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Methodology for Evaluating Freight Transportation Energy Contingency Strategies

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ABSTRACT

THE POTENTIAL impacts of a petroleum supply disruption on the U. S. freight transportation system can be severe, as suggested by the relatively mild disruptions of 1973-4 and 1979. This paper is concerned with the evaluation of freight transportation energy contingency strategies which can be implemented in times of petroleum supply disruptions to minimize the resulting adverse system-wide impacts. Specifically, a methodology is presented whereby potentially viable contingency strategies can be screened (evaluated) with regard to their ability to mitigate the impacts of forecasted petroleum supply disruptions. The methodology, which utilizes disaggregate freight demand models, has been developed with considerable flexibility to permit evaluation of a wide range of contingency strategies under various levels of petroleum supply disruption. In this paper, the methodology is applied to forecast the effects of a 23% petroleum supply shortfall, thereby providing the reader with some idea as to the level of forecasting detail and the potential applications of the proposed methodology and resulting computer model.

INTRODUCTION

The dependence of the U.S. freight transportation system upon petroleum means that it will face dramatic increases in operating costs during a petroleum supply shortfall. Actions carriers can take in response to this problem include improving the fuel efficiency of their operations and increasing the rates they charge for their services. In order to maximize profits, they can be expected to concentrate on improving the energy efficiency of their operations, thus maintaining as much of their business as possible, and raising their rates to meet the increased operational costs.

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Since the carriers they must use for transporting their goods and materials are taking such actions, and consumer demand is altered by the petroleum shortfall, shippers would face the combination of increased production costs, reduced levels of transportation service, increased transportation costs, and reductions in the demand for their products in such a situation. Actions they can take in response include 1) reducing the quantity of goods and materials they ship, 2) reducing the lengths of haul on their shipments, 3) increasing the sizes of their shipments, and 4) changing the mode used in transporting their shipments. In order to maximize their profits, shippers will likely attempt to minimize their total costs through some combination of the last three of the alternative actions.

This situation is illustrated in an aggregate nature by Figure 1. If carrier supply and shipper demand functions are represented by S_0 and D_0, respectively, carriers will provide q_0 units of transportation service and shippers will pay them p_0 per unit under a pre-shortfall competitive market. However, the increase in petroleum prices under shortfall conditions leads to a reduction in the shippers' demand for transportation from D_0 to D_1. At the same time, increased operating costs force carriers to cut their supply of transportation from S_0 to S_1, thus resulting in a new equilibrium of q_1 units at price p_1 in an environment free from price controls.

The magnitude of such price increases and service reductions is largely a function of the shortfall magnitude. While the 1973-4 and 1979 supply shortfalls reached maximums of only about 14 and 7 percent on a nationwide basis, respectively, several carriers, notably the owner-operator truckers, experienced difficulty obtaining the fuel they needed and voiced their displeasure with high fuel prices and governmental contingency actions (for example, the 55-mph speed limit and delayed rate increases). Similarly, shippers registered complaints upon the granting of what they felt were excessive rate increases by the Interstate Commerce Commission.

