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This paper uses data envelopment analysis (DEA) to examine the relative technical efficiency of the Washington State Ferry (WSF) routes operating in Puget Sound. This is the largest ferry system in the country. It is publicly operated and does not face direct competition from any other agency, public or private. Therefore whether or not the ferry routes operate efficiently is a natural question. DEA is being used increasingly for measuring technical efficiency in non-profit settings such as health care and education, where prices of inputs and outputs may either be unavailable or artificially set. Because DEA does not require prices to measure efficiency, the technique has an advantage in these arenas. This paper first uses DEA to measure the relative technical efficiency of each WSF route using two different comparison sets. Returns to scale are then evaluated for each route in three successive years (1995-1997). Finally, a Malmquist productivity index is calculated in order to evaluate total factor productivity over the three-year period. For further evaluation this index is then divided into two components: technical change and efficiency change.

Overall, the findings show that most of the ferry routes operate in an efficient manner. The results do, however, show routes where there may be room for improvement and they provide a means to pinpointing areas where WSF may want to focus attention when making management decisions.

Evaluating the Efficiency of the Washington State Ferry Routes Using Data Envelopment Analysis.

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Evaluating the Efficiency of the Washington State Ferry Routes Using Data Envelopment Analysis

INTRODUCTION

Attaining efficiency in production is recognized as being necessary for most producers to continue to operate. Inefficient producers are generally forced out of business by competitors. However there are many industries that do not operate in a perfectly competitive market. So how producers perform when competition does not exist is an appropriate question.

This paper examines efficiency in this type of industry. The Washington State ferry routes are not subject to competition. The ferry routes are publicly administered, and there are no other providers of automobile ferry service in the Puget Sound area. Here, technical efficiency will be evaluated using data envelopment analysis (DEA). The paper will then examine scale efficiency and total factor productivity. The results are presented in an attempt to identify areas for possible improvement in production.

Traveling across water is an everyday part of life for the people living in the area around Puget Sound. Puget Sound separates the city of Seattle from the Kitsap Peninsula, which in turn is separated from the Olympic Peninsula by another body of water, Hood Canal. All this water is not devoid of land however. From Vashon Island in the southern part of the Sound to the San Juan Islands in the north, many islands sprout up throughout the length of Puget Sound. Some of these islands, such as Whidbey Island, which houses a naval base, are important economic sites for the region. Some of these islands are not accessible via bridges, so traveling from one area to another via water has become vital to the people around this area.

Ferryboats were first developed to simply carry people from place to place, but have blossomed into much more than 'people carriers'. Today, Washington State Ferries (WSF) is the largest ferry system in the country with twenty-four ferries operating on eleven different routes throughout the greater Puget Sound area. Essentially, the ferries extend the Washington highway system. By transporting vehicles across the water, the ferries allow, not only people, but also other important items, such as commercial goods and mail to be delivered to places that either would not be served without water transit, or, to places that are not conveniently reached via roadways. For instance, Vashon Island and the San Juan Islands do not have bridge access, so vehicles can only be brought onto the islands via boat. It is possible for vehicles to drive to the Kitsap Peninsula but driving entails traveling around Puget Sound instead of across it, which consumes more time. Usually people want to save time whenever possible, especially when commuting to work. The ferries fill a very important role in the lives of commuters traveling from the Kitsap Peninsula every day because downtown Seattle is within walking distance of the ferry terminal on Seattle's waterfront. Many people live on the west side of Puget Sound and work either in Seattle or somewhere else on the east side of the water.

The ferries on Puget Sound also provide an enormous amount of recreational opportunities. For instance ferry rides themselves can be an attraction that many people enjoy. But, the main role of ferries is to supply transportation. Providing access to various recreational areas has made the ferries indispensable to tourism in northwestern Washington. The San Juan Islands attract hundreds of thousands of tourists each year who, without ferries, would not be able to enjoy the Islands' beautiful scenery or participate in Island activities.

Until 1951 the ferries on Puget Sound were all privately owned and operated. However, some aspects of the business, such as the fares being charged, were regulated by state agencies. After World War II ended, the amount of ferry traffic declined dramatically. By 1947, only the Puget Sound Navigational Company (PSN) remained in business. During that same time employees of PSN received a wage increase gained mainly through efforts of their union. These events led PSN to petition the state for a fare increase. The state denied the request. In 1948 PSN, citing financial concerns, shut down ferry service on Puget Sound. Service resumed only after state approval of the requested fare increase. But the cessation of ferry service and the resulting public impact caused state agencies to seek a solution that would guarantee a similar disruption would not occur again.

Despite reluctance from PSN and after two years of negotiation, the state assumed control of all ferry operations in Puget Sound by purchasing or leasing most of the assets owned by PSN. Though determined to be in the public's best interest, this action was originally intended to be only a temporary solution. State agencies continued to explore other options for traveling from one side of Puget Sound to the other, including analyzing the possibilities for building bridges above the water or digging tunnels below the water. Eventually these alternatives were rejected for a variety of reasons. Specifically the idea of building bridges across Puget Sound was discarded. With the exception of a floating bridge that was built on Hood Canal, between the Kitsap Peninsula and the Olympic Peninsula, it was decided that having to allow for other marine traffic, as well as tidal and weather factors made the feasibility of building a network of bridges prohibitive. Therefore, the ferries continue to be vital to life in the Puget Sound area and the ferry system remains under the control of Washington State. Figure 1 shows an illustration of the Puget Sound area and the various ferry routes.

