Freight Service Quality Cost Economics and a Hypothetical Railroad Example

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Service quality is an integral aspect of the freight transportation process. Variations in service quality have a direct effect on shipper resource consumption, which in turn affects both the demand and supply aspects of freight transportation. In this paper, the cost (supply) aspects of freight service quality are examined. Emphasis is on the implications for carriers and transportation analysis, with the primary goal of providing some concrete understanding of these issues. This goal is achieved by using a hypothetical railroad example to explore and illustrate a freight service quality model. The example is based on an engineering model of railroad operations that captures the essence of run-through train operations. The example also serves a secondary goal of fostering general understanding of railroad service quality. After the freight service quality and railroad operating models are reviewed, a more detailed discussion of service quality economics, focused on the interaction between carrier operating variables, service quality variables, and carrier and shipper cost, is presented. In particular, the implications of three conclusions are examined: (a) the most economically efficient service quality level is obtained by minimizing the full cost of transportation—the sum of carrier costs and service sensitive shipper costs; (b) this service quality level is also profit-maximizing for the carrier; and (c) transportation cost analysis should be based on the full cost of transportation instead of carrier costs alone. The negative consequences of disregarding these conclusions are illustrated with the railroad example.

"In a railroad system ideally organized from the economic point of view we should expect the transit time of a particular service to be cut down whenever the consequent reduction of inventory costs exceeds the costs of providing this faster service," (*1*, p. 116).

"Shippers are faced with ordering costs, inventory costs, stockout costs, and a variety of other costs which vary with the type and quality of the transportation purchased. These costs are equally relevant to the analysis of the efficiency of the freight transport system but are often ignored or treated incorrectly," (*2*, p. 500).

Service quality is an integral aspect of the freight transportation process. Variations in service quality have a direct effect on shipper resource consumption; one example is the inventory cost associated with goods-in-transit. In turn, this resource consumption affects both the demand and supply aspects of freight transportation. Therefore, shippers, carriers, and transportation analysts in general should all be concerned with the impact of freight service quality. However, of these three groups, only shippers have begun to fully recognize its significance and the direct impact it has on their cost structure and ultimately on their profit. Examples of this recognition include the use of mechanisms such as just-in-time delivery.

Carriers have reacted to this increased shipper sensitivity by paying greater attention to the demand or marketing aspects of freight service quality. Individually, they have improved overall service quality and introduced new services, with the goal of attracting new traffic and retaining current traffic in an increasingly competitive transportation market.

However, there is little evidence that carriers have paid significant attention to the supply or cost aspects of service quality. That is, carriers generally have not explicitly considered the efficiency factors associated with service quality in the joint utilization of carrier and shipper resources. Like other production efficiency considerations, this may have a direct impact on carrier profit. Traditional transportation economic analysis has also largely ignored the effects of freight service quality.

A general model of freight service quality and carrier economics presented by Brown (*3*) addresses both the demand and supply considerations. Three of the major conclusions in the paper concern transportation cost and supply:

- At any given volume level, the most economically efficient service quality is one that minimizes the full cost of transportation—the sum of carrier costs and service sensitive shipper costs. This optimal service level is called quality efficiency (QE).
- QE is also profit maximizing for the carrier (at the given volume level).
- No matter what service quality level is implemented, transportation cost analysis should be based on the full cost of transportation instead of only carrier costs.

These points are reflected in the quotations at the beginning of this paper.

In Figure 1, the two dashed cost curves indicate how shipper inventory and carrier expenses might respectively vary with a single service quality variable; the solid full cost curve is the sum of these expenses. Beckmann et al. (*1*) indicated that the most efficient service quality level minimizes the full cost of transportation; this QE service quality level is indicated by Z^* in Figure 1. The Beckmann quotation also suggests that it is in the carrier's self-interest to implement this service

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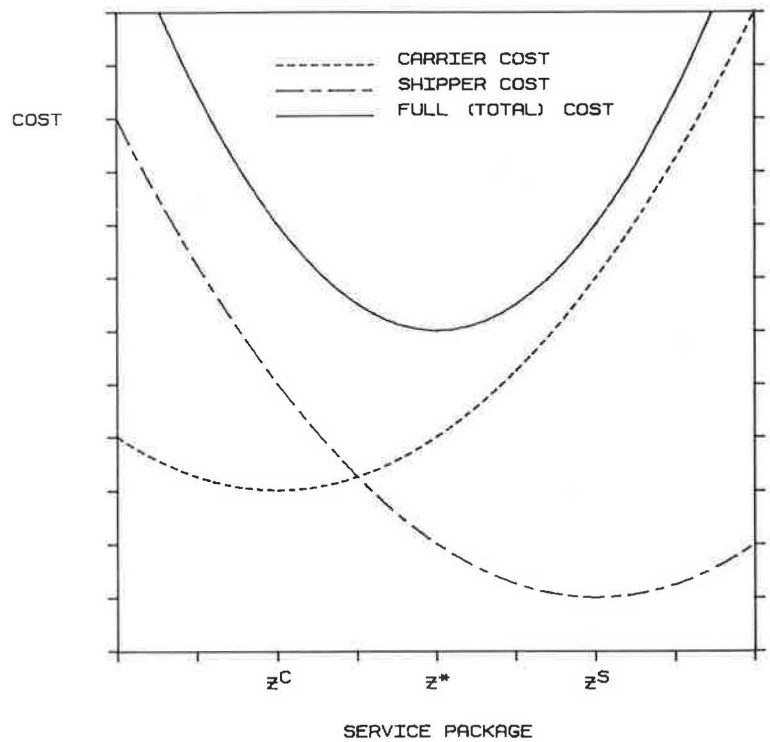

FIGURE 1 Illustration of freight service quality cost economics.

quality level (i.e., QE maximizes carrier profit). However, QE is not always implemented. In particular, if the carrier effectively ignores shipper satisfaction and concentrates on controlling its own costs, then pure carrier cost minimization (CCM) is a likely alternative to QE; this quality policy is indicated by Z^c in Figure 1. In this paper, CCM provides a useful reference point for comparison with QE.

The Nason and Kullman quotation (*2*) indicates that, in addition to defining the optimal service quality level, full cost is also appropriate for general transportation economic analysis, such as carrier profit, cost, and regulatory policy analysis. Nason and Kullman specify several internal shipper cost elements that vary with freight service quality. These cost elements reflect resources that are as integral to the provision of transportation service as are the resources consumed by the carrier and should be considered in any broad-based economic evaluation of freight service. By including these elements, the full cost of transportation accounts for all resource consumption associated with the provision of freight service (ignoring externalities). Transportation economic analysis based on carrier cost alone is incomplete and potentially misleading.

The primary goal of this paper is to provide a more concrete understanding of the cost (or supply) aspects of the freight service quality model. This is accomplished by establishing a relationship between specific service quality variables and carrier operating variables through a simple operations model based on railroad technology. Thus, the service quality model and its implications may be discussed with respect to tangible attributes such as dollars, miles per hour, transit time, train length, and horsepower. Fostering general understanding of railroad freight service quality economics is a secondary goal of this paper. The limited example presented here captures the essence of run-through train operations.

The cost aspects of the service quality model are introduced next, followed by an overview of the railroad operations model. The railroad model is then implemented to illustrate and support a more detailed discussion of freight service quality cost economics. This paper and another by the author (*3*) are based on the author's doctoral dissertation (*4*).

