ECONOMIC ANALYSIS OF A DEMAND-RESPONSIVE PUBLIC TRANSPORTATION SYSTEM

Thomas F. Golob and Richard L. Gustafson,
General Motors Research Laboratories

The concept of a demand-responsive transportation system, using driver-operated vehicles providing door-to-door service, has received attention as a possible solution to certain urban transportation problems. The economic feasibility of such a system should be evaluated before it is considered for implementation. This paper discusses the methodology and results of a case study analysis of the economic feasibility of a many-to-many demand-responsive transportation system in a chosen U.S. city. Ridership was estimated by means of the market research tools of in-depth group surveys and home interviews. A flexible cost model was developed to evaluate the cost of serving various hourly distributions of demand. The estimated demands for each of a series of alternative levels of service and fare were then applied to this cost model, and the profit or loss was calculated for each level of service and fare. The sensitivity of the profit or loss to changes in demand distributions and to changes in various cost parameters was also investigated.

•THE Transportation Research Department of the General Motors Research Laboratories has conducted a study to design a demand-responsive public transportation system and to evaluate the technical and economic feasibility and the potential social and political acceptance of such a system within the environment of a selected case-study community. The system is called the Demand-Responsive Jitney System, abbreviated D-J. The D-J system is perceived of as providing door-to-door service upon user request and would utilize driver-controlled, rubber-tired vehicles. Users would share use of the vehicles in order to minimize costs. Generically similar systems have been studied under such titles as Geni, Dial-A-Bus and DART (1, 3, 5, 7, 10, 11).

Two phases of the D-J system study—measurement of user preferences and system simulation—have been discussed in earlier papers (6, 9), and the overall D-J system study has also been reported on in another paper (2).

The case-study community is a fast-growing incorporated city within a major metropolitan area. The area of the city is approximately 36 sq mi and has a population of approximately 200,000 persons. The majority of the residents are blue-collar middle-income workers, and 5 percent of the residents are retired. Only 2.5 percent of the households in the community do not have a car available. The transit system in the community offers only limited service, and only 1 percent of all internal home-based trips are made by public transit. Ninety percent of these home-based internal trips are made by automobile and 9 percent are made by school bus.

The economic analysis was divided into three major parts: a cost model, a revenue model, and a profit model. A flow diagram of the economic analysis is shown in Figure 1. Major inputs to each part of the analysis are shown in the diagram.

The objectives of the cost model were to define a fine-grained system structure that identifies the essential components required for adequate operation of the D-J system

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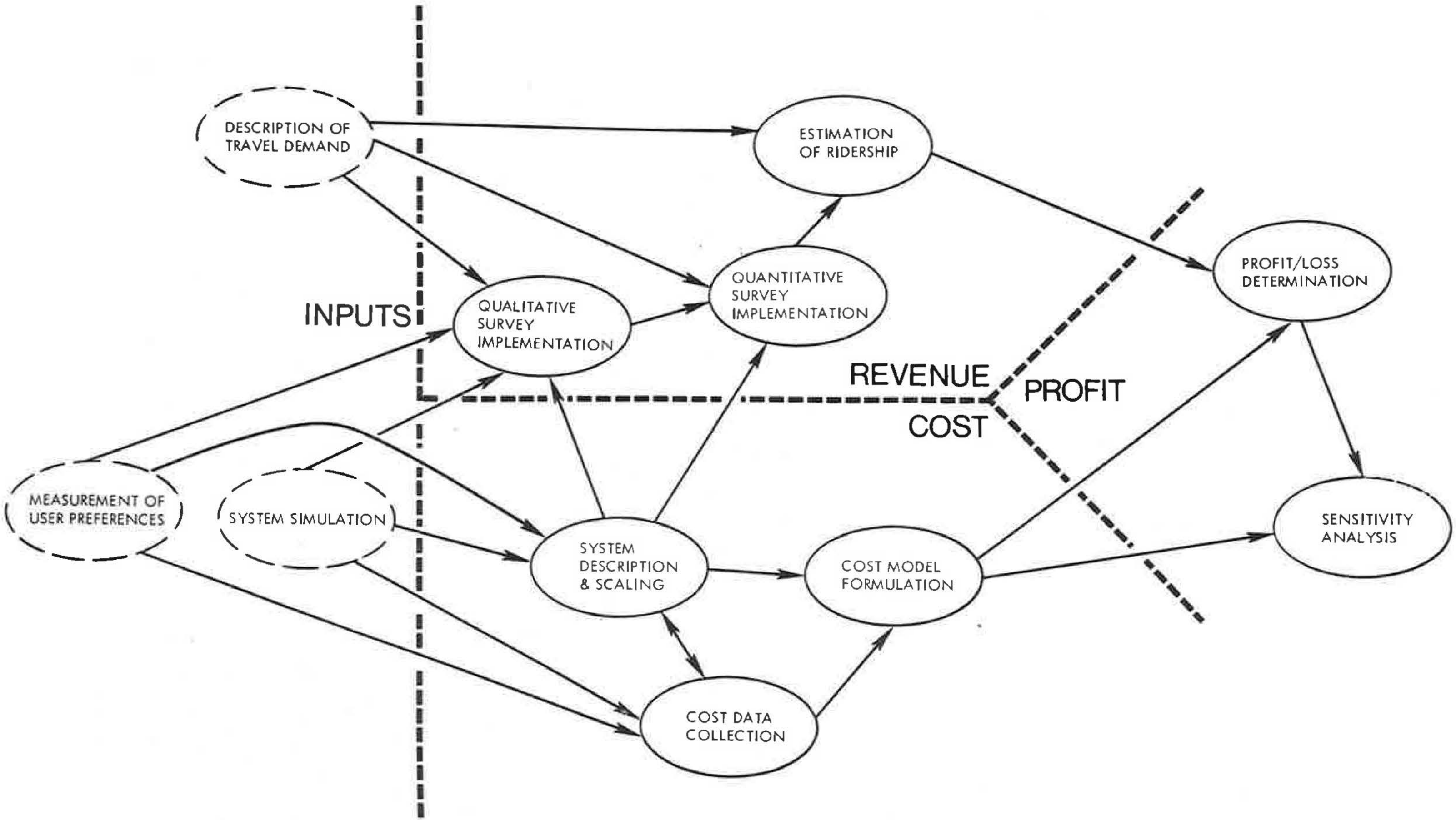

