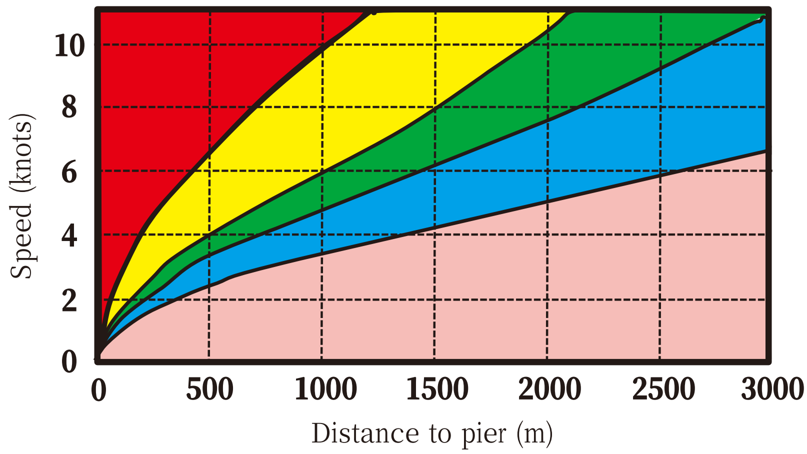
Wind Speed	12.4	m/sec
Relative Wind Angle	45	Degree(0 ～ 180) (Every 10 degree)
Long. Wind Force: RL	15.5	ton
Ship's Kind	1	GEN/PCC/CTNR : 1 Pax : 2, Tank/Bulk : 3





In addition to this spreadsheet, it is also effective to consider the manoeuvrability of the vessel in preparing speed reduction guidelines in graphic format. The guidelines should be posted on the bridge, with copies kept in storage. The guidelines can be provided to the pilot as reference material for information exchange upon boarding to assist in communication.

Guidelines for reducing speed while maneuvering for approach



(For container vessels, PCCs, LNG carriers.)

The above diagram shows an example of a speed reduction guideline for adjusting speed during the approach based on the distance remaining and speed, in consideration of the safety margin.

In this region, the safety margin is zero when full astern engine thrust is used for braking. Remaining speed plotted further to the left enters the danger zone with overrun beyond the scheduled stopping point.

In this region, the vessel stops before the scheduled stopping point if slow – full astern engine thrust is used for braking. Control of the vessel may be lost if reverse thrust is used (quasi danger zone).

In this region, the safety margin is zero with dead slow astern engine thrust used for braking (caution zone).

In this region, the safety margin is 0.3 – 0.6 with dead slow astern engine thrust used for braking. It is possible to control the vessel within this range (control possible zone).

Control of the vessel is possible in this region, however the effects of external forces (wind) will be considerable if speed is reduced excessively (caution required in this zone if external forces are present).

Verify displacement of vessel, power at engine astern, and power of tug, verify the distance and time required to stop during maneuvering for approach, and maneuver the vessel with a safety margin.

7-4 Control of Berthing Velocity When Approaching the Pier

Incidents of failure to control berthing velocity when approaching the pier (use of a tug or bow thrusters to move the vessel sideways to the berth) despite maneuvering the vessel as scheduled in terms of speeds, and consequent damage to the pier, fenders, and the hull of the vessel are common.

Conventionally, the vessel approaches at an angle on a face line of the pier, the bow line is taken, and the stern is pushed to the pier. This method is still used with vessels of up to 20,000GT, however larger vessels generally approach and position parallel to the pier at a distance of 1.5 – 2 times the beam, and are then pushed sideways onto the pier by a tug (parallel approach).

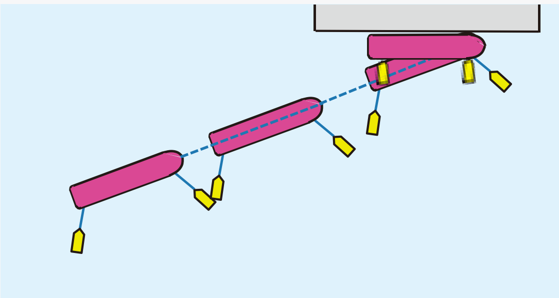
Advantages and disadvantages of the parallel approach compared to the conventional method are as follows.

