replaced could be added to the respective values of operating energy for a more complete comparison of dial-a-ride with alternate modes. Because only 10 percent of the total energy is involved in vehicle manufacture and because dial-a-ride has shown only a minimal propensity for replacing automobiles in most cases, such a calculation would almost certainly reinforce the conclusion that dial-a-ride is an energy-intensive means of moving people.

CONCLUSIONS

Policy makers must apply their own priorities to this analysis in attempting to assess the utility of dial-a-ride in specific applications. Clearly, the dial-a-ride style of transportation carries significant energy penalties that must be considered along with its amenities. As energy prices increase, it is doubtful that dial-a-ride will emerge as the ultimate public transportation substitute for the private automobile.

What should be dial-a-ride's long-term objective? In one scenario described by Ward (9), dial-a-ride would serve as a public transportation market development tool in suburban areas. Having coaxed people out of their automobiles (with substantial monetary and energy subsidies), dial-a-ride would eventually lead to a greater relative proliferation of lower cost, fixed-route elements as ridership density (riders per square kilometer per hour) increased. By that time many people would have recognized the considerable travel-time savings involved in foregoing the doorstep service and walking a few blocks to the nearest bus stop. Energy intensiveness would be much lower than for pure dial-a-ride service because, with a line bus, there is little or no marginal fuel consumption associated with serving additional passengers, up to the capacity constraint of the vehicle. (Each passenger added to a dial-a-ride vehicle does increase energy consumption because of the necessity to route the vehicle to his or her origin and destination.)

Certain improvements can be expected in the efficiency of dial-a-ride. Vehicle fuel economy should improve as the automobile and small-bus industries become more serious about designing more efficient vehicles. Diesel-powered dial-a-ride vehicles will probably become more common. Increased use of day-in-advance prebooking of trips would allow more careful consideration of vehicle routing and manipulation of customer requests than does a random influx of telephone calls for immediate service. Carefully structured fare policies can help discourage nonessential trips and encourage group riding. Tough policies on no-shows can help reduce unproductive vehicle movements. Drivers can play a major role by developing more conservative driving habits, thoroughly learning the service area to avoid unnecessary deviations, and turning off their engines while waiting for their next tours.

If these measures and others fail to produce significant improvements in energy efficiency, perhaps dial-a-ride will have to be reserved for those who need it most. Many operations are currently limited to designated user groups such as the elderly and the handicapped. Depending on the rate of increase in energy prices, dial-a-ride may be increasingly restricted to such groups. All dial-a-ride costs and benefits must be considered, of course, as such decisions are made.

The challenge to dial-a-ride operators is clear. By striving for higher productivity, choosing fuel-efficient vehicles, and instituting thoughtful operating policies, dial-a-ride operators may be able to reduce the energy (and dollar) costs of dial-a-ride and thereby make this popular service a more acceptable transportation option for the future.

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Methodology for the Analysis of Local Paratransit Options

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A system of models has been developed that is capable of predicting the performance characteristics of transit service for the purpose of analyzing a wide range of local transit-service alternatives. Patronage and demand forecasting issues are treated parametrically. Local transit is de-

signed to serve access and egress trips bound to and from a regionally oriented line-haul transit system as well as shorter local circulation trips. The model system presented is capable of treating a wide range of modes that can offer such local transit service. In addition to conventional transit and jitney services, which follow fixed routes, point-deviation and checkpoint route-deviation transit can be investigated. More flexible modes, such as checkpoint subscription bus, doorstep subscription bus, and doorstep, many-to-many, dynamically routed transit (dial-a-ride), can also be examined. Comparisons can be made both between alternatives and between operating policies (such as vehicle size and route spacing) within any single alternative. The model system has been designed to predict four important consequences of implementing local transit service: user level of service, operator cost, pollutant emissions, and energy (fuel) consumption. Results from a sample model application are presented. Use of the system would allow a wide range of alternatives to be tested before significant demonstration and experimentation efforts or implementation funds are committed. Such tests can be integrated with corridor and regional analyses on both policy and planning levels of detail.

This paper presents a system of models that is capable of representing the performance of a number of local transit modes, that is, the access modes for a regionally oriented line-haul system as well as neighborhood circulation systems. A comprehensive set of options can be compared relatively quickly and inexpensively by using this methodology. Depending on the level of detail of the required input information, the model system can be applied to planning decisions that involve vehicle size, route and stop spacing, or the resolution of policy issues such as the desirable locations of dial-a-ride and the potential benefits of integrating various components of the public transportation sector. The models were developed as part of a regionwide study of the potential impacts of major diversions to the transit mode (1) and were used to estimate possible economies of scale or service improvements or both without detailed design of bus routes on the local level.

