Reanalysis of the Revised EEDI Parameters for Inland Ships of Bangladesh

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Abstract

A revision of the Energy Efficiency Design Index (EEDI) formulation was previously proposed to be useful for inland ships of Bangladesh. The study had incorporated the shallow water effect using Schlichting's method, however, the evaluation and presentation of Schlichting's results did not cover all range of ship parameters. In addition to that, the previous proposal was not based on field studies and the consideration main engine's Maximum Continuous Rating (MCR) was not appropriate. This study has corrected the previously proposed EEDI formulation for inland ships of Bangladesh based on the physical investigation. In this regard, 15 inland ships of Bangladesh (05 cargo, 05 oil tanker and 05 passenger ships) have been physically investigated. The impact of shallow water effect on EEDI was assessed based on field study, which was compared with approved methods. It was assumed with reasonable considerations that the bank/restricted channel effects on the ship are negligible. The MCR was also fixed based on the field study. It was found that the deviations of Schlichting's results varied from 31.34% to 81.46% in comparison to the investigated results. The deviations of results calculated by Lackenby and Barras methods were varied from 10.10% to 43.83% and -22.19% to 16.53% to the field studies. In addition to that, MCR has been measured for the same 15 ships. Investigated results show that the average MCR for inland cargo and oil tankers of Bangladesh is 70% whereas it is 80% for passenger ships. Based on the key findings of the field studies, a revised EEDI formulation is proposed for the inland ships of Bangladesh.

1. Introduction

The adopted EEDI formulation by IMO [1] to increase the energy efficiency of sea-going ships is successful so far [2]. In 2015, 932 million tonnes of CO₂ were emitted globally from the maritime shipping sector, which is 2.6% of the global, which has been reduced from 2.9% of the global share from 2011 [3]. At the same time, inland shipping had only a 0.22% share of global shipping. Though the global share of CO₂ emission from inland shipping is relatively very small (more than 11 times smaller) the absence of appropriate energy and emissions benchmark for Inland Waterway Self-Propelled ships is a large impediment to performance improvements of inland ships [4].

EEDI by IMO is not suitable for assessing the energy and environmental efficiency of inland navigation vessels [5]. In general, inland ships require more power at the same speed in comparison to similar types of open water/seagoing ships [6], primarily because of the shallow water effect. Since this effect varies with channel depth and width, a generalized EEDI reference line is not possible in a similar fashion to IMO.

Shallow and restricted water effects, different fuel qualities (to reduce operational cost), increase in engine power requirement, reduction in carrying capacity, cargo availability, etc. forbid the use of existing EEDI formulation for inland waterways of Bangladesh. Hasan and Karim [7] considered these. However, the procedure followed for shallow water effect calculation by Hasan and Karim was the famous Schlichting method [8]. The evaluation and presentation of Schlichting's results did not cover all range of ship parameters. The assumption of equal wave resistance by Schlichting in deep and shallow water when the lengths of the ship-generated waves are the same is questionable [9]. For the frictional resistance, Schlichting derived an empirical correction in terms of an assumed overspeed along the hull dependent on the ratio of

Hull Midship Area and Depth of the water. However, its value was derived from his model-test data, to cover the remaining gap in total resistance after the wave correction had been made, and with some support from velocity measurements in the model basin. Now this wave resistance correction is a severe simplification. It assumes that ship waves propagate with the same speed as the ship, which is only true for transverse waves. Also, the wave resistance depends not just on wavelength but also on wave amplitude. An effect of additional sinkage in shallow water is disregarded. Therefore, the wave resistance correction cannot be expected to be accurate; and its deviations are implicitly incorporated in the frictional-resistance correction, found by correlating with the model-test data. Moreover, Schlichting's model tests were just for 3 cruisers of that era, with extreme slenderness and rather high speeds.

International Towing Tank Conference [10] approved two procedures for power trials in shallow water, namely Lackenby [11] and the Raven [12] methods. The Raven method does not provide any formulation, rather it is a procedure for a series of tests, which starts with CFD analysis. Later, this analysis is validated with model test and trial data. In practice, this is a very accurate process, but not a generalized process. In addition to that, the builder, owner, and verifier must agree upon this process, as stated in the ITTC guideline [10].

