Design and Evaluation of Passenger Ferry Routes

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Abstract

This article introduces a planning framework for improving and best utilizing existing water and ferry resources. It presents an analysis framework and formulation for designing and evaluating passenger ferry routes. The motivation for this work emanates from problems encountered by the ferry service in Hong Kong, including the continuous loss in ferry patronage. This loss is believed to be caused by the ferry's relatively poor level of service and intense competition from more attractive alternatives. The article reports on an evaluation and design methodology for the entire passenger ferry network, consisting of a framework with operational objective functions that takes into account passengers, operator, and community interests. This framework considers both the evaluation of existing ferry routes and the design of new ones. The methodology presented combines the philosophy of mathematical programming approaches and decision-making techniques, allowing the user to select an efficient solution from a number of alternatives. The evaluation procedure established provides practical and measurable criteria for evaluating the "goodness" of each route and for comparison between sets of routes at the network level.

Introduction

The motivation for this study arose from problems encountered by the ferry service in Hong Kong (HK), where the role of ferry service has been shrinking as evidenced by the loss in both market share and actual patronage against a background of

strong overall growth in travel demand during the last 20 years. Traditionally, ferry services excel where they provide direct service between two terminal points or where the provision of land-based transport would require major infrastructure investments in terms of time and cost. With the continuous expansion of road and rail networks in HK in the last 30 years, the former advantages of the ferry have, to a large extent, disappeared for the island's inner harbor routes (IH) and, more recently, for some of the outlying island routes (OI), long considered a stronghold for ferry operations.

Many of the problems facing the ferry industry are driven by forces that will continue to prevail in the future as land-based transport networks and the economy further develop. Because of the low infrastructure cost required for ferry services in comparison with other public transit modes, and the fact that a ferry trip is often part of a trip chain, it is worthwhile to develop ways to improve the ferry network design by making it both more attractive and more efficient. Thus, the ferry routes do not have to be viewed as point-to-point systems because in many respects these routes can act similarly to bus and rail routes. This study, while using the HK ferry network as an example, provides measurable criteria and tools for evaluating the quality of each route and for comparing the sets of routes at the network level.

This article begins with a literature review of transit route design methods. The second section outlines the framework of the entire study and its methodology. The third segment, which is the core of the research, establishes and interprets the framework, notation, and objective functions of the ferry network design problem by using a detailed example. The case study of HK, utilizing a multiobjective approach, is discussed briefly in the fourth section. Finally, the last part provides concluding remarks.

Literature Review

This section presents a review of papers that propose methods for optimizing the configuration of transit routes systems. Fundamentally, a passenger ferry routing system has the same characteristics as any other transit system in terms of objectives, constraints, and integration consideration. Baaj and Mahmassani (1991, 1992, 1995) develop transit network design methods based on artificial intelligence (AI). The methods are based on a typical formulation of the network

design problem as a programming problem with minimal frequency, load factor, and fleet size constrains.

Ramirez and Seneviratne (1996) propose two methods for route network design under multiple objectives using GIS. Both methods involve ascribing an impedance factor to each possible route and then choosing those that have the minimum impedance. Pattnaik et al. (1998) present a methodology for determining route configuration and associated frequencies using a genetic algorithm. In genetic algorithms, solutions are chosen from a large set of possibilities in an iterative process, where the chances of a solution surviving through the iterations are higher if it yields a high value to a given fitness function.

Soehodo and Koshi (1999) formulate a programming problem for designing transit routes and frequencies. Similarly to other models, the problem is solved by first creating all feasible routes and then choosing an optimal subset. In addition to some traditional components, such as minimal frequency and fleet size constraints, the problem has some unique elements, such as the inclusion of private car user costs, transit passenger crowding costs, and transfer costs to the minimized objective function. Bielli et al. (2002) describe another method for designing a bus network using a genetic algorithm. As in other genetic algorithms, each population of solutions goes through reproduction, crossover, and mutation manipulations whose output is a new generation of solutions. In the proposed model, each iteration involves demand assignment on each network of the current set of solutions and a calculation of performance indicators based on the assignment results.