SERVICE ALTERNATIVES

The following local service options were investigated: conventional fixed route, nondeviating jitney, point deviation, checkpoint route deviation, checkpoint subscription, doorstep subscription, and dynamically routed transit.

Nondeviating jitney service resembles conventional fixed-route service except that (a) passengers can board (by hailing) and alight anywhere along the route and (b) a greater number of smaller vehicles provide a frequency that is significantly higher than that offered by typical fixed-route operation. Checkpoint route deviation resembles standard route-deviation operation; however, premium deviations are not made to the doorstep but to a finite number of designated checkpoints on request. Point-deviation service makes scheduled stops at a sequence of checkpoints and is free to take any path between checkpoints; doorstep deviations are accommodated on request. Checkpoint subscription services closely parallel standard (doorstep) subscription operation except that passengers are required to walk short distances to a relatively small number of common checkpoints to meet the bus. Because checkpoints resemble bus stops, checkpoint subscription service resembles conventional fixed-route service. The fact that checkpoints vary in response to prearranged passenger requests distinguishes checkpoint subscription from fixed-route service. Dynamically routed transit, commonly called dial-a-ride, is a many-to-many, areawide service that is also quite responsive with regard to time of request. This service offers less direct routing than subscription service but greater spatial and temporal flexibility in trip making.

Within any of these modes of local transit service, a number of service options can be varied to alter the cost as well as the level of service provided. Such options include (a) route spacing, for those modes with routelike structure; (b) checkpoint or stop spacing where appropriate; (c) vehicle size; (d) design load factor; and (e) fleet size, which affects frequency in routelike modes and all level-of-service components for demand-responsive operations. The model system is capable of considering service guidelines (maximum allowable wait time or walk distance) and of rejecting mode service option combinations that violate these planner-specified constraints.

MODELING

Approach

The method of analysis described in this paper is designed to examine the level of service attainable and the corresponding system cost of local transit at given levels of ridership for various operating policies. The models may be used to examine local options in the context of a particular regional transit-network alternative.

Figure 1 shows the overall model framework. The model is divided into supply, cost, and impact components. Complete model specifications are given by Batchelder and others (1, 2).

Issues of Modeling Process

Equilibrium

The supply model framework represents only half of the real-world process. Later versions of the model will include the demand as well as the supply relations. Significant prior work has been done elsewhere on demand modeling (9); therefore, this effort focuses on the supply side. Load factors have been set as a given condition, and demand has been parametrically varied.

Network

The models, being primarily a policy tool, do not include a specific local network; input data requirements are thus significantly reduced. A number of parameters, e.g., route spacing, stop spacing, vehicle size, and speed, are used to represent design options. The local service area itself is fixed at the outset and is representative of a previously defined catchment area of a line-haul station on a regional transit network. The specification of local services to be offered and the assignment of trips to local services are based on the previous designation of line-haul routes and terminals (transfer points).

Local Circulation Versus Collection-Distribution Service

Local transit services play two roles in a regional transit system:

1. Local transit serves collection and distribution trips associated with the line-haul network. This function is particularly important in peak periods when commuter travel to major activity centers predominates.
2. Local transit serves short-haul circulation trips within individual neighborhoods or suburban towns.

Thus, although small zones (census tracts) may be the finest level of data available, a local service district, or set of related and contiguous zones, was defined as the unit for local transit analyses. Trips between zones within the local service district are assumed to use only the local transit system and are called circulation trips.

Clear differences in local service alternatives also become evident when they are examined with respect to the two trip types. Flexible demand-responsive services provide a more evenly distributed quality of service for many-to-many local circulation trips. Fixed-route service, on the other hand, may offer some portions of these trips shorter travel times and leave other portions without any reasonable level of service. Thus, a fixed-route operation may be serving a different set of trips than the flexible service.

In conducting the comparison of alternative modes for this analysis, data were prepared for fixed, deviating, and flexible bus services where only the flexible alternative consisted of specially tailored service: subscription for many-to-one trips and dynamically routed transit service for many-to-many trips. Fixed-route and deviating alternatives were assumed to provide service for both circulation and collection-distribution service.

