Model Design of Inter-Island Ships Base on Transport Demand and Port Facility

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Abstract—Inter-island transportation plays an important role in order to strengthenen inter-island connectivity in Indonesia. The challenge in organizing the inter-island transportation in Indonesia is availability of ro-ro ferry corresponding to port class, trajecy distance and demand of transport service in each inter-island transportation network. The port class becomes constrain of ship tonnage to able to operate in a route. This means that port class also become constrain for ship dimension and capacity. In ither hand, demand of transport capacity and ship speed are dependent of service transport demand and trajecy distance. This paper discusses regarding concept design model of ro-ro ferry. This model is formulated based on analysis results of technical specification consist of main dimension, tonnage, loading capacity and ship speed regarding operation pattern of inter-island transport. The ship length and breadth are estimated by using matrix approach to arrange vehicle in main deck. The ship height and draught are estimated through empirical approximation of ratio between ship length and ship height and ratio between ship breadth and ship draught. The ship tonnage is estimated by using empirical formula. The maximum speed of ship is determined from result of resistance analysis of sample ships. The technical specification of ship is separated base on the port class. Following the obtained loading capacity and ship speed, operation pattern and transport capacity in a certain route is determined base on port class and trajecy distance. Finally, model design of ro-ro ferry consist of design requirement (loading capacity and ship speed) is obtained base on demand of service transport for each route considering port class and trajecy distance. The main dimension is estimated base on required loading capacity. The maximum speed is determined to be validated with required speed.

Keywords—Inter-Island Transport, Ro-Ro Ferry, Model Design

I. INTRODUCTION

Intern-island transportation is play an important role in sea transportation in order to strengthenen the inter-island connectivity. The inter-island transportation in Indonesia was organized as a part of land transportation. Service of the inter-island transportation was conducted by placement and operating ships continously and regularly in every route of inter-island network. The ship type required to be operated in a inter-island transportation trajecy is a ro-ro ferry.

The inter-island transportation network consist of port and route. Two ports is connected by one route. Base on port hierarchy of Indonesia, the port class is devided into three classes [7], port capacity for berthing service is determined based on ship tonnage (GT). The first class is a port to be able to service ships with gross tonnage (GT) more than 1000 GT, the second calss is that for ships between 500 GT and 1000 GT and the third class is that for ships with capacity less than 500 GT. These ports capacity was referred as variable of main facility of port at sea within this paper.

 Following the regulation about mechanism of determination and formulation for calculating tariff of inter-island transportationa in Indonesia [8], the ship tonnage was classified base on 8 group of trajecy distance range from ships tonage of about 300 GT for trajecy distance not more than 1 miles to ships tonage of about 1500 GT for trajecy distance larger than 120 miles. If the classification of trajecy distance is related to the port class corresponding to the ship tonnage, it can be concluded that the port class III was provided for route with trajecy distance less than 10 miles, the port class II for route with trajecy distance between 10 miles to 80 miles and the port class I was provided for the route with trajecy distance more than 80 miles. In practical point of view, the port capacity is more correlated to ship tonnage to be operated in a certain route corresponding to demand of transport service. This is based on evidence that ships with tonage more than 1000 GT was operated in trajecy distance less than 10 miles especially in the route with high demand of transport service [1]. Oppositely, ships with tonnage less than 500 GT or even more less than 300 GT may also be operated in a trajecy distance more than 80 miles.

As explained in the previous second paragraph, the ship tonnage to be operated in an inter-island route depends on the port class. The ship tonnage directly affect the ship dimension. As the ship loading consist of vehicle and passenger to be located in the deck area, the length and the breadth of ship depend on her loading capacity. In the other hand, the ideal of maximum ship speed is influenced by
proportion of length and breadth of ship. The draught, height and freeboard of ship should exactly correspond to the proportion of length and breadth. The ratio between breadth and draught and the freeboard of ship is related to ship stability.

Based on trajec distance, operation frequency per unit time of service depends on ship speed. In principle, maximum service frequency for each route should be the same. However, for a certain distance difference, number of operated ships is larger in longer trajec distance. The loading capacity and service frequency become main variable in determination of transport capacity of inter-island transportation. Maximum transport capacity in a certain route of inter-island transportation depends on maximum loading capacity of a ship to be operated corresponding to the port class. The maximum transport capacity was referred as standard or parameter of transport service demand.

This paper discusses regarding model design of ro-ro ferry operates in Indonesia base on service transport demand corresponding to port class and trajec distance. Model of concept design is formulated base on relation between port hierarchy and trajec distance with technical specifcation of ship and its implication on transport capacity of route.

Tonnage, dimension, speed and loading capacity of ro-ro ferry will be grouped base on ship tonnage in accordance with port hierarchy. As the standard of maximum demand of transport service, the maximum of transport capacity of route was also grouped refer to the port classification. The maximum transport capacity was confined only for one trajec in every route, in other word, there is only one quay for every port noose. The model design of ro-ro ferry to be formulated in this paper consist of estimation of loading capacity as function of demand of transport service in every class of port, determination of main dimension as function of loading capacity and estimation of maximum ship speed. Here, the loading capacity means the number of car to be accomodated in vehicle deck area.