Wan and Lo (2002) develop a network design model with an explicit consideration of intermodal and interroute transfers. The model has two separate phases. First, the points that are to be connected with a direct service are determined in a heuristic algorithm. Next, an actual bus route system is built in a mixed integer linear programming problem. Yan and Chen (2002) present a method for designing routes and timetables that aims to optimize the correlation between bus service supply and passenger demand. The method is based on the construction of two timespace networks: a fleet flow network and a passenger flow network.

Tom and Mohan (2003) continue the development of genetic methods for route network design. In the current model, frequency is the variable, and thus it differs from earlier models in terms of the adopted coding scheme. While fixed string length coding and variable string length coding were used in previous models, the simultaneous route and frequency coding model is proposed here.

The literature review provided in this section is intended to shed light on what methodologies and quantitative methods were recently used to overcome the planning issues of transit network design. In the following section a different concept with the idea to bridge between theory and practice is presented.

Overview of the Study

The overall description of the entire ferry study methodology (Ceder 2001) appears in Figure 1. This overview is arranged by the main input and outcome elements for each of the twelve elements listed in the figure.

Data Collection Stage

This element is related to the data collection stage of existing ferry routes and candidate routes. The outcome is derived by tabulating the ferry route characteristics. These characteristics include: average travel time (peak, off-peak), distance, average passenger loads (peak, off-peak), vessel's speed and capacity, competition measures of bus and rail in terms of fares, travel time, and frequency. In addition, this element summarizes information on passengers' satisfaction and complaints.

Current Vessel Types and Piers

Apart from site visits, all major operators in HK have been consulted on a wide range of issues: vessel type, fleet size, staffing level, vessel performance, and berthing operation.

Legal Issues of Ferry Operation

This element, which is only indirectly related to the main body of the study, addresses legal issues of ferry operation and suggests amendments.

Design of Survey and Data Collection Processes

The purpose of this element is twofold: (1) to prepare adequate data and information input for the forecast and evaluation analyses, and (2) to establish proper databases to be updated continuously for future use.

Theory and Methods of Designing New and Improved Ferry Routes

This element emphasizes the construction of objective functions and measures from the user (passenger), operator, and government perspectives. The objective functions and measures evaluate the "goodness" of the ferry route and compare it to other sets of routes.

INPUT		ELEMENT	OUTCOME
Ferry Route Description; Travel Times Fares and Frequencies of Ferry and Transit Competitors; Vessel and Interchange characteristics	1	Review of Existing and Candidate Routes	Matrix presentation of Routes and their characteristics
Operation characteristics, list of Operators, Vessel types, and Berthing characteristics	2	Review of Vessels and Berthing Facilities	Evaluation of Vessel and Pier characteristics
Emergency Scenarios, Existing Legal Issues	3	Review of Legal Framework	Amendments to Existing issues, Additional Regulations
Existing Ferry Routes and Transit Competitors; Planning information; HK Planning information	4	Survey and Data Collection	Data Stratified by Zones, Ferry Routes, Commuters and Non-commuters, and Patronage characteristics
User, Operator and Government Perspectives; Available Operational Data	5	Development of Tools for Route Quality Evaluation	Formulation of Objective Functions and Models to attain the objectives
Survey Data; Known Forecasting Models; Planning Assumptions	6	Development of Methods for Ferry Patronage Forecasting	Models for Predicting Patronage Changes, and Sensitivity of Variables
Capital Cost Data; Operating Cost and Administration Data	7	Development of Financial Model	Cash Flow Model with Equity and Project IRR, Break-even Fare and Demand
Forecasting Methods; Survey Data; Planning Matrices	8	Analysis of Survey and Forecasting Results	Forecasting Demand and Demand Elasticities for Fares, Travel Times, Waiting Times, Walking Times, and Comfort items
Financial Model; Route Quality Evaluation Method	9	Analysis of Financial and Route Quality Results	Viability Determination; Financial Optimal Operation; Quality Ranking of Routes
Forecasting Methods; Route Quality Evaluation Method; Financial Model	10	Preparation of Guidelines and Simplified tools for TD future use	Computerized Excel Tools with Instructions
Results from Survey, Forecasting, Financial and Route Quality Evaluations	11	Establishing the Recommended Set of Ferry Network Between 2000-2006	Recommended Network of Ferry Routes Comprised of Existing and New Routes
The Outcomes of All the Above Mentioned Components	12	Establishing the Study Recommendations	List of Recommendations