If such problems arose under short-

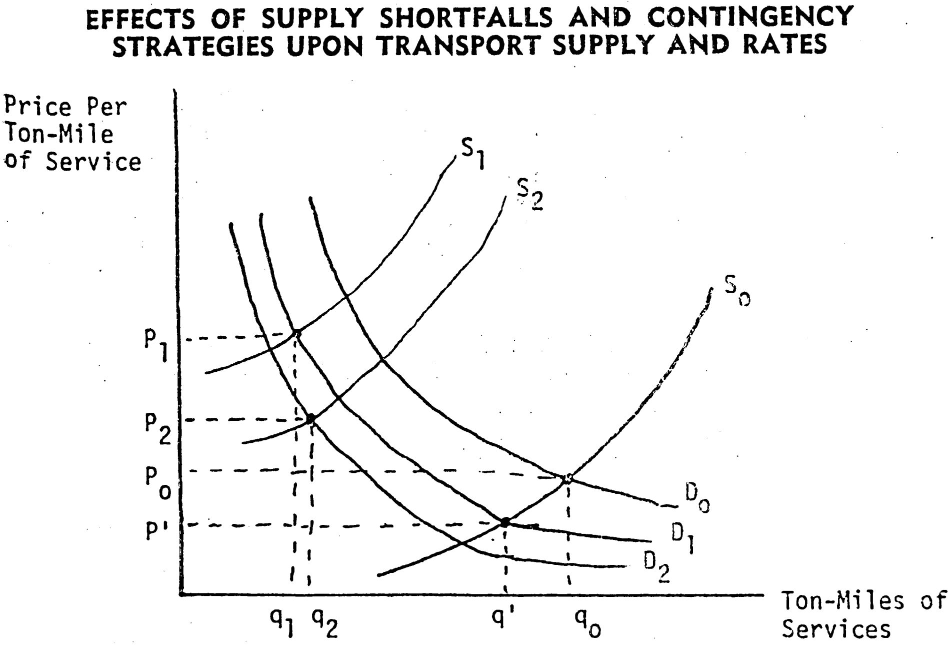

FIGURE 1

falls which were relatively mild, compared to the calamitous supply disruptions which are conceivable under present circumstances, the freight transportation system would likely be subjected to major service limitations, price increases, and service level reductions. Therefore, carriers and shippers could well benefit from contingency strategies which lower operating costs (and thus—see Fig. 1—shift carriers' supply from S_1 to S_2) and reduce the demand for transport (reducing demand from D_1 to D_2), and, as a result, lower the unit cost of transportation (from P_1 to P_2) as well as increasing the amount of transport service (from q_1 to q_2).

This paper thus presents, in summary form, a methodology that can be used in the screening (preliminary evaluation) of contingency strategies which may be called for in order to remedy these effects. The evaluation framework for this methodology is summarized in the first section, while the procedures for estimating the impacts of supply shortfalls and contingency strategies are discussed in the second and fourth sections, respectively. Results of applying this methodology to a 23 percent supply shortfall scenario are discussed in the third section, and the paper is closed with a brief summary of the work.

1. SCREENING METHODOLOGY FRAMEWORK

The screening of potential emergency energy conservation strategies should consist mainly of the preliminary evaluation of the costs, benefits and feasibility of strategy implementation. Since such strategy impacts are largely a function of the effects of the underlying petroleum supply shortfall, an analysis of the effects of the shortfall must precede and be consistent with any analysis of strategy costs and benefits. Whereas the benefits and costs of strategy implementation include changes in the quantity and distribution of tons, ton-miles, fuel consumption, and costs by commodity group and mode of transport, these factors should be included in the generation of the shortfall base case.

In order to estimate these changes with a satisfactory level of accuracy, the analysis procedure must simulate the freight transportation decision-making process. Chiang et al (Ref. 1) identify the firm receiving the shipment as the basic decision-making unit. In the short run, these decisions are limited to the transport mode, shipment size, and shipment origin (or length of haul). Since the most significant problems resulting from an energy emergency are likely to be fairly short term phenomena, the methodology of analysis used in this study simulates the effects of the shortfalls and strategies upon this decision-making process.

The shipper's logical objective is to minimize the sum of the logistics costs given the levels of service and rates offered by the carriers which could feasibly transport the shipment. Therefore, the analysis must be capable, for each shipment, of estimating the levels of service and rates corresponding to each carrier/shipment size combination and how they will be altered by the supply shortfall and contingency strategy implementation. Since the shortfall induced changes in level of service and increases in rates can vary dramatically among carriers, the total logistics costs of a shipment may well be minimized by a change in carrier or shipment size.

The process for performing the analysis of transportation and distributional impacts is outlined in Figure 2. Changes in production levels are esti-