II. RESEARCH METHODOLOGY

This research was conducted with four analysis steps consist of : formulation for estimating maximum speed of ro-ro ferry, classification of ro-ro ferry based on port hierarchy, estimation of loading capacity of inter-island transportation route according to the port hierarchy and hierarchy of model design for ro-ro ferry.

Formulation for estimating the maximum speed of ro-ro ferry was conducted through resistance analysis of 50 sample ships with 5 variation of ship breadth as shown in Table I. The length and the breadth of ships was estimated as function of loading capacity of vehicle [2] with the equations as follows:

\[ LBP = \frac{(\Sigma (C_1 L_1 V_1) + Dfa (C V -1))}{Lr} \]  
\[ B = \frac{(\Sigma (R_1 V_1 B_1) + Ds (Rv -1)) + 2 Dvp + 2 Dps}{Lr} \]  

Here \( C_1, V_1, Dfa, C, \) and \( Lr \) are the number of coulom for each vehicles classification, length of each vehicles classification, distance between the vehicles in one coulom, number of coulom and ratio between the length of vehicle deck and the length between perpendicular of ship, respectively. \( Lr \) was determined to be 0.9. \( Rv, Bv, Ds, Rv, Dvp, \) and \( Dps \) indicate the number of row for each vehicles classification, breadth of every class of vehicles, distance between the vehicles in one row, the number row, the distance between the vehicles with the border of vehicles area and the distance between the border of vehicles area and the ship side, respectively . Following technical guidance of requirement for minimum service of river, lake and inter-island transportation in Indonesia [10], \( Dfa, Ds, \) dan \( Dvp\) are determined to be 0.3 meters, 0.6 meters and 0.6 meters, respectively. While \( Dps \) is determined to be 1.5 meters.

The ship length \( (LBP) \), height \( (H) \), and draught \( (T) \) for every variation of breadth \( (B) \) are determined within range of ratio of main dimension of ro-ro ferry operating in Indonesia [2]. The ship height and her draught are determined to be the same for every breadth variation.

### TABLE I. MAIN DIMENSION AND LOADING CAPACITY

<table>
<thead>
<tr>
<th>Length Series</th>
<th>Code</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>B6</th>
</tr>
</thead>
<tbody>
<tr>
<td>B (m)</td>
<td>9.00</td>
<td>11.70</td>
<td>14.40</td>
<td>17.10</td>
<td>19.80</td>
<td></td>
</tr>
<tr>
<td>H (m)</td>
<td>2.70</td>
<td>3.51</td>
<td>4.12</td>
<td>5.08</td>
<td>6.61</td>
<td></td>
</tr>
<tr>
<td>Code</td>
<td>LBP (m)</td>
<td>T(m)</td>
<td>CB</td>
<td>Load capacity/Lr (Vn)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L5</td>
<td>29.11</td>
<td>10</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L6</td>
<td>35.00</td>
<td>12</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L7</td>
<td>40.89</td>
<td>14</td>
<td>0.55</td>
<td>0.55</td>
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<td></td>
</tr>
<tr>
<td>L8</td>
<td>46.78</td>
<td>16</td>
<td>0.55</td>
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</tr>
<tr>
<td>L9</td>
<td>52.67</td>
<td>18</td>
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<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L10</td>
<td>58.56</td>
<td>20</td>
<td>0.55</td>
<td>0.55</td>
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<td></td>
</tr>
<tr>
<td>L11</td>
<td>64.44</td>
<td>22</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L12</td>
<td>70.33</td>
<td>24</td>
<td>0.55</td>
<td>0.55</td>
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<td></td>
</tr>
<tr>
<td>L13</td>
<td>76.22</td>
<td>26</td>
<td>0.55</td>
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</tr>
<tr>
<td>L14</td>
<td>82.11</td>
<td>28</td>
<td>0.55</td>
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</tr>
<tr>
<td>L15</td>
<td>88.00</td>
<td>30</td>
<td>0.55</td>
<td>0.55</td>
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<td></td>
</tr>
<tr>
<td>L16</td>
<td>93.89</td>
<td>32</td>
<td>0.55</td>
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</tr>
<tr>
<td>L17</td>
<td>99.78</td>
<td>34</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L18</td>
<td>105.67</td>
<td>36</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L19</td>
<td>111.56</td>
<td>38</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L20</td>
<td>117.44</td>
<td>40</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L21</td>
<td>123.33</td>
<td>42</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L22</td>
<td>129.22</td>
<td>44</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Value of \( Bn \) and \( Ln \) indicate number of row and column of goup IV of vehicles loaded, respectively. The subscript \( n \) indicates variation of ship breadth and length. Vehicle dimension shown in Table 2.