Figure 1. Overview of the Major Elements of the Entire Study

Construction of Forecasting Methodology for Ferry Patronage

This element, which analyzes ferry patronage for 2000 and 2006, is based on three parts: (1) identification of main attributes and their weights in affecting potential ferry patronage, (2) demand prediction using a calibrated growth factor from past ferry demand figures for any projected changes on the established ferry routes, and (3) transit modal split between specific origin-destination (O-D) pairs on any new ferry routes and/or changes in fares and/or journey times in the transit competitors.

Development of the Financial Model and Its Modules

This model considers (1) capital cost of vessels, octopus fare equipment, and pier development for new routes; (2) operating costs of staffing, maintenance, and administration; and (3) revenue from farebox, concessions, advertisements, and freight.

Results from Survey and Forecasting Analyses

The survey results include the elasticities of fare, travel time, waiting time, walking time, and comfort items for changes in the ferry demand. Survey results come from both commuters and noncommuters. Results from noncommuters are important for gaining information on tourism flows and weekend patronage. In addition, the survey results reveal a certain picture with respect to arrivals and departures from ferry piers (walk or transit). The forecasting results produce O-D matrices for daily, peak, and off-peak ferry patronage for 2000 and 2006, and for the existing and candidate routes.

Evaluation of Existing and Candidate Ferry Routes

Financial results point out the nonviable routes and then group them under essential (captive users) and nonessential (noncaptive users) routes. For essential unviable routes, the financial results contain break-even fares, break-even demand, packaging potential, and possible changes in the operating characteristics. Some of these results appear in this work.

Practical and Simplified Excel Tools

The main tools for future HK Transport Department (TD) use are: (1) model split database file for demand forecasting, (2) financial model with the study data and results, and (3) quality of routes model with the study data and results. All the Excel tools can be updated easily.

Recommendations for Existing and Candidate Routes

This element summarizes the results from the ninth element—evaluation of existing and candidate ferry routes using financial and quality approaches—and partially appears in this work. It provides recommendations for existing and candidate routes, and suggests the best-suited set of routes to serve HK between 2000 and 2006. It proposes that some existing routes should be dropped, and some candidate new routes be added.

Study Recommendations

The last element in Figure 1 establishes recommendations primarily regarding the outlying islands, inner harbor, and vehicular ferry routes. In addition, other recommendations are specified to cover issues of government support, vessels, fares, and regulations.

Optimal Design and Evaluation of Routes

The overall ferry route design approach is similar to that which appeared in Ceder (2003), but with different framework and objective functions. The following presents the formulation of the approach and an example used as an explanatory tool.

Formulation

The formulation in this research considers a connected network composed of a directed graph G = {N,A} with a finite number of nodes |N| connected by |A| arcs. In this section, transit stands for ferries and vehicles—for ferry vessels. The following notations are used:

Route	is the progressive path initiated at a given transit terminal and terminated at a certain node while traversing given arcs in sequence
Transfer path	is the progressive path that uses more than one route
R = {r}	equals the set of transit routes
TP = {tr}	denotes the set of all transfer paths
S = {sp}	is the set of all shortest paths
N_r	equals the set of nodes located on route r