Figure 1. Flow diagram of D-J economic analysis.

and to develop equations that accurately measure costs and are consistent with current and projected public transpotation costs. The three distinct tasks of the cost modeling are system description and scaling, cost data collection, and actual cost-curve formulation.

A detailed system description was formulated and cost estimates were calculated. Realistic cost estimates for the entire operating day were generated by a consideration of the hourly distribution of demand. Factors were introduced to account for the potential inefficiency that the transportation system encounters when the demand level varies during an operating day. Both peak demand and demand for each particular hour were considered in determining the hourly costs of operation. With these considerations, a cost model was developed, and the estimates of hourly cost were expressed as a function of both the peak demand and the demand for the hour in question.

The development of the cost model for the D-J system is consistent with traditional economic procedures but is also specifically tailored to the demand-responsive transportation concept. The model is parametrically determined and as such is applicable to areas other than the case-study community by changes in one or more input variables.

The objectives of the revenue model were to establish a realistic estimation of ridership in the case-study community for alternate D-J system designs and alternate fare levels and to establish distributions of this demand with respect to time of day, trip purpose, and traveler socioeconomic and demographic variables. Included in this effort are qualitative survey implementation, quantitative survey implementation, and actual estimation of ridership.

An attitudinal survey was employed to ascertain responses from potential users of the D-J system as to whether they would use the system in various travel circumstances and for various system fares and service levels. The survey consisted of two parts. First, a qualitative survey was conducted to aid in designing the extensive quantitative survey and to gather information concerning consumer reaction to the proposed D-J system. Second, a quantitative survey was conducted in the case-study community to provide the quantitative data as the basis of the estimations of ridership on the D-J system. The data from the quantitative survey were applied together with data describing the total travel demand in the case-study area to generate the hourly distributions of D-J demand.

The objectives of the profit model were to determine the profitability of alternate D-J system configurations in the case-study community and to assess the sensitivity of the costs to various cost parameters and to accuracy in ridership estimations. The profit model can be separated into a profit-loss determination task and a sensitivity analysis task. In the profit model, the estimated ridership distributions for the case-study community were applied together with the cost equations to determine the profitability of the D-J system.

COST MODEL

The system description and scaling phase of the cost model involved an identification of the D-J system structure, a description of all elements required for operation of the system, and a determination of the scale of each element. An attitudinal-survey-based measurement of user preferences for the D-J system (4, 9) was used to guide system description. The scale (amount or size required) of each system element was determined as a function of the hourly distribution of D-J demand (determined by the revenue model) and two service parameters exogenous to the economic analysis—maximum specified waiting time prior to vehicle pickup and maximum specified D-J to private automobile travel-time ratio. The system simulation study (6) determined the number of vehicles required to service any specified demand and the average speed of the vehicles in servicing these demands. The system simulation also provided data on vehicle capacity requirements and computer specifications. The following is an outline of the system structure:

A. Operational subsystem
   1. Vehicle subsystem:
      Vehicle characteristics

Passenger provisions
Driver provisions
Safety provisions
Reliability and maintainability provisions

2. Roadway subsystem:
   Shelters
   Parking areas
   Turnouts
   Access signal lights
   Street service signs
   Driver lounges
3. Communications and control subsystem:
   Customer to control center communications
   Control center to vehicle communications
   Control center communications equipment
   Control center input-output devices
   Control center computer (required for computer control and digital communication option only)
   Vehicle location equipment (required for manual control and voice communication option only)
4. Fare collection subsystem:
   Vehicle-mounted equipment
   Security provisions

B. Support subsystem (equipment)
   1. Vehicle support:
      Vehicle operational support station
      Vehicle scheduled maintenance station
      Vehicle overhaul station
      Vehicle emergency support truck
   2. Roadway support
   3. Communications and control support:
      Customer to control center communications
      Vehicle and control center communications equipment support station
      Control center input-output devices and control center computer
   4. Fare collection support:
      Fare collection support station
      Exact fare refunds

C. Expendable parts and materials
   1. Operational subsystem expendable material
   2. Operational subsystem parts:
      Vehicle parts
      Roadway parts
      Communications and control
      Fare collection
   3. Support subsystem expendables
   4. Support subsystem parts

D. Real property
   1. Operations complex building
   2. Support complex building
   3. Vehicle parking
   4. Personnel parking
   5. Customer and visitor parking
   6. Land

E. Services
   1. Operational subsystem labor:
      Vehicle drivers

Telephone operators
Dispatcher
Controller (required for manual control and voice communication option only)
2. Support subsystem labor:
Vehicle support
Roadway support
Communications and control support
Fare collection support and station attendant

F. System software
1. Operational subsystem specifications
2. Support subsystem specifications
3. Expendable parts and materials specifications
4. Real property specifications
5. Service specifications

G. System implementation plan
1. Operational subsystem implementation plan
2. Support subsystem implementation plan
3. Expendable parts and materials implementation plan
4. Real property implementation plan
5. Services implementation plan
6. Software implementation plan
7. Fare structure plan
8. System introduction plan

H. System management
1. Operational subsystem
2. Support subsystem
3. Expendable parts and material
4. Real property
5. Services
6. Software
7. System implementation
8. System operation

Only the major elements are listed in this outline; the more detailed structural levels developed in the system description are omitted.

