or by having a separate DAR operator, as is being done in Rochester.

Service and Operations Strategies

Several additional lessons have been learned from the five years of DAR operating experience in Rochester. The most significant are discussed below.

Replacing Fixed-Route Services

Where transit habits have already formed around an established fixed-route network, DAR should be used to supplement these services rather than replace them unless the DAR service offers indisputably higher service levels or is much less costly than the existing fixed-route service. When the superiority of DAR is less certain, it may be better for DAR and fixed-route services to coexist temporarily until habits change and to encourage the transition by means of an active marketing campaign that stresses the benefits of one mode over the other.

Striving for Simplicity and Stability

PERT management, in trying to fine-tune the system and respond quickly to its perceived shortcomings, instituted a rapid succession of service and fare changes, especially between 1974 and 1976. Some innovations, such as zonal fare systems, were quite complicated, and users were often confused by the constant shuffling of service alternatives. Fine-tuning the system can thus be counterproductive if it is done too frequently or if it complicates the overall operation. A service should be easy to understand and simple to use. Frequent service changes should be avoided, and any changes should be well publicized.

Selecting the Type of Vehicle

There are a multitude of small transit vehicles on the market, many with poor or unknown track records. An operator would be wise to select one vehicle with which other operators have been satisfied and prepare the system's maintenance shop to deal with that one type of vehicle.

Opting for Computerized Scheduling and Dispatching

Computerized scheduling and dispatching are expensive but have worked well in the two service areas operated by RTS. In a large, regionwide DAR system characterized by many service areas, computerization may reduce control-room operating costs; there is no consensus, however, that service quality or vehicle productivity can be improved by computerized dispatching or even that existing scheduling algorithms are effective under conditions of high demand and high vehicle density. Additional research is needed to define the proper role for computerized scheduling and dispatching.

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Many persons provided information for this paper, including staff members from the Rochester-Genesee Regional Transportation Authority; Regional Transit Service, Inc.; the Massachusetts Institute of Technology; and Paratransit Enterprises, Inc.

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Hybrid Paratransit Service

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