= Advantages =

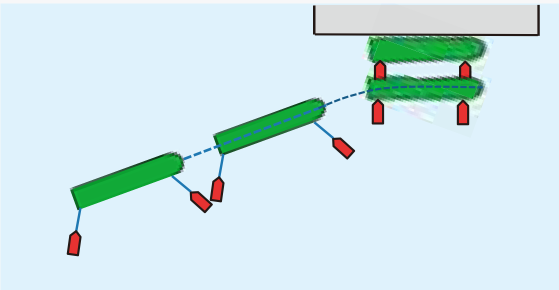
- While this depends on the layout of the pier, a mistake in reducing speed does not result in damage to the pier. When the pier is of considerable length, a mistake in speed control **simply results in overrunning the scheduled stop position, and does not result in damage to the pier.**
- With the conventional method, container ships etc. with large bow flares sometimes damage cranes etc. overhanging the pier. **This risk is much reduced with the parallel approach**.
- The attitude of the vessel is more easily controlled with the parallel approach, **facilitating response to rapid changes in external forces**.

= Disadvantages =

- **An extra 10 – 20 minutes is required** to reach the pier.



Up to 20,000GT (conventional method)
20,000GT (parallel approach)



Large vessels exceeding 20,000GT
(parallel approach)

7-4-1 Berthing Velocity Control

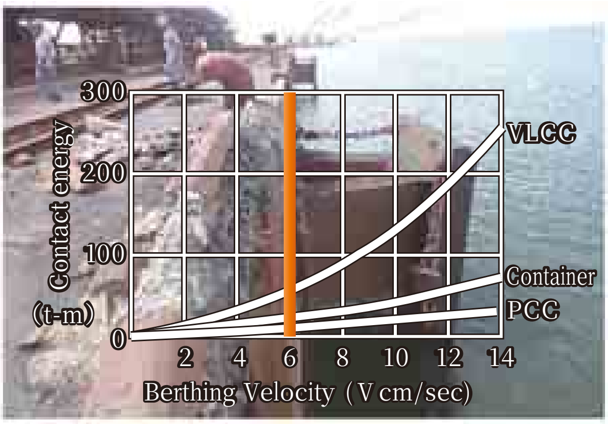
Piers and mooring facilities are based on the largest vessel type to be accommodated, and are normally designed for a speed of 15cm/sec when approaching the pier. Vessels generally approach at a maximum speed of 10cm/second, with large vessels and VLCCs approaching at 5cm/sec. These speeds allow absorption of the energy of the vessel when contacting the pier fenders, and prevent damage to the hull and the pier.

The energy of the vessel when contacting the pier can be calculated with the following equation, and is proportional to the square of the speed of contact.

$$E = \frac{1}{2} \times \frac{W'}{g} \times V^2 \times C$$

E ：Contact energy（ton-m）
W' ：W (displacement tonnes × tranverse additional mass coefficient (1-0 – 2.0)
g ：Acceleration due to gravity（m/sec^2）
V ：Berthing Velocity（m/sec）
C ：Energy diminuition coefficient due to turning etc.

Using an additional mass coefficient of 1.8, and C of 0.5 in the above equation, a container vessel with a displacement of 50,000 tonnes approaching the pier at a speed of 10cm/sec has a contact energy of approximately 23 tonne-m. This is equivalent to a 1 tonne motor vehicle colliding with a wall at 80km/h.



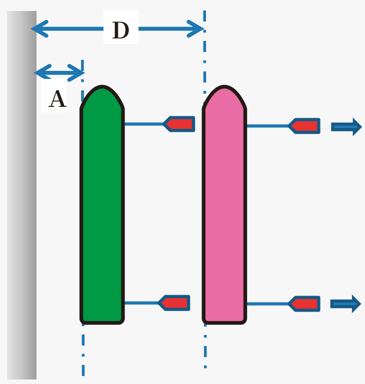
7-4-2 Safety Margin in Relation to Speed when Contacting the Pier

As with the speed reduction plan, the safety margin for speed when contacting the pier must also be investigated. When a vessel with berthing velocity of Vcm/sec receives a constant braking force by a tug from a point Dm from the pier, and stops Am from the pier, the safety margin is calculated as follows.

$$\text{Safety Margin (R)} = \frac{A}{D}$$

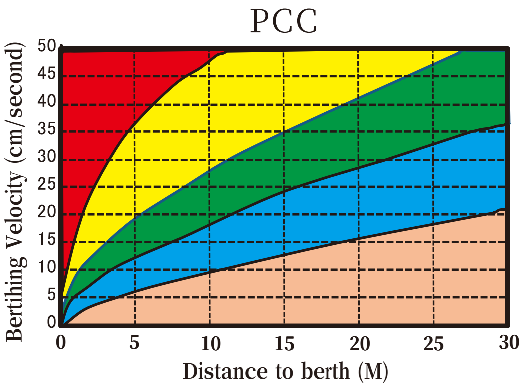
D： Distance from braking start point to pier