The cost-data collection phase involved the determination of the unit cost of each system element in the system description. Interest rates and amortization periods were determined for capital cost elements. The data were derived from previously published cost studies and from information obtained from bus, taxi, and limousine operator, vehicle manufacturers, and computer and communications companies.

The cost-curve formulation phase involved the aggregation of unit-cost functions in order that the total cost of the D-J system could be expressed in terms of the hourly demand distribution to be served and the exogenous variables. The distribution of demand over n-hours of system operation was described by 2n parameters, the demand for each hour (d_i, i = 1 to n), and the ratio of the demand for each hour to the peak-hour demand (ρ_i, i = 1 to n). The two service parameters were both assigned two values, and four system configurations were thus identified through the combinations of these parameters. The four systems, for which separate cost models were developed, are as follows:

System	Waiting Time (sec)	Ratio of D-J and Automobile Travel Time
A	15	2:1
B	25	2:1
C	15	3:1
D	25	3:1

The fixed costs of operation are determined only by the peak hourly demand that establishes the necessary system capacity. The variable costs of operation are dependent on the demand for each hour and thus must be calculated for each hour during which the system is in operation. Moreover, it is unrealistic to assume that labor efficiency is perfect or that exactly as many drivers (and related service personnel) would be available as would be needed to service the demand for any particular hour other than the peak hour. It was assumed that drivers would work in shifts of some guaranteed minimum time duration, and, if the demand at a certain hour was below that of the previous hour (requiring less vehicles to be utilized), an excess number of drivers would be on duty at that time. In order to account for this labor inefficiency caused by the fluctuating characteristic of the hourly demand distribution, it was assumed that the number of drivers employed during a certain hour would be the number needed to service the demand for that hour (as determined by the system simulation) plus one-half of the number needed to service the difference in demand between that hour and the peak hour.

These cost effects attributed to the distribution of demand were handled by separately determining the costs of each hour of operation and then aggregating these hourly costs over all hours of system operation to arrive at a total daily cost. The cost of serving demand levels up to 2,500 demands per hour were calculated from the aggregation of the unit-cost functions for each element of the system, given the service parameters defining the system. These costs were calculated also as a function of the ratio ρ_i. Curves of hourly cost, c_i, versus hourly demand, d_i, parameterized by ρ_i were thus generated. The curves for system D are shown in Figure 2. The curves for systems A, B, and C are similar.

The costs for each value of ρ were regressed on demand, and it was found that a linear relationship accounted for at least 98 percent of the variance in each case. The

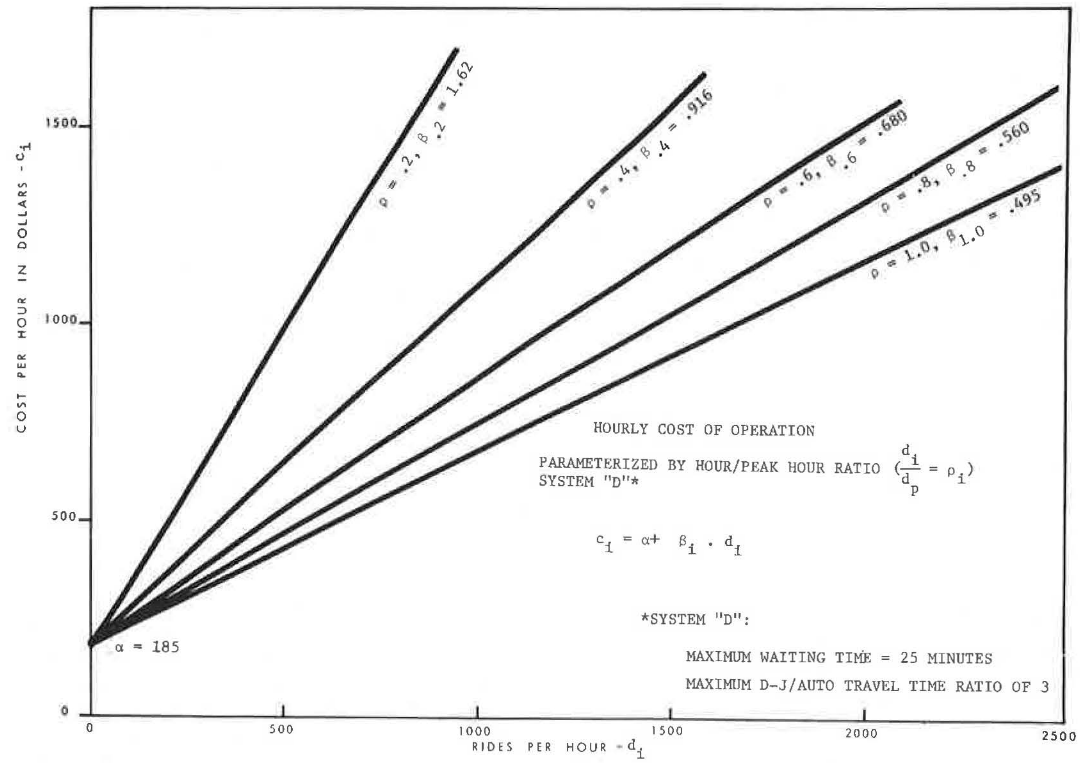

Figure 2. System D cost curves.

equations for system D are shown in Figure 2. For a particular system, the intercept of the linear cost equations, α, represented the fixed cost for the system and was independent of ρ. The linearity of the parameterized cost curves can be explained by the fact that the D-J system is labor intensive, and the relationship between vehicles needed (and hence driver and supporting labor) and demand served was found through applications of the simulation model in the case-study area to be approximately linear.