Models

Fixed Route

The fixed-route model, which is based on the work of Ward (3), assumes one or more sets of parallel routes operating within a rectangular local service district (Figure 2). Routes within each set converge at zone boundaries to allow for transfers between individual bus routes by intradistrict circulation travelers. In reality, these points would probably be located at line-haul stops to serve the dual purpose of transfer for both local and line-haul trips. The fixed-route program tests a wide range of alternatives by varying vehicle size and route spacing.

The model first computes a design volume based on input travel data disaggregated by trip type (e.g., circulation) and direction. (Input data are based on the assignment of origin-destination transit volumes to regional transit lines.) Other input data include bus-stop spacing, dwell and layover times, base bus speed, zone dimensions, average passenger travel distances, duration of service, and limits for the variable parameters of vehicle size and route spacing. The model determines the frequency of service and the fleet size required to transport the passenger volume, at a given load per vehicle, subject to walk and wait-time constraints. Model output includes supply measures such as fleet size, vehicle hours and kilometers, and level-of-service measures including wait, walk, and travel time.

Nondeviating jitney was analyzed within the context of the fixed-route model; small vehicles were used and fixed bus stops eliminated. The actual number of stops made was assumed to be a function of Poisson arrivals along a route with defined time and distance intervals.

Deviating Bus

The deviating bus model is an extension of the fixed-route model (Figures 3 and 4). For either the point-deviation or the checkpoint route-deviation operation, the model computes the percentages of users who request deviations based on geometry and maximum allowable walk distances specified by the analyst. The expected (probabilistic) number of stops and deviations made by an average bus on a single round trip and the resulting round-trip length are calculated. For the point-deviation service, a "traveling salesman" tour is assumed for the doorstep pickups and drop-offs between fixed checkpoints. Various route and checkpoint spacings can be tested by the model.

Flexible Transit Service

1. Subscription bus model—Subscription service (Figure 5) is provided for peak-period collection and distribution (back-haul) trips as part of the flexible alternative (3). Specific zone to line-haul station (many-to-one) services are specified at the outset of the analysis and tested by the model. A service area is assumed to be divided into small sectors, each served on a continuous basis by a single vehicle. That vehicle's trip may thus be divided into line-haul travel and collection tour portions. Given vehicle size, load factor, trip density (trips per square kilometer per hour), speed, service area, and line-haul station locations, round-trip travel time and fleet size are determined. Both checkpoint and doorstep subscription options for various vehicle sizes can be tested by the model.
2. Dynamically routed transit model—The many-to-many, districtwide, dynamically routed transit model (Figure 6) describing system performance was statistically fit by using ordinary least squares regression on data produced by a simulation model. The simulation itself, originally developed at the Massachusetts Institute of Technology for the Computer-Aided Routing System (CARS) project, has itself been validated by using data collected during the Haddonfield, New Jersey, demonstration (4, 8). Given volume, area, base bus speed, and a target level of service, response and travel times are calculated along with the fleet size necessary to attain that level of service.

Because subscription service would be provided during peak hours by the same basic fleet as that used for dynamically routed transit, a minimum vehicle size required for dynamically routed transit operation is computed based on Poisson multiple-server queuing theory to ensure that smaller vehicle sizes are not tested by the subscription model. Queuing theory also provides a useful productivity measure—the dead-time fraction, or the fraction of time a dynamically routed transit vehicle would be idle.

Measures

Output of the models includes various measures of impedance (level of service) and resource expenditure.

Level of Service

For evaluation purposes, the overall average level of service offered by each service alternative was computed. Level-of-service components such as in-vehicle and out-of-vehicle time (walk, wait, response, or schedule delay) are of varying importance in the overall perception of service quality. Thus, the impedance measure is a weighted sum of the individual components that reflects the differences in wait time at a bus stop, wait time in the home, and the inconvenience of meeting scheduled departures. The relative impedance weights were determined by analyzing data and results of a line-haul access study discussed by Liou and Talvitie (5).

Cost

Service cost per passenger, without consideration of fares or revenues, was used as the major evaluation measure. Annual direct and indirect operating costs, labor costs, and fleet capital costs are calculated by the model based on input unit costs (6). Supply model out-

Figure 1. Model framework.