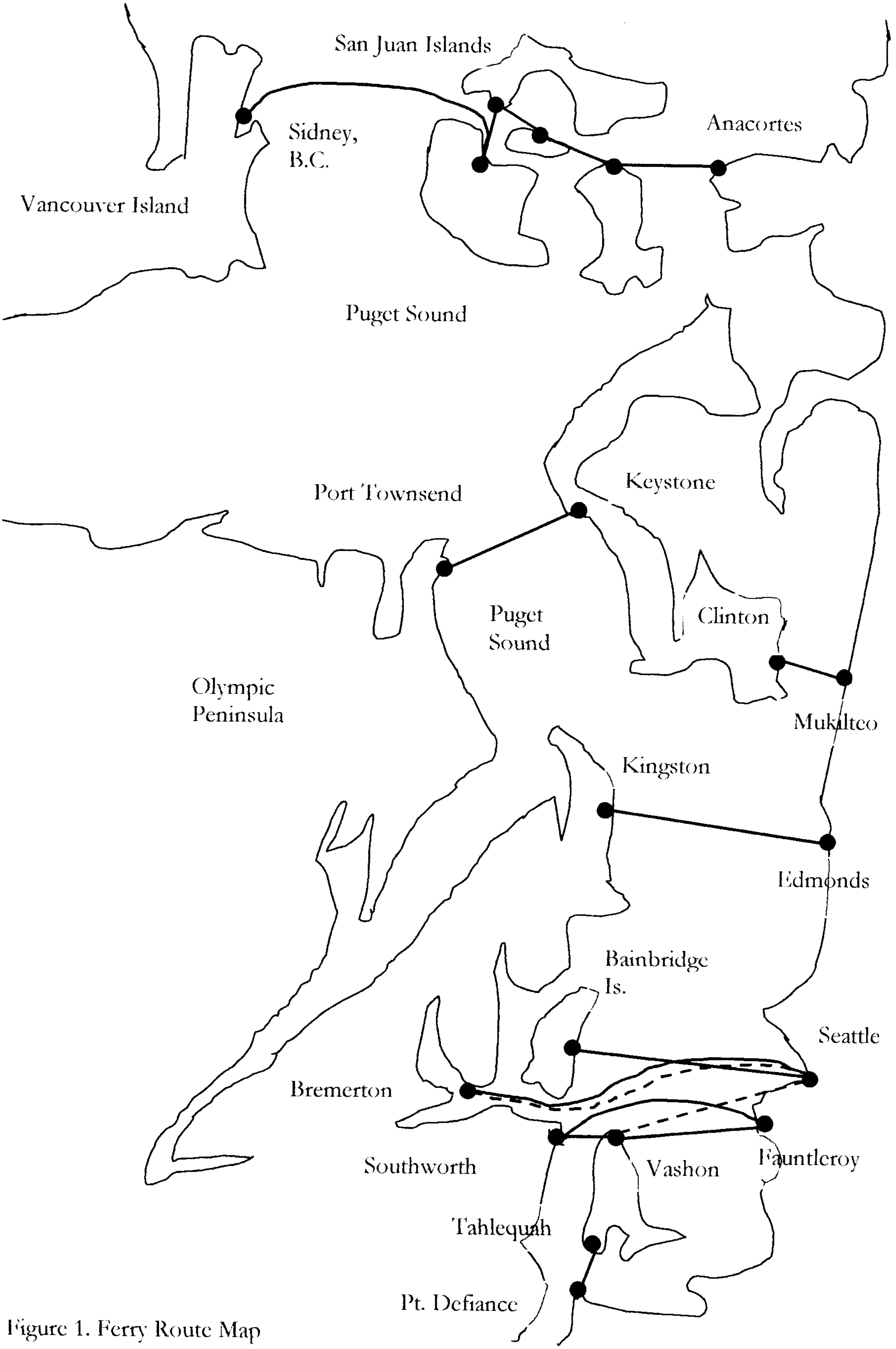

Figure 1. Ferry Route Map

Because the ferries continue to be publicly operated, a question arises as to how productive the system is. Traditional economic thought assumes that private ownership and competition leads to efficiency and increases in productivity. In a competitive market, there are incentives to maximize profit by operating as efficiently as possible. Conversely, public agencies are commonly thought to operate with extreme inefficiencies. Furthermore, in the public sector there seem to be no economic incentives to increase productivity because managers of public operations do not share in any increased profit resulting from increases in efficiency. Indeed, the incentives that do exist for managers of public entities may actually be more political in nature than economic.

In addition, the goal of private firms is assumed to be the maximizing of profit which should lead to incentives to operate as efficiently as possible. However, the same assumption can not be made for public enterprises. They may have an entirely different goal such as maximizing output rather than profit (Weisbrod, 1988). This being the case, it is entirely possible that the entity does not operate as efficiently as it could. Given the fact that the Washington State Ferry System is publicly operated and seeks to provide any amount of output that is demanded, this paper examines the efficiency and productivity of the operation.

RESEARCH METHOD (DEA)

Economists and business managers have long recognized the importance of the relationship between efficiency and production. A firm that is operating efficiently is producing the maximum amount of output, given the amount of inputs being used in the production process. Conversely, an inefficient firm can increase production without having to increase the amount of inputs used. However, in order to attain efficiency, it is imperative to be able to determine whether or not firms are already operating efficiently. If the firm is not operating efficiently, then being able to measure the amount of the inefficiency also becomes necessary.

There are various approaches to measuring productivity and efficiency. Each approach has advantages and disadvantages. For instance, economists generally use multiple regression for empirical studies, including studies on productivity. Often regression is used to estimate a production function where output is a function of various inputs. Based on this function, the amount of output produced by a particular firm can be predicted, given the amount of inputs the firm uses. Because this function essentially represents an average production function for the industry, analyzing the residuals determines where a firm is operating relative to this average. Any firm not producing on or above the average is not producing the maximum amount of output possible, given the amount of inputs being used, and is therefore determined to be inefficient. Although it is not known precisely how many observations are needed to make multiple regression an accurate measurement technique, the common thought is that more is better. Generally, as the number of observations increases, the amount of error decreases.

As an alternative to estimating a production function, Farrell (1957) introduced the idea of measuring relative technical efficiency by establishing which firms in an industry operate the most efficiently. These firms are considered benchmarks and form a best practice frontier to which all other firms in the industry are compared. This technique does not require assuming a functional form for the production function. Nor does it require assigning weights to the various inputs as regression does. In addition, the frontier that is established is not an estimate of average production, but rather an estimate of the best production in the industry. And since this technique estimates *observed* behavior, the frontier can be established with only 2 observations. However, as with multiple regression, the accuracy of the estimated frontier increases as the number of observations increases. As a way to calculate the efficiency of each firm relative to this frontier, Charnes, Cooper, and Rhodes (1978) expanded Farrell's work by presenting a linear programming technique called data envelopment analysis (DEA).

Advantages of DEA

There are distinct advantages in using DEA for some studies of efficiency. The first advantage is that DEA does not require the estimation of a production function. This is a big advantage because assuming a functional form is the basis for multiple regression analysis, but it is difficult to do. If an error occurs when making this assumption, then the results of the entire study will not be accurate. By using DEA for estimating productivity, the difficult task of assuming any sort of functional form becomes unnecessary.

DEA also has the capability of including multiple outputs in the model. Multiple regression analysis uses only one. Therefore, if more than one output is produced by one entity, then all of the outputs must be combined into one before multiple regression can be used. By doing so, each output must be assigned a weight of some sort. All output could be considered of equal importance, or some output could be assigned higher importance by being given a greater weight. Using DEA avoids the entire process of assigning weights to various outputs because it is capable of allowing each entity to produce multiple outputs.

These advantages make using DEA an attractive alternative for measuring productivity and efficiency in some situations. In fact, Charnes, Cooper, and Rhodes specifically introduced DEA as a tool to analyze behavior of entities in public settings where the value of inputs and outputs may be ambiguous because they are non-marketable. They showed that by using DEA to identify areas of inefficiency managers could possibly improve performance even when such improvement does not result in increased profit. Specific examples of efficiency studies using DEA have been in the areas of hospitals (Ozcan, 1995) and education (Diamond and Medewitz, 1990) where goals other than maximizing profit are the norm.

Using DEA, Ozcan showed that inefficiency in the provision of hospital services exist in urban markets due to overcapacity. He further stipulates the implications of the study suggest any health care reform undertaken by legislators should include reduction of this overcapacity. The education study was a little different in that Diamond and Medewitz were attempting to determine whether or not a specific program was efficient in improving economics education at the high school level. But the ultimate goal was still to identify whether or not this program was an area where policy makers could focus their attention to improve performance. After considering the advantages to DEA and examining the use of this technique in prior studies, DEA became a reasonable choice for the purposes of this paper because WSF is a public enterprise that produces multiple outputs. Furthermore, WSF is subsidized by taxes, leading to the conclusion that it does not seek to maximize profit.

With additional data DEA has even more capabilities. For instance, many times economists are also interested in examining costs of production. If, along with input quantities, the prices of inputs are also known, DEA can measure allocative, or economic efficiency as well as technical efficiency. Measuring technical efficiency involves establishing a best practice frontier, whereas allocative efficiency involves moving along a frontier. This movement represents the tradeoffs made when choosing between different input bundles. Choosing an input bundle that minimizes costs of production leads to allocative efficiency. Although this paper only examines technical efficiency measurements, allocative efficiency is an important topic that can be examined in future studies.

Data Requirements

DEA uses actual observed data to measure relative technical efficiency. The observed data are drawn from a group of entities that use similar inputs to produce similar outputs. However, even if the types of inputs and outputs are similar for every entity in the group, the amounts of inputs used and the amount of output produced by each individual entity will vary. Therefore, the specific data that are needed to produce the measurements of efficiency are the quantities of inputs and outputs associated with each entity.