All sample ships have the same characteristics of hull form. The stern has transom form with normal stem without bulbous bow. The hull form coefficient consist of the block coefficient is 0.55, the midship coefficient is 0.94, the waterline coefficient is 0.83 and the prismatic coefficient is 0.58. An example of hull form of sample ships in Table 1 is shown in Figure 1.

![Fig. 1. An example of hull form of sample ships](image)

The resistance of sample ships was estimated for speed variation until 22 knots with interval of 0.5 knots. The resistance of sample ships were estimated by using Holtrop Method [5]. According to the obtained resistance, estimation
of the recommended maximum ship speed was formulated with the following step:

a. Estimation of ratio between resistance and cumulative loading capacity of all sample ships (RLRc) using the following equation:

\[ RLRc = \frac{\sum (Vmr, RLR_i)}{\sum Vmr_i} \]  \hspace{1cm} (3)

\( Vmr_i \) is the maximum speed in knot of each sample ships with smaller resistance compared with the other sample ships within the same group of breadth and \( RLR_i \) indicates the ratio between resistance in maximum speed and loading capacity of each sample ships in Newton per vehicle unit (N/Vunit).

b. Estimation of speed for each sample ships according to ratio between resistance and cumulative loading capacity (RLRc) referred to point a. \( RLRc \) between the calculated ship speed is determined by linear interpolation.

c. Formulation for estimating ship speed (V) as function of ship length (LBP) and breadth (B) using regression approach with ship speed as independent variable obtained in point b.

d. The formula for calculating ship speed in point c then compared with ship speed obtained as function of Froude number [4] shown in the equation (4).

\[ V = Fn \times (gL)^{0.5} \]  \hspace{1cm} (4)

\( V \) is the ship speed in m/s. \( Fn \) is Froude number. Here, the Froude number was determined to be 0.294 according to the block coefficient \((CB)\) of sample ships of 0.55 [4]. The ship length is LBP in meter.

The second step is classification of ro-ro ferry corresponding to hierarchy of port. Determination of main dimension of sample ships and their grouping for classification purpose are conducted with the following steps:

a. Determination of vehicles area and loading capacity by using matrix simulation approach for car placement in car deck or main deck of ro-ro ferry. Length of the vehicle area \((Lva)\), breadth of vehicle area \((Bva)\) and loading capacity \((Lc)\), respectively were determined by using the equations (5) – (7) as follows:

\[ Lva = (\Sigma (Cv_i \times Lv_i)) + Dfu \times (Cv - 1)) \]  \hspace{1cm} (5)

\[ Bva = (\Sigma (Rv_i \times Bv_i)) + Ds \times (Rv - 1)) + 2Dvp \]  \hspace{1cm} (6)

\[ Lc = (\Sigma (Rv_i \times Cv_i \times Iv_i)) \]  \hspace{1cm} (7)

\( Iv_i \) indicates index conversion unit for each vehicle group as shown in Table II.

b. The length between perpendiculars \((LBP)\) as function of length of vehicle area \((Lva)\) was estimated by using the equation (8) as follow.

\[ LBP = \frac{Lva}{Lr} \]  \hspace{1cm} (8)

\( Lr \) indicates the ratio between the length of vehicle area and the ship length \((Lva/LBP)\). The value of \( Lr \) was determined to be 0.9.

c. The ship breadth \((B)\), the ship height \((H)\) and the ship draught \((T)\) were estimated from ratio of main dimension by using the equation as follows [2].

\[ LBP/B = 0.594 LBP^{0.4832}; \pm 0.512 \]  \hspace{1cm} (9)

\[ LBP/H = 5.2463 (LBP/B)^{0.6792}; \pm 1.592 \]  \hspace{1cm} (10)

\[ B/T = 1.1765 (B/H)^{1.617}; \pm 0.569 \]  \hspace{1cm} (11)

d. Estimation of maximum speed using equation obtained in the first step analysis.

e. The gross tonnage \((GT)\) was calculated by using the equation (12) as follows [9].

\[ GT = (0.2 + 0.02 \log_{10} Vr) \times Vr \]  \hspace{1cm} (12)

where \( Vr \) is volume of ship tonnage defined as volume of closed area of ship hull and volume of closed area of superstructures \((Vss)\). The volume of ship hull and the volume of superstructures of ro-ro ferry can be estimated by using the formulae proposed by Asri [3] as follows.

\[ Vh = 1.04 LBP \times B \times C \times (1.25 \times H/T - 0.25) \]  \hspace{1cm} (13)

\[ Vss = LBP \times B \times (0.0036 LBP \times B + 0.6677) \]  \hspace{1cm} (14)

Here the block coefficient is mean of block coefficient. It was assumed to be 0.6.

e. Classification of dimension, speed and loading capacity base on tonnage of ro-ro ferry in accordance with port hierarchy.