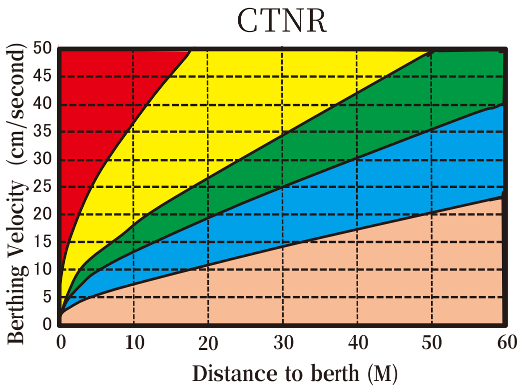
A：Distance remaining from vessel stop point to pier

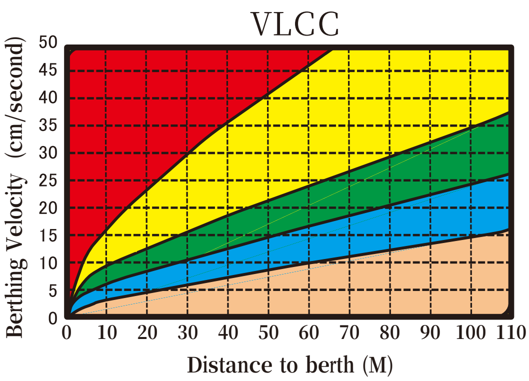


The vessel stops immediately after commencing braking if R = 1. The vessel stops at the scheduled stop point if R = 0. A questionnaire given to pilots showed that the safety margin used for safe approach to the pier keeping the vessel's attitude when towed at Slow by a tug is **0.3 – 0.6.**

As with the speed reduction plan, it is important to employ a graph.







In this region, the safety margin is zero when two tugs brake the vessel at full speed.

In this region, the safety margin is zero when a tug brakes the vessel at half speed.

In this region, the safety margin is zero when a tug brakes the vessel at slow speed.

In this region, the safety margin is 0.3 – 0.6 when a tug brakes the vessel at dead slow. Adjustment of speed approaching the pier in this region is recommended.

In this region, control is possible, however the vessel is readily susceptible to external forces.

8. Preventing Damage to Harbour Facilities

As decribed above, maneuvering of a vessel under its own power inside the harbour during entry and exit presents difficulties. External forces such as wind have a particularly large effect when holding and changing course, holding speed, and when controlling the attitude of the vessel.

When approaching and leaving the pier, it is necessary to understand the effects of external forces, and to use assistance such as tugs, main engines, and bow thrusters to **control the attitude and speed of the vessel appropriately while maneuvering.**

It is important not to leave all the operation of the vessel to the pilot. Rather, the captain and pilot should discuss the procedure for operation, and ensure that all bridge crew understand the way to put the necessary bridge resource management into practice thoroughly, and are thus able to reduce the number of incidents of damage to harbour facilities.

In discussions with the pilot at entry and exit from harbour, it is **necessary for the captain to plan the procedure for entry and exit in advance.**

8-1 Bridge Resource Management During Harbour Entry and Exit S/B

The following points are required to consider thorough bridge resource management at harbour entry and exit.

- Consult with the navigator on the day prior to harbour entry for a briefing on harbour entry and exit procedures.
- When the pilot boards the vessel, present the pilot card (see Attachment (2)), and explain draft, displacement and other points of special note.
- Obtain information from the pilot on where the tug is to be taken up, whether the pier is to be approached on the ship ' s port or starboard side, and the number of mooring lines etc. to be used. If there is time available, verify the requirements for maneuvering of the vessel (e.g. turning point).
- Ensure that the officer on the bridge reports engine speed (when engines are operated), and that the helmsman reports rudder status as appropriate. When the engine is stopped in the final stages of approaching the pier, the officer may begin tidying up the bridge and he / she may neglect to report the berthing velocity of the vessel. It is important that the required information (e.g. ahead/astern speed, berthing velocity) is reported appropriately until an instruction is received from the captain that it is no longer necessary.
- Officers stationed at the bow and stern report repeatedly on movement of the tugs.
- In non-English-speaking regions in particular, the pilot and captain of the tug frequently converse in the local language, and information on movement of the tug may not reach the captain of the vessel. It is important that officers stationed at the bow and stern report concisely whether the tugs are pushing or pulling the vessel, and in which direction etc.
- Mooring lines are set in consultation with the pilot. Even after the lines are tied on the bitts, they are generally left un-tensioned (with no slack). It is important to follow the instructions of the ship navigator when winding in mooring lines to control the attitude of the vessel.
- It is always necessary to verify any doubts. This applies not only the captain, but also to the crew. The captain is responsible for creating an atmosphere in which this behavior is encouraged.