It is important to acknowledge that many factors can influence the efficiency of a producer. Some of these factors are controllable, or discretionary. But there are other factors that are beyond the control of decision-makers such as tidal and weather conditions. These inputs are referred to as nondiscretionary inputs. Although both types of inputs can impact efficiency, the analysis here only includes discretionary inputs that can be varied by managerial decisions. Therefore any inefficiencies found may be attributable to either discretionary or nondiscretionary factors. Although this paper focuses on the first step of determining whether or not inefficiency exists, by conducting further research it may be possible to pinpoint sources of inefficiency. Such studies are beyond the scope of this paper but may be topics suitable for subsequent research papers in the event that inefficiencies are found here.

Each of the entities in the data group is referred to as a decision-making unit (DMU). A DMU can be any entity, such as a firm or a hospital that uses inputs to produce either a single output or multiple outputs. In this case the DMUs are the various ferry routes on Puget Sound. With the exception of the passenger only routes, these DMUs produce more than one output because both vehicles and passengers are transported.

DEA uses the input and output data from each DMU to formulate a best practice frontier. This frontier establishes which DMUs produce a given amount of output while using the least amount of inputs. This is different from a production frontier because it is determined from observed behavior in the industry. A production frontier is an estimate of possible behavior. However, the efficiency implications of the frontiers are similar. In DEA (as with production frontiers) any data point not lying on the frontier is presumed to be inefficient because the DMUs that lie on the frontier have used less inputs to produce the same amount of output.

Graphical Illustration

The easiest way to understand DEA may be graphically. Together a number of DMUs form a comparison set to which each individual DMU is compared. A best practice frontier is established and any DMU not lying on that frontier is deemed to be inefficient.

Figure 2 shows a graph of three individual DMUs, each using two inputs, x_1 and x_2. To simplify the example, assume all the DMUs produce an equal amount of only one output. Keeping in mind that minimizing the amount of inputs used is desirable, line segments can be drawn between DMUs using the fewest amounts of inputs. By doing so the data is enveloped from below to form somewhat of an isoquant, which creates a frontier. Figure 2 shows DMU_1 and DMU_2 are both efficient, lying on the best practice frontier (points C and A respectively). DMU_3, on the other hand, is obviously inefficient. This DMU lies off of the frontier and uses more of both inputs to produce the same amount of output as DMU_1 and DMU_2.

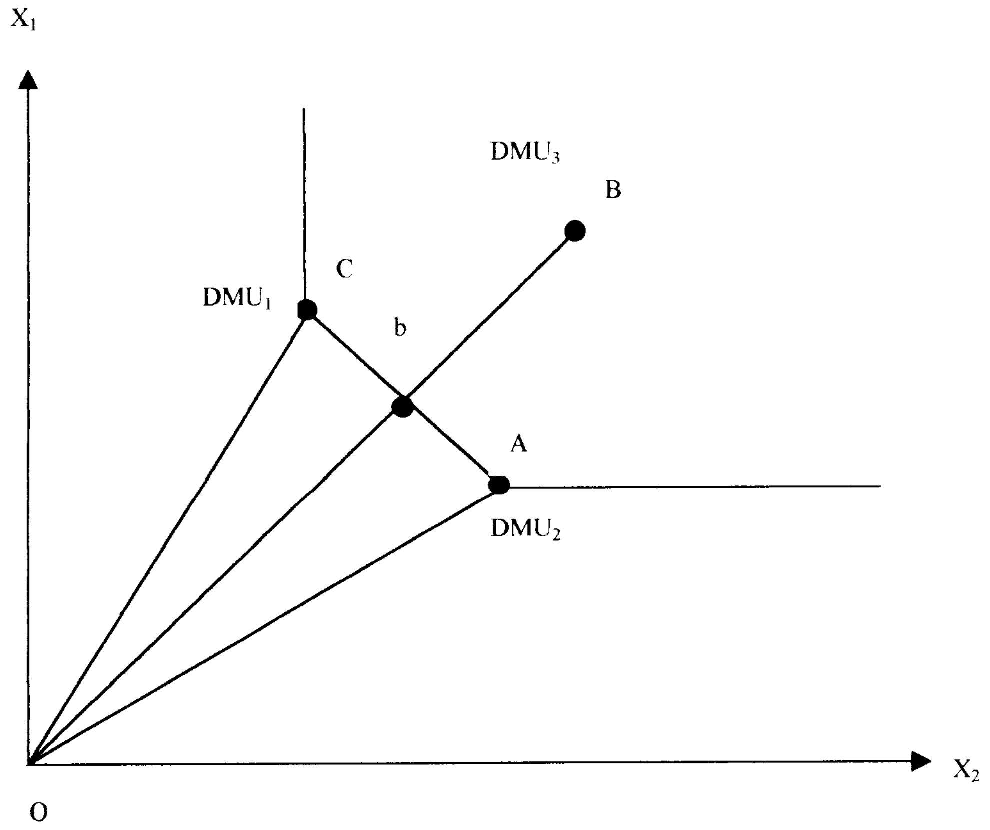

Figure 2. DEA Graph

Ratios are used to measure the efficiency of each DMU. To calculate these ratios the first step is to draw straight lines from the origin to every DMU. Each of those lines will either end on the frontier or will cross it. These line segments are shown in Figure 2 as OA, OB, and OC.

The next step is to generate the efficiency ratios. These ratios are calculated by dividing the length of the line segment from the origin to the best practice frontier by the length of the line segment from the origin to each DMU. If the DMU lies on the frontier, both of the line segments will be of equal length, the ratio will equal one, and the DMU is considered efficient. If the DMU does not lie on the frontier, the lengths of the line segments will be different, the ratio will be less than one, and the DMU will be considered inefficient. In this example the efficiency ratios are $OA/OA = 1$, $Ob/OB < 1$, and $OC/OC = 1$. These ratios are all consistent with DMU_1 and DMU_2 being efficient while DMU_3 is inefficient[1]. The next section shows the linear programming model that numerically calculates these efficiency measurements.

Linear Programming Model

Each DEA model employs dual optimization problems that result in measurements of efficiency. The model can maximize the amount of output possible, given an amount of inputs. The other possibility is to minimize the amount of inputs, given an amount of output. In this case, the minimization problem is used and the objective is to choose a minimum bundle of inputs that will produce a given amount of output.

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[1] For additional details on DEA, see Farrell (1957), Fare and Grosskopf (1996), and Silkman (1986).

Suppose there is a group of I DMUs. Each DMU_i, i = 1,...,I, has a corresponding input vector, X_i and a corresponding output vector, Y_i. The vector X_i is comprised of observed quantities of inputs, x_j, j = 1,...,J, associated with DMU_i. Similarly, the vector Y_i is comprised of observed quantities of outputs, y_k, k = 1,...,K, associated with DMU_i. A J x I input matrix, X, is created from the input vectors and a K x I output matrix, Y, is created from the output vectors. These matrices contain all of the observed input and output data and serve as the comparison set for each DMU that is evaluated. (Remember that the data from the DMU being evaluated is also included in the comparison set.)

By forming a linear programming model using these matrices, a measure of efficiency (θ) can be calculated. This is done by comparing the vectors of input and output quantities from each DMU to the input and output vectors of the other DMUs in the comparison set. This comparison determines whether or not the DMU being evaluated is using the least amount of inputs to produce the amount of outputs that it is producing. If the DMU is found to be using more inputs than is necessary, the model further determines the amount by which inputs can be decreased while still allowing the same amount of outputs to be produced. The linear programming model is as follows[2].