The third step is estimation of transport capacity of inter-island transportation through the following steps.
a. Estimation of ship speed dan pattern of time operation in each trajectories distance with the following equation.

\[ St = c \, Pt \] (15)

\[ Vo = Rd / St \] (16)

\[ Ff = \text{int} \left[ \frac{Ust}{(Pt + St)} \right] \] (17)

\( St \) and \( Pt \) indicate sail time and time of ship in port, respectively designated in hour/trip. \( Pt \) was determined to be 1 hour/trip [6]. \( c \) is integer with minimum value of 1 and its maximum value is determined until \( Vo \) the same as maximum speed \( (V_{max}) \) obtained from the equation in the first step of analysis. \( c \) was also confined with operation frequency \( (Ff) \) atleast 2 trips for longest trajecit distance \( (Rd) \) (mile) per unit time service \( (Ust) \). In accordance with estimation of maximum load capacity, \( Ust \) was determined to be 24 hours/day.

b. Determination of number of ship departured \( (Nsd) \) successively in each noose port with the following equation.

\[ Nsd = \frac{(Pt + St)}{Pt} \] (18)

c. Determination of operation frequency \( (Ff_n) \) of each ship according to successive departure using the equation (19) as follow.

\[ Ff_n = \text{int} \left[ \frac{(Ust - (n - 1) \, Pt)}{(Pt + St)} \right] \] (19)

\( n \) is departure order of each ship.

d. Estimation of total operation frequency \( (Fft) \) and total service frequency \( (Fs) \), respectively using the equations as follow.

\[ Fft = 2 \, (\Sigma Ff_n) \] (20)

\[ Fs = 2 \, (\Sigma Ff_n + (Nsd - 1)) \] (21)

The calculated operation frequency \( (Ff_n) \) is arrival of ship crossing to destination port in a unit time service. There is only one of several operated ships using equal operation time with the unit service time. The other ships are still able to depart in running time or service day but the arrival time is in the next service day. Therefore, the number of departured ships \( (Nsd) \) become addition factor in determination of total service frequency. As the ship departure from noose port, multiplier 2 was used in the equations (20) ans (21) in order to obtain the total frequency.

e. Determination of ship operated \( (Nf) \) by using the equation (22) as follow.

\[ Nf = 2 \, Nsd \] (22)

f. Estimation of transport capacity of route \( (Tc) \) as function of total service frequency \( (Fs) \) and loading capacity \( (Lc) \) with the following equation (23).

\[ Tc = Fs \, Lc \] (23)

The last step is formulation of model design of ro-ro ferry namely concept design. Discussion in this step is continuation of the previous step, consist of:

a. Formulation for estimating loading capacity \( (Lc) \) as function of transport service demand \( (Td) \) using the equation (24) as follow.

\[ Lc = c \, \frac{(Td)}{(Td_{max})} \] (24)

Here, \( c \) was determined by regression analysis of relation between \( Lc \) and ratio \( Td/Td_{max} \). Maximum demand of transport service \( (Td_{max}) \) was used as constrain variable for service capacity corresponding to port hierarchy. Data of \( Lc \) and \( Td \) are calculated data obtained in second step of analysis. The value of \( Td \) was taken from transport capacity of crossing route \( (Tc) \) according to loading capacity \( (Lc) \) of operated ship. \( Td_{max} \) is taken as the largest value of loading capacity of crossing route \( (Tc) \) in each route group corresponding to port hierarchy.

b. Formulation for estimating main dimension of ro-ro ferry referring results of the second step. The main dimension consists of ship length \( (LBP) \) as function of loading capacity \( (Lc) \), ship breadth \( (B) \) as function of \( LBP \), ship height \( (H) \) as function of \( LBP \) and \( B \), and draught \( (T) \) as function of \( B \) and \( H \). Formulation for estimating the draught is also conducted by considering effect of ratio between breadth and draught \( (B/T) \) and ratio between freeboard and breadth \( (Fb/B) \) for ship stability point of view. The vertical center of gravity significantly decreases when \( B/T \) is larger than 5.5 but righting arm tends to increase as ratio \( B/T \) increases [3]. Maximum righting arm tends also to increase as ratio \( Fb/B \) increases but the alteration of righting arm is not significant when this ratio is larger than 0.08.

c. Formulation for determining maximum speed. This part is to confirm analysis results obtained in part A (Formulation for determining maximum ship speed).

### III. RESULTS AND DISCUSSION

**A. Formulation for Determining Maximum Speed**

According to calculation results of resistance for sample ships, the ships with larger length in the same breadth group have smaller gradient of resistance increasing due to increase the ship speed. Therefore, the ship with larger length have smaller resistance compared with the ships with smaller length in a certain range of ship speed as shown in Figure 2. Every group of breadth has similar trend of resistance alteration.

![Fig. 2. Resistance of sample ship as function of ship speed](image-url)
Ships with larger dimension in length have larger resistance compared with others sample ships on their maximum relative speed in the same breadth group. As gradient of difference in resistance become more larger when the ship length increases, ratio between resistance and loading capacity (R/Lc) become larger for ships with larger dimension in length.