PROCEDURE FOR ANALYSIS OF TRANSPORTATION AND DISTRIBUTIONAL IMPACTS OF CONTINGENCY STRATEGIES

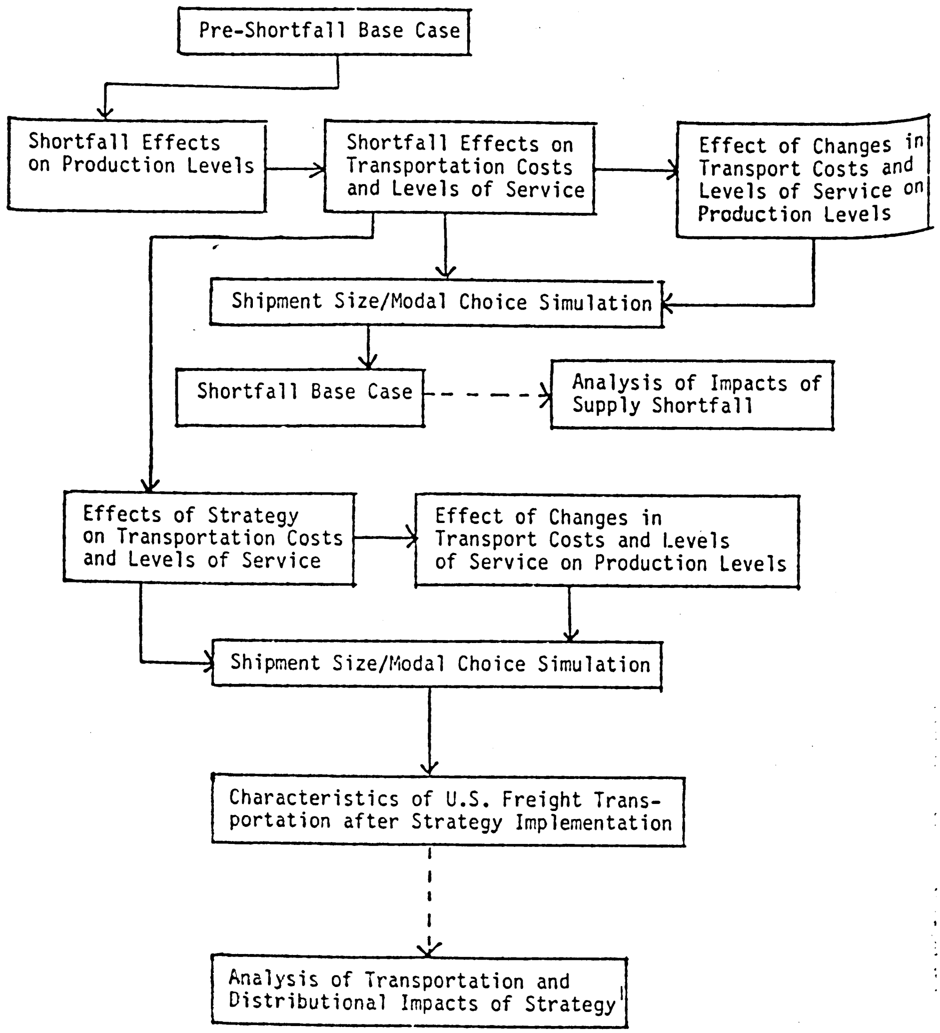

FIGURE 2

mated by commodity sector, while level of service and cost changes are estimated by mode and commodity sector.

In addition to these changes, several other contingency strategy characteristics must be considered in their evaluation. First, secondary economic impacts (i.e., employment) and the predictability of all of the impacts should play a major role in the implementation decision process, as a large shortfall will likely produce a catastrophic economic climate, so any strategy which might lead to additional negative effects would not be desirable.

Secondly, financial constraints during such economically difficult times necessitate a minimization of implementation expenditures, while the likely rapid and dramatic rise in costs would favor strategies which could be implemented quickly. Finally, the strategy must be enforceable and free from any political or physical barriers which would prevent implementation.

These additional evaluation dimensions are difficult, if not impossible, to quantify. Therefore, several qualitative components will have to be undertaken in conjunction with the quantitative analysis methodology presented in Figure 2. One possible means of using these analyses in selecting contingency strategies for implementation is to compare the effects of its implementation with the problems posed by the corresponding shortfall scenario. Since the shippers and carriers hurt most by the shortfall will have the greatest need for help, a strategy which is expected to better counteract the problems posed by the supply shortfall should, all else being equal, be favored.

The application of the analysis procedures summarized in Figure 2 to a supply shortfall and to contingency strategies is discussed in the next two sections and in the final section.

2. SELECTION OF MODELING APPROACH

In selecting the modeling approach to be used in this study, three aspects of the problem must be considered: 1) the choice of model type, 2) choice of specific model within the chosen type, and 3) formulation or selection of an appropriate data base from which modeling forecasts can be made.