Lackenby [11] extended the well-known Schlichting method towards smaller effects and has cast it into a simpler form. This method is approved internationally and by ITTC and is much easier to be used for research purposes where many ships are under consideration. In the 7th Asia-Pacific Workshop on Marine Hydrodynamics [13] compared the experimental data to evaluate the Lackenby method. When CFD and experimental findings are compared, Lackenby's shallow water resistance yields a higher total resistance value. Raven [14] also mentions this result, stating that the Lackenby approach yielded greater total resistance estimates.

Barrass [15] on the other hand has produced a very simple formula and is easy to use for all channel configurations. However, his formula overestimates ship squat due to its simplicity. Moreover, using bigger squat values than real ones can be considered a precautionary measure in terms of navigation safety in shallow waters.

Though both Lackenby [11] and Barrass [15] methods have limitations, this research selected the method described by Lackenby for theoretical calculation which has been approved by ITTC [16]. In addition to that, the procedure as proposed by Barras [15] has also been calculated to compare both theoretical results. Finally, both results have been evaluated with the physical measurement for Bangladeshi inland ships.

2. Brief Description Of Eedi By Imo

EEDI in its simplest form can be expressed as follows [17]:

$$\begin{aligned}
\text{EEDI} &= \frac{\text{CO}_2 \text{ Emission}}{\text{Transport Work}} \\
&= \frac{\text{Power} \times \text{Specific Fuel Consumption} \times \text{CO}_2 \text{ Conversion factor}}{\text{Factors} \times \text{Capacity} \times \text{Speed}} \\
&= \frac{\left(\prod_{j=1}^n f_j \right) \left(\sum_{i=1}^{n_{ME}} P_{ME(i)} \times C_{FME(i)} \times SFC_{ME(i)} \right) + (P_{AE} \times C_{FAE} \times SFC_{AE}) + \left(\prod_{j=1}^n f_j \sum_{i=1}^{n_{PTI}} P_{PTI(i)} \times C_{FAE} \times SFC_{AE} \right) - \left(\sum_{i=1}^{n_{eff}} f_{eff(i)} \times P_{AEeff(i)} \times C_{FAE} \times SFC_{AE} \right) - \left(\sum_{i=1}^{n_{eff}} f_{eff(i)} \times P_{eff(i)} \times C_{FME} \times SFC_{ME} \right)}{f_i \times f_c \times f_1 \times f_W \times \text{Capacity} \times V_{REF}} \quad (1)
\end{aligned}$$

Equation 1 of EEDI contains different constants and coefficients. The definition and meaning of those are described in IMO MEPC resolution, as shown in following Table 1 [17]:

Table 1
Description of different parameters of EEDI by IMO

Parameter	Description
P_{ME}	75% of the main engine MCR (Maximum Continuous Rating) in kW
C_{FME}	The non-dimensional conversion factor for the main engine between fuel consumption and CO ₂ emission
SFC_{ME}	Certified Specific Fuel Consumption of the main engine in g/kWh
P_{AE}	Auxiliary Engine Power
C_{FAE}	The non-dimensional conversion factor for auxiliary engine between fuel consumption and CO ₂ emission
SFC_{AE}	Certified Specific Fuel Consumption of the main engine in g/kWh
$P_{PT(i)}$	75% of rated power consumption of shaft motor
$f_{eff(i)}$	Availability factor of innovative energy efficiency technology
$P_{AEff(i)}$	Auxiliary power reduction due to innovative electrical energy-efficient technology
$P_{eff(i)}$	The output of innovative mechanical energy-efficient technology for propulsion at 75% main engine power
f_j	Correction factor to account for ship specific design elements. (E.g. ice-classed ships, shuttle tankers)
f_i	Correction factor to account for ship specific design elements. (E.g. ice-classed ships, shuttle tankers)
f_c	Cubic capacity correction factor (for chemical tankers and gas carriers)
f_l	The factor for general cargo ships equipped with cranes and other cargo related gear to compensate for a loss of deadweight of the ship
Capacity	1. For Passenger Vessel: Gross Tonnage (GT). 2. For Cargo and Oil Tanker: Computed as a function of Deadweight as indicated in 2.3 and 2.4 of MEPC 245(66) (MEPC 245(66), 2014) "2014 Guidelines on the calculation of the Attained EEDI for new ships"
f_w	Non-dimensional coefficient indicating the decrease of speed in representative sea condition of wave height, wave frequency & wind speed
V_{ref}	Ship speed in nautical miles per hour at P_{ME}
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3. Methodology To Revise Eedi Parameters For Inland Ships Of Bangladesh