N_{tr}	represents the set of nodes located on transfer path tr
N_{sp}	is the set of nodes located on the shortest path sp
d_{ij}^{r}	equals passenger demand between i and j, i, j, $\in$ N, riding on route r
d_{ij}^{tp}	is passenger demand between i and j along the transfer path tr
d_{ij}^{sp}	denotes passenger demand between i and j along their shortest path
F_{r}	is vehicle frequency associated with the route r
F_{min}	is the minimum frequency (inverse of policy headway) required
t_{ij}^{r}	is travel time between i and j on route r
t_{ij}^{tp}	equals travel time between i and j on transfer path tr
t_{ij}^{sp}	represents travel time between i and j on the shortest path
t_{r}	is the overall travel time on route r between its start and end
L_{r}	denotes maximum passenger load on route r
W_{r}	equals passenger waiting time on route r
d_{o}	represents desired occupancy on each vehicle (load standard)
a_{tp}^{r}	equals 1, transpfer tp contains route r 0, otherwise

The transit route design problem is based on two main objective functions, min Z_1 and min Z_2, across the different sets of transit routes:

$$Z_1 = \alpha_1 \sum_{i,j \in N} Wt(i,j) + \alpha_2 \sum_{r} Esh_r + \sum_{i,j \in N} [\alpha_3 Ph(i,j) - \alpha_4 Dph(i,j)] \qquad (1)$$

$$Z_2 = NF \tag{2}$$

where:

Ph (i,j)   is passenger-hours between nodes i and j,i, j $\in$ N. It is defined as passengers' riding time in a transit vehicle on an hourly basis. It measures how much time is spent by passengers in vehicles between the two nodes

Dph (i,j)   is the difference in passenger-hours between Ph (i,j) and the total passenger-hours from i to j when only using the shortest path, i, j $\in$ N

Wt (i,j)   equals the waiting time between nodes i and j, i, j $\in$ N. It is defined as the amount of time passengers spend at the transit stops between the two nodes

Esh_r denotes empty space-hours on route. It is defined as the unused seats in a transit vehicle on an hourly basis. Empty space-hours measures the unused capacity on vehicles

NF   is the fleet size; that is, the number of transit vehicles needed to provide all trips along a chosen set of routes

α_k equals monetary weights, k=1, 2, 3, 4 (see next section)

Objective Functions. The objective functions take into account three perspectives: the passengers, the operator, and the community. A good transit route is defined as an attractive one from all the three perspectives.

The first straightforward objective is to minimize the total waiting time of the passengers. This is strictly from the perspective of the transit user. The formulation of this objective takes the following form:

$$\min \ \alpha_1 \sum_{i, j \in N} Wt \ (i,j) \tag{3}$$

where:

α_1 is the monetary value of one hour waiting time

The second objective is to minimize the total unused seat capacity as to allow for a more viable transit service. This is strictly from the perspective of the operator who wants to see more usage of the available transit seats. The following is the formulation of this objective:

$$\min \ \alpha_2 \sum_r Esh_r \tag{4}$$

where:

α_2 is the equivalent of one hour average monetary revenue divided by the average number of hourly boarding passengers. The objective is to minimize the total monetary value of the unused seat capacity

The third objective is to minimize the total loss if all transit passengers switched to the shortest path. This objective attempts to take into account the comparison between the transit route and its best competitor, which is usually the private car, or in certain cases the aircraft or railway. This objective represents the perspectives of the government and the transit passengers, and takes the following form:

$$\min \ \Delta \ = \ \sum_{i,\,j \in N} [\alpha_3 Ph\,(i,\,j) - \alpha_4 Dph\,(i,\,j)] \tag{5}$$

where:

α_3 is the equivalent of a one-hour difference in average cost between riding the shortest (and more expensive) path and the transit route

α_4 equals the monetary value of one hour in-vehicle time

The value of Δ is the total monetary loss (or saving, if it is negative) if all the transit passengers are switched to the shortest path.

where:

$\alpha_3 Ph$ is the total monetary loss, with respect to cost only, if all the transit passengers are switched to the shortest path

$\alpha_4 Dph$ equals total monetary value of the time saved if all the transit passengers are switched to the shortest path

The fourth objective is to minimize the number of vehicles to carry on the determined frequencies (timetables). This is strictly the operator perspective that wants to perform all the transit trips using the minimum number of vehicles. This objective takes the form:

min NF (6)

Objectives (3), (4), and (5) are all in passenger-hour cost, therefore for simplicity, could be summed up to min Z_1 as shown in equation (1). Objective (6) stands alone to some extent and is termed min Z_2 as in Equation (2).