The choice of model type must be made in light of the forecasting requirements of the modeling system. In order to evaluate freight energy contingency strategies, it is desirable to forecast changes in the demand for fuel, tons, ton-miles, logistics costs, and transportation costs by commodity sector and mode. To achieve these forecasting requirements three general modeling approaches can be considered: 1) aggregate, 2) disaggregate deterministic and 3) disaggregate probabilistic.

Aggregate freight models continue to be the most widely used freight demand forecasting technique. Their popularity arises from their relatively small data requirements and the fact that they are well known to most researchers and have been extensively applied in many non-freight subject areas such as passenger transportation, macroeconomic analysis and land use. Essentially, four major aggregate modeling approaches can be identified: 1) regression analysis, 2) econometric models including simultaneous equation systems, 3) input-output models and 4) economic base studies. Although these four alternative aggregate approaches cover a wide range of techniques that address the freight demand issue, they were not considered to be appropriate for the analysis of freight contingency strategies due to their general lack of theoretical validity, their insensitivity to level of service changes, and their dependency on the data base with which they were calibrated.

Given the deficiencies of aggregate approaches, it became apparent that some disaggregate modeling techniques would be preferred. The class of disaggregate deterministic models (Ref. 12) provides a theoretically appealing approach to the modeling of freight demand in that individual firms are viewed as exercising a logistics strategy that minimizes purchase and logistics cost given the level of inputs required for production processes.

This minimization is achieved by the selection of purchasing origin of inputs, shipment size, and transport mode. Such models provide a great level of detail in that a wide variety of level of service attributes can be considered in the logistics cost function, and commodity flows by mode can be readily estimated by aggregation of individual firm choices. However, disaggregate deterministic models suffer from drawbacks relating to the large data requirements associated with disaggregation to the firm level and the assumption that each firm acts optimally, not taking information on the firm's actual origin/mode/shipment size choices into account.

In recognition of the optimality assumption of deterministic disaggregate approaches, probabilistic disaggregate freight models were developed. Such models again view the individual firm as the decision making unit attempting to minimize a logistics cost function, but in this case a random component is added to the logistics cost function to account for the omission of unobservable cost components, measurement error, and other possible sources of error. If it is assumed that the random component is independently and identically Gumbell distributed, the resulting model can be formulated in the standard logit form as described in Ref. 13. Chiang et al (Ref. 1) have calibrated such a model, using maximum likelihood techniques, based on the actual observed origin/mode/shipment size preferences of the firms in a data base primarily based on the 1972 Census of Transportation Commodity Survey.

Given the intent of the current study, this disaggregate probabilistic model was adopted as the core model to the freight demand modeling system, with modifications to include the option of the water mode. Since this model requires disaggregate data on 1) firm annual use rates, 2) modal fuel and operating costs, 3) commodity purchase price, shelf life, length of haul, and value, 4) modal wait times, circuity, travel time reliabilities, mean transport times, energy intensities, claim settle time, and percentage of goods lost or damaged, and due to the unavailability of a current disaggregate data source that contains the detail of inputs required in the disaggregate model, it was necessary to develop a simulated data base constructed from up-to-date aggregate data and distributional information from earlier disaggregate samples.

In constructing this data base, the methodology proposed by Mannering and Harrington (Ref. 14), which employs the use of constructed probability density functions and Monte Carlo simulation techniques to create a sample of input attributes, was applied in conjunction with a series of updated regression models that were calibrated to predict disaggregate level freight rates, percentage of goods lost or damaged, mean travel times, and travel time reliabilities. (These regression models are described in detail in Ref. 5). The resulting simulated data base is sufficiently detailed to permit application of the modified disaggregate probabilistic model. Moreover, the fact that this probabilistic model includes a large number of transport level of service characteristics makes it quite suitable to the evaluation of freight energy contingency strategies.

3. ESTIMATED EFFECTS OF A 23 PERCENT SUPPLY SHORTFALL

The first step of this process, which Figure 2 identifies to be the estimation of the petroleum supply shortfall effects on sectoral production levels, was performed by Argonne National Laboratory excluding consideration of the effects of the shortfall-induced freight transportation cost increases (Ref. 2). Referring back to Figure 1, these results indicate the distribution of freight shipments and fuel demand at price p' and quantity q'. Therefore, in order to characterize freight transport under supply shortfall equilibrium (p_1, q_1), the effects of changes in transport costs and levels of service upon sectoral production levels and the distribution of freight transport demand is estimated through a modeling system based on the disaggregate mode/shipment size model developed by Chiang et al discussed above.