The methodology for revising EEDI of IMO parameters to be useful for inland ships of Bangladesh will follow the similar procedure by Hasan and Karim (Hasan and Karim, 2019) and MEPC Resolution [17] by IMO. The major changes of the methodology followed by Hasan and Karim [7] are presented in Table 2. The methodology for fixing capacity based on cargo availability and carbon content of fuel remained the same as proposed by Hasan and Karim [7].

Table 2
Changes in methodology and reasons

Change	Previous methods	Proposed methods	Reason
Incorporation of shallow water effect	Hasan and Karim [7] used Schlichting's [8] and Barras [15] methods.	The physically measured result compared with Lackenby [11] and Barras [15] methods	Lackenby [11] is approved by ITTC. Kept Barras's [15] method for comparison.
Fixing the maximum continuous rating (MCR)	The engine output of the main engine was calculated from the Holtrop-Mennen methods [18, 19, 20]	Engine output of the main engine was taken from the Engine curve.	Use of engine curve will provide more accurate information of MCR

3.1. Theory of speed drop due to the shallow water effect

Ships plying on shallow water can easily be affected by the limited draft due to the squat effect. The water velocity is accelerated around the hull as the draft limitation restricts the water flow. This increase in water velocity results in a higher drag and eventually reduces the ship's hull efficiency. After a certain speed of the vessel, this shallow water effect becomes very pronounced. Any ship (regardless of its size) navigating through restricted waterways is heavily affected by these hydrodynamic effects.

3.1.1. International Towing Tank Conference (ITTC) guideline

ITTC recommended in the 'Procedures and guidelines for preparation, conduct and analysis of speed/power trials'

[10] that, if the water depth is less than the larger of the values obtained from the following two formulae, shallow water correction may be applied:

$$h = 3\sqrt{B \cdot T_M} \text{ and } h = 2.75 \frac{V_S^2}{g}, \text{ Where,}$$

h: Water depth in meter

B: Ship's breadth in meter

T_M: Draught at midship in meter

V_S : Ship's speed in m/s

g : Acceleration of gravity in m/s^2

If the above conditions are satisfied and the effect of shallow water on a ship's speed needs to be predicted, ITTC recommended the Lackenby method [11] or the Raven Shallow Water Correction Method [12]. This method does not provide any formulation, rather it is a procedure for a series of tests, which starts with CFD analysis. Later, this analysis is validated with model test and trial data. In practice, this is a very accurate process, but not a generalized process. In addition to that, the builder, owner, and verifier must agree upon this process, as stated in the ITTC [10] guideline. On the other hand, the Lackenby method [11] provides simple formulas and guidelines which are very handy. For this reason, Lackenby's [11] method is considered in this study.

3.1.2. Ship speed loss prediction (Lackenby's method)

The shallow-water correction method most often used is that of Lackenby [11]. It modifies the speed-power curve by correcting the measured speed, assuming unchanged power. Lackenby [11] extended Schlichting's [8] diagrams towards smaller effects and has cast it into a simpler form. This speed correction follows from:

$$\frac{\partial V}{V} = 0.1242 \left(\frac{A_M}{H^2} - 0.05 \right) + 1 - \sqrt{\tanh \left(\frac{gH}{V^2} \right)}, \text{ Where,}$$

V = Open water speed (m/s)

∂V = Reduced speed due to shallow water effect (m/s)

A_M = Midship Sectional Area under water (m^2)

H = Water depth (m)

g = Gravitational Force (m/s^2)

3.1.3. Ship speed loss prediction (Barras method)

The method as described by C. B. Barras [15] the speed losses are calculated in percentage at different Water depth (H)/Ship's draft (T) ratios. Barras proposed two different equations primarily to cover first a range of H/T from 1.10 to 1.50 and secondly a range of H/T values from 1.50 to 3.00. The first range was selected because at this range the most dangerous situations occur, leading to possible groundings. The second range is lead to grounding at high speed, which is less probable. The equations produced by the author of this book were:

% loss in speed = $60 - (25 \times H/T)$, for H/T of 1.1–1.50

% loss in speed = $36 - (9 \times H/T)$, for H/T of 1.5–3.00,

where,

H = Water depth in meter

T = Draft of the ship in meter

3.1.4. Assumptions on the considerations of the effects of confined waters on ship resistance

In this research, the effect of the riverbank on the resistance has not been considered and assumed to have a negligible effect. As stated in the ITTC report [16] the influence of riverbank is negligible when the channel width (W) to the ship breadth (B) ratio is greater than 4. Without any exception, the maximum breadth of the inland ship of Bangladesh is 14 meters. Only very few passenger ships have breadth larger than that. A vessel with a 14-meter breadth when moves through a channel of width less than 56 meters, only then the river bank effect will increase the resistance. However, it is very unlikely in Bangladesh that, a vessel having a breadth of 14 meters, plys through a narrow channel of width less than 56 meters.

The water depth of a certain route is not uniform. For this reason, the effect of shallow water will not be uniform as well. This research relies on the river water depth data at certain points only, which are measured daily by different government organizations of Bangladesh. Therefore, in this research, the average speed as measured in a certain route has been considered as the gained speed after overcoming the average effect of shallow water. In addition to that, the measured highest speed in each case has been considered as the achieved speed without any effect of shallow water, because in these routes there may be certain regions where the depth of water may be quite high than the measured depth at different locations.

3.2. Investigated results on shallow water effect for the Inland Ships of Bangladesh

To find the actual shallow water effect on ship speed, ship speed at service condition was measured for 15 vessels (05 from general cargo ships, 05 from oil tankers and 05 from passenger ships). Android-based app (Speedometer GPS) was used to measure ship speed using satellite. The travelled routes were different and water depths were varied. For this reason, measured speed also varied for the same RPM of the engine. The average speed has been considered as the gained speed after the shallow water effect.

Tables 3 and 4 present the investigated results of the 05 general cargo ships. In Table 3, investigated ship particulars, travelled route through the inland waterways of Bangladesh, travelled distance and water depths at different points are shown. The water levels of the selected river routes in Table 3 were found from the Bangladesh Inland Water Transport Authority [21], data from the 'Flood Forecasting & Warning Centre' of the Bangladesh Water Development Board [22] and data from Chittagong Port Authority. Table 4 presents the speed measured for investigated ships at different locations. Measured top speed in each case has been considered as the achieved speed without any effect of shallow water. Since the measured speed drop due to the shallow water effect was not uniform, it has been presented in a range. To compare the theoretical speed, drop due to the shallow water effect, the same effect has been calculated by the methods explained by Schlichting [8], Lackenby [11] and Barras [15]. The deviations of calculated results from investigated results by those methods have been presented in Fig. 1. In a similar process, as explained above, 05 inland oil tankers

and passenger ships of Bangladesh have been investigated and presented in Tables 5, 6 and Fig. 2 (for oil tankers) and 7, 8 and Fig. 3 (for passenger ships).

Table 3
Investigated cargo ship's particulars, route, water depth

Ship's Dimension (m)	Travelled Route	Distance (km)	Water depth (m)	Average water depth (m)
G.C-1: LXBXT = 47.24X07.95X2.55	Dhaka to Chandpur	68.22	1. Milbarak, Dhaka, Buriganga River: 4.10 m 2. Mirkadim, Dhaleshwari River: 3.50 m 3. Char Ramdaspur, Meghna River: 4.05 m	3.88
G.C-2: LXBXT= 63.00X11.60X3.00	Meghnaghat, Naryanganj to Chittagong	273.89	1. Gazaria, Munshiganj, Meghna River: 4.90 m 2. Char Ramdaspur, Meghna River: 4.50 m 3. Chittagong, Karnaphuly River: 5.03 m	4.81
G.C-3: LXBXT = 66.00X10.98X3.00	Rupshi, Narayanganj to Chittagong	275.75	1. Narayanganj, Shitalakhya River: 4.6 m 2. Mirkadim, Dhaleshwari River: 3.60 m 3. Char Ramdaspur, Meghna River: 3.77 m 4. Chittagong, Karnaphuly River: 4.39 m	4.09
G.C-4: LXBXT= 43.76X7.77X2.29	Fatullah, Narayanganj to Baghabari	189.86	1. Fatullah, Buriganga River: 4.10 m 2. Mirkadim, Dhaleshwari River: 5.10 m 3. Char Ramdaspur, Meghna River: 4.050 m 4. Bhagyakul, Munshiganj, Padma River: 4.30m 5. Aricha, Manikganj, Jamuna river: 7.25m 6. Baghabari, Sirajganj, Jamuna River: 3.90m	4.78