Calculation of Z_1 and Z_2 Elements. In the previous section the objective functions of the transit network design problem are established. The next step is to apply them to the HK ferry network and to assess the quality of existing and candidate routes. The general framework of the quality of ferry routes evaluation is shown in Figure 2 in flowchart format. The framework covers the following eight steps for a design year and for a given ferry route or a set of routes:

1. Use a forecasting method to calculate the average O-D demand for peak, off-peak, and daily.

2. Use given minimum frequencies and desired occupancies for peak and off-peak period to calculate peak and off-peak frequencies.

3. Calculate Wt for peak, off-peak, and daily periods.

4. Calculate Esh for peak, off-peak, and daily periods.

5. Use the travel time information of the ferry, best transit competitors, and ferry and bus for certain O-D to calculate Ph and Dph for peak, off-peak, and daily periods.

6. Use the information of ferry travel times to determine the required fleet size, especially for peak period and off-peak period, for estimating the number of crew required.

7. Evaluate the cost of $\alpha_1 Wt$, $\alpha_2 Es$, Δ, Z_1, and Z_2 based on the cost estimates of α_i, i = 1, 2, 3, 4.

8. Use the components of Z_1 and Z_2 to compare different alternative ferry routes, if any, or individual routes. Use these measures for establishing recommendations.
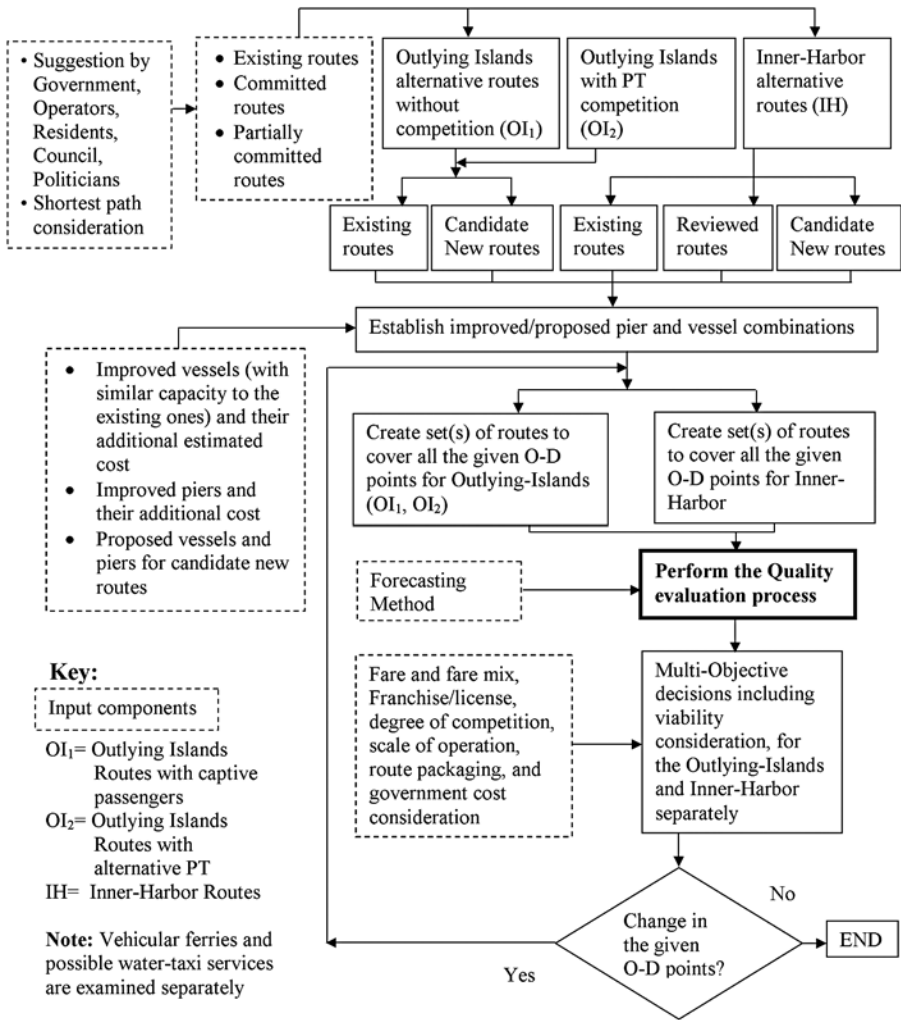
Figure 2. Evaluation Framework of Ferry Routes