One of the important questions for a many-to-many D-J system is, At what point does the cost of a manually routed and scheduled system exceed that of a computer-aided system? For system D the manually routed system was found to be less expensive than the computer-routed system for peak-hour demands (ρ_1 = 1) of less than 225. The costs associated with the computer-routed system (the curves for system D shown in Fig. 2) are below those associated with the manual system at all points above this level of peak-hour demand, and the difference between the costs of the two systems increases with increasing demand.

REVENUE MODEL

The first part of the revenue model, the qualitative attitudinal survey, served (a) to aid in the construction of the home interview questionnaire needed to quantify consumer demand and (b) to seek qualitative information as to how and why people would react to the introduction of such a transportation system into the case-study community. Specifically, the survey provided data needed to answer the following questions:

1. What do residents of the case-study community feel are the system's most important advantages and disadvantages?
2. What actions and strategies will be required to implement the system?
3. What problems might arise if such a system were implemented in the case-study community at the present time?

Inputs to the qualitative survey phase included information regarding preferred system design, determined through the analysis of user preferences (4, 9); the system configurations for which ridership was to be estimated, determined by the combinations of the two exogenous service parameters; the range of fare for which ridership was to be estimated, determined by preliminary analysis of the cost model; and information regarding the types of trips and characteristics of the trip-makers, determined from the description of travel demand in the case-study community (based on a previous extensive transportation survey).

The qualitative survey was composed of five in-depth group interview sessions; the participants in each session were drawn from residents in the case-study area who were all classified into one of the following five market subgroups: housewives; female heads of households employed full-time in the community; male heads of households employed full-time in the community; teenagers; and adults from households in which a car was not available. Each session involved approximately ten respondents sitting in discussion for 1½ hours with a trained market research analyst. The analyst posed subjects for discussion, encouraged group participation in discussing these subjects, challenged individual responses, and forced respondents to clarify or rationalize opinions. Attempts were made both during and after the sessions by the analyst and by observers to hypothesize the consumer opinions reflected by the groups.

The use of in-depth group interviews for the pre-testing of questionnaires is an accepted market research procedure and guards against the introduction of a questionnaire containing ambiguous or misleading descriptions or instructions in a quantitative survey. The use of the in-depth interviews to gain insight into peoples' perceptions of the D-J system provided valuable information for analyzing the social and political acceptance of the system, for validating and clarifying the measurements of user preferences concerning the system design, and for developing market strategies. Both the qualitative and the quantitative surveys were developed jointly by the Transportation Research Department and an experienced market research firm. The surveys were implemented by the market research firm in order to ensure objectivity on the part of the interviewers and respondents.

The quantitative survey phase of the revenue model represented the major data collection effort of the ridership estimation phase of the D-J system study. Interviews were conducted with residents of the case-study community at their places of residence to gather information on their anticipated use of the D-J system if it were implemented in the community. The survey was administered by trained interviewers, and visual aids were used to describe the D-J system. Every attempt was made to present the D-J system design in a thorough, straightforward manner that would not bore the respondents with numerous details but that would leave the respondents with a clear, unbiased picture of what the system would be like if it were implemented in the case-study community.

The questions contained in the home-interview questionnaire can be classified into two categories: questions dealing with the respondents' demographic and socioeconomic characteristics and questions dealing with the respondents' attitudes toward use of the D-J system. Three groups of attitudinal questions were used to provide information needed for the ridership estimates. First, questions concerning the projected percentage of D-J usage for each type of trip investigated supplied the information needed to estimate the demand for the D-J that would be diverted from existing modes of transportation. Second, questions concerning the projected numbers of additional trips that would be made on the D-J system that are not now being made on existing modes supplied data on the elastic or latent component of demand. Third, questions concerning the characteristics of particular trips reported as being switched from existing modes to the D-J system supplied supplementary data on user behavior necessary for the comprehensive analysis of ridership on the new system.

Almost 1,100 home interviews were conducted in the case-study community during the spring of 1970. A modified probability procedure was used to identify the sample of households, and specific quota requirements guided the selection of the respondents. A predetermined procedure was used to replace sample households at which an interview could not be obtained after two call-backs. At least 10 percent of each interviewer's returns were validated by means of a telephone inquiry.

The home-interview survey provided data on the percentage of total trips of a particular type that respondents reported would be switched to the D-J system. For each of nine respondent types (each representing a quota sample) and seven trip types (such as shopping trips or work trips), the mean percentage of D-J usages was established for a matrix of 16 system configurations. The system configurations are determined by the combination of each of the four system service specifications (systems A, B, C, and D) with each of the four fares ($0.50, $0.75, $1.00, and $1.25).