For ships in the same group of length between perpendicular, the ratio between resistance and loading capacity (R/Lc) for ships with larger breadth is larger than the smaller ones except for ships in the breadth series 6 (the sample ships with largest breadth) which are have smaller ratio R/Lc compared with the others group of breadth.

The smallest ratio of R/Lc is 1685.543 Newton per unit dimension of vehicle (N/Vu). This is for sample ship of B6L11 series. The largest ratio of R/Lc is 4293.871 N/Vu for sample ship of B5L20 series. Using the equation (3), the cumulative ratio of R/Lc for all sample ships is 3414.015 N/Vu. According to this cumulative ratio of R/Lc, the ship speed can be estimated as shown in the following Table III.

<table>
<thead>
<tr>
<th>TABLE III. RECOMMENDED MAXIMUM SPEED OF SAMPLE SHIPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length Series</td>
</tr>
<tr>
<td>B (m)</td>
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<tr>
<td>-------</td>
</tr>
<tr>
<td>B5</td>
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<tr>
<td>B4</td>
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<td>L21</td>
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<tr>
<td>L22</td>
</tr>
</tbody>
</table>

*Ship speed with ratio (R/Lc) = 3414.015 N/Vu

Figure 3 shows ship speed according to the ship speed shown in Table III as function of ship length and breadth.

The ship speed has high linear correlation with the length between perpendicular (LBP). However, the ratio between ship length and ship breadth (LBP/B) needs to be included as variable in order to consider effect of ship breadth on the ship speed. The unit for speed variable (LBP + LBP/B) is meter and unit for the ship speed is meter per second (m/s). Therefore, the axis value used here is root square of product between gravity acceleration and the number of speed variable shown as axis in Figure 3. Base on results of regression analysis as shown in Figure 3, the maximum speed (Vmax) of ro-ro ferry may be estimated by using the equation (25) as follow.

\[ V_{\text{max}} = 0.729 \left( \frac{g (LBP + LBP/B)^{0.5}}{0.7295} \right) \]

If the ship speed is calculated by using the equation (25), the obtained result is different with the ship speed used to develop the regression equation (see Table IV). The difference between the obtained speed and the data is 0.239 percent.

The calculated speed for ships with larger ratio of LBP/B become larger than that for smaller ratio for sample ships with the same length between perpendicular. This is because of addition of LBP and LBP/B in the equation (25). Using the Froude number formula in the equation (4), the same speed will be obtained for ships with the same length between perpendicular even the breadth of ships is different. As shown in Figure 3, generally the ship speed obtained from the equation (25) is larger than that obtained by Froude number approach. The difference is ranged from 1.92 knots up to -0.80 knots or 19.93% to -3.95% with mean of 0.62 knot or 5.01%.

B. Classification of Ro-Ro Ferry Base on Port Hierarchy

There are 884 variation of column arrangement of vehicles was performed in order to estimate the main dimension of sample ships. Variation for single arrangement for vehicles class of IV, V, and VI consist of 19, 14, and 10 arrangement. Variation for combination arrangement between class vehicles of IV and V, class vehicles of IV and VI and class vehicles of V and VI with arrangement of 158, 109 and 77, respectively. Variation for three combination between the class vehicles of IV, V and VI with 497 arrangement.

Using the equation (5), range of length of vehicle area (Lva) for the 884 variation of column arrangement of vehicles is obtained between 19.6 meters to 117.1 meters. Within this range, there are only 553 variation of length of vehicle area.

The breadth of vehicles class IV, V, and VI is the same, namely 2.1 meters. By using the equation (6), alternative for breadth of vehicle area is obtained to be 6.0 meters for arrangement of 2 row vehicles, 8.7 meters when the vehicles are arrange to be 3 row, 11.4 meters for 4 row of vehicles, 14.1 meters in cases of 5 row and 16.8 meters when the number of row become 6 vehicles.

As explained in the previous two paragraphs, there are 553 alternative for length of vehicle area (Lva) and 5 alternative of breadth of vehicle area (Bva). However, only 886 variation of vehicle area (Lva x Bva) was choosen through analysis of combination between Lva and Bva. As variable for length and breadth of ship, combination between

Fig. 3. Recommended maximum speed of sample ships

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the length and the breadth of vehicle area was determined following proportion of length between perpendicular and ship breadth as implicated in the equation (9).

The length of vehicle area (Lva) is function of number of column for each group vehicle (C). The breadth of vehicle area (Bva) is function of number of row for each group vehicle (R). Loading capacity (Lc) for every combination of Lva and Bva is calculated by using the equation (7). Range of loading capacity is obtained from 7.509 vehicles in combination of Lva = 19.6 meters and Bva = 6.0 meters to 132.906 vehicles in combination of Lva = 117.1 meters and Bva = 16.8 meters. Range of the loading capacity and length of vehicle area for each group of ship breadth is shown in Figure 5.