The input for the quality of routes evaluation is derived from

- a given ferry route or set of routes;
- O-D demand for peak, off-peak, and daily;
- travel times for peak and off-peak for each direction;

- round-trip times for peak and off-peak;
- average vessel capacity;
- desired occupancy (% of seat capacity) for peak and off-peak;
- minimum frequency for peak and off-peak; and
- minimum relevant (same segment as the ferry or the ferry and bus for certain O-D pairs) travel time of best (shortest time) transit competitor.

In the next section the route quality evaluation method is interpreted using a detailed example.

Example

The objective function Z_1 is based on the so-called load profile. It is a histogram describing the number of passengers on board the transit vehicle vs. the transit route length (in distance or time units). Figure 3 provides an example of calculations. Figure 3c shows a load profile between North Point (NP) and Kowloon Point (KP) in HK.

The first element in Z_1 in Equation (1) is the total wait-time hours both at the transit stops and during transfers. This element represents the passenger perspective; its calculation is based on the maximum load point method for deriving the transit vehicles frequency (Ceder 1984) during the time covered by the passenger demand matrix:

$$F_r = \max\left[\frac{L_r}{d_o}, F_{min}\right] \tag{7}$$
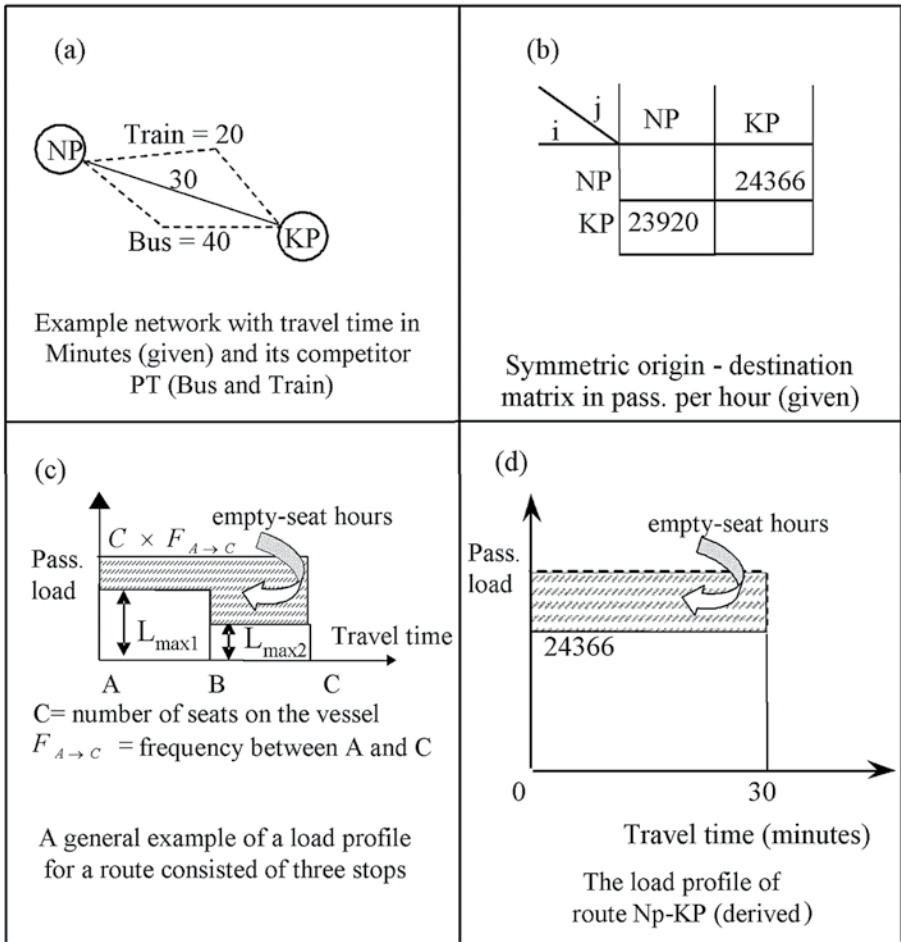
If $F_r = F_{min}$, the load profile will have no effect on the frequency determination.