Ship's Dimension (m)	Travelled Route	Distance (km)	Water depth (m)	Average water depth (m)
G.C-5: LXBXT= 71.94X13X4.00	Meghnaghat, Nataryanganj to Chittagong	273.89	1. Gazaria, Munshiganj, Meghna River: 5.45 m 2. Chandpur, Meghna River: 4.43 m 3. Chittagong, Karnaphuly River: 4.98 m	4.97

Table 4
Investigated cargo ship's speeds during the investigation

Ship ID (m)	Service speed (Knot)	Shallow water speed (Knot)	Actual shallow water effect	Lackenby (1963)	Barras (2004)	Schlichting (1934)
G.C-1	9.5	7.50-8.00	16%-21% (Average 18.50%)	19.93%	22.31%	4.04%
G.C-2	10.0	7.50–8.50	15%-25% (Average 20%)	20.61%	21.57%	2.79%
G.C-3	10.5	7.50-8.00	24%-29% (Average 26.50%)	29.47%	25.92%	6.20%
G.C-4	9.5	8.00–9.00	5%-16% (Average 10.50%)	10.83%	17.21%	1.95%
G.C-5	10.5	7.50–8.50	19%-29% (Average 24%)	28.73%	28.94%	3.47%

Table 5
Investigated oil tanker's particulars, route, water depth and speeds during the investigation

Ship's Dimension (m)	Travelled Route	Distance (km)	Water depth (m)	Average water depth (m)
O.T-1, LXBXT= 50.67X10.68X1.80	Fatullah, Narayanganj to Baghabari	189.86	1. Fatullah, Narayanganj, Buriganga River: 3.85 m 2. Mirkadim, Dhaleshwari River: 5.10 m 3. Char Ramdaspur, Meghna River: 3.35 m 4. Bhagyakul, Munshiganj, Padma River: 3.90 m 5. Arihca, Manikganj, Jamuna river: 5.00 m 6. Baghabari, Sirajganj, Jamuna River: 2.90m	4.02
O.T-2, LXBXT= 57.24 X10.00X1.80	Dhaka to Chandpur	68.22	1. Milbarak, Dhaka, Buriganga River: 3.90 m 2. Mirkadim, Dhaleshwari River: 3.50 m 3. Char Ramdaspur, Meghna River: 3.84m	3.75
O.T-3, LXBXT= 70.80X12.50X4.00	Meghnaghat, Naryanganj to Chittagong	273.89	1. Gazaria, Munshiganj, Meghna River: 5.00 m 2. Chandpur, Meghna River: 4.80 m 3. Sadarghat, Karnaphuly River: 5.00 m	4.93
OT-4, LXBXT = 53.00X11X1.8	Godnail, Narayanganj to Barishal	134.56	1. Godnail, Narayanganj, Shitalkhya River: 3.79 m 2. Munshiganj, Dhaleshwari River: 3.50 m 3. Char Ramdaspur, Meghna River: 3.49m 4. Barishal, Kirtankhola River: 2.15 m	3.23

Ship's Dimension (m)	Travelled Route	Distance (km)	Water depth (m)	Average water depth (m)
OT-5, 49.50X10.00X2.00	Dhaka to Bhairab	110.81	1. Milbarak, Dhaka, Buriganga River: 4.00 m 2. Munshiganj, Dhaleshwari River: 3.80 m 3. Gazaria, Munshiganj, Meghna River: 2.60 m 4. Ashuganj, Meghna River: 3.60 m	3.50