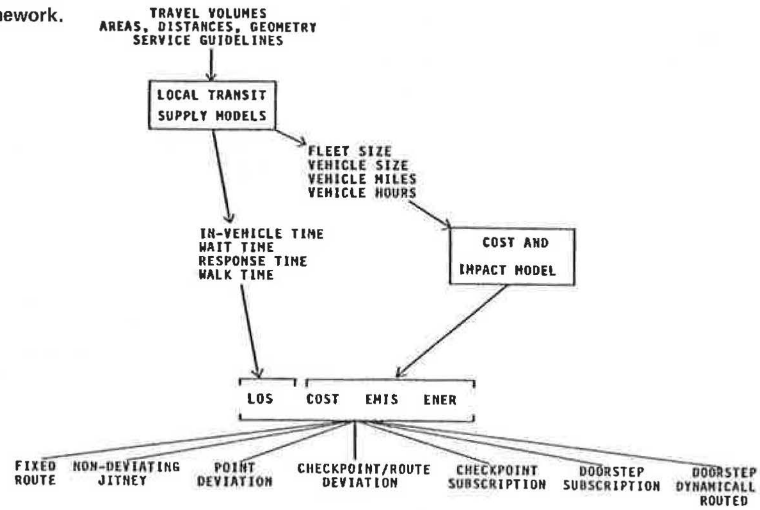


Figure 2. Fixed-route service for a single zone.

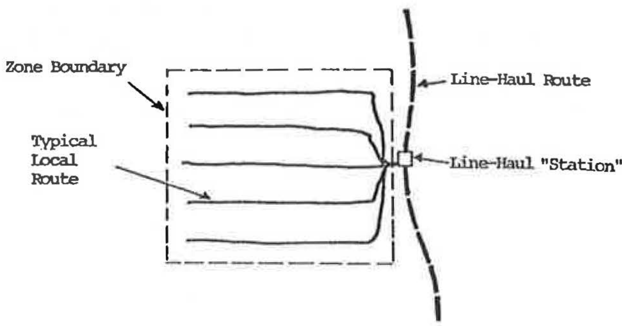


Figure 3. Local point-deviation service.

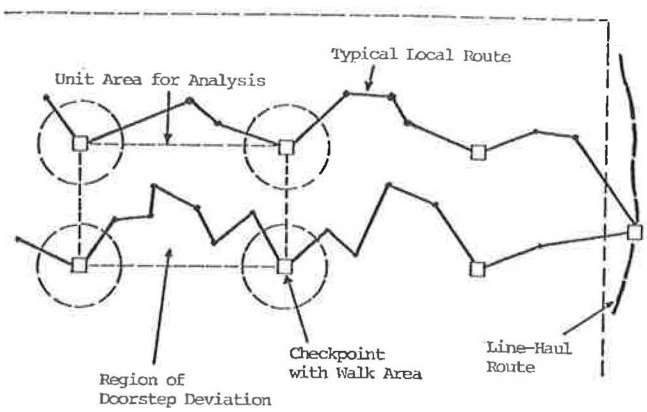


Figure 4. Local checkpoint route-deviation service.

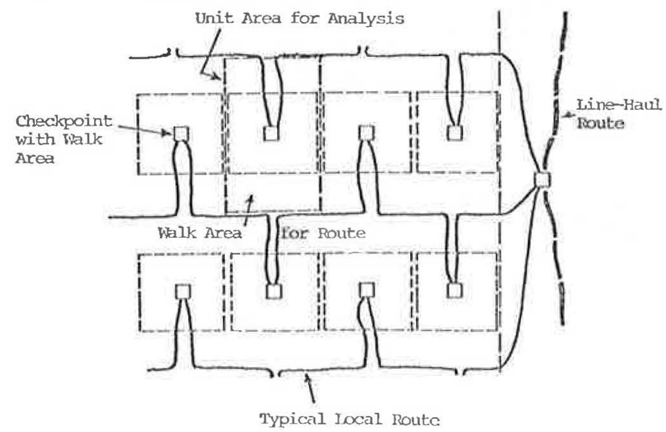
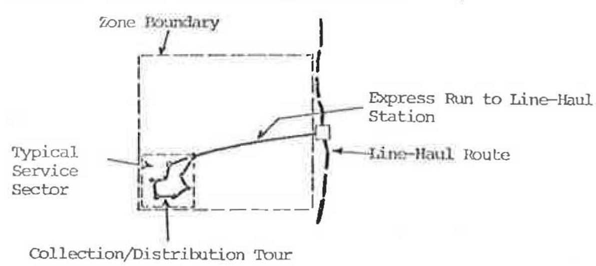


Figure 5. Flexible local service alternative: subscription bus.



puts, such as fleet size and vehicle hours of service and kilometers of travel, and peak and off-peak fleet cost-allocation factors are input to the cost models.