Figure 4 shows the length of vehicle area as a function of loading capacity. The length between perpendicular of ship as function of length of vehicle area was calculated by using the equation (8) for each variation of vehicle area (Lva x Bva). The obtained range of length between perpendicular is 21.778 meters for loading capacity of 132.91 vehicles (Vu) in the combination of Lva = 117.10 meters and Bva = 16.80 meters.

Figure 5 shows the length of vehicle area as a function of loading capacity. The length between perpendicular of ship as function of number of row for each group vehicle (R) is function of number of row for each group vehicle (i). The breadth of vehicle area (Bva) as function of length between perpendicular (Lva) is function of number of row for each group vehicle (i).

Figure 5 shows the variation of dimension, tonnage, and speed of ro-ro ferry in loading capacity group.

The height and draught of ship for every dimension of length and breadth are also shown in Figure 5. These dimension were calculated by using the equation (10) and the equation (11), respectively. The ship speed for every variation of main dimension was estimated by using the equation (25) as well as shown in Figure 5.

There are 886 variation of main dimension of ship sample through analysis as explained the previous three paragraphs. The gross tonnage for all sample ships was calculated by using the equation (12) – (14). The sample ships with length (LBP) larger than 59.889 meters with breadth (B) larger than 14.642 meters have gross tonnage larger than 1.500. The main dimension and the ship speed shown in Figure 5 are only for sample ships with gross tonnage less than 1.500 GT.

Regarding the port hierarchy, operational classification of ro-ro ferries was determined as shown in Table IV.

TABLE IV. CLASSIFICATION OF RO-RO FERRIES BASE ON PORT

<table>
<thead>
<tr>
<th>Tonnage Groups</th>
<th>Ship’s Tonnage</th>
<th>LBP (m)</th>
<th>B (m)</th>
<th>H (m)</th>
<th>T (m)</th>
<th>Vmax (knot)</th>
<th>Lc (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>244</td>
<td>29.11</td>
<td>9.49</td>
<td>2.59</td>
<td>1.79</td>
<td>11.56</td>
<td>10.00</td>
<td></td>
</tr>
<tr>
<td>347</td>
<td>35.00</td>
<td>9.89</td>
<td>2.83</td>
<td>1.96</td>
<td>12.35</td>
<td>12.00</td>
<td></td>
</tr>
<tr>
<td>394</td>
<td>31.33</td>
<td>11.75</td>
<td>3.07</td>
<td>2.10</td>
<td>11.80</td>
<td>16.13</td>
<td></td>
</tr>
<tr>
<td>472</td>
<td>40.89</td>
<td>10.29</td>
<td>3.05</td>
<td>2.13</td>
<td>13.05</td>
<td>14.00</td>
<td></td>
</tr>
<tr>
<td>477</td>
<td>35.00</td>
<td>11.89</td>
<td>3.21</td>
<td>2.20</td>
<td>12.28</td>
<td>18.00</td>
<td></td>
</tr>
<tr>
<td>496</td>
<td>35.78</td>
<td>11.92</td>
<td>3.23</td>
<td>2.23</td>
<td>12.37</td>
<td>18.84</td>
<td></td>
</tr>
<tr>
<td>523</td>
<td>36.89</td>
<td>11.96</td>
<td>3.27</td>
<td>2.26</td>
<td>12.51</td>
<td>18.96</td>
<td></td>
</tr>
<tr>
<td>545</td>
<td>43.89</td>
<td>10.49</td>
<td>3.16</td>
<td>2.22</td>
<td>13.38</td>
<td>15.02</td>
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</tr>
<tr>
<td>628</td>
<td>40.89</td>
<td>12.11</td>
<td>3.44</td>
<td>2.36</td>
<td>12.99</td>
<td>21.00</td>
<td></td>
</tr>
<tr>
<td>803</td>
<td>46.78</td>
<td>12.34</td>
<td>3.61</td>
<td>2.51</td>
<td>13.63</td>
<td>24.00</td>
<td></td>
</tr>
<tr>
<td>992</td>
<td>52.33</td>
<td>12.54</td>
<td>3.78</td>
<td>2.65</td>
<td>14.28</td>
<td>26.83</td>
<td></td>
</tr>
<tr>
<td>1004</td>
<td>52.67</td>
<td>12.56</td>
<td>3.79</td>
<td>2.66</td>
<td>14.23</td>
<td>27.00</td>
<td></td>
</tr>
<tr>
<td>1117</td>
<td>48.33</td>
<td>14.40</td>
<td>4.08</td>
<td>2.80</td>
<td>13.74</td>
<td>33.06</td>
<td></td>
</tr>
<tr>
<td>1231</td>
<td>58.56</td>
<td>12.78</td>
<td>3.97</td>
<td>2.79</td>
<td>14.78</td>
<td>30.00</td>
<td></td>
</tr>
<tr>
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<td>52.67</td>
<td>14.52</td>
<td>4.18</td>
<td>2.91</td>
<td>14.18</td>
<td>36.00</td>
<td></td>
</tr>
<tr>
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<td>13.00</td>
<td>4.14</td>
<td>2.93</td>
<td>15.30</td>
<td>33.00</td>
<td></td>
</tr>
<tr>
<td>1496</td>
<td>56.78</td>
<td>14.64</td>
<td>4.31</td>
<td>3.01</td>
<td>14.57</td>
<td>38.79</td>
<td></td>
</tr>
</tbody>
</table>