For system A at $0.50 fare (most preferred system), the highest percentage of D-J usages was indicated by teenagers (shopping and social-recreation trips), members of no-car households (shopping and personal business trips), and housewives in one-car households (shopping trips). For system D at $1.25 fare (least preferred system), the highest usages were indicated by members of no-car households (shopping, personal business, and social-recreation trips). The teenagers and housewives who indicated extensive use of the most preferred system showed a relatively elastic demand with respect to fare and service times and consequently indicated little use of the least preferred system. The demand by members of no-car households was relatively inelastic.

In the third phase of the revenue model—the estimation of ridership on the D-J—an extensive home-interview study previously conducted in the case-study community for a metropolitan area-wide transportation study provided the data base needed to translate figures on percentage of D-J usage into actual one-way trip counts. The survey, conducted approximately 4 years before the ridership estimation survey, estimated the number of internal person trips generated by residents of the community on a given weekday as a function of the time of day, purpose of trip, and socioeconomic and demographic characteristics of the trip-maker.

Counts of the total internal one-way trips by person type, trip type, and time of day were obtained from the transportation survey data by aggregating the responses on a basis consistent with the coding scheme utilized for the ridership estimation survey. The D-J trips for each hour of the day were estimated by multiplying the number of potential trips in that hour by the percentage of D-J usage for that person and trip type combination and that system configuration under consideration. The trips for all combinations of person and trip types for each hour were summed to establish the distribution of D-J trips for the system configuration. One such distribution is shown in Figure 3. The general shape of the graphed distribution is characteristic of all of the distributions. The distribution of estimated D-J trips does, however, exhibit a shape different from that of the distribution of total trips because for each hour there is a different mix of trips by respondent type and trip type, and consequently a different mix of percentage of D-J usage figures is applied to obtain the assignment. In general, trips during the early evening hours are less easily switched to the D-J because a high proportion of these trips is made by male heads of households who indicated a lower percentage of D-J usage.

Curves of the total percentage of D-J usage versus system fare for each of the four systems—so-called modal-split curves—are shown in Figure 4. These curves are well-behaved in the sense that the partial derivatives of demand with respect to fare, waiting time, and riding time all exhibit the expected negative sign. Demand is relatively more sensitive to riding time than to waiting time (each parameter calibrated in the units used in the attitudinal survey) because systems B and C are trade-offs in these parameters and system B dominates system C in terms of demand.

The elastic or latent component of demand for the D-J system is measured in terms of additional trips that would be made on the D-J system but that are not currently being made because of unavailability of transportation at certain times. Estimates of latent demand were not included in distributions of assigned D-J trips because of serious questions as to respondents' ability to forecast such changes in their trip-making behavior and because of the objective to provide conservative ridership estimates. The latent demand estimates were used, however, in evaluating the impact of the D-J system and in studying the total system patronage picture.

All respondents indicating greater than 5 percent usage of D-J system A (maximum specified waiting time of 15 min and maximum specified D-J to automobile travel-time ratio of 2) at $0.50 fare were questioned as to the number of additional trips for each trip purpose (except work trips) they would make on the D-J. Statistics on the mean number of added trips per month per person were consequently generated for each combination of respondent and trip type. The highest numbers of mean-added trips

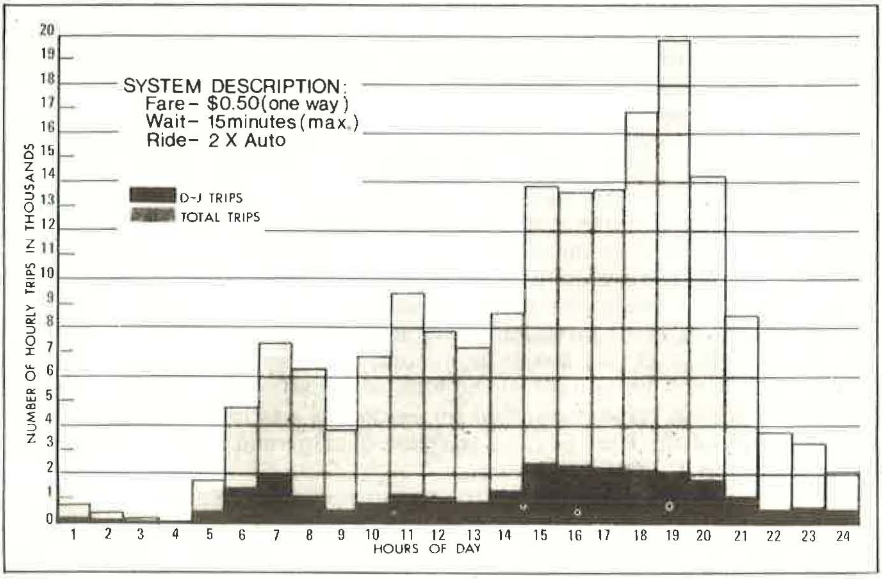

Figure 3. System A hourly diversion to D-J.