FREIGHT SERVICE QUALITY COST MODEL

Production cost functions are used by economists and others to address issues such as basic questions of production efficiency and industrial organization. As discussed previously, the production of freight service requires the consumption of both carrier and shipper resources. The costs associated with both sets of resources are internalized in the service production process and are affected by the service quality. In this section, the cost portion of the freight service quality model is summarized and discussed. In the model presented here, a single carrier provides a single service to one or more shippers; shippers are treated as a relatively homogeneous aggregate group. This relatively simple version of the service quality modeling framework allows one to focus on and clarify some central issues.

The freight service quality model includes three cost functions that correspond to the three curves in Figure 1. Each specifies cost (per unit time) as a function of annual freight volume v and service quality z. The functions are carrier cost

$C(v, z)$, shipper cost $S(v, z)$, and the full cost of transportation:

$$T(v, z) = C(v, z) + S(v, z)$$

For this simple application, freight volume is the total annual volume summed over all shippers. The service package z is a vector of one or more service quality variables; a two-variable service package is specified later.

A service quality variable is an observable characteristic of the freight service, which affects both the carrier's cost and the shipper's cost. In addition to average transit time, other possible service quality variables include transit-time variability, loss and damage, and shipment size. These variables are distinguished from related carrier operating variables, such as speed and frequency, that are not always observable by the shipper.

For this application, the carrier provides the same service quality to all shippers [a multiple service package extension is presented elsewhere (*4*)]. The carrier cost function explicitly acknowledges the functional relationship between carrier cost and service quality level. For example, improving reliability by increasing train frequency may require a larger labor expense.

Shippers are simply consumers of freight transportation and active customers of the carrier. Shipper cost $S(v, z)$ includes the opportunity costs of all shippers, which directly vary with the service quality variables; these are typically inventory costs. The volume argument allows these internal shipper cost elements to also vary in a generalized way with annual volume. The shipper cost function does not include the freight charge paid to the carrier; the freight bill does not (in this model) directly vary with the service quality variables, and more important, it does not represent additional resource consumption by the combined shipper-carrier entity. (Instead, the freight bill may be viewed as a transfer payment within the combined entity.)

Formally, a quality policy is a rule that specifies the quality level implemented by the carrier as a vector function of the volume level. The QE and CCM quality policies are respectively indicated by an asterisk and a superscript c and defined by minimizing full cost and carrier cost with respect to service quality:

$$Z^*(v) = \underset{z}{ARG\ MIN}\ T(v, z) \quad (1)$$

$$Z^c(v) = \underset{z}{ARG\ MIN}\ C(v, z) \quad (2)$$

where *ARG MIN* denotes the service quality vector (service package), which minimizes the objective function.

The QE policy is fundamentally important because it specifies the socially optimal service quality level for every volume level (with respect to technical efficiency). Furthermore, QE also maximizes carrier profit. This should provide the carrier with sufficient motivation for implementing this quality policy. However, successful implementation requires a management structure sufficiently fine-tuned to discern and fully exploit all quality-related profit opportunities. No management is perfect, and carriers sometimes fail to explore these opportunities.

The CCM policy provides an alternative for comparison with QE. CCM generally does not maximize carrier profit. However, a carrier will tend toward CCM if it is overly concerned with internal cost control and relatively insensitive to shipper satisfaction. For example, this is a likely outcome with the classical railroad management structure, in which the viewpoint of the operations department eclipses input from the marketing (traffic) department (*5*).

DESCRIPTION OF MODEL UNDERLYING RAILROAD EXAMPLE

The primary focus of this paper is a hypothetical railroad example that provides a framework for discussing the service quality economic concepts introduced above, in the context of realistic freight operations. The example is based on a model that was originally designed to examine relatively detailed considerations, such as the tradeoff between unit crew cost and train frequency in terms of the total labor cost when implementing QE. In the present context, the detail adds to the realism and thus increases the illustrative power of the example. In this section, the transportation context is described, shipper cost and transit time are discussed, railroad cost elements are described, and model implementation issues are addressed. A complete description of this model is available elsewhere (*4*).

Transportation Process

In this model, a railroad provides through train service from a single origin yard to a single destination yard. The railroad has two operations decision variables: annual train frequency and train cruising speed. Shippers are responsible for getting shipments to the origin yard and picking up at the destination yard (like some types of railroad intermodal service).

The scheduled headway between successive train departures is inversely proportional to train frequency. It is assumed that shipments arrive at a constant rate, are loaded on identical freight cars, and leave on the next train scheduled for departure. The locomotive horsepower per revenue ton assigned to each train is a function of cruising speed. Both the number of cars and the number of locomotives per train are continuous variables in this model. A lag between the scheduled and the actual departure allows time for loading the last shipments, attaching power, and other unexpected delays. On actual departure, trains accelerate up to the cruising speed.

The only stops between the origin and destination yards are for crew changes, where the trains brake to a stop, wait for the actual crew change and any required tests and inspections, and accelerate again up to cruising speed. The number of crews per train along the route is a continuous variable determined by the average crew district length and trip distance. The route is assumed to be entirely level and straight. At the destination yard, the locomotives are disconnected from the train, and after a short unloading process, the shipments are available to the shippers.

Shipper Cost and Transit Time

For this application, the service package is defined by two service quality variables, average transit time in hours (μ_t), and transit-time standard deviation (σ_t):

$$z = (\mu_t, \sigma_t)$$

Shipper cost is linear on both service quality variables and proportional to the total annual volume.

$$S(v, z) = v \cdot (U_\mu \cdot \mu_t + U_\sigma \cdot \sigma_t) \quad (3)$$

This shipper cost formulation is based on work documented elsewhere (*4*). The shipper unit-cost coefficients U_μ and U_σ are parameters of the railroad model.

Shippers may vary in their individual sensitivities to transit-time characteristics (because of different commodity values and other factors). Equation 3 imposes a loose restriction on the shipper mix by fixing the aggregate unit-cost characteristics when averaged across the individual shippers on a per-unit-volume basis.

Transit time begins when the shipment arrives at the origin yard and ends when it is available to the shipper at the destination yard. This includes five types of time segments: (a) waiting for scheduled departure, (b) delay before actual departure, (c) interval of continuous train movement (within a crew district), (d) crew change delay during which the train is stationary, and (e) unloading and other delay at destination yard.

Each of these time segment types is stochastic. The waiting time at the origin yard has a uniform probability distribution over the scheduled headway between trains. The standard deviation for each of the other four time segment types is determined by multiplying an average time value by an externally specified coefficient of variation. Exogenous average time values are also specified for three of these time segment types: delay before actual departure, crew change delay, and destination yard delay.

Each interval of continuous train movement includes one acceleration period, one cruising speed period, and one braking period. The time and distance required to accelerate from a stop to cruising speed, and to brake to a stop from cruising speed, are all functions of the cruising speed. The average interval of continuous movement is thus a function of cruising speed and average crew district length.

Railroad Cost

Four railroad cost elements are included in the carrier cost function. These are the annual cost of train crew labor (LC) and diesel fuel (FC), and the implied annual rentals associated with both railroad cars (CC) and power (PC):

$$C(v, z) = LC + FC + CC + PC$$

The formulation of each cost element includes a unit-cost parameter. For example, annual train labor cost is the product of train frequency, number of crew districts, and unit crew cost. On the basis of empirical studies (*6*), annual fuel consumption is assumed to be proportional to work performed by locomotives during acceleration and while cruising, which is primarily a function of annual volume and cruising speed. Annual car rental is the product of annual volume, average transit time, and cost per available car hour, divided by the net capacity of each car. Locomotive rental is similarly based on the available horsepower hour between actual departure and arrival.