Table 6
Investigated oil tanker's speeds during the investigation

Ship ID (m)	Service speed (Knot)	Shallow water speed (Knot)	Actual shallow water effect	Lackenby (1963)	Barras (2004)	Schlichting (1934)
O.T-1	9.50	7.50-8.00	16%-21% (Average 18.50%)	17.62%	15.90%	3.61%
O.T-2	8.50	7.00-7.50	12%-18% (Average 15%)	17.33%	17.25%	2.11%
O.T-3	10.50	7.50–8.50	19%-29% (Average 24%)	28.30%	29.19%	3.57%
OT-4	9.50	7.00-7.50	12%-24% (Average 18%)	29.55%	19.85%	6.81%
OT-5	8.50	6.50-7.00	18%-24% (Average 21%)	22.20%	20.25%	2.72%

Table 7

Investigated passenger vessel's particulars, route, water depth and speeds during the investigation

Ship's Dimension (m)	Travelled Route	Distance (km)	Water depth (m)	Average water depth (m)
P.V-1, LXBXT= 48.56X8.75X1.62	Dhaka to Sureswar, Shariyatpur	85.82	1. Milbarak, Dhaka, Buriganga River: 3.90 m 2. Munshiganj, Dhaleshwari River: 3.40 m 3. Sureswar, Padma River: 2.75 m	3.38
P.V-2, LXBXT= 45.95X09.15X1.40	Dhaka to Tushkhali, Pirojpur	249.89	1. Milbarak, Dhaka, Buriganga River: 4.00 m 2. Munshiganj, Dhaleshwari River: 3.40 m 3. Char Ramdaspur, Meghna River: 3.88m 4. Barishal, Kirtankhola River: 2.23 m	3.38
P.V-3, LXBXT= 67.47X10.98X1.70	Dhaka to Chandpur	68.22	1. Milbarak, Dhaka, Buriganga River: 4.0 m 2. Mirkadim, Dhaleshwari River: 4.42 m 3. Char Ramdaspur, Meghna River: 4.0 m	4.14
P.V-4, LXBXT= 54.29X10.84X1.60	Dhaka to Patuakhali	197.10	1. Milbarak, Dhaka, Buriganga River: 4.00 m 2. Munshiganj, Dhaleshwari River: 3.20 m 3. Char Ramdaspur, Meghna River: 3.80 m 4. Patuakhali, Patuakhali River: 2.93m	3.48
P.V-5, LXBXT = 85.34X13.57X1.80	Dhaka to Barishal	147.61	1. Milbarak, Dhaka, Buriganga River: 4.00 m 2. Munshiganj, Dhaleshwari River: 3.40 m 3. Char Ramdaspur, Meghna River: 4.0 m 4. Barishal, Kirtankhola River: 4.45 m	3.96

Table 8
Investigated passenger vessel's speeds during the investigation

Ship ID (m)	Service speed (Knot)	Shallow water speed (Knot)	Actual shallow water effect	Lackenby (1963)	Barras (2004)	Schlichting (1934)
P.V-1	11.5	8.50–9.50	17%-26% (Average 21.50%)	28.56%	17.22%	14.05%
P.V-2	12.0	8.50–9.50	21%-29% (Average 25%)	29.16%	14.27%	16.25%
P.V-3	13.5	10.50–11.00	18%-22% (Average 20%)	29.83%	14.08%	17.12%
P.V-4	10.0	7.50–8.50	15%-25% (Average 20%)	24.16%	16.43%	7.31%
P.V-5	12.5	10.50–11.00	12%-16% (Average 14%)	32.85%	16.20%	14.27%

Table 9 summarizes the average speed drops in the shallow water of those investigated ships. In addition to that, the average of theoretical results by Schlichting [8], Lackenby [11] and Barras [15] and average deviation from the investigated results for each type of ship are also presented.

Table 9
Average shallow water effects by investigations and theoretical methods

Type of investigated ships	Average speed drop (Investigated)	Average speed drop by different methods and deviation from the investigation					
		Lackenby (1963)	Deviation (%)	Barras (2004)	Deviation (%)	Schlichting (1934)	Deviation (%)
Cargo Ships	19.90%	21.91%	10.10%	23.19%	16.53%	3.69%	-81.46%
Oil Tankers	19.30%	23%	19.17%	20.49%	6.17%	3.76%	-80.52%
Passenger Ships	20.10%	28.91%	43.83%	15.64%	-22.19%	13.80%	-31.34%

3.3. Fixing the main engine MCR and P_{ME} considering shallow water effect.

A previous paper by Hasan and Karim [7] has suggested 60% MCR based on the average of verified ship data. As mentioned in Table 2, the ship data verification process was based on the Holtrop-Mennen methods [18, 19, 20], which requires too many ships data/information. Unavailable ship data/information was assumed in most cases by Hasan and Karim [7].