For each of a number of "pseudo" firms[1] within each commodity sector, the modeling system (NAFDEM) generates estimates of the firm's annual use rate[2] of the shipped good and various shipment attributes (density, value, length of haul, and liquid, solid, or gaseous state) from appropriate probability distributions.[3] A shipment size is selected for each of twelve mode/shipment size combinations at random from within specified weight ranges, and the modal lengths of haul are calculated from modal circuity estimates (Ref. 4).

The travel time, service reliability, probability of loss and damage, and rate expected for each of the twelve alternative shipments are then estimated from models presented in References 5-8.[5] Upon application of the estimated service, shipment, and firm attributes to the functions presented in Reference 1,[6] the utility realized by a shipper is estimated as a function of the transportation costs, capital carrying costs, order costs, shipment loss in value, annual use rate, shipment value, and length of haul associated with each movement.

Adjustments must be made, however, in the utility functions in order to account for changes in freight transportation over the time since the model was calibrated. Therefore, the constant terms for all twelve of the mode/shipment size options are adjusted following an iteration procedure proposed by Harrington and Mannering (Ref. 9).

The pre-shortfall probability of selection of mode/shipment size combination i by pseudo firm k within commodity sector j (P_{ijk}) is then estimated using the standard logit formula, which leads to estimates of the pre-shortfall levels of sectoral logistics costs (LC_{jk}) and mode/shipment size ton-miles (TM_{ij}), with

$$LC = \sum_{K} (\sum_{i} p_{ijk} LC_{ijk} Q_{jk}) \quad (1)$$

$$TM_{ij} = \frac{\sum_k P_{ijk}Q_{jk}d_{njk}}{\sum_{i \epsilon n} \sum_k P_{ijk}Q_{jk}d_{njk}} TM_{nj} \qquad (2)$$

where Q_{ik} represents firm k's annual use rate of commodity j, d equals the shipment's length of haul, and n indicates the mode (instead of mode/shipment size combination).

Effects of the supply shortfall upon sectoral output and the distribution of ton-miles are then forecast through appropriately adjusting the rate models to reflect the impacts of the fuel price increase. While the average increase in the rates charged by a mode is assumed to equal the increase in modal fuel costs, longer haul shipments will experience proportionally larger increases due to the greater significance of fuel costs on such movements. Therefore, the rate models are altered to reflect this pattern, with the length of haul coefficients in these models assumed to vary in proportion to the variable costs realized in the movement of each shipment. The constant coefficients in the rate models are then adjusted so that the predicted rate increase for a shipment with mean values for all of the sectoral attributes is equal to the corresponding increase in fuel costs. Applying these revised rate models to each shipment, the change in transport costs faced by each firm (from R_{jk} to R'_{jk}) is estimated as a weighted average of the rates charged on individual shipments.

The effects of these changes in transport costs upon the sectoral production levels are then estimated using elasticity estimates based upon an earlier study of the relationships between sectoral output and transportation efficiency (Ref. 10). While the proportional changes in sectoral outputs are presented in that study for changes in rail and truck efficiency, the simulation model used in this analysis requires an estimate of the proportional changes in sectoral output as the result of a change in the costs of the modes of transport actually used. Such an elasticity is estimated by assuming the estimated output responses to changes in modal efficiency are proportional to the corresponding modal share of sectoral output. As a result, the sectoral output elasticity (Z_j) is estimated as a weighted average of the two observations of modal responsiveness.

The dramatic rise in transportation costs brought about by such a large shortfall would make such costs a more significant portion of a firm's operating costs, so firms will be made significantly more sensitive to transport cost changes in the studied scenario. Assuming the elasticities will double during the 23 percent shortfall scenario yields reasonable results, so such elasticity estimates are used to estimate the change in a firm's annual use rate (from Q_{jk} to Q'_{jk}), with

$$Q'_{jk} = \left(\left(\frac{R'_{jk}}{R_{jk}Q_{jk}} \right)^{Z_j} Q_{jk} \right)^{(1/(1-Z_j))}. \qquad (3)$$

The resultant changes in the utilities realized by each pseudo firm from selecting each of the twelve mode/shipment size options are then estimated by applying the revised rates and outputs to the appropriate terms in the firm's utility function. The revised probabilities of selecting each mode/shipment size combination are then estimated using the standard incremental logit model form.