These four cost elements account for most of the above rail operating costs, which have a direct relationship with the two service quality variables. However, other railroad cost elements, such as track maintenance and investment, also have a significant relationship with freight service quality. For example, poor quality track may impact service quality directly through loss and damage, or indirectly through speed restrictions. Furthermore, improving service quality through increased train frequency reduces the usable time windows available for track maintenance activities, and thereby may increase track maintenance costs (*7*). Therefore, the analysis presented in this paper is primarily illustrative, and although incomplete, still offers some understanding of railroad service quality economics.

Implementation Issues

The horsepower, acceleration, and braking functions required for the railroad cost elements are implemented with a simple train performance calculator (*4*). Horsepower per net ton is determined by equalizing the available tractive effort of the locomotives with the total train resistance at cruising speed. An iterative algorithm is used to simulate train acceleration, whereas train deceleration is approximated with a constant braking rate.

Most of the parameter values for this example are presented in Table 1; others include such train performance calculator parameters as car resistance coefficients. The derivation or rationale for all of the parameter values is discussed elsewhere (*4*). For the purposes of this hypothetical example, these values only need to be realistic. Most are based on empirical data or expert opinion. The shipper unit-cost coefficients are the most arbitrary; they were calibrated so that the model would yield reasonable and illustrative results. An extensive sensitivity analysis with respect to these two coefficients indicated that they have no effect on the general observations presented here.

The cost-minimization problems associated with the QE and CCM policies (Equations 1 and 2) were solved with a basic pattern-search type vector optimization procedure in conjunction with a golden section line-search (*8*), based on the two operating variables.

DISCUSSION OF HYPOTHETICAL RAILROAD EXAMPLE

In this section, a hypothetical example based on the railroad model is examined with respect to the freight service quality cost model. The discussion focuses on efficiency and cost analysis implications for carriers and transportation economists. The relationships among operating variables, cost, and

TABLE 1 PARAMETER VALUES FOR RAILROAD EXAMPLE

LOCOMOTIVE PARAMETERS		
A_P	Axles/Locomotive	4
E_P	Efficiency	0.83
HPL	Horsepower/Locomotive	3,000
R	Fuel Consumption Rate (Gallons/Million Foot-Pounds)	0.028
U_P	Unit Cost ($/Available Horsepower Hour)	0.006
W_P	Weight (Tons/Locomotive)	130
f	Coefficient of Adhesion between Wheel and Rail	0.25
RAILROAD CAR PARAMETERS		
A_C	Axles/Car	4
TW_C	Tare Weight (Tons/Car)	30
U_C	Unit Cost ($/Available Car Hour)	0.75
v_C	Net Capacity (Tons/Car)	70
TRAIN CREWS		
d_L	Crew District Length (Miles)	150
U_L	Unit Cost ($/Crew)	700
OTHER RAILROAD PARAMETERS		
b	Braking Rate (MPH/Second)	2.2
U_f	Unit Fuel Cost ($/Gallon)	0.5
SHIPPER UNIT-COST COEFFICIENTS		
U_μ	Average Transit-Time Unit-Cost ($/Ton-Day)	2.0
U_σ	Transit-Time Standard Deviation Unit-Cost ($/Ton-Day)	2.0
TRANSIT-TIME PARAMETERS		
μ_2	Average Delay before Actual Departure (Hours)	2.0
V_2	Actual Departure Delay Coefficient of Variation	0.1
V_3	Continuous Movement Coefficient of Variation	0.1
μ_4	Average Crew Change (Hours)	0.25
V_4	Crew Change Coefficient of Variation	0.5
μ_5	Average Unloading and Other Destination Delay (Hours)	2.0
V_5	Destination Delay Coefficient of Variation	0.1
INDEPENDENT VARIABLES		
d	Trip Distance (Miles)	1,500
v	Annual Volume (Tons)	500,000

service quality for fixed annual volume are examined first, followed by the effects of annual volume variability.

Operating Variables, Cost, and Service Quality

In this section, service quality and cost are presented as functions of the operating variables, carrier and full cost are examined as functions of service quality, and the QE and CCM quality policies are compared. The discussion is focused on the contour surfaces presented in Figures 2–9. These surfaces were developed by implementing the railroad model for each of 1,116 operating variable ordered pairs, with annual volume fixed at 500,000 tons (Table 1). The train frequency range (Figure 2) implies that train length will vary from 18 to 143 cars, and as a consequence of the cruising speed range, horsepower per net ton will vary from 0.29 to 5.07.

Service Quality and Cost as Functions of Operating Variables

A carrier generally cannot implement the service package directly. Rather, service quality variables are functions of the operating variables, and the carrier implements the service

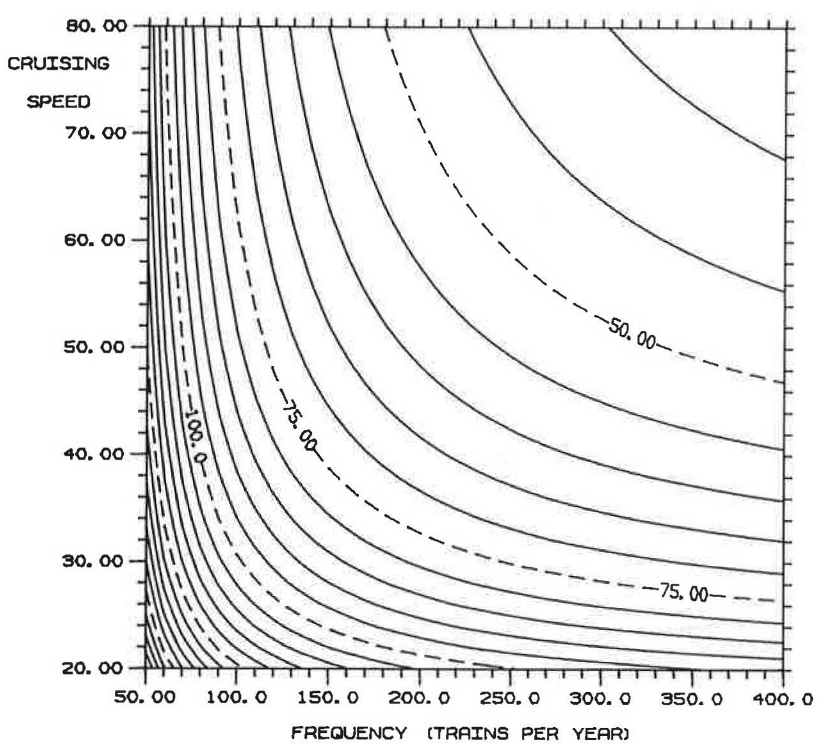

FIGURE 2 Average transit time (hours) as a function of operating variables.

package indirectly by choosing values for the operating variables (train frequency f and cruising speed s):

$$z = z(f, s): \mu_t = \mu_t(f, s) \text{ and } \sigma_t = \sigma_t(f, s) \quad (4)$$

In this model, service quality is not a function of annual volume, except through the indirect medium of quality policies. In other applications, service quality may be modeled as a direct function of annual volume; for example, this may reflect the effects of congestion.

The two service quality variable functions [$\mu_t(f, s)$ and $\sigma_t(f, s)$] are depicted in Figures 2 and 3, respectively. In this instance, average transit time is strongly affected by both operating variables with diminishing returns (Figure 2) (i.e., further increases in either operating variable will yield smaller decreases in average transit time). In Figure 3, it is evident that transit-time standard deviation is almost solely a function of train frequency (with diminishing returns). This reflects the effect that train frequency has on the wait before scheduled departure. Cruising speed would have a greater impact in Figure 3 if V_3 were set at a higher value in Table 1. For more typical railroad operations with mixed-freight trains, missed connections in intermediate yards are the main cause of transit-time variability (*9,10*). Figures 2 and 3 are conceptually important because they illustrate the link between the carrier's operating variables and the quality of its product.