The objective is to minimize θ_i: (1)

subject to: $Y\lambda_i \geq Y_i$

$\theta_i X_i \geq X\lambda_i$

$\lambda_i \geq 0$

[2] The exposition of the model used in this paper is adapted from Charnes, Cooper, and Rhodes (1978) and Fare, Grosskopf, and Lovell (1994).

The minimization problem is repeated and a value for θ is calculated for each DMU in the set with the optimal solution for the problem being $\theta = 1$. At that point the DMU lies on the frontier and is deemed to be efficient. If $\theta < 1$ the DMU is not efficient and the amount of inputs used can be decreased while maintaining the level of output produced. For example if the model calculates $\theta = .75$ it means that the DMU could produce the same amount of output with 75% of the inputs currently being used. Inputs can be decreased by 25% while continuing to produce the observed amount of output.

In this model DMU_i is being evaluated and X_i and Y_i are the input and output vectors associated with that DMU. λ_i, i = 1,...,I, is a vector of weights computed within the model to allow expansion or contraction of the input and output bundles to attain feasible input and output levels. By not imposing any restrictions on the summation of the vector of weights, a constant returns to scale technology is modeled. This is because it is assumed that a firm will increase inputs until output increases at the same rate. In other words, it is beneficial to a firm to operate at constant returns to scale. Assuming that the best performing firm in an industry operates at constant returns to scale, if there are no restrictions imposed on the vector of weights in the model, then this firm would be given all the weight when establishing returns to scale technology for the industry. If the sum of the weights is less than or equal to 1 ($\sum_{i=1}^{I} \lambda_i \leq 1$), then the firm operating at constant returns to scale cannot get all the weight when establishing scale technology for the industry. In fact, this restriction gives weight to firms operating at decreasing returns to scale. Finally, if the vector of weights is restricted to sum to 1 ($\sum_{i=1}^{I} \lambda_i = 1$), then firms operating at increasing returns to scale are given weight when establishing scale technology for the industry. In so doing we allow for variable returns to scale technology. So by adjusting the constraint on this vector of weights, the minimization problem can model different scale technologies. In later sections, the paper will make these adjustments and show how they can be used to evaluate scale efficiency.

Additionally, all the models in this paper assume strong disposability of inputs. This implies that inputs can be increased without decreasing outputs. This assumption can be seen in the second constraint of the minimization problem. Changing the constraint to $\theta X_i = X\lambda_i$ models weak disposability of inputs because it restricts the expansion of inputs. Weak disposability of inputs is an appropriate assumption when analyzing congestion.

Congestion is an important topic but one that is not addressed in this paper. As the next section shows, the data in this study does not contain any land-based information. This type of data would be important to include if congestion were to be studied. Consequently, although changing the constraint is a fairly simple programming adjustment, interpreting the results of that change could be misleading. Therefore, while congestion is an important topic, it is beyond the scope of this paper, but may be suitable for future studies.

SELECTION AND CALCULATION OF INPUTS AND OUTPUTS

The Washington State Ferries' (WSF) Planning Department and Budget Department provided most of the reports from which the data for this paper were derived. Specifically they supplied a fuel report that contained fuel consumption per ferry per fiscal year. They provided a vessel usage report that contained information on which vessels operated on which routes each year. And they provided route statement summaries that contained the number of vehicles and passengers that traveled on each route per fiscal year. These reports were combined with public information such as ferry schedules and the Washington State Ferries Two-Year Operations Reports for 1993/1995 and 1995/1997 to obtain the data needed to carry out the linear programming models.

It is assumed that administrative and other land-based personnel spend labor-hours on more than one ferry route. It is also assumed that some capital is used to benefit more than one ferry route. Although these inputs are important in the production process, it was impossible to allocate all labor and capital among the various ferry routes using the information available. Other factors, such as weather and tidal conditions can also impact efficiency but do not fall under the control of WSF decision-makers. These factors, referred to earlier as nondiscretionary inputs, are unforeseeable occurrences, and as such, could not be included as inputs. Consequently, the inputs that were chosen reflect those that could be allocated to individual routes and could be controlled by WSF managers.

As was noted earlier, DEA requires input and output quantities. Standard microeconomic theory uses labor and capital as inputs for production. In this case, using the information provided by WSF, proxies that could be stated in terms of quantities were found for these two inputs. Crew-hours were used as a proxy for the labor input. These amounts were calculated using the number of trips scheduled on each route per year, the crossing time of each trip, and the number of crew required for each trip, with the latter figure being adjusted according to the vessel used.

The remaining input quantities needed for this study were proxies for capital. They included the vehicle capacity and passenger capacity of each route and the amount of fuel consumed per route, all calculated per fiscal year. The capacity quantities were calculated using the number of trips scheduled per route each year, the vessel usage report, and the Two-Year Operations Reports. The operations report provided the vehicle and passenger capacities of each vessel. After determining which vessels were used on each route, the total capacities of each route, per fiscal year, was calculated. The fuel usage report provided the quantity of fuel consumed by each vessel. This information combined with the vessel usage report, made it possible to compute the amount of fuel consumed on each route per fiscal year.

The output quantities were much easier to calculate. The output quantities used in the models were vehicle-miles and passenger-miles. The route summaries provided by WSF contained the actual numbers of vehicles and passengers that traveled on each route per fiscal year. These figures multiplied by the length of each ferry route (in miles) became the output quantities used for the DEA models.

Obviously, most of these calculations depended on the number of ferry trips scheduled per year. It is true that not all routes scheduled are completed due to various circumstances such as emergency vessel maintenance or tidal conditions that do not allow ferry travel. However, all of the calculations done to determine input quantities for this paper use the number of trips scheduled, not the number of trips completed. Any cancellations in ferry service would presumably cause a decrease in observed output quantities. Because the model uses actual output quantities to determine efficiency, by using the number of trips scheduled to calculate the input quantities, the impact of cancelled trips will be reflected in the resulting efficiency ratios.

When calculating the input and output quantities for routes that served more than two ports, the information provided by WSF did not include separate information for each port served. Therefore certain assumptions were made to allow the necessary data to be derived. For instance, the Fauntleroy/Vashon/Southworth route is somewhat circular. During the course of one ferry trip, the vessel may travel directly from one port to another, or it may stop at a third port. Because of this, the miles traveled on each trip may vary. To account for this when computing output quantities, an average trip length was calculated and then used to derive total passenger-miles and vehicle-miles traveled on that route.[3]

The same problem arose when calculating the output quantities for the Anacortes/San Juan Islands route and the Anacortes/Sidney, BC route because, again, more than two ports may be served on each ferry trip. Once again an average mileage was calculated for these routes and used to derive passenger-miles and vehicle-miles traveled on those routes.

An additional problem arose with the two routes originating from Anacortes because the crossing time of each trip also varies. The reason for this could be the speed of the ferry used or perhaps the tidal conditions that change throughout the day cause differences in ferry speed. In any case, crossing times are needed to calculate crew-hours. So an average crossing time was calculated and used to derive crew-hours for these routes.

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[3] Using average trip length or average crossing time to calculate input and output quantities can lead to inaccuracies in the estimated frontier. However after experimenting with hypothetical increases and decreases in the relevant input and output quantities, no discernable differences arose in the efficiency measurements between the frontiers calculated using averages and the frontiers calculated using hypothetical values.

The input and output quantities calculated for the years 1995-1997 are summarized in Table 1, Table 2, and Table 3.