Impact Models

Easily quantifiable impacts of interest to transit planners include the energy and environmental effects of transit use. Per-passenger fuel consumption and pollutant emissions were chosen as the appropriate model outputs. Carbon monoxide, hydrocarbons, and oxides of nitrogen were the pollutants viewed as most significant. Both energy and environmental impacts are related to vehicle kilometers of travel and are easily computed (6).

Productivity

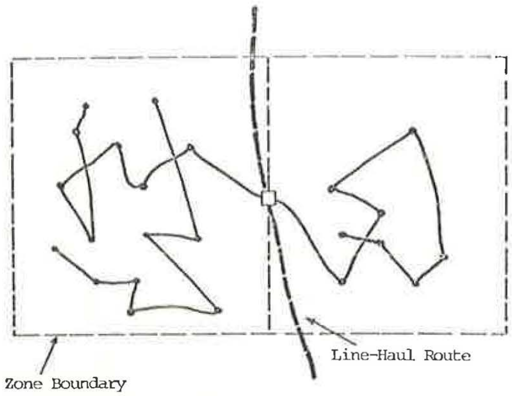
Variables such as passenger trips per vehicle hour, passenger kilometers per seat kilometer, and dead-time fraction for dynamically routed transit are useful for the evaluation of relative operating productivity. Such measures are used in determining system economics and potential economies of scale.

MODEL APPLICATION

The model components (i.e., fixed, flexible, and hybrid service) were applied to an analysis of a high-density suburban district over a wide range of peak-period modal splits. This application of the model was part of a study of the design implications of major diversions to transit (1, 2). Thus, the range of mode splits was considerably greater than that presently experienced with flexible modes.

The models produce data on numerous alternative system designs according to input guidelines. Analysis of these data led to a number of conclusions.

Figure 6. Flexible local service alternative: dynamically routed transit.



Economies of Scale

Direct operating costs per passenger for alternative service options were plotted as functions of trip density; level of service (weighted travel time or impedance) was held constant. Figure 7 shows a typical result. Each point in the figure represents the vehicle-size and route-spacing alternative that produces the least cost while meeting the specified service standard [in this case equal to 3.6 (perceived) min/km (5.8 min/mile), including out-of-vehicle time].

All modes tested reveal economies of scale, although at diminishing rates. These economies result primarily from the ability to use larger vehicles and still maintain frequent service, which yields increased driver and vehicle productivity at high modal splits.

Comparison of Modes

Figure 7 clearly shows fixed route to be the least cost option for providing good peak-period service in an inner suburban district [population density of 2200 to 2500 persons/km^2 (6000 to 7000 persons/mile^2)] over a broad range of trip densities. Figure 8, which plots direct operating costs for a range of service levels at the lowest modal split examined, confirms this dominance: Points closer to the origin are desirable, and thus shorter travel times are provided at lower operating

Figure 7. Direct operating cost versus trip density for various service options and resulting increase in modal split.

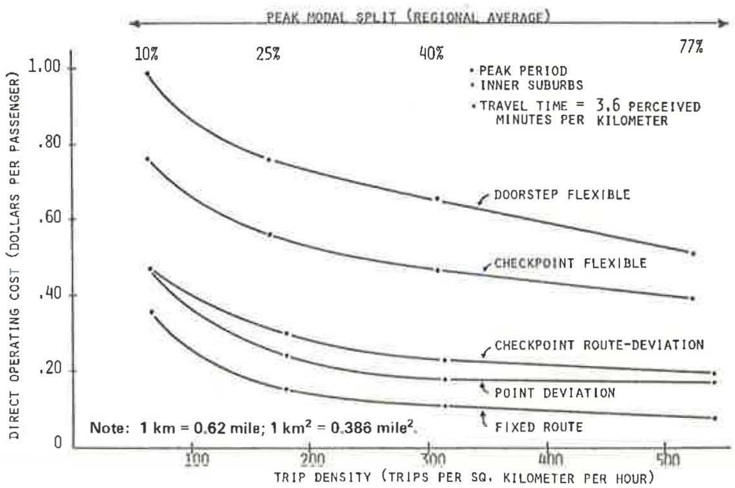


Figure 8. Local service performance at 10 percent peak modal split.

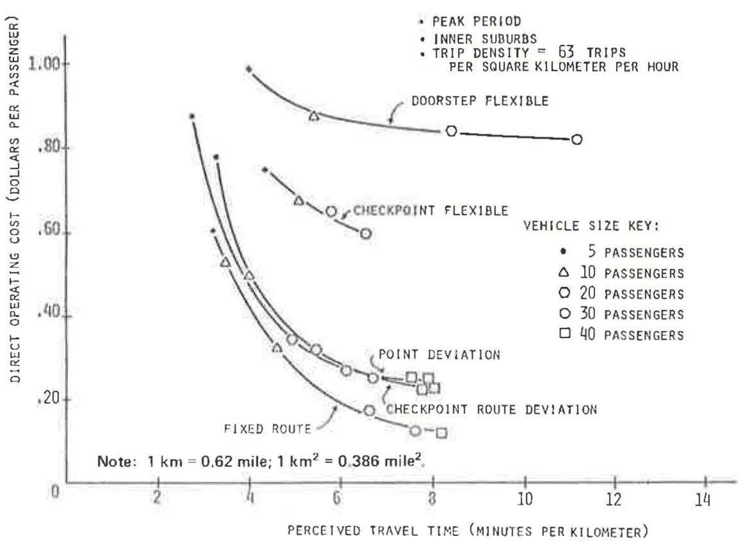


Figure 9. Sensitivity of operating cost to labor structure.

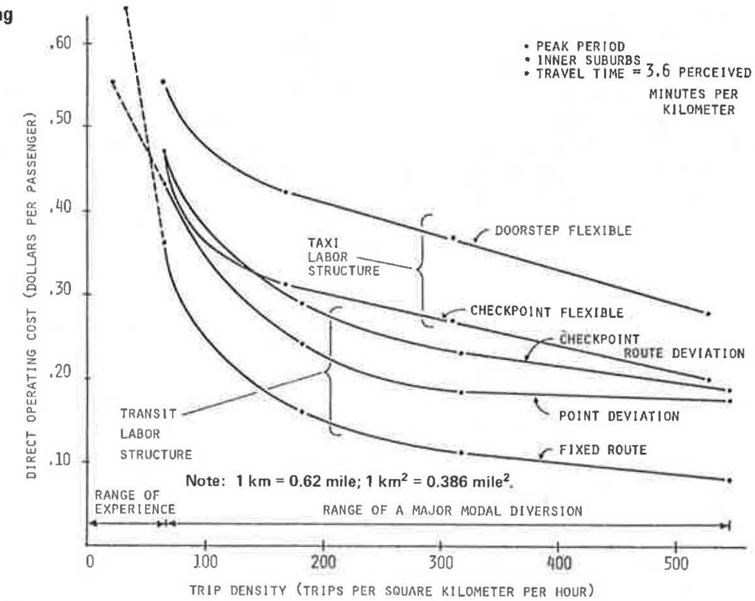
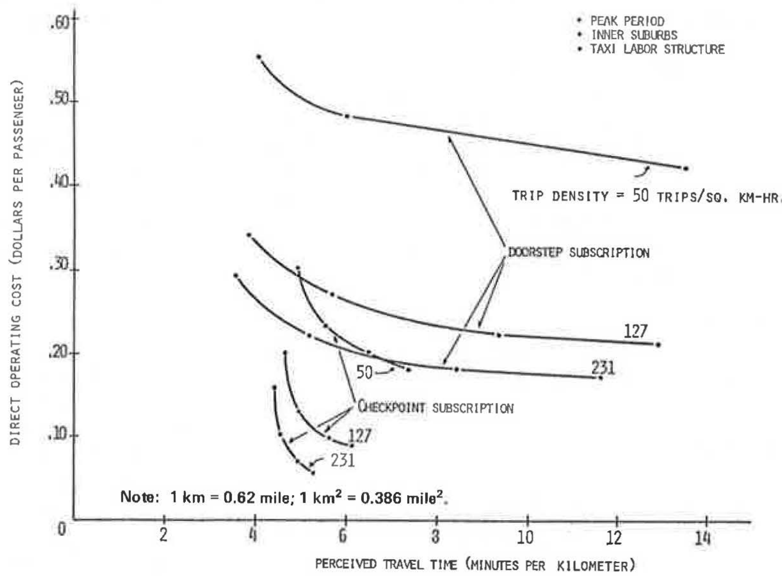


Figure 10. Subscription service performance.



costs. The sensitivity of cost to changes in service varies dramatically by mode, and the route-based modes are the most sensitive, i.e., have the steepest slopes. Increases in vehicle size, which cause increased headways and poorer service, result in large cost savings for these modes because of increased driver productivity. (Fixed-route bus, as analyzed in this study, includes a non-deviation-jitney alternative operated with automobile-size vehicles.) At the other extreme, doorstep flexible operation, an increase in vehicle size increases the length of the collection tour and results in insignificant cost savings.