In this study, MCR was considered from the practically measured 15 ships that were used to identify the average shallow water effect. During the physical investigation, the main engine RPM was measured when the ship started to move at continuous RPM for the maximum possible time. A digital tachometer was used for RPM measurement. The main engine load at the MCR was found from the Engine performance curve.

Following Tables 10, 11 and 12 present the onboard measured RPM data and corresponding main engine loads for Inland General Cargo Ships, Oil Tankers and Passenger Ships, chronologically.

Table 10
Main engine rpm and engine load at actual for 05 Inland Cargo Vessels of Bangladesh

Ship's ID	Main Engine Power (HP)	Engine RPM at service speed	Main Engine Load (Average)
G.C-1	350X1	1395	78.00%
G.C-2	350X2	1402	80.00%
G.C-3	350X2	1275	61.00%
G.C-4	350X1	1380	76.00%
G.C-5	720X2	1044	64.50%

Table 11
Main engine rpm and engine load at actual for 05 Inland Oil Tankers of Bangladesh

Ship's ID	Main Engine Power (HP)	Engine RPM at service speed	Main Engine Load (Average)
O.T-1	350X2	1320	67.00%
O.T-2	300X2	1320	65.00%
O.T-3	818X2	1256	77%
OT-4	300X2	1290	60%
OT-5	350X1	1395	76%

Table 12
Main engine rpm and engine load at actual for 05 Inland Passenger Ships of Bangladesh

Ship's ID	Main Engine Power (HP)	Engine RPM at service speed	Main Engine Load (Average)
P.V-1	350X2	1420	82%
P.V-2	300X2	1620	70%
P.V-3	750X2	1269	82%
P.V-4	350X2	1395	78%
P.V-5	1000X2	846	90%

The average main engine loads of investigated ships are

- a. 71.90% for General cargo ships
- b. 69% for Oil Tankers
- c. 80.40% for Passenger Ships

Fixing 70% MCR for General Cargo and Oil Tanker seems reasonable. For passenger ships, MCR can be 80%, which is the average of the investigated ships' MCR.

4. Result

Section 3 has explained the required changes of $EEDI_{BD}$ parameters established previously by Hasan and Karim [7]. Based on the new physical investigations, the changed values of those parameters have also been proposed. Following Table 13 summarizes those proposals.

Table 13
Comparison of the value of different EEDI parameters as defined by IMO and those for inland ships of Bangladesh.

EEDI Parameter	Defined by Hasan and Karim [7]	Revised value for the inland ship of Bangladesh
MCR	60%	70% for Cargo and Oil Tanker and 80% for Passenger Ships
P_{ME}	60% of the main engine MCR in kW	Main Engine power at 70% MCR for Cargo and Oil Tankers and 80% for the Passenger Ships
V_{REF}	Ship speed is at P_{ME} (at 60% MCR)	Ship speed at P_{ME} , incorporating the average shallow water effect (at 70% MCR for cargo and oil tanker and at 80% MCR for passenger ships)
Capacity	85% of the design dead weight for Cargo and Oil Tankers but 100% Gross Tonnage (GT) for passenger ships	The proposal by Hasan and Karim [7] was found reasonable.
Carbon Content of Diesel oil	0.76	The proposal by Hasan and Karim [7] was found reasonable.
C_F (non-dimensional conversion factor between fuel consumption and CO_2 emission based on carbon content.)	C_F : Carbon Content in the fuel X (Molecular weight of CO_2 /Molecular weight of Carbon) = $0.76 \times (44/12)$ = 2.787 gm CO_2 /gm fuel	The proposal by Hasan and Karim [7] was found reasonable.

4.1. Sample Calculation

Based on the revised value, a good number of inland General Cargo, Oil Tanker and Passenger Ships of Bangladesh were taken into consideration to calculate $EEDI_{BD}$. Table 14 shows sample calculation using IMO defined EEDI formulation and using the revised EEDI parameters for Bangladesh ($EEDI_{BD}$).