Table 1. 1995 Input and Output Quantities

Route	*Inputs*				*Outputs*	
	Vehicles	Passengers	Crew-hours	Fuel	Vehicle-miles	Passenger-miles
Pt Def/Tahlequah	1,024,495	8,897,918	30,870	208,645	738,167	1,302,775
Sea/Vashon(po)	20,410[4]	1,414,400	8,828	363,266	0	2,359,389
Brem/Sea (auto)	1,180,780	13,194,200	105,142	2,052,494	12,376,363	35,291,129
Brem/Sea (po)	0	937,750	12,503	286,474	0	4,094,077
Bainbridge/Sea	3,467,936	35,252,000	139,557	3,337,329	19,063,104	55,163,152
King/Edmonds	3,084,160	47,668,000	126,644	2,569,429	9,755,408	19,676,010
Clinton/Mukilteo	3,416,120	31,558,400	87,765	1,120,154	5,546,948	10,358,298
Pt Town/Key	725,850	7,742,400	38,712	393,539	1,924,671	4,225,368
Faun/Vash/South	6,025,780	60,010,110	198,594	1,625,647	6,136,425	10,756,086
Anacort/Sid BC	113,980	1,457,500	33,833	1,217,841	2,124,990	7,596,414
Anacort/San Juans	1,410,411	18,882,450	170,989	2,029,758	12,370,446	28,737,522

[4] In 1995 and 1996 WSF used ferries with the capacity to carry vehicles for a limited number of runs on this passenger-only route.

Table 2. 1996 Input and Output Quantities

Route	*Inputs*				*Outputs*	
	Vehicles	Passengers	Crew-hours	Fuel	Vehicle-miles	Passenger-miles
Pt Def/Tahlequah	1,027,215	8,920,461	30,954	222,884	759,621	1,322,998
Sea/Vashon(po)	32,760	1,499,150	9,028	381,224	0	2,375,892
Brem/Sea (auto)	1,191,610	13,247,100	105,481	1,964,881	11,397,646	35,913,392
Brem/Sea (po)	0	916,250	12,217	285,622	0	4,399,644
Bainbridge/Sea	3,475,762	35,336,500	139,878	3,256,165	19,148,975	57,902,845
King/Edmonds	2,962,580	45,917,300	121,320	2,547,015	10,610,543	21,092,760
Clinton/Mukilteo	3,433,730	31,721,600	88,221	1,042,063	5,695,830	10,525,210
Pt Town/Key	861,900	9,193,600	45,968	433,693	1,685,139	3,790,224
Faun/Vash/South	5,963,850	59,394,015	196,709	1,762,317	6,349,528	11,190,606
Anacort/Sid BC	110,540	1,365,500	33,934	548,785	2,131,102	7,552,942
Anacort/San Juans	1,414,680	18,465,300	170,434	2,798,750	12,766,446	29,115,306

Table 3. 1997 Input and Output Quantities

Route	*Inputs*				*Outputs*	
	Vehicles	Passengers	Crew-hours	Fuel	Vehicle-miles	Passenger-miles
Pt Def/Tahlequah	1,014,010	8,659,704	30,868	202,359	781,259	1,359,677
Sea/Vashon(po)	0	1,265,250	8,435	323,319	0	2,614,620
Brem/Sea (auto)	1,116,670	12,377,400	103,610	2,012,982	11,340,978	36,603,204
Brem/Sea (po)	0	936,750	12,490	308,549	0	4,346,386
Bainbridge/Sea	3,473,594	35,190,500	139,628	3,453,509	19,317,673	57,952,579
King/Edmonds	3,016,320	47,130,000	122,538	2,539,623	10,750,610	21,488,366
Clinton/Mukilteo	3,420,060	31,700,160	88,276	1,137,530	5,835,298	10,742,488
Pt Town/Key	738,000	7,606,320	39,360	450,669	1,868,321	4,144,249
Faun/Vash/South	6,136,060	62,276,430	203,573	1,820,439	6,408,920	11,090,932
Anacort/Sid BC	111,160	1,387,000	33,722	1,119,995	2,030,445	7,085,756
Anacort/San Juans	1,314,080	16,698,740	155,633	2,247,850	12,904,518	29,017,164

DEA RESULTS

First, one best practice frontier was estimated for each individual year. This produced efficiency ratings for each ferry route in 1995, 1996, and 1997 respectively. In this study the data from each year was kept separate making three data sets with 11 DMUs in each set. Each DMU was then compared to the other DMUs from that same year.

The results of this study are shown in Table 4. The number associated with each DMU is the efficiency rating. Each rating is the solution to the minimization problem in equation (1). These models allow for variable returns to scale so an additional constraint is included in equation (1); $\sum^{I}_{i=1} \lambda_i = 1$. The majority of the routes in 1995 had efficiency ratings of 1.0. Again, a 1.0 rating indicates that DMU is a benchmark relative to the other ferry routes in that year. In other words, any route with a 1.0 efficiency rating lies on the best practice frontier. Any route with an efficiency rating less than 1.0 lies off the frontier and is deemed relatively inefficient. These inefficiencies will be discussed further below.

Efficiency ratings in 1996 and 1997 are quite similar. Those years also have a majority of 1.0 ratings. In addition, all routes with a 1.0 rating in 1995 continue to have that same rating in 1996 and 1997 with the exception of the Port Townsend/Keystone route in 1996. In that year the efficiency rating for this route fell to .9244 but rose to 1.0 again in 1997. This route is particularly susceptible to tidal conditions and ferry service can be interrupted for this reason. In 1996 the tidal conditions may have forced changes in service that led to lower efficiency for this route. Since the rating rose again in 1997, it may not be an area for concern. But it might be a route to monitor for changes in the future.

Table 4. Ferry Route Efficiency Ratings per Fiscal Year

Route	*1995 Efficiency Rating*	*1996 Efficiency Rating*	*1997 Efficiency Rating*
Pt Def/Tahlequah	1.0000	1.0000	1.0000
Sea/Vashon(po)	1.0000	1.0000	1.0000
Brem/Sea (auto)	1.0000	1.0000	1.0000
Brem/Sea (po)	1.0000	1.0000	1.0000
Bainbridge/Sea	1.0000	1.0000	1.0000
King/Edmonds	.6645	.7311	.7621
Clinton/Mukilteo	.8605	.9896	.9282
Pt Town/Key	1.0000	.9244	1.0000
Faun/Vash/South	.6479	.6459	.6328
Anacort/Sid BC	1.0000	1.0000	1.0000
Anacort/San Juans	1.0000	1.0000	1.0000

Another item to note is that the efficiency rating for the Kingston/Edmonds route rose from .6645 in 1995 to .7311 in 1996. One possible explanation for this increase is that the Edmonds ferry terminal was under construction for a period of time in 1995. Ferry service continued during the time of construction, but modifications were made to the route. One of the changes was that service to and from Kingston was routed to the Seattle terminal instead of Edmonds. This could account for the lower rating in 1995. This route will be examined again in more detail later in the paper.

A somewhat similar situation exists with the Clinton/Mukilteo route because the terminals may be impacting the efficiency ratings on this route. The Mukilteo terminal location makes access to the ferries difficult and congestion problems periodically arise. WSF has made attempts to improve access to and from the terminal so efficiency may increase on this route in the future. Also, improvements were made to the Clinton terminal in the 1995/1997 biennium. Depending on when the actual improvements occurred, this may account for the rise in the efficiency ratings from .8605 in 1995 to .9896 in 1996.

The Fauntleroy/Vashon/Southworth route has the lowest rating in all three years. As was noted earlier, this route is unique in that it serves three ports instead of the usual two and is somewhat circular in nature. (See Figure 1.) On some trips all three ports are served. At times the ferry may not take the shortest possible route between two ports, but instead, may travel via the third port. In other words, a ferry may travel from Southworth to Vashon via Fauntleroy or from Fauntleroy to Vashon via Southworth thereby turning what would normally be a short 10 or 15 minute trip into a 45 minute journey. This type of scheduling may have affected the efficiency ratings for this route.