The expected wait time for passengers on route r is half of the transit vehicle headway where passengers arrived randomly to the transit stop and the headway is distributed in a deterministic manner (Marguier and Ceder 1984):

$$w_r = \frac{1}{2F_r} \tag{8}$$

hence,

$$\sum_{i,j \in N} Wt(i,j) = \sum_{r \in R} \frac{1}{2F_r}\left(\sum_{i,j \in N_r} d_{ij}^r + \sum_{ij \in N_{tp}} d_{ij}^{tp} a_{tp}^r\right) \tag{9}$$

Figure 3. Example of the Construction of the Load Profile

In the example shown in Figure 3, one obtains:

$$\sum_{i,j \in N} Wt(i,j) = \frac{1}{2 \cdot 24366/800} (24366) = 400 \ \text{passenger-hours}$$

where:

d_o equals 800 (in this example a vessel with maximum 1,000 seats and desired peak occupancy of 80% is used)

The second element of Z_1 in Equation (1) describes the total empty-space hours or empty-seat hours (when d_o equals the number of seats on the transit vehicle). This element represents an unproductive measure for the operator (e.g., unused seat capacity). Its formulation is

$$\sum_r \text{Esh}_r = \sum_{r \in R} [\max(L_r, F_{min} \cdot d_o)]t_r - \sum_{i,j \in N} \text{Ph}(i,j) \tag{10}$$

In Figure 3

$$\text{Esh}_r = (30 \cdot 1000 - 24366) \cdot 30/60 = 2817 \text{ passenger-hours.}$$

The first part of the third element of Z_1 in Equation (1) is total passenger-hour in the routing system

$$\sum_{i,j \in N} \text{Ph}(i,j) = \sum_{r \in R} \sum_{i,j \in N_r} d_{ij}^r t_{ij}^r + \sum_{tr \in TP} \sum_{ij \in N_{tp}} d_{ij}^{tp} t_{ij}^{tp} \tag{11}$$

where, for the example in Figure 3d:

$$\sum_{i,j \in N} \text{Ph} = (30 \cdot 24366)/60 = 12183 \text{ passenger-hours}$$

The second part of the third element in Equation (1) is the total passenger-hour difference between on r and on the shortest path sp

$$\sum_{i,j \in N} \text{Dph}(i,j) = \sum_{i,j \in N} \text{Ph}(i,j) - \sum_{sp \in S} \sum_{i,j \in N_{sp}} d_{ij}^{sp} t_{ij}^{sp} \tag{12}$$

where for the Figure 3d example:

$$\sum_{i,j \in N} \text{Dph}(i,j) = 24366 \cdot (30 - 20)/60 = 4061 \text{ passenger-hours.}$$