After applying this procedure to a sample of twenty-five "pseudo" firms within each of thirty-seven commodity sectors, the results are aggregated to the sectoral and modal levels to indicate the expected changes in costs, ton-miles, and fuel consumption. Modal fuel estimates are generated by multiplying the estimated number of ton-miles by the estimated energy intensity of transport for each mode/shipment size combination presented in References 2,4, and 11.

Following this procedure, the effects of a 23 percent supply shortfall are estimated for the second quarter of 1982. The consumption of diesel fuel is expected to fall by about 20 percent with such a shortfall, and the macro-economic changes in industrial output are expected to reduce the fuel demand by about 1.7 percent (Ref. 2), so transportation rates are expected to lead to about an 18.3 percent reduction in freight transport fuel consumption. Such a cutback in consumption is realized with a fuel price increase from $1.30 to $6.50.

While this estimate does seem to be quite high, there are three evident explanations for such an extreme price rise. First, this model operates solely upon the prices faced by the carriers and shippers and fails to take into account the reductions in real income which would accompany such a shortfall. If it was possible to include a measurement of such an effect, the price increase would be less significant.

Second, the model which served as a basis for estimation of the macro-economic effects of the supply shortfall assumes that a significant portion of the revenues realized from the windfall profits tax is returned to consumers, thus greatly reducing the fall in real income and its effects on the demand for freight transportation before the freight rate increases are taken into account. Such an increase in the macroeconomic effects would reduce the cut in demand which is needed solely from transport cost increases.

Finally, modal service levels were assumed to be unchanged in this scenario. While this does seem to be an unreasonable assumption, it was made due to the inability to forecast how modal service levels will change during a shortfall and in order to present a true "do-nothing" scenario from the carrier standpoint. Therefore, the price increases to achieve the designated fuel consumption reduction would likely be significantly smaller if numerous likely reductions in service levels were included.

The results of the shortfall scenario analysis are summarized in Table 1. Outside of the pipeline mode, water traffic is cut by the least, air traffic is cut somewhat, and the demand for truck transportation falls the most. In addition, there is a general shift to increased shipment sizes, as firms find such a change to be advantageous since the associated rate reductions serve to offset the dramatic rate increases induced by the shortfall. However, this shift is not as substantial as could be expected since the reduction in sectoral outputs make the non-transport logistics cost increases associated with larger shipment sizes a much more significant factor.

TABLE 1

CHANGE IN TON-MILES BY MODE/SHIPMENT SIZE COMBINATION

(1982-Second Quarter-23% Supply Shortfall)

	Due Solely to Transport Costs	Overall Shortfall Effects*
Rail Forwarder	—16.6%	—20.7%
TOFC	—18.2%	—22.2%
Carload	—15.9%	—20.1%
Multiple Carload	—20.5%	—24.4%
Total Rail	—18.1%	—22.2%
LTL	—20.7%	—23.4%
TL	—20.5%	—23.2%
Private Truck—LTL	—24.0%	—26.5%
Private Truck—TL	—21.9%	—24.5%
Total Truck	—21.3%	—23.9%
Independent Shipment	— 6.6%	— 8.5%
Container	— 8.9%	—10.8%
Charter	— 9.3%	—11.2%
Total Air	— 7.7%	— 9.5%
Water	— 1.3%	— 7.7%
Pipeline	0%	— 2.4%
Grand Total	—10.3%	—14.1%

*These estimates assume the modal changes due solely to the shortfall macroeconomic effects are distributed among the shipment size options in the same relative manner as estimated for the transport costs.

While total logistics costs are reduced by about 4 percent, the ton-miles of service provided is cut by over 10 percent, so the shippers actually experience about a 7 percent increase in logistics costs per ton-mile of transport. These reductions in ton-miles vary tremendously among commodity sectors, with the construction; rubber and miscellaneous plastics products; fabricated metal products; and motor vehicles and equipment sectors all suffering greater than 30 percent cuts in ton-miles.