With engineering models such as the one used for this paper, carrier cost is more naturally presented as a function of the operating variables than as a function of the service quality variables. Equation 4 may be used to specify either carrier, shipper or full cost as a function of annual volume and the operating variables. For example, with carrier cost:

$$C(v, z) = C[v, z(f, s)] = C(v, f, s) \quad (5)$$

The shipper cost and full cost functions, $S(v, f, s)$ and $T(v, f, s)$, are similarly derived; all three functions are respectively depicted in Figures 4–6 (with fixed annual volume).

The importance of shipper satisfaction is often publicly recognized by carrier representatives, and it is systematically addressed in the day-to-day operations of some carriers. However, in practice, many carriers may find this issue elusive because of the difficulty of specifying a relationship between carrier operating variables and shipper satisfaction. Shipper cost is one measure of shipper satisfaction, and Figure 4 is a graphical depiction of such a relationship. Although such a specific relationship may be impossible to delineate in the real world, a working approximation could still be useful. In this example, shipper cost strictly decreases with both operating variables; in particular, cost appears to be approximately inversely proportional to both variables. As might be expected, this cost surface is quite similar to the average transit-time surface presented in Figure 2.

In Figures 5 and 6, both carrier cost and full cost appear to be convex functions of the operating variables. The two cost-minimizing points (L) correspond respectively to the CCM and QE policies. Annual carrier cost is minimized in Figure 5, with 58 trains per year and a 28 mph cruising speed; further reduction in either operating variable will result in equipment cost increases greater than the savings in labor or

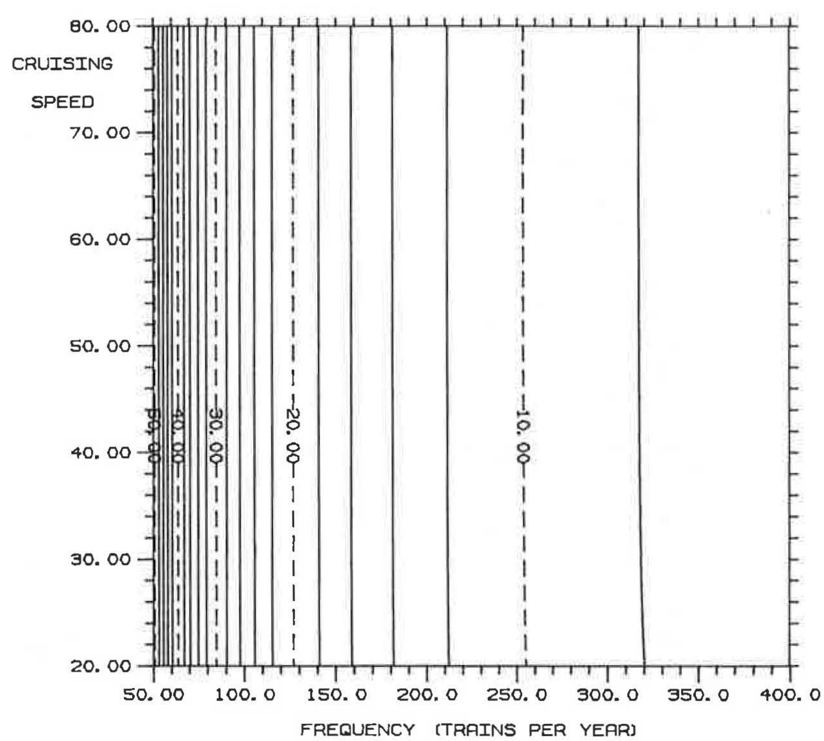

FIGURE 3 Transit-time standard deviation (hours) as a function of operating variables.

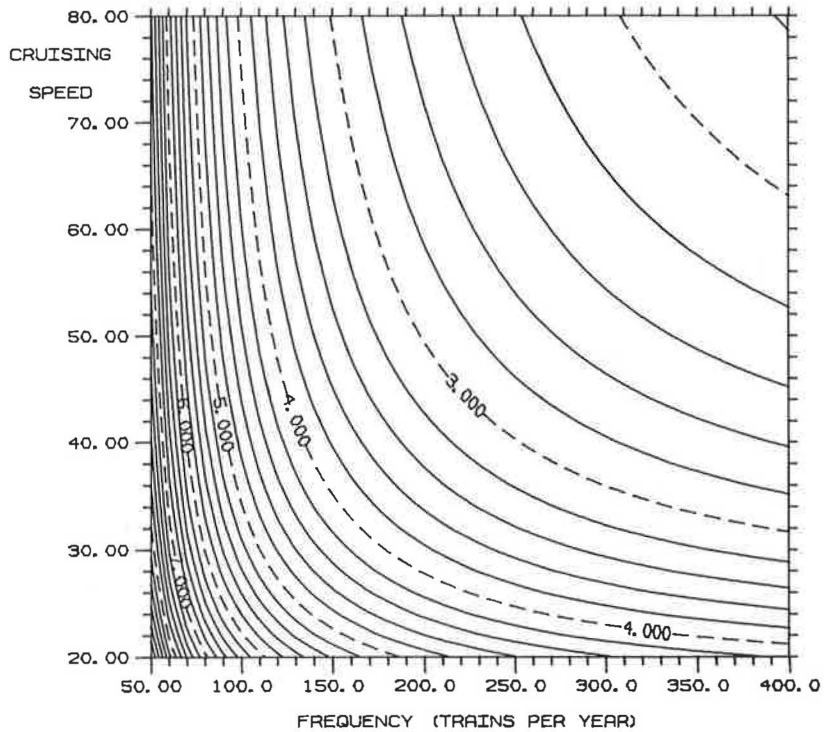

FIGURE 4 **Shipper cost surface ($million/year) as a function of operating variables.**

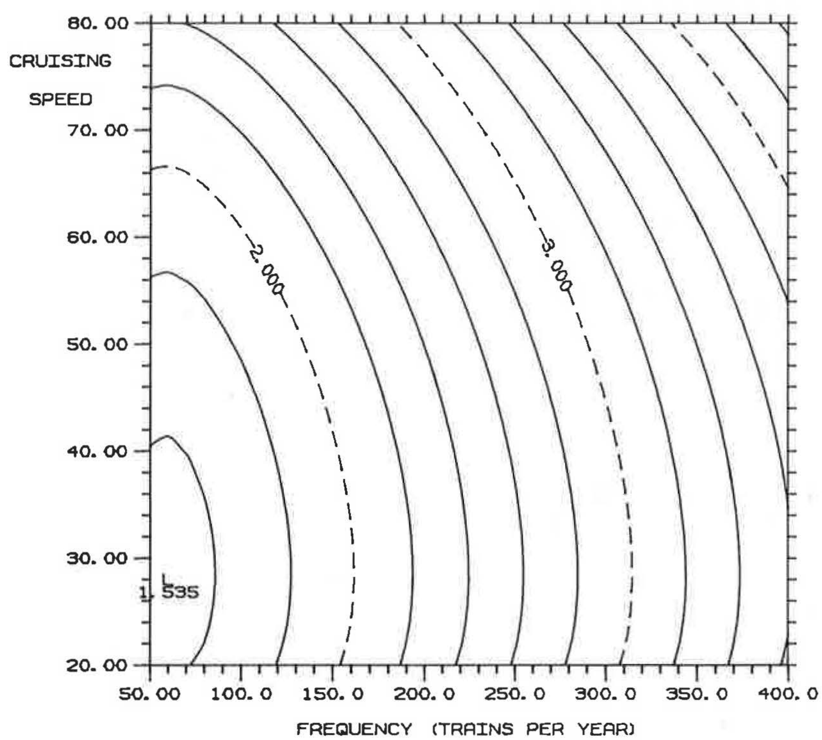

FIGURE 5 **Carrier cost surface ($million/year) as a function of operating variables.**