Estimation of Z₂

The second objective function, Z_2, is an estimate for the fleet size required to carry the entire matrix of the passengers' demand. The fleet size required for a given ferry route is primarily based on the timetable (frequencies). The minimum num-

ber of vessels required is derived from the Round Trip Time (RTT) for a given route. That is, a particular ferry departing, say, at 7:00 am at KP can carry out the next trip from KP only after it came back to KP. If RTT = 40 minutes, then this ferry can be responsible for a departure at KP from 7:40 am and on. All the departures made from KP after 7:00 and before 7:40 *must* be made by other ferries. If one looks at all the time windows of RTT and determines the number of independent departures, a list of these numbers (of departures) can be established. The maximum value in this list is, as can be understood, the minimum number of vessels required. This idea is demonstrated in Equation 12 with a small example for RTT = 30 minutes and a given timetable from which min NF = 4 vessels. Note that RTT is comprised of 10 elements as shown in Figure 4. In addition, the example problem shown in Figure 3 is also used for the minimum number of vessels. The combined data of this example problem with RTT = 75 minutes result in 38 vessels for the peak hour.

Given the frequency (time table) for a ferry route in a period (peak, off-peak)

$$\text{Min N} = \text{Max number of departures in a time window} \begin{bmatrix} \text{RTT across the peak (usually) period} \\ \text{(operator perspective)} \end{bmatrix}$$

RTT= travel time + berthing time + alighting time + layover time
+ boarding time+ travel time + berthing time + alighting time
+ layover time + boarding time

Example: RTT= 30 min.,   Timetable:

Min N= 4

Figure 4. Minimum Fleet Size Calculation

Multiobjective

The four main objectives in Equations 3, 4, 5, and 6 present a multiobjective picture for each route and can be evaluated separately. However, since the first three objectives are all in monetary units for passenger-hours, it is possible to combine them into one function: Z_1 as is indicated in Equation 1, and to examine Z_1 against the number of vessels required (and/or their capital cost) formulized as Z_2 in Equation 2.

The multiobjective perspective allows the decision-maker to select a solution based on the relative measures of the objective functions. This multiobjective stage is the last step in the quality of routes evaluation process. Its exact formulation and possibilities appear in Ceder (2003).

Hong Kong Case Study

The quality of the routes evaluation procedure establishes practical and measurable criteria for evaluating the "goodness" of each route and makes comparisons between the routes. This evaluation procedure ranks the various routes (or various sets of routes) and helps to prepare recommendations on adequate frequencies and possible improvements in vessel type and pier. In the HK study it was found that for $\Delta > 0$ (see Equation 5, for Δ explanation) a switch of passengers from ferry to its best transit competitor will result in monetary loss to passengers (also a loss from a governmental standpoint). Thus, there is good reason to further check and maintain the ferry route. If $\Delta < 0$, then by switching (theoretically) ferry passengers to the best transit mode, the passengers will gain, and the overall situation will benefit from closing the ferry route. Figure 5 illustrates one result in HK concerning the existing and candidate viable routes for 2006; such recommendations should commensurate with other nonquantitative factors.

Figure 5. Map of Existing and Candidate Outlying Islands Routes

Concluding Remarks

The main purpose of this research is to introduce practical planning and evaluation methods to assess existing and candidate ferry routes by taking into account the interests of passengers, operators, and the community. The ferry routes do not necessarily have to be point-to-point systems and in many respects these routes can act similarly to bus and rail ones. The first part of this study constructs a planning framework on how to improve and make the best use of existing water and ferry resources. The second part provides a procedure that incorporates optimization and enumeration processes to derive the minimal Z_1 objective function. This procedure, while searching for min Z_1, also creates various Z_2 solutions—each associated with a different Z_1 solution. The multiobjective framework developed was successfully utilized in a case study of the large Hong Kong ferry network. This multiobjective perspective allows the decision-maker to select a solution based on the relative measures of the objective functions.

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