Two basic questions can be raised at this point:

1. Do the models reflect the real world, where successful flexible operations have been developed to replace failing fixed-route service?
2. If so, do other modes dominate at the lower trip densities that occur in the off-peak and in other parts of the metropolitan area?

Further examination of the model results helps to answer these questions and provides insight into the operation of local transit.

Labor Cost Sensitivity

Most flexible operations do not face the high cost of unionized transit labor but more closely resemble the taxi situation. If taxi labor costs are assumed for flexible transit options, significantly lower wage rates make these services more competitive. Figure 6 should be compared with Figure 9. At the lowest modal split examined, costs for checkpoint subscription with dynamically routed transit circulation are only 20 percent more than those for fixed route and 8 percent cheaper than those for deviating bus. Fixed route, however, still dominates.

Trip Density

The range of trip densities found in existing flexible-route services seldom exceeds more than the 14 to 18 trips/($km^2 \cdot h$) [40 to 50 trips/($mile^2 \cdot h$)] served by the Regina, Saskatchewan, and Bay Ridges, Ontario, systems (7). Thus, there is no inconsistency between the results obtained here and the successful operation of existing flexibly routed services. The previous figures do indicate, however, that, if demand density passes certain thresholds, then the types of service provided should change in the direction of less spatial responsiveness.

Flexible Service Operation

In this study, flexible service is provided by a composite of doorstep dynamically routed transit for intradistrict circulation travel and subscription service (either doorstep or checkpoint) for collection-distribution travel to and from line-haul stations. Significant improvements in productivity (accompanied by decreases in per-passenger costs) can be obtained by serving more passengers at each stop with checkpoint subscription and thereby reducing the time of a collection-distribution tour. However, because passengers would no longer be served by door-to-station service, it is expected that these improved productivities would be "bought" with degraded levels of service.

Surprisingly, Figure 10 shows that the checkpoint service provides higher quality service (lower travel time) for all trip densities and for all but the smallest vehicle size, as well as less expensive operation, which was expected. Thus, the required walk distance is more than compensated for by the reduction in the collection-distribution tour that results from multiple pickups at each checkpoint. This effect, therefore, is even more pronounced as vehicle size and trip density increase.

In addition to the above, investigation of various time periods and areas in the metropolitan region tends to show flexible and hybrid (deviating) services in a different light. Whereas fixed route tends to dominate in high-density inner suburbs in the peak, the off-peak and the outer suburbs are more suited to flexible service, probably because of more dispersed trip patterns and street configurations.

SUMMARY AND CONCLUSIONS

Although only a small sample of the results that can be produced by using the models are illustrated in this paper, the models do assess various impacts. They may be useful in revealing the dominance of one particular option over another, pinpointing the thresholds at which alternative policies begin to offer better solutions, and aiding the analyst in other sketch-planning tasks for local transit.

The analysis tool developed in program package form can be extended and refined considerably. Among the areas that call for further work are

1. Automation of the evaluation and selection process;
2. Inclusion of demand models;
3. Refinement of the DRT model so as to increase sensitivity to local transit trip and street patterns;
4. Extension to checkpoint DRT, premium taxi, car pooling, van pooling, and park-and-ride.

The models may be used by a transit analyst to investigate local service alternatives on a macroscale as well as at a finer level of detail. In an overall metropolitan area study, this is useful for indicating which local districts and during which time periods fixed, deviating, or flexible local transit service should be provided. In a long-term study of a dynamic demand situation, the model may help to determine at which point in time it may be advantageous to modify service so as to gain efficiency and reduce subsidies. On the finer level of analysis, preliminary estimates of fleet size and overall cost of service in an area, as well as the comparison of checkpoint and doorstep alternatives and different geometric options (such as route spacing and stop spacing), can be made.

The model has conveniently integrated present understanding of some widely different services and has already proved to be useful in analyzing alternative local transit-service policies.

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