Table 14
Sample calculation of different values of EEDI for inland cargo ship of Bangladesh

Vessel's Basic parameters: Length: 71.94 m, Breadth: 13 m, Draft: 4 m, Block Coefficient: 0.794			
	EEDI by IMO	Previous EEDI_{BD}	Updated EEDI_{BD}
Installed Engine Power (kW)	1075	1075	1075
P _{ME} (kW)	806	644	756
MCR (%)	75%	60%	70%
Main Engine RPM at MCR (% of the maximum engine RPM)	90%	84.50%	88.50%
Open water speed at MCR (kW)	10.50	10.00	10.40
River depth (m)	Not considered	4.97	4.97
Shallow water effect	Not considered	4% (Schlichting (Schlichting, 1934) method)	28.73% (Lackenby (Lackenby, 1963) method) 28.94% (Barras (Barras, 2004) method)
C _{FME} (Diesel oil)	3.206	2.787	2.787
SFC _{ME} (g/kWhr)	190	190	190
P _{AE} (kW)	53	53	53
C _{FAE} (Diesel oil)	3.206	2.787	2.787
SFC _{AE} (g/kWhr)	200	200	200
P _{PT(i)} , f _{eff(i)} , P _{AEff(i)} , P _{eff(i)}	0	0	0
f _j , f _i , f _c , f _l , f _w	1	1	1
Capacity (Tonne)	2200	1870	1870
V _{REF} (knot)	10.50	9.60	7.48 (Lackenby) 7.46 (Barras)
Index value (gram/kW.hr)	22.75	19.84	22.15

5. Discussion

The average actual shallow water effect varied from 19.30% – 21.10% considering 5 measured ships of each type (total 15 ships). Since this effect mainly depends upon the clearance under the keel, different ship drafts will produce different amounts of effect in the same channel. Practically it is not possible to fix a single

factor of speed deduction while considering the shallow water effect. Based on the actual measurement, a 20% speed drop can be considered due to the shallow water effect to establish $EEDI_{BD}$ baselines for inland general cargo, oil tanker and passenger ships of Bangladesh.

$EEDI_{BD}$ for any new inland Bangladeshi ship, the individual shallow water effect can be calculated theoretically at the design stage. The calculated values by Lakenby [11] and Barras [15] methods are nearer to the actual. However, for all 3 types of vessels, results calculated by Schlichting [8] are much lower than the investigated results. Therefore, both Lakenby [11] and Barras [15] methods can be used for new ships instead of Schlichting [8].

6. Conclusion

Although inland shipping accounts for only 9% of the total CO_2 emissions of global shipping [3], attempts to reduce CO_2 from its current level can be very important for individual countries from an economic and environmental perspective. Restrictions on inland navigation will vary from country to country because of the differences in geographical conditions. As a result, a generalized EEDI like for sea-going ships is not possible. This reanalysis is a step to modify EEDI formulation to be applicable for inland ships of Bangladesh.

As mentioned in Section 3.1.4 the effect of the width of narrow riverbanks on ship resistance has not been considered. The assumption is seemed fairly all right and explained in the same Section. However, for future research, these effects can be taken into consideration to justify the assumption.

Declarations

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Author Contributions

Conceptualization, S.M. Rashidul Hasan; Methodology, S. M. Rashidul Hasan; Software, S. M. Rashidul Hasan; Validation, S. M. Rashidul Hasan and Md. Mashud Karim.; Formal analysis, S. M. Rashidul Hasan.; Investigation, S. M. Rashidul Hasan, resources, S. M. Rashidul Hasan and Md. Mashud Karim; Writing—original draft preparation, S. M. Rashidul Hasan; Writing—review and editing, S. M. Rashidul Hasan and Md. Mashud Karim; Visualization, S. M. Rashidul Hasan.

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Not applicable.

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Competing interests

The authors declare that they have no competing interests.

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Figures

Figure 1

Deviation in shallow water effect by different methods from the investigated result for Cargo Ships

Figure 2

Deviation in shallow water effect by different methods from the investigated result for Oil Tankers

Figure 3

Deviation in shallow water effect by different methods from the investigated result for Passenger ships