* Group of ship tonnage according to national port hierarchy [7]
C. Transport Capacity of Crossing Route

Specification of sample ships used to estimate capacity of inter-island transportation were shown in Table V. Alternative ship to be able to operate in a certain route has different maximum speed and loading capacity. Using the equation (15) - (17), the obtained operational speed are the same for several different traject distance. Figure 6 shows alteration trend of operational speed as a function of traject distance for the first sample ship with gross tonnage of 244, maximum speed of 11.56 knots and the loading capacity of 10 $V_u$.

Sail time of ship ($St$) will be longer for longer traject distance. Therefore the number of ships to be able to depart from the departure port ($Nsd$) is higher for traject with longer distance, for example 2 ships for traject distance between 0.5 miles to 11 miles, 12 ships for the traject distance between 116 miles to 127 miles. Here, $Nsd$ is calculated by using the equation (18).

Operation frequency ($Ff$) to be able to reach depends on depart order. The first departure ship will reach higher operation frequency. For example, operation frequency for ship to be departed at the first time for the traject distance of 0.5 miles and 11 miles is 12 trips/day. The second departed ship will reach only 11 trips/day.

The operation frequency can be calculated by using the equation (20). Calculation results show that the operation frequency for shorter traject distance is higher than that for longer traject distance. Maximum trip of 48 per day can be reach for traject distance of 0.5 miles and 11 miles. The maximum trip for one day is only 26 trips for traject distance of 116 miles and 127 miles. These frequency includes the last depart even the ship will arrive at destination port in next day. Service frequency can be estimated by using the equation (21). Base on this equation, the service frequency is the same for all traject distance. That is 48 trips per day as shown in Figure 6.

In order to reach service frequency of 48 trips per day, the number ships to be operated depend on traject distance as shown in Figure 6. 4 ships are necessary for traject distance of 0.5 miles and 11 miles. For traject distance of 116 miles and 127 miles, 24 ships are necessary in order to reach 48 trips per day. This ship demand is calculated using the equation (22).

With service frequency of 48 trips per day and the loading capacity of 10 $V_u$ then the route capacity is determined to be 480 $V_u$ per day. This transport capacity is the same in all traject distance. This transport capacity was calculated by using the equation (23).

Figure 6 show an example of operation pattern of inter-island transportation with ship specification of 244 GT, $V_{max}$ = 11.57 knots and $Lc$ = 10 $V_u$. If speed of operated ship is higher and larger loading capacity, the traject distance will be longer and the total transport capacity becomes larger. According to alternative ships to be operated, the total transport capacity base on port class is shown in Table V.

D. Model Design of Ro-Ro Ferry

1) Determination of Loading Capacity: Corresponding to the loading capacity ($Lc$) of operated ship, transport capacity of route ($Tc$) as shown in Table VI. Within this analysis, the transport capacity was assumed as transport demand ($Td$). Maximum transport demand ($Td_{max}$) to be serviced in a route with port class of III, port class II, and port class I is 883 $V_u$, 1288 $V_u$, and 1862 $V_u$ respectively. The equation (24) shows that loading capacity ($Lc$) is estimated as function of ratio of transport demand and maximum transport demand ($Td/Td_{max}$) as shown in Figure 7.

![Fig. 6. Operation pattern of inter-island transportation](Image)

![Fig. 7. Loading capacity as function of service transport](Image)
service frequency \((F_S)\) is smaller than \(F_{S_{\text{max}}}\) and loading factor is smaller than 100\%. Therefore, estimation of loading capacity \((L_c)\) as function of transport service demand \((T_d)\) can be formulated as follows:

\[
L_c = 18.396 \left(\frac{T_d}{883}\right) \left(\frac{48}{F_S}\right) / L_f \quad (26)
\]

\[
L_c = 26.830 \left(\frac{T_d}{1288}\right) \left(\frac{48}{F_S}\right) / L_f \quad (27)
\]

\[
L_c = 38.792 \left(\frac{T_d}{1862}\right) \left(\frac{48}{F_S}\right) / L_f \quad (28)
\]

The equations \((26) – (28)\) are equations to estimate the loading capacity for each route of inter-island transportation with port class of III, II, and I. These three equations valid only for demand of transport service \((T_d)\) of car group IV, V, ans VI (see Table II). \(T_d\) is amount of vehicle after multiplied by their conversion index, respectively (see Table II). The value of \(T_d/T_d_{\text{max}}\) should be smaller than one. This means that \(T_d\) should be smaller than \(T_d_{\text{max}}\). The service frequency \((F_S)\) should not be exceeded 48 trips per day. Considering the main dimension of ship and port class, \(F_s\) and \(L_f\) are estimated with loading capacity \((L_c)\) is not larger than the value of coefficients in the equations \((26) – (28)\).