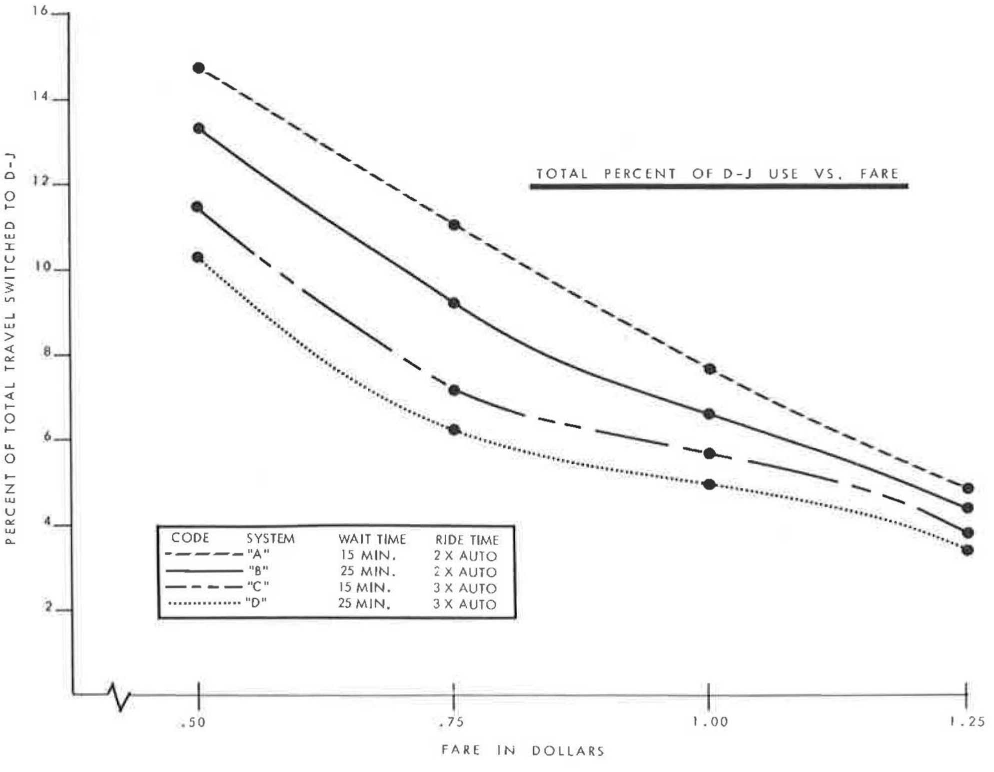

Figure 4. Modal-split curves.

were found for teenagers (social-recreation trips and shopping trips) and housewives in one-car households (personal business and shopping trips).

The statistics on added trips per month per person were translated to statistics on added trips per day per person and this figure was applied to the total D-J trips assigned for each person and trip type combination to generate the total added trips per day. For system A at $0.50 fare, the total number of added trips is 478. This number represents less than 5 percent of the total D-J trips assigned and represents approximately 0.5 percent of the total number of internal trips in the case-study community.

PROFIT MODEL

The profitability of the D-J system was determined by comparing the total daily cost (determined by the cost model) to the total daily revenue (determined by the revenue model). Profitability curves were generated for the four systems, each at four fare levels (Fig. 5). The system profit as determined by the profit model is approximately $80 per day for system D at $1.25 fare. Losses are projected for all other D-J systems over the entire range of fares for which demand was estimated.

Without financial assistance system D at $1.25 fare is the only profitable alternative, but with a willingness of a community to accept financial losses the optimal system depends on the size of the accepted loss and the objectives of the system operator. If the operator's objective is to maximize ridership, system D is the optimal system for losses up to $400 per day. For losses between $400 and $750 per day, system B has the highest ridership. System A is the busiest system in terms of ridership for losses greater than $750 per day. If we assume that the objective of the operator is to minimize the fare with the least amount of loss, system D offers the lowest fare for any level of financial loss.

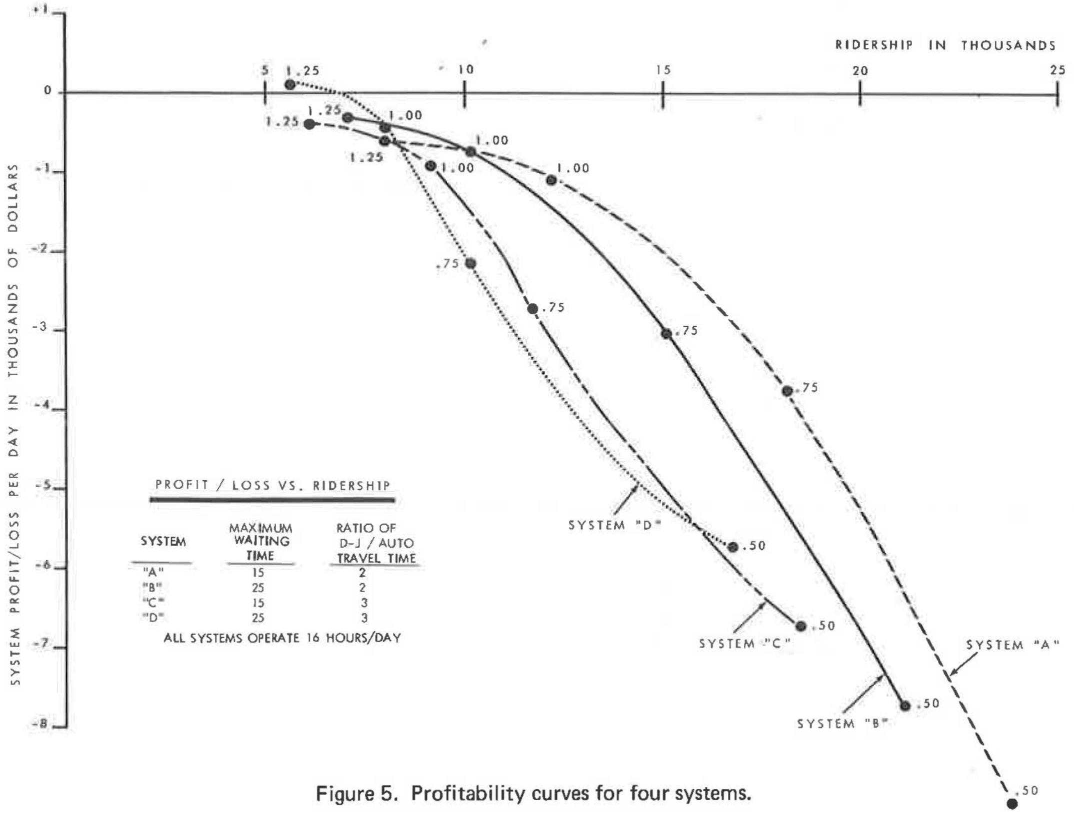

Figure 5. Profitability curves for four systems.