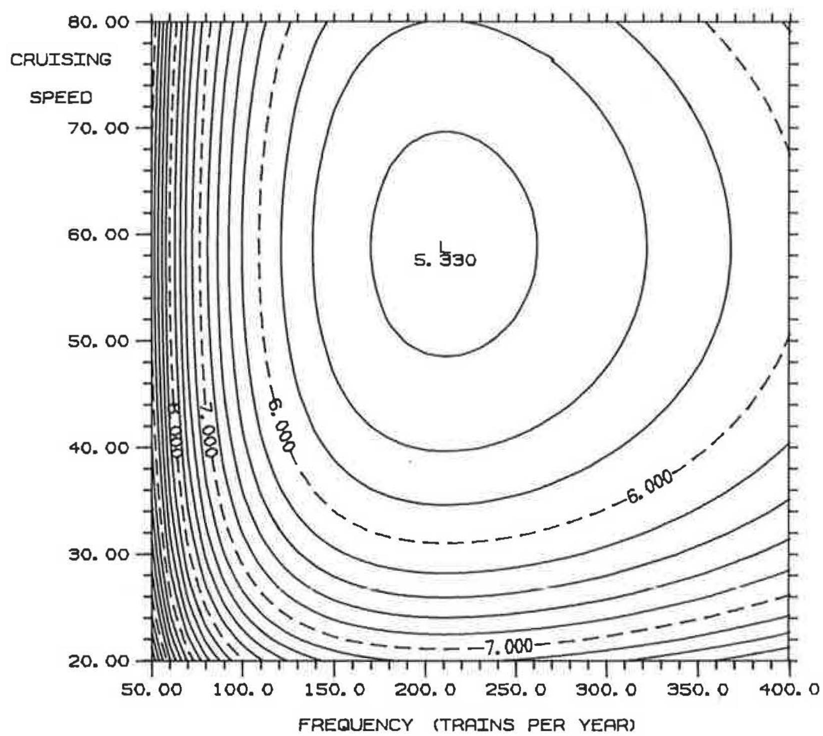

FIGURE 6 Full cost surface ($million/year) as a function of operating variables.

fuel costs. As expected, significantly larger operating variable values are required to minimize full cost (Figure 6). Both cost-minimizing points are discussed further in the following two sections.

Costs as Functions of Service Quality

In the service quality model, carrier, shipper, and full costs are all conceived as functions of service quality variables—not carrier operating variables. The conceptual distinction is that service quality is observable by both carrier and shipper, whereas operating variable values might be only known to the carrier. This distinction has practical implications; for example, contractual service quality commitments by a carrier to a shipper must be based on criteria that can be verified by both shipper and carrier.

Shipper cost is already fully specified as a function of the service package (Equation 3). Carrier cost and full cost are respectively presented as functions of the two service quality variables in Figures 7 and 8 (the bordered stairstep domain area was obtained by superimposing Figure 2 on Figure 3). Each of these cost surfaces is a transformation of one of the previously discussed relationships between cost and carrier operating variables. For example, the carrier cost surface depicted in Figure 7 is a transformation of the surface presented in Figure 5.

The functional relationship between carrier cost and service quality may be as difficult to specify as the relationship between shipper cost and carrier operating variables, and it is equally important. From the shipper's perspective, service quality variables define the carrier's product and its value. Therefore, for effective product management, the carrier must have some understanding of the relationship between its cost structure and the service quality it provides. Equation 5 indicates how such a relationship may be established by combining current knowledge of carrier cost and service quality (as functions of the operating variables). This is essentially how Figure 7 was obtained from Figures 2, 3, and 5.

The natural expectation is that carrier cost should rise with better service quality, and hence decrease with both elements of this service package. However, in Figure 7, carrier cost increases with at least one of the service quality variables for more than three-fourths of the domain area (and with both variables in the region directly northeast of the CCM point *L*). Because shipper cost strictly increases with both quality variables, it does not make sense for the carrier to offer a service level where carrier cost also increases with either variable (because it could otherwise simultaneously reduce its own costs and increase the quality of its service). In Figure 1, the service quality region to the left of Z^c is similarly irrational.

It cannot be assumed that carriers will never operate in this irrational service region. For example, the railroad industry has sought to decrease the time cars spend in intermediate switching yards, with the twin goals of improving overall service quality and reducing carrier operating costs through higher rolling stock utilization (*9*). If both goals are simultaneously accomplished, the carriers must have previously provided this type of irrational service quality.

Full cost as a function of the service quality variables is presented in Figure 8. The cost minimizing point *L* indicates

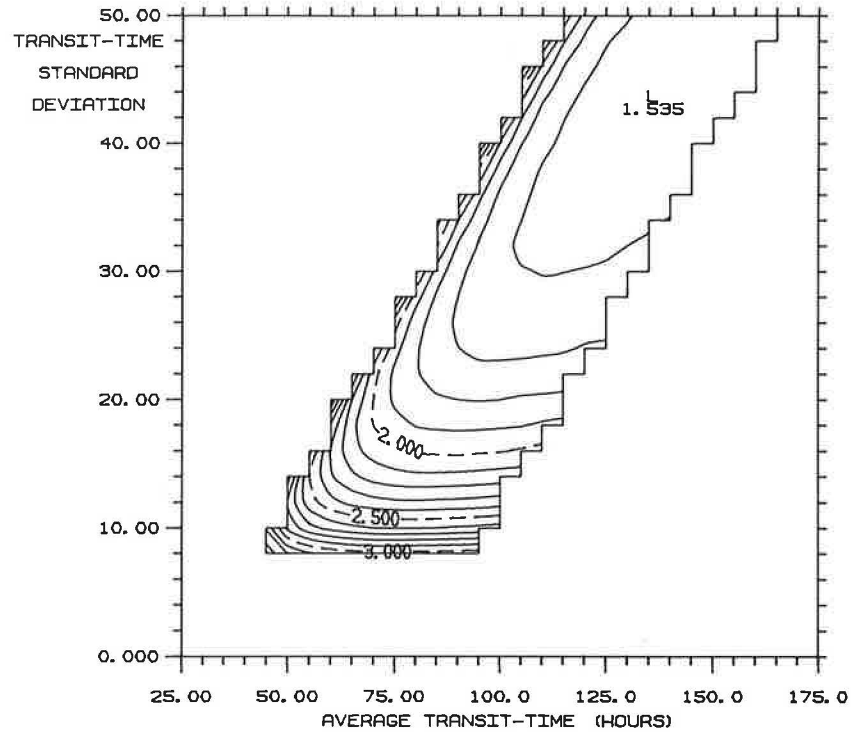

FIGURE 7 Carrier cost surface ($million/year) as a function of service quality variables.