It is also interesting to note that since the time these data were gathered, the Washington State Ferries have decreased the inputs used on this route. One of the ferries previously used on the route has been exchanged for a ferry with less vehicle and passenger capacity. Taking this action is consistent with the findings in this paper, but if the study were done again, using more recent data, perhaps the relative efficiency of this route would be improved due to the change in input quantities.

In addition, the data for these three ports is consolidated into one route. If it were possible to separate the data into three distinct routes, (Fauntleroy/Vashon, Fauntleroy/Southworth, and Southworth/Vashon) the results may be different. It is conceivable that one or more of these three routes could be inefficient and, by consolidating the data, make all three appear inefficient.[5]

3-Year Consolidated Data Set

Next, the data from all three years was combined to make a single data set consisting of 33 DMUs. Combining the data expanded the comparison set so that each route in every year was compared to the other 32 routes regardless of the year. This results in only one best practice frontier being estimated.

Comparisons between the best practice frontier with the expanded data set and the 3 frontiers formed from separating the data by year can give managers an idea of whether or not technology has changed drastically over the 3 year period. Each frontier is formed with the assumption of a given state of technology. This technology is constant across routes so even a drastic change in technology between years may not be seen in the individual best practice frontiers because the relative efficiencies would remain fairly stable. But, if there are large inconsistencies between the results of the consolidated data set and the individual data sets, it may be an indication of technological change. Later in the paper technological change is discussed in more detail. Here indications are that technology did not vary much because the comparisons between the consolidated frontier and the 3 individual year frontiers do not reveal major discrepancies.

[5] The model was also run without including data from this route. However, eliminating the route from the model did not alter the efficiency ratings of the other routes because it was not a benchmark.

The results for this section are shown in Table 5. Some of the 1.0 efficiency ratings from the previous section do not hold once the comparison set is expanded. For instance, the Point Defiance/Tahlequah route rates a 1.0 in each year when the data is separated by year. When the data is consolidated, this route has a 1.0 efficiency rating only in 1997. In this case, the 1997 Point Defiance/Tahlequah route is found to be efficient and is therefore considered a benchmark. In 1995 and 1996 this route was less efficient than in 1997 so those DMUs are not benchmarks and their efficiency ratings are lower than 1.0. In essence, with the expanded comparison set there are more possibilities for technical efficiency and more possibilities for inefficiencies as well.

Table 5. Ferry Route Efficiency Ratings with 3-year Consolidated Data Set

Route	*DMU No. (1995)*	*Efficiency Rating*	*DMU No. (1996)*	*Efficiency Rating*	*DMU No. (1997)*	*Efficiency Rating*
Pt Def/Tahlequah	1	.9818	12	.9588	23	1.0000
Sea/Vashon(po)	2	.9555	13	.9343	24	1.0000
Brem/Sea (auto)	3	1.0000	14	1.0000	25	1.0000
Brem/Sea (po)	4	.9970	15	1.0000	26	.9781
Bainbridge/Sea	5	.9938	16	1.0000	27	1.0000
King/Edmonds	6	.6614	17	.7268	28	.7333
Clinton/Mukilteo	7	.8555	18	.9402	29	.8826
Pt Town/Key	8	1.0000	19	.8403	30	.9178
Faun/Vash/South	9	.6439	20	.6130	31	.5986
Anacort/Sid BC	10	.9943	21	1.0000	32	.9738
Anacort/San Juans	11	1.0000	22	.9043	33	1.0000

Evaluating Scale Efficiency

The study next turns from technical efficiency to the idea of scale efficiency. This analysis will determine what type of returns to scale each route exhibits. If the route is operating with constant returns to scale, it is determined to be scale efficient. If scale efficiency does not exist, then DEA can ascertain whether the scale inefficiency is due to increasing returns to scale or decreasing returns to scale. To do these tests the linear programming model must be adjusted. The previous models allowed for variable returns to scale technology. To test for scale efficiency the model is run and an estimate for θ is found using both constant returns to scale and variable returns to scale. Eliminating any constraint on $\Sigma^{I}_{i=1} \lambda_i$ will allow for constant returns to scale technology. For further analysis on scale inefficiency, the model must be adjusted once again. This adjustment enables comparisons to be made that will determine whether any scale inefficiencies that are found are caused by increasing or decreasing returns to scale. To do this the model is run with technology restricted to non-increasing returns to scale. Constraining λ such that $\Sigma^{I}_{i=1} \lambda_i \leq 1$ accomplishes this.

For this analysis all routes are separated by year and three different estimates for θ were found, θ_{VRS}, θ_{CRS}, and θ_{NIRS} for each route. Comparing the results of the first two estimates for θ will determine whether or not scale efficiency exists. If $\theta_{VRS} = \theta_{CRS}$ the route exhibits scale efficiency because that route has the same efficiency relative to both technologies. If, however, the results are not equal, ($\theta_{VRS} > \theta_{CRS}$) then the route is scale inefficient because that route is more efficient relative to the variable returns to scale technology than it is relative to the constant returns to scale technology. In order to determine whether increasing or decreasing returns to scale are causing this scale inefficiency the efficiency rating relative to the nonincreasing returns to scale (θ_{NIRS}) must be utilized.

After determining that scale inefficiency exists, ($\theta_{VRS} > \theta_{CRS}$), θ_{CRS} is compared to θ_{NIRS} for each route. If $\theta_{CRS} < \theta_{NIRS}$ then that route is operating closer to the nonincreasing returns to scale technology than it is to the constant returns to scale technology. This means that the route must be operating at decreasing returns to scale because by definition nonincreasing returns to scale technology does not allow for increasing returns to scale. Therefore all entities operating efficiently relative to this technology are operating either at constant returns to scale or decreasing returns to scale. And it has already been established that the route is not operating at constant returns to scale. If the efficiency ratings are equal in these two models, ($\theta_{CRS} = \theta_{NIRS}$) then the route is operating at increasing returns to scale because the route is not operating at constant returns to scale or at decreasing returns to scale. The relevant comparisons are summarized below:

If $\theta_{VRS} = \theta_{CRS}$ then scale efficiency exists.

If $\theta_{VRS} > \theta_{CRS}$ then scale inefficiency exists.

If $\theta_{CRS} = \theta_{NIRS}$ then increasing returns to scale exist.

If $\theta_{CRS} < \theta_{NIRS}$ then decreasing returns to scale exist.

Tables 6, 7, and 8 show the efficiency ratings for each route with the various technology restrictions and the applicable comparisons. The results of these comparisons show that all of the routes, with one lone exception, are either scale efficient or operating with increasing returns to scale. The one exception is the 1996 Anacortes/San Juan Islands route, which appears to exhibit decreasing returns to scale.