Measuring the effect of lower demand on profitability is important in case the actual demand does not equal the estimated demand. The estimated demand levels for system D were reduced in five steps (by 10, 20, 30, 40, and 50 percent), and the profit model was applied with each of these five reduced-demand levels (Fig. 6). The hourly distribution was assumed to be the same. The profit function indicated that the actual demand had to be 93 percent of the estimated demand in order for the system to break even in terms of costs and revenues.

Several cost inputs were varied to determine the sensitivity of profit to these factors. Three cases are analyzed here: (a) federal grant for two-thirds of the capital investment, (b) interest rates of 5 percent and 15 percent in addition to the nominal rate of 10 percent, and (c) wage rates of $2.00, $2.75, $3.25, and $5.00 in addition to the nominal $3.90-wage rate.

Figure 7 shows the profit-loss curves for systems receiving a federal capital grant. All systems are financially feasible in the higher range of fares. The break-even system with the highest ridership is system A with a fare level slightly below $1.00 and a ridership of approximately 14,000 rides per day. The effect of the capital grant is a substantial increase in both level of service (in terms of waiting and riding times) and ridership for systems generating a net profit.

Because the D-J system is labor intensive (approximately 65 percent of total costs are for labor), the cost of the system proved not to be very sensitive to changes in the interest rate but quite sensitive to wage rate changes. The prevailing wage rate of $3.90 for unionized transportation workers in the central city of the major metropolitan area adjacent to the case-study community was used. After cost calculations accounting for sick leave, vacation, fringe benefits, and taxes, the effective wage rate was found to be $5.40. A $2.00 per hour wage rate for drivers (as opposed to $3.90) would lower the break-even fare for system D below $0.75, and ridership could be increased

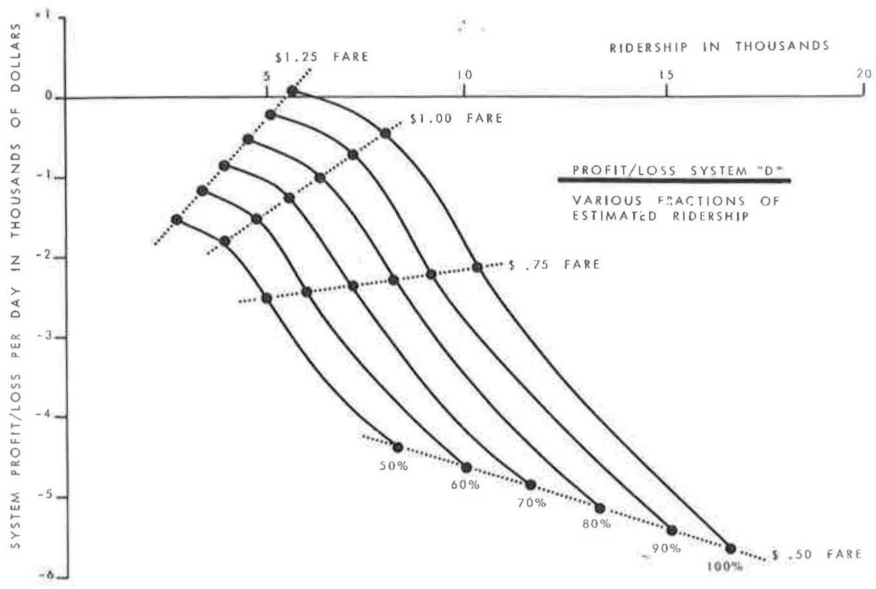

Figure 6. D-J reduced-demand levels.

to 17,000 per day (Fig. 8). The break-even point for system D, at $3.25 per hour, is approximately at $1.00 fare. A $5.00 per hour wage rate would result in unprofitable operation for all systems for any service level and for all fares investigated. With lower wage rates the profitability of the system is significantly increased.

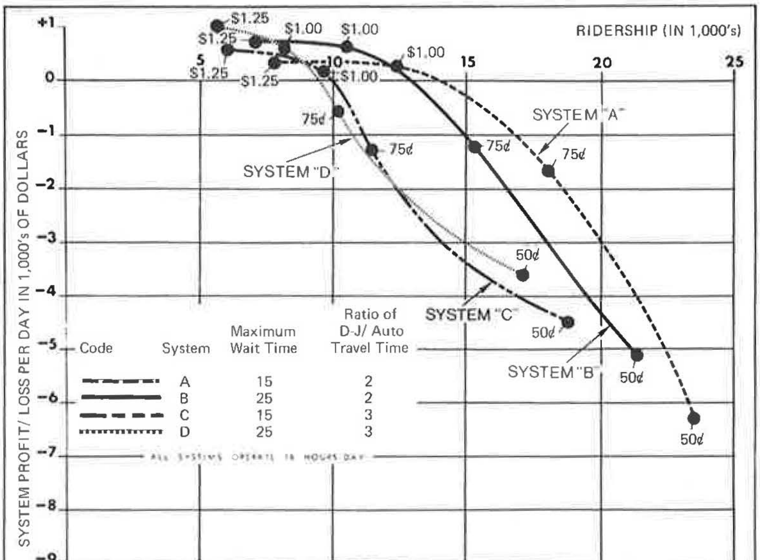

Figure 7. Profit-loss versus ridership (two-thirds capital grant).