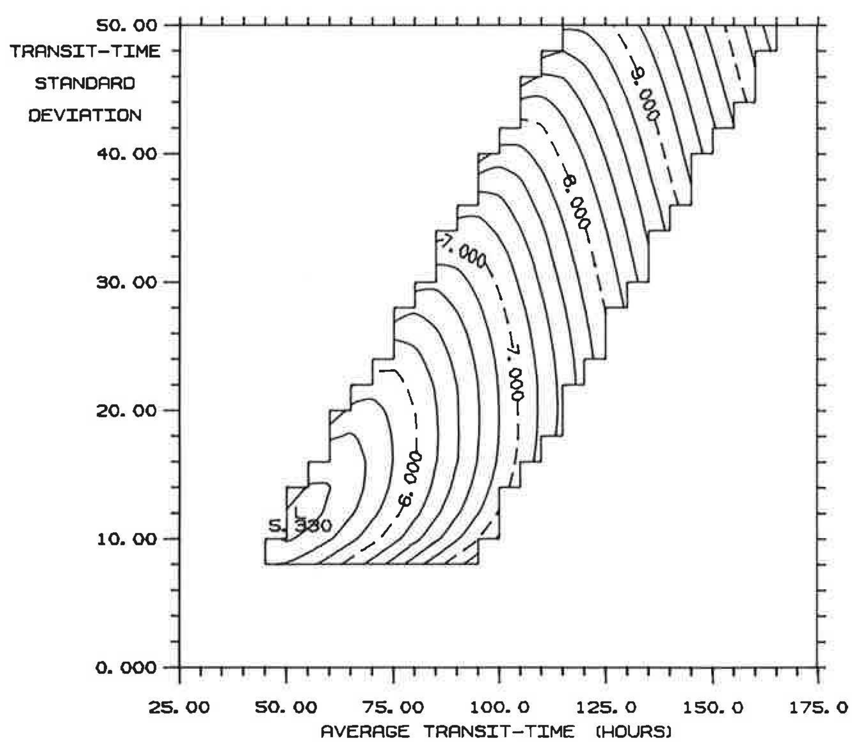

FIGURE 8 Full cost surface ($million/year) as a function of service quality variables.

quality efficiency. As expected, QE offers significantly better service quality than the CCM service package. Further improvements in service quality from this point would result in carrier cost increases greater than the shipper cost savings.

Quality Policy Comparison with Fixed Annual Volume

The full-cost minimizing point in Figures 6 and 8 and the carrier-cost minimizing point in Figures 5 and 7 suggest a comparison of the QE and CCM policies. The pertinent information is summarized in Table 2. The difference in profit between any two quality policies is equal to the full-cost difference (*3*), and as previously discussed, QE is both socially optimal and carrier profit maximizing. In this case, by implementing CCM instead of QE, the carrier would sacrifice 3.683 million dollars in annual profit.

As discussed at the beginning of this paper, implementing QE is not easy and CCM may be tempting; after all, CCM minimizes all carrier costs. In this example, the carrier can reduce the specified operating costs almost in half by running trains once instead of four times a week and cutting the cruising speed in half. However, in order to keep the same traffic level, the carrier would have to compensate the shippers for the lower service quality with a rate cut equal in value to the $4.769 million increase in shipper costs. When the carrier cost savings of $1.077 million are combined with this lost revenue, carrier profit is diminished by the specified increase in full cost. In this way; profit maximization compels the railroad to consider the most efficient joint use of carrier resources and relevant shipper resources.

A carrier implements a given quality policy via operating variables. In the real world, it may be difficult to precisely determine and enforce the QE operating variable values. This raises the question of potential full cost (and hence profit) sensitivity to errors in these variables. From the *L* in Figure 6, full cost increases faster for lower operating variable values than it does for higher values. Thus, for each of the two operating variables in this example, it would be better to err on the higher side than by the same amount on the lower (CCM errs on the low side). This effect is caused by the shape of the shipper cost surface (Figure 4), which may be typical for a large class of shippers (*4*).

TABLE 2 QUALITY POLICY COMPARISON

	Quality Policies QE	CCM	Difference Value	Percent
ANNUAL COST IN MILLIONS				
Carrier Cost	$2.612	$1.535	-$1.077	-41%
Shipper Cost	2.718	7.478	4.760	175%
Full Cost	$5.330	$9.013	$3.683	69%
CARRIER OPERATING VARIABLES				
Frequency (Trains Per Year)	210.84	57.90	-152.94	-73%
Cruising Speed (mph)	58.77	28.36	-30.41	-52%
TRAIN CHARACTERISTICS				
Cars	33.88	123.37	89.49	264%
Locomotives	1.75	1.48	-0.27	-15%
Horsepower Per Revenue-Ton	2.217	0.515	-1.702	-77%
SERVICE QUALITY VARIABLES				
Average Transit-Time	53.22	135.77	82.55	155%
Standard Deviation	12.01	43.69	31.68	264%
Coefficient of Variation	0.226	0.322	0.096	43%

Effects of Annual Volume

Transportation analysis, and economic analysis in general, is often concerned with the effects of annual volume variability. Discussed in this section are the effects of annual volume on costs, service quality, and operating variables. Quality policies are used to reduce the complex interaction among these parameters, and thus facilitate an indirect examination. In this section, the preceding comparison of the QE and CCM quality policies is extended, followed by a discussion of the use of full cost in transportation economic analysis, focusing on returns-to-scale.

Further Quality Policy Comparison

By definition, a quality policy specifies each service quality variable as a function of volume. Furthermore, any quality policy may be used to define new cost functions whose only independent variable is volume. For example, with the QE policy and the carrier cost function:

$$C^*(v) = C[v, Z^*(v)]$$

The other QE cost functions, $S^*(v)$ and $T^*(v)$, and CCM cost functions $C^c(v)$, $S^c(v)$ and $T^c(v)$ are similarly defined. Quality policies also allow carrier operating variables to be presented as functions of volume.

Both the QE and CCM policies were analyzed and compared with respect to annual volume for eight trip distances from 50 to 3,000 mi. For each trip distance, 31 annual volume values were examined, spread approximately logarithmically from 10,000 to 10 million revenue tons. Some of the results for a 1,500-mi trip are shown in Figures 9–13. The 500,000 net-ton tic in the middle of each graph indicates the fixed volume situation addressed previously. The graphs developed for the other seven trip distances are generally similar to these figures, and support the observations presented here. Some of the results for the two smallest distances (50 and 100 mi) were relatively extreme, but these trip distances are outside the normal railroad service market.

The cost functions of the two quality policies are compared in Figure 9. These percent values correspond to those presented in Table 2. For all three costs, the absolute percentage impact decreases as volume increases. These curves are virtually identical for each of the six larger trip distances. For the two smaller distances, the percentage impact becomes smaller significantly more quickly with increasing volume.

The impact on full cost (and profit) associated with implementing CCM instead of QE was discussed previously with respect to Table 2. Figure 9 augments that discussion by allowing one to extend the conclusions over a broad volume range. Over this range, the carrier is able to significantly reduce its own costs by implementing CCM instead of QE. However, the result is much higher shipper and full costs, and hence lower carrier profits. The full cost curve in Figure 9 indicates that the relative impact declines with volume. However, the decline is gradual and the relative impact is still significant (49 percent) at the highest volume level considered. Furthermore, the absolute dollar impact significantly increases with annual volume.