Table 6. 1995 Scale Efficiency Comparisons

Route	*Efficiency Rating (VRS)*	*Efficiency Rating (CRS)*	*Efficiency Rating (NIRS)*	*Comparison*	*Returns to Scale*
Pt Def/Tahlequah	1.0000	.5805	.5805	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Sea/Vashon(po)	1.0000	.8008	.8008	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Brem/Sea (auto)	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
Brem/Sea (po)	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
Bainbridge/Sea	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
King/Edmonds	.6645	.6366	.6366	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Clinton/Mukilteo	.8605	.8141	.8141	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Pt Town/Key	1.0000	.8025	.8025	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Faun/Vash/South	.6479	.6194	.6194	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Anacort/Sid BC	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
Anacort/San Juans	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant

Table 7. 1996 Scale Efficiency Comparisons

Route	*Efficiency Rating (VRS)*	*Efficiency Rating (CRS)*	*Efficiency Rating (NIRS)*	*Comparison*	*Returns to Scale*
Pt Def/Tahlequah	1.0000	.5795	.5795	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Sea/Vashon(po)	1.0000	.7152	.7152	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Brem/Sea (auto)	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
Brem/Sea (po)	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
Bainbridge/Sea	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
King/Edmonds	.7311	.7084	.7084	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Clinton/Mukilteo	.9896	.9294	.9294	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Pt Town/Key	.9244	.6607	.6607	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Faun/Vash/South	.6459	.6127	.6127	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Anacort/Sid BC	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
Anacort/San Juans	1.0000	.8570	1.0000	$\theta_{CRS} < \theta_{NIRS}$	Decreasing

Table 8. 1997 Scale Efficiency Comparisons

Route	*Efficiency Rating (VRS)*	*Efficiency Rating (CRS)*	*Efficiency Rating (NIRS)*	*Comparison*	*Returns to Scale*
Pt Def/Tahlequah	1.0000	.6725	.6725	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Sea/Vashon(po)	1.0000	.8908	.8908	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Brem/Sea (auto)	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
Brem/Sea (po)	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
Bainbridge/Sea	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
King/Edmonds	.7621	.7514	.7514	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Clinton/Mukilteo	.9282	.8936	.8936	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Pt Town/Key	1.0000	.7221	.7221	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Faun/Vash/South	.6328	.6132	.6132	$\theta_{CRS} = \theta_{NIRS}$	Increasing
Anacort/Sid BC	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant
Anacort/San Juans	1.0000	1.0000	1.0000	$\theta_{VRS} = \theta_{CRS}$	Constant

For this paper, a specific production function was not assumed, estimated, or tested. However, production functions generally exhibit increasing returns, constant returns, and decreasing returns to scale depending on the amount of output produced. At high levels of output decreasing returns to scale are common. Private firms would not choose to operate in this region, but WSF is not a private firm. And according to the Washington State Ferries Two-Year Operations Report for 1995/1997, this agency focuses, in part, on the needs of its customers and seeks to meet customer demand. In this case the Anacortes/San Juan Islands route is one of the busiest routes in the WSF system during the tourist season. It is possible that in 1996 there was an exceptionally high volume of tourist traffic making the total output for that year abnormally high. It could be that while attempting to serve as many customers as possible, the route operated in the portion of the production function that exhibits decreasing returns to scale.

Malmquist Productivity Indexes

The final section of this paper looks at changes in the total factor productivity of each ferry route over time. Whereas the previous sections evaluated the ferry routes in only one given time period, t, this study utilizes two time periods, t, and t+1. By introducing an additional time period, the model can determine whether or not technology is changing over time. This is determined by examining any movements that the best practice frontier may be undergoing over time. For example, a shift in the frontier that is inward toward the origin represents an increase in technology. This means the amount of inputs required to produce a given amount of output decreases from one time period to the next.

Additionally, this section looks at changes in efficiency over time. A frontier is formed for each time period and the efficiency of the ferry routes in each time period is established using the frontier from that same time period. The efficiency of each route improves as the data point for that route moves closer to the relevant frontier.

The results of this type of analysis are given in the form of Malmquist Input-based Productivity Indexes. In order to calculate these indexes, four linear programming equations must be solved. They are similar to equation (1), but they include time period t+1. Defining A, B, C, and D to be the solutions to these equations, they are as follows.

$$A = \text{Minimize } \theta_i: \tag{2}$$

$$\text{subject to: } Y^t\lambda_i \geq Y^t_i$$

$$\theta X^t_i \geq X^t\lambda_i$$

$$\lambda_i \geq 0$$

$$\sum\nolimits^I_{i=1} \lambda_i = 1$$

$$B = \text{Minimize } \theta_i: \tag{3}$$

$$\text{subject to: } Y^{t+1}\lambda_i \geq Y_i^{t+1}$$

$$\theta X_i^{t+1} \geq X^{t+1}\lambda_i$$

$$\lambda_i \geq 0$$

$$\sum\nolimits^I_{i=1} \lambda_i = 1$$

$$C = \text{Minimize } \theta_i: \tag{4}$$

$$\text{subject to: } Y^t\lambda_i \geq Y_i^{t+1}$$

$$\theta X_i^{t+1} \geq X^t\lambda_i$$

$$\lambda_i \geq 0$$

$$\sum\nolimits^I_{i=1} \lambda_i = 1$$

$$D = \text{Minimize } \theta_i: \tag{5}$$

$$\text{subject to: } Y^{t+1}\lambda_i \geq Y_i^t$$

$$\theta X_i^t \geq X^{t+1}\lambda_i$$

$$\lambda_i \geq 0$$

$$\sum\nolimits^I_{i=1} \lambda_i = 1$$

The Malmquist Input-Based Productivity Index is then calculated as:

$$M_i^{t+1} = (A)/(B) * [(B)/(C) * (D)/(A)]^{1/2} \tag{6}$$

There are two components of the Malmquist productivity index. The first is a measure of efficiency change and is the part of equation (6) that is not in brackets. This measurement is a ratio of the efficiency measurements in the time periods, t, and t+1. This ratio indicates whether or not the ferry route is moving closer to the relevant frontier. The second component is a measure of technical change. Here, the location of the frontier in period t is compared to the location of the frontier in period t+1. In doing so, any shifts that take place in the best practice frontier can be seen. These shifts would indicate a change in technology over time. This measurement is the section of equation (6) that is enclosed in brackets.

Interpretation of the numerical values of these two components is different from the previous technical efficiency measures. In this case a result less than 1 shows an increase in the component being measured, whereas a result greater than 1 indicates a decrease. For example, a result less than 1 for the efficiency change component indicates that, over time, the route is moving closer to the best practice frontier and is thus becoming more efficient. Moreover, if the technology change component is less than 1 it indicates that the frontier has indeed moved toward the origin and that technology is improving. The product of these two components produces the Malmquist index. If the Malmquist index is less than 1, then an improvement in total factor productivity has taken place. Conversely, if this index is greater than 1, productivity has decreased on that route. It is important to realize that because the Malmquist index is a product of two components, a decrease in either efficiency or technology can be offset by an increase in the other to produce an overall increase in total factor productivity.

The results of this particular analysis are summarized in Table 9.

Table 9. Malmquist Productivity Indexes

	1995			*1996*		
Route	*Malmquist Index*	*Efficiency Change*	*Technical Change*	*Malmquist Index*	*Efficiency Change*	*Technical Change*
Pt Def/Tahlequah	1.0415	1.0000	1.0414	.9258	1.0000	.9258
Sea/Vashon(po)	1.0727	1.0000	1.0727	.8032	1.0000	.8032
Brem/Sea (auto)	1.0748	1.0000	1.0748	.9534	1.0000	.9534
Brem/Sea (po)	.8800	1.0000	.8800	1.0501	1.0000	1.0501
Bainbridge/Sea	.8805	1.0000	.8805	1.0272	1.0000	1.0272
King/Edmonds	.9100	.9089	1.0012	.9885	.9593	1.0304
Clinton/Mukilteo	.9092	.8696	1.0456	1.0672	1.0661	1.0010
Pt Town/Key	1.1965	1.0818	1.1060	.9405	.9244	1.0174
Faun/Vash/South	1.0508	1.0031	1.0475	1.0241	1.0207	1.0033
Anacort/Sid BC	.7772	1.0000	.7772	1.2961	1.0000	1.2961
Anacort/San Juans	1.0622	1.0000	1.0622	.8899	1.0000	.8899

Both increases and decreases in overall productivity can be seen but the largest fluctuation was in the Anacortes/Sidney, BC route. The efficiency change ratio for this route is 1.0 in both 1995 and 1996 which indicates that over the time period studied (1995-1997) the efficiency of this route did not change. However the technical change ratio in 1995 is .7772 which indicates an increase in technology between 1995 and 1996. But the technical change ratio in 1996 is 1.2961, showing a large decrease in technology between 1996 and 1997. Therefore a corresponding decrease in productivity took place during that same time as well. It is interesting to note that WSF had planned to discontinue this route in

October of 1997 but that action has been delayed due to a negative public response. WSF still plans to discontinue service, but the current plan is to do so gradually to allow other travel options to become established.