The carriers and especially a number of the shippers would therefore greatly benefit from the implementation of a number of effective contingency strategies. The modeling system can also be used to simulate the effect of a number of strategies upon the distribution of freight transport costs and demands.

4. CONTINGENCY STRATEGY EVALUATION PROCEDURE

The simulation model described in the preceding sections of this paper is structured such that a wide range of freight energy contingency strategies can be readily evaluated. The procedure for the evaluation of contingency strategies is to 1) estimate the changes in modal level of service and transport cost associated with implementing the strategy and 2) using these estimates in the modeling system to forecast resultant impacts on the distribution of ton miles, fuel consumption by mode/shipment size combinations, and sectoral outputs.

In estimating the effects of contingency strategies on modal level of service and transport costs, it is necessary to concentrate on the effects such strategies will have on individual firm logistics costs and commodity use rates. The impacts on logistics costs can be accounted for by establishing the contingency strategy's effects on shipment travel times, service reliability, service frequency, operational costs, energy intensities by mode/shipment size combinations, and firm commodity use rates. Once these effects have been established, the logistics costs for each firm are revised to reflect the impacts of the strategy, and the modeling system can be applied to forecast resultant changes in such factors as mode/shipment size selection probabilities and distributions of freight flows. The forecasts of the selected contingency strategy's impact on the overall freight transportation system can then be determined readily from the aggregation of the forecasted impacts on the freight shipping behavior of the assessed individual firms.

To provide some idea as to the type of contingency strategy that may be considered for evaluation in the modeling system, examples are presented and classified into those that reduce the demand for fuel by increasing system or vehicle efficiency. Strategies aimed at increasing system efficiency include increasing load factors (consolidating shipments or relaying truck size and weight restrictions), reducing congestion (terminal satelliting or avoiding peak hour operations), increasing use of intermodal operations, reducing total hauling distances (through circuity reductions), and increased use of the most efficient vehicles. Meanwhile, vehicle efficiency may be increased through actions such as the adaptation of available technologies, improved maintenance, driver training, and traveling at more efficient speeds. All of the preceding strategies can be represented and evaluated in the modeling system using the general firm level approach described above.

5. SUMMARY AND CONCLUSIONS

This paper presents a modeling methodology that has been developed for the evaluation of the effects of petroleum supply shortfalls and subsequent energy contingency strategies upon the demand for freight transportation and fuel consumption by mode, shipment size, and commodity sector. The methodology is based on a disaggregate probabilistic model of shipper choice of mode and shipment size which accounts for a wide range of shipper logistics costs. This disaggregate choice model is used in conjunction with a variety of simulation techniques that are used to minimize costs and to provide detailed forecasts.

The sample application forecasts the consequences of a 23% petroleum shortfall during the second quarter of 1982. The results of this application indicated an expected decline in the total tonnage shipped, in response to higher fuel rates and the lower demand for goods in general, along with significant modal shifts towards the more circuitous modes of water and rail. Forecasts of impacts of this type, which can be analyzed in great depth due to the high level of forecasting detail provided by the model, can serve as a basis from which national and individual firm freight related policies can be formulated in response to petroleum supply disruptions.

In conclusion, the forecasting of freight demand under petroleum shortfalls and energy contingency strategies is a difficult task. The modeling methodology presented in this paper, although limited to some extent by possible inaccuracies arising from the use of simulated data, provides a reasonably comprehensive and accurate approach to accomplish this task. Moreover, the use of simulation procedures, although potentially limiting accuracy, greatly reduces the costs associated with applying the model, and therefore, forecasts of the wide range of areas that influence freight transportation can be made at very modest user time and computer costs.

ACKNOWLEDGEMENT

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FOOTNOTES

1 The firms are referred to as "pseudo" firms since their attributes are synthesized from probability distributions.

2 The number of pounds of the specified good or material used per year by the shipper.

3 Shipment attributes and annual use rates are respectively based upon the data presented in Reference 3 and a version of the data base used for calibrating this model in Reference 1 which has been adjusted to reflect changes in sectoral outputs over the elapsed time period.

4 The weight ranges are those specified within Reference 9.

5 Details concerning these models, input data, and NAFDEM are presented in Reference 9.

6 The water mode utility function is assumed to differ from the multiple carload utility function by only a constant term.

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