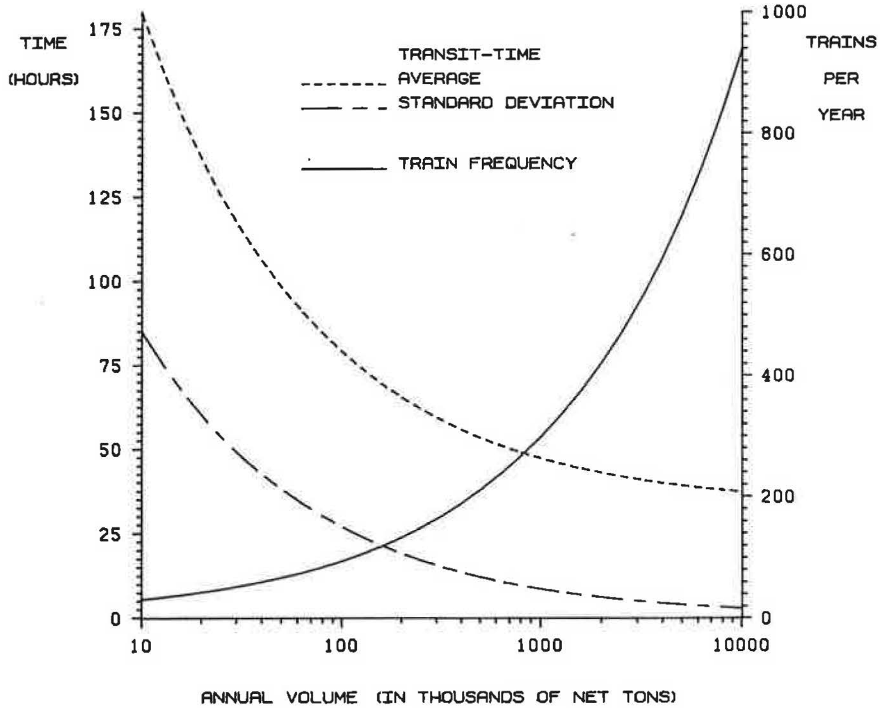

FIGURE 10 Train frequency and service quality with QE policy.

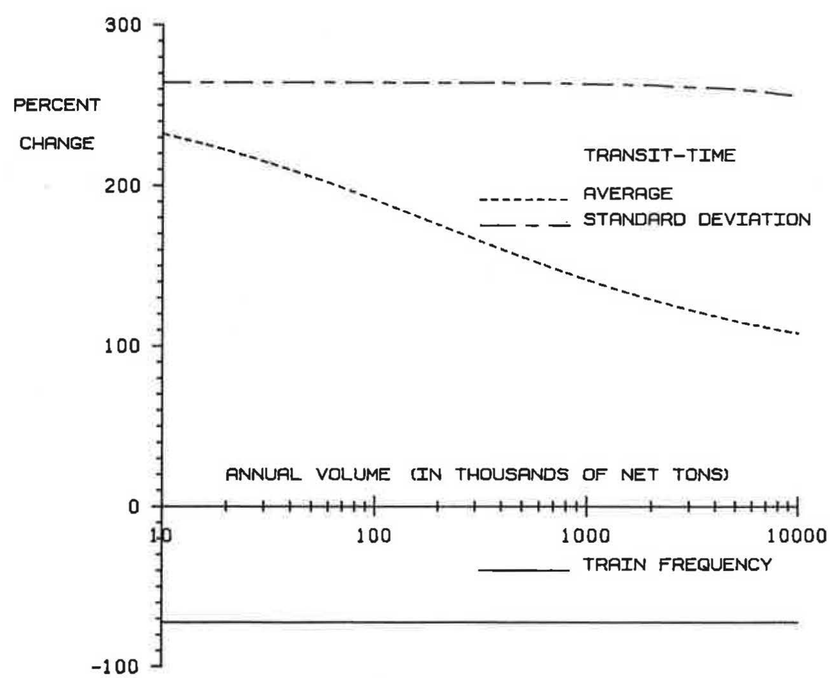

FIGURE 11 Train frequency and service quality percent differences of CCM with respect to QE.

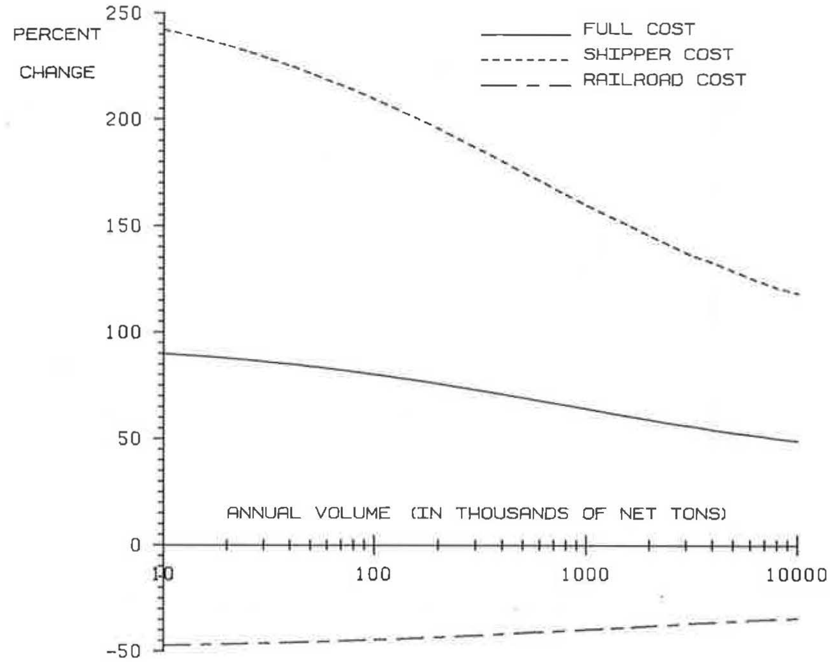

FIGURE 9 Cost percent differences of CCM with respect to QE.

QE train frequency and service quality variables are presented in Figure 10. Cruising speed is not presented because it is substantially unaffected by volume; for all trip distances and volumes considered, the QE cruising speeds are within a 2-mph range, and the CCM cruising speed range is less than 1 mph (typical cruising speed values are presented in Table 2). The shape of the three curves in Figure 10 is almost exactly the same for all eight trip distances and both quality policies, but with different vertical scales.

The relative differences between QE and CCM, in train frequency and service quality variables, are presented in Figure 11. These percent values also correspond to those presented in Table 2. The train frequency percent difference is within 0.5 percent of −72.25 percent, and the cruising speed percent difference is approximately −52 percent for all volumes and trip distances considered. These relatively constant values were unexpected and merit further investigation. The range of the average transit-time curve is larger for smaller trip distances, and it is smaller for larger distances. The range of the standard deviation curve in Figure 11 is only 9 percentage points; it is significantly larger only for the two smallest distances. This relative flatness might be explained by the strong relationship between the standard deviation and train frequency (see Figure 3). From Figures 10 and 11, it is clear that both service quality variables had a significant impact throughout the volume range on the shipper cost increase depicted in Figure 9.

Transportation Cost Analysis—Returns-to-Scale

In conventional microeconomic models, the cost function of the firm is responsible for specifying the efficiency of the production process. However, in the production of freight service, full cost, not carrier cost, captures the essence of carrier efficiency in creating value (independent of market demand considerations). Therefore, at least theoretically, transportation economic analysis should be based on the full cost (*3*,*4*).

The examination of average and marginal cost geometry with respect to variations in quantity is central to traditional microeconomic cost analysis. The interaction between these two cost curves may be summarized by the degree of scale economies, defined here as the ratio of average to marginal cost. This measure may be applied to the full, carrier, and shipper cost functions (*3*), as presented in Figures 12 and 13 for QE and CCM, respectively. Returns-to-scale are said to be increasing, constant, or decreasing as the degree of scale economies is greater than, equal to, or less than unity.