As was noted earlier, the Edmonds ferry terminal was under construction in 1995. That being the case, it might be logical to expect that the technical change component of the Malmquist index would show an improvement in technology. However, the results do not indicate technology improved in either 1995 or 1996 because the technical change ratios are both greater than one for this route. But after examining all of the ratios more closely, the results seem more appropriate. In fact, the Malmquist indexes show that the Edmonds/Kingston route actually increased in total factor productivity over the time period studied because the Malmquist index in both 1995 and 1996 is less than 1.0. In addition, the efficiency ratios in 1995 and 1996 are less than 1.0, indicating that over time, the efficiency of the route improved. So, although there may not have been an improvement in technology, the terminal construction may have allowed the route to operate more efficiently leading to an overall improvement in total factor productivity.

SUMMARY

It is important to acknowledge that the research done in this paper analyzed the efficiency of the ferries only during the actual travel time. Other factors can influence the performance of each ferry route, including terminal facilities and port accessibility, which are land-based, but still considered discretionary. In addition there are nondiscretionary factors such as weather and tidal conditions that can impact efficiency but do not fall under the control of decision-makers. But evaluating efficiency in some way is necessary. In a competitive situation, a producer would be forced out of business if inefficiencies were allowed to continue. In a case such as the Washington State Ferries competition does not exist, but tax dollars are being spent to provide this service. The public therefore has an obvious interest in the efficiency of the routes. Because decision makers are ultimately accountable to the public they also need to be interested in making each route as efficient as possible.

This particular research does not attribute inefficiencies to specific sources. Rather it attempts to identify areas where management may want to focus attention when making production decisions by determining those areas that are relatively less efficient. After examining the research, it seems as if most of the Washington State ferry routes are operating in an efficient manner and may not need special attention from management. However, a few routes such as Edmonds/Kingston and Fauntleroy/Vashon/Southworth indicate possible room for increases in efficiency. WSF has indeed taken steps to improve these routes by terminal renovation and decreasing input capacity. In the case of Edmonds/Kingston, the improvement can even be seen in the research. Also, in the case of Mukilteo/Clinton, plans are pending on terminal improvements that may lead to increases in efficiency similar to the progress made in the Edmonds/Kingston route. Other areas where the routes are less than efficient, such as the Point Townsend/Keystone route, the inefficiency may be due to circumstances beyond management control.

DEA proved to be the logical choice for making efficiency assessments for this paper. With very little additional data and/or small alterations to the models, the research can be expanded. Specifically, this methodology can be used to explore the areas of congestion and allocative efficiency. This paper first examined relative technical efficiency. Each ferry route was then evaluated with regard to scale efficiency, which is one component of technical efficiency. Congestion is another component. Using the original data, but adjusting the model slightly to assume weak disposability of inputs instead of strong disposability can yield important information on the congestion component of technical efficiency. Congestion is a big concern for Washington State Ferries so research in this area could be very beneficial. Moreover, if input prices are added to the data set, allocative efficiency can also be examined for each route. Minimizing input costs as well as input quantities is an important aspect of production decisions. Research on allocative efficiency would be extremely helpful when making those decisions. Although congestion and allocative efficiency are beyond the scope of this paper, additional DEA studies in these areas could be very valuable to the Washington State Ferries and to the public.

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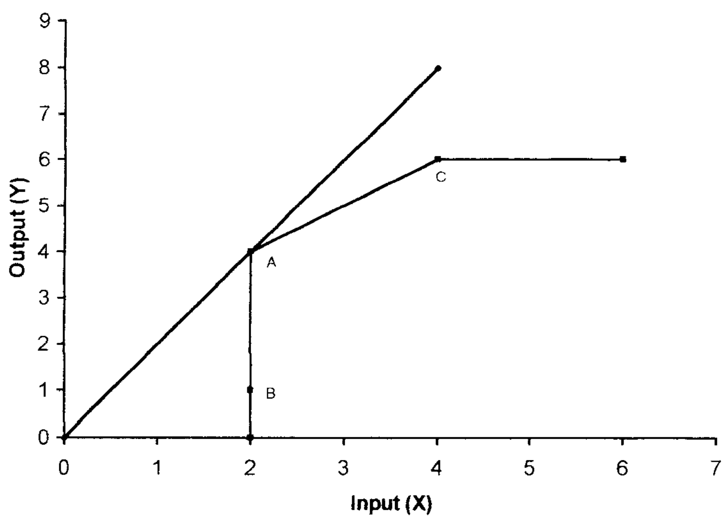
APPENDIX

A numerical example and a graph may help to understand how changing the restriction on the sum of the vector of weights leads to modeling different scale technologies. To keep the example simple, assume there are three firms operating in an industry. Each firm uses one input (X) to produce one output (Y). The specific quantities of X and Y associated with each firm are outlined below.

Firm	X	Y
A	2	4
B	2	1
C	4	6

Figure A.1 illustrates the production of each firm graphically. Assuming firm A operates at constant returns to scale, the ray from the origin through point A represents the production technology for the industry. The linear expansion of firm A's production is used because this leads to the greatest level of output with the smallest quantity of input. Thus, firm A is referred to as the "best producing" firm.



Returns to Scale Graph

To see how this corresponds to the assumption that the sum of weights from the linear programming model is unrestricted, note that for this example the model is:

Minimize θ_i:

Subject to $\lambda_1 4 + \lambda_2 1 + \lambda_3 6 \geq Y_i$

$\theta_i X_i \geq \lambda_1 2 + \lambda_2 2 + \lambda_3 4$

$\lambda_1, \lambda_2, \lambda_3 \geq 0$

where $\lambda_1, \lambda_2, \lambda_3$ are the weights for firms A, B, and C, respectively.

When there are no restrictions on the sum of the vector of weights ($\Sigma^I_{i=1} \lambda_i$), one firm can be chosen to represent the production technology for the entire industry. In this case it would be firm A because it is the best producing firm in the industry. The vector of weights would be (λ_1, 0, 0), where λ_1 can take on any nonnegative value. This defines the linear expansion shown in figure A.1.

Any restrictions imposed on the sum of the weights means that other firms must be considered when establishing technology for the industry. To model nonincreasing returns to scale, the sum of the weights is restricted to be less than or equal to one. In this case, firm A's output can still be contracted along line segment 0A, but can no longer be expanded along the ray extending to the northeast of A because that requires $\lambda_1 > 1$. To produce more than 4 units of output, positive weight must be placed on firm C. All convex combinations of A and C's production are attainable, but firm C is operating at decreasing returns to scale because output increases less than proportionally to the input with movement from point A to point C. The production technology therefore exhibits nonincreasing returns to scale: it consists of the ray from the origin to point A (constant returns to scale), plus the line connecting points A and C and the horizontal line extending to the right of point C (decreasing returns to scale).

If the sum of the weights must equal exactly one then all three firms must be given weight when establishing overall technology for the industry. Now, X must be greater than 2 so firms cannot operate on line segment 0A. The production technology consists of the vertical segment from (2,0) to point A (increasing returns to scale) plus the region of decreasing returns to scale from before. This represents variable returns to scale.