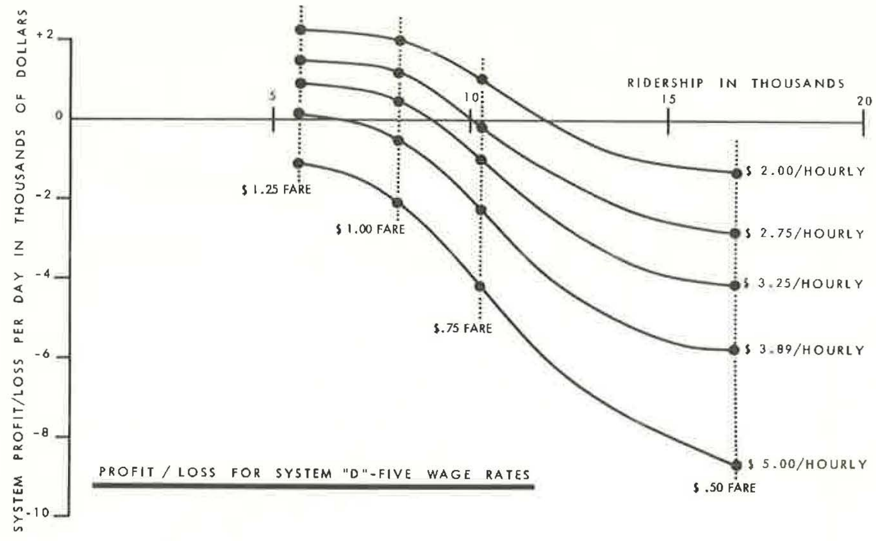

Figure 8. System D profit-loss wage rates.

SUMMARY AND CONCLUSIONS

Through application of the revenue model, the highest estimated ridership on the D-J system in the case-study community was found to be approximately 15 percent of all internal trips for the system with a fare of $0.50 and shortest specified service times. The lowest estimated ridership was approximately 3.5 percent of all internal trips for the system with a fare of $1.25 and longest specified service times. All of the market subgroups stratified in the survey sample indicated significant use of the systems at $0.50 fare. In general, the demand was for shopping and work trips in contrast to social-recreation and personal business trips. At this low level of fare, the D-J systems would indeed compete with the existing automobile mode of travel.

For systems at $1.25 fare, demand varied considerably among market subgroups and trip purposes. Housewives and teenagers in one-car households indicated substantial use of the system for shopping trips, secondary workers indicated use for work trips, and members of no-car households indicated use for shopping and personal business trips. It is postulated that the demand for the $1.25 systems is directly related to the availability of an automobile; those people who do not have access to an automobile or cannot drive would use the system for the most essential types of trips. At this high level of fare, the D-J systems provide a complement rather than a substitute for the automobile mode.

Latent demand, as measured by the increase in the number of trips being made as the result of the availability of the new mode, was small even for the $0.50 system with the shortest specified service times; an increase in total internal trips of 0.5 percent of all trips was recorded for this system. The impact of a D-J system in the case-study community should therefore be considered in terms of providing a competitive or complementary mode to the automobile (depending on the fare level) rather than in terms of solving serious transportation problems of immobility.

The system described as including service guarantees of 25 min maximum waiting time, a maximum D-J and automobile travel-time ratio of 3:1, and a $1.25 fare was financially self-supporting and would serve 5,600 demands per day. All other systems were not financially self-supporting. The cost estimates utilized appropriately high wage and interest rates, and conservative estimates of system profitability resulted.

Both computer- and manually-routed systems were studied, and the manually-routed system was economically superior only for fewer than 225 demands per hour. Also, the possibility of an incorrect demand estimation was investigated, and it was found that in order for the D-J system to break even the ridership would have to be at least 93 percent of the estimate.

The possibility of a federal grant for two-thirds of the capital investment was investigated and found to substantially enhance the profitability of the system. A system with 15 min maximum waiting time and a D-J and automobile maximum travel-time ratio of 2:1 would be financially feasible at less than $1.00 fare; more than 14,000 demands per day could be served by this system.

The sensitivity of system cost to changes in the wage rate and interest rate was analyzed. Because the system is quite labor intensive, cost was highly sensitive to changes in the wage rate. A reduction in the wage rate of $0.65 ($3.89 to $3.25) results in the lowering of the break-even fare for system D from $1.25 to less than $1.00, increasing daily ridership from 7,000 to 9,000 riders per day. Changes in the interest rate did not have as great as effect on system costs.

In brief, for the case-study community one configuration of the D-J system was found to be marginally profitable, and the application of federal capital assistance grants resulted in all systems becoming profitable over a considerable range of fares. The sensitivity of costs to labor rates and the high-wage scale in the case-study community is a severe test of the financial feasibility of the D-J system. Conversely, the relatively low sensitivity of system costs to capital cost items allows a high degree of variability in these items without an adverse effect on profitability estimates and consequently adds to the degree of confidence to these estimates.

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