With the service quality cost model, economies-of-scale should be based on the full cost of transportation, instead of the traditional carrier cost measure. For example, with the numeric example presented by Brown (*3*), the full cost returns-to-scale are constant for the perfectly competitive carrier, whereas the carrier-cost based measure indicates increasing returns (a perfectly competitive firm has constant returns-to-scale). Figures 12 and 13 indicate the difference between the full cost and railroad cost measures, and hence the potential error of using carrier cost returns instead of full cost returns.

With both the numeric and railroad examples, the magnitude of this error is greater if CCM is implemented instead of QE. It is ironic that when the carrier ignores the effects of service quality and the importance of full cost (by implementing CCM instead of QE), it becomes even more important for the outside economist or cost analyst to consider these effects (by using full cost returns instead of carrier cost returns). An explanation for this phenomenon may be based on the fact that full cost degree of economies is equal to an

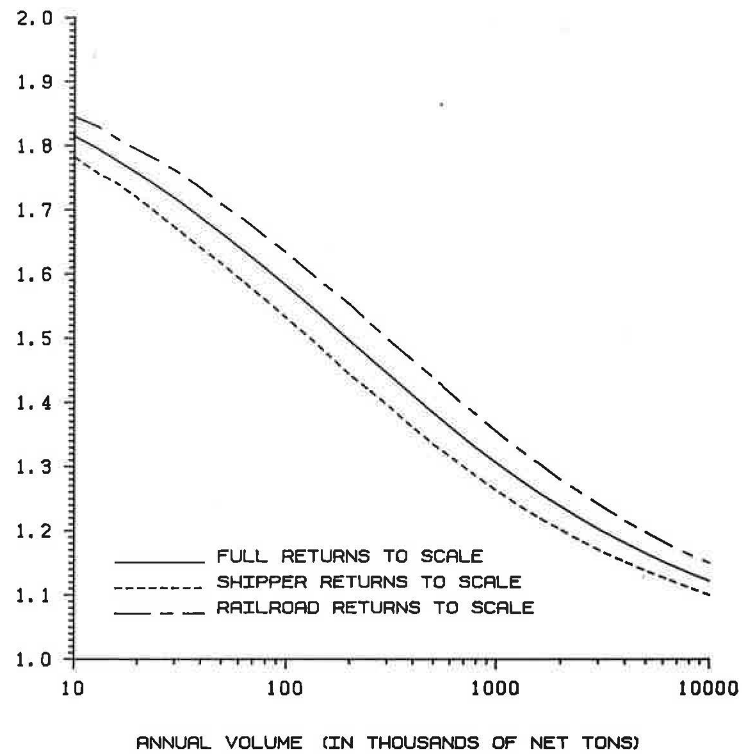

FIGURE 12 **Degree of scale economies with the QE policy.**

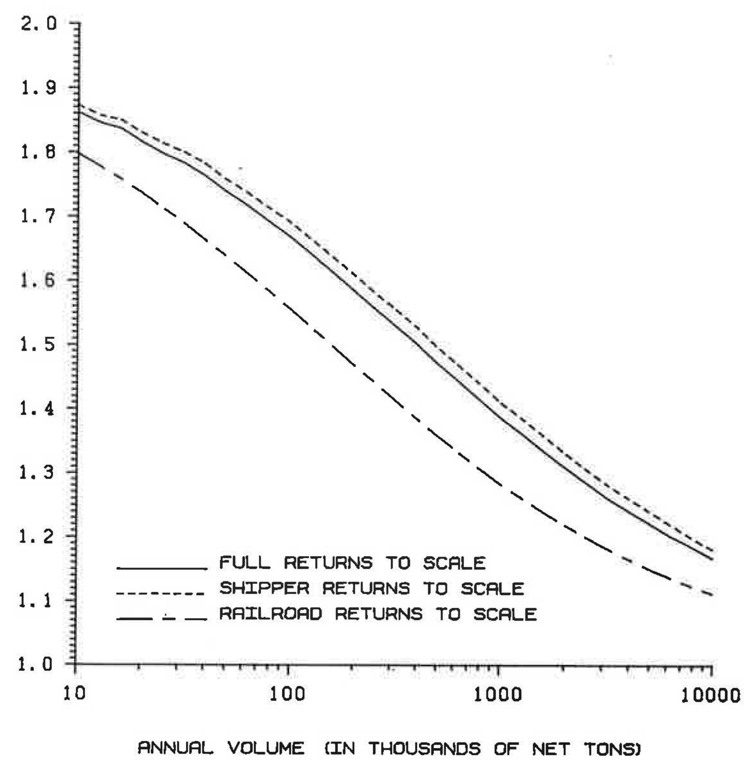

FIGURE 13 **Degree of scale economies with the CCM policy.**

average of the carrier cost and shipper cost economies, weighted by their respective marginal cost functions (*3*). The CCM carrier marginal cost is generally smaller than the QE carrier marginal cost, whereas the CCM shipper marginal cost is greater than the QE shipper marginal cost. Therefore, the full cost economies curve will generally lie between the carrier and shipper economies, and closer to the carrier cost curve with QE (Figure 12) than with CCM (Figure 13).

In trying to address the difference between the true (full cost) economies and the value obtained from carrier costs alone, the analyst cannot make an a priori assumption about the sign of this error. For instance, in this railroad example, the error leads to an overestimation of returns-to-scale if QE is implemented, and an underestimation if CCM is implemented; in the numeric example, returns-to-scale are overestimated with both quality policies. The sign is determined by the relative magnitudes of the shipper and carrier returns within the previously discussed weighted average formulation of full cost returns.

It should not be concluded from Figures 12 and 13 that railroading is characterized by increasing returns-to-scale. As previously discussed, this analysis has been limited to a few above rail cost elements directly related to service quality. These elements do not include any capacity constraint and, given the nature of the operating variables, inherently imply a declining marginal cost curve. If other cost elements, such as maintenance-of-way, are properly included, then average costs may increase at some point (*7*).

CONCLUSION

This examination of freight service quality cost economics, with the railroad example, fosters a practical understanding of the service quality model. In particular, it demonstrates the importance of quality efficiency and the full cost of transportation. Implications for the carrier and transportation analyst are emphasized, and the negative consequences of disregarding these implications are illustrated with the railroad example. For the carrier, this is reflected in lost profits; for the analyst, it means potentially erroneous conclusions. The examination also augments our general understanding of railroad service quality economics.

This paper, and other work by the author (*3,4*), indicate the need for further inquiry in three areas. The first area concerns the theoretical structure of the freight service quality model. This would include more rigorously establishing the underlying aspects of the model in terms of welfare theory and extending the model to explicitly consider multiple shippers and carriers, with separate service packages specified for individual carrier-shipper pairs.

The second area includes efforts by individual carriers to understand their full cost structure and then implement quality efficiency. This may be a challenging undertaking, especially for railroads, for which the same trains and fixed facilities are used for shipments with very different sensitivities to service quality. Tools such as the MIT Service Planning Model (*10*) may help rail carriers in this endeavor, and shipper cost functions might be based on commodity characteristics or shipper surveys or both.

The third area involves further use of detailed operating models to explore the service quality model and its implications. This last area would provide a bridge between the theoretical efforts and practical applications. For example, a more detailed model of branchline and mainline railroad operations could be developed in conjunction with a model of truck-load trucking to examine the competitive and value creation aspects of service quality and related public policy issues. Whereas this paper uses a simple model of freight operations to facilitate an understanding of the service quality model, these future research efforts would focus on using the service quality modeling framework to further the understanding of freight operations.

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