2) Determination of Main Dimension: Estimation of loading capacity as function of length and breadth of vehicle area has been discussed in point B. The length of vehicle area was estimated using polynomial regression as function of loading capacity. The equation for estimating the length of vehicle area is different in five alternative breadth of vehicle area as shown in Figure 4.

The length between perpendicular \((L_{BP})\) is estimated by using the equation \((8)\) as function of length of vehicle area. The ship breadth is estimated by using the equation \((9)\) as function of \(L_{BP}\). This estimation of ship breadth is also conducted under consideration that the ship breadth is also function of breadth of vehicle area as shown in the equation \((6)\). The equation for estimating ship breadth as function of \(L_{BP}\) is shown in Figures 5.a – 5.c.

Base on analysis explained in the previous two paragraphs, \(L_{BP}\) and \(B\) of ro-ro ferry can be estimated as function of loading capacity \((L_c)\). The equation is devided base on loading capacity group as follows:

a. Loading capacity \((L_c)\) between 7.509 \(V_u\) and 15.283 \(V_u\)

\[
L_{BP} = (2.65 L_c - 0.3)/0.9 
B = 0.0674 L_{BP} + 7.532
\]  

\[
(29)
\]

\[
(30)
\]

b. Loading capacity \((L_c)\) between 15.396 \(V_u\) and 33.000 \(V_u\)

\[
L_{BP} = (1.7667 L_c - 0.3)/0.9 
B = 0.0376 L_{BP} + 10.576
\]  

\[
(31)
\]

\[
(32)
\]

c. Loading capacity \((L_c)\) between 33.057 \(V_u\) and 60.302 \(V_u\)

\[
L_{BP} = (1.325 L_c - 0.3)/0.9 
B = 0.0283 L_{BP} + 13.032
\]  

\[
(33)
\]

\[
(34)
\]

There are 886 variation of length and breadth of ships can be obtained from series analysis in Part B (Classification of Ro-Ro Ferry According to Port Hierarchy). The height and draught of ship corresponding to these length between perpendicular and breadth of ship can be estimated from the equation \((10)\) and the equation \((11)\), respectively. Following the equations \((10) – (11)\), the ship height is calculated as function of length between perpendicular and ship breadth. The ship draught is formulated as function of ship breadth and also ship draught. The formula to estimate the ship height and the ship breadth are shown in the equations \((35) – (36)\).

\[
H = (L_{BP}^{0.3208} B^{0.6792}) / 5.2463
\]  

\[
(35)
\]

\[
T = (B^{-0.167} H^{1.167}) / 1.1765
\]  

\[
(36)
\]

The obtained main dimension of ro-ro ferry by using these equations for sample ships shown in Table IV, the ratio between breadth and draught \((B/T)\) is ranged from 4.220 up to 5.805 and the ratio between freeboard and breadth \((F_b/B)\) is ranged between 0.081 and 0.096. The range of these two ratio is similar with result of previous research [3]. However, stability analysis should be conducted in advance especially for ships with ratio of length between perpendicular and breadth \((L_{BP}/B)\) smaller than 2.275. A ship with ratio of length between perpendicular and breadth \((L_{BP}/B)\) less than 2.275, the ratio between breadth and draught \((B/T)\) becomes larger than 5.5. As result, the critical of vertical center of gravity significantly decreases [3].

3) Determination of Ship Speed: The equation for estimating maximum speed was shown in the equation \((25)\). This equation is used to determined the speed of sample ships using in this research. The maximum speed is used as variable to restrict maximum distance of route to be serviced by ro-ro ferry as shown in Table V. The effective service speed for each route can be estimated by using the equation \((16)\) associated with the equations \((15) – (17)\). Estimation of effective service speed shown in Figure 6 is example of using these equations.

IV. CONCLUSION

The calculation results and analysis regarding effect of port class, traject distance and technical spesification on model design of ro-ro ferry, some conclusion can be remarked as follows:

1. The transport sevice demand for car to be serviced in a certain route is different of each port class. Those are 883 units per day for port class III, 1288 units per day for port class II and 1862 unit per day for port class I.

2. The maximum traject distance corresponding to the maximum ship speed, is also different depending on the port class with minimum frequency of 2 for one ship operated in a day. The traject distance of 135 miles is maximum traject distance for port class III, 156 miles for port class II and 168 miles for port class I, respectively.

3. The loading capacity of ro-ro ferry was estimated based on service transport demand. The maximum load capacity for ship tonage less than 500 GT or port class III is 18.40 vehicle units. For ships with tonage larger than 500 GT
and smaller than 1000 GT or port class II is 26.83 vehicle units. For ship with tonnage large than 1000 GT and smaller than 1500 GT or port class I is 38.79 vehicle units.

4. The main dimension and service speed of ro-ro ferry are estimated based on the loading capacity considering the loading capacity corresponding to the three group of ship tonnage and port class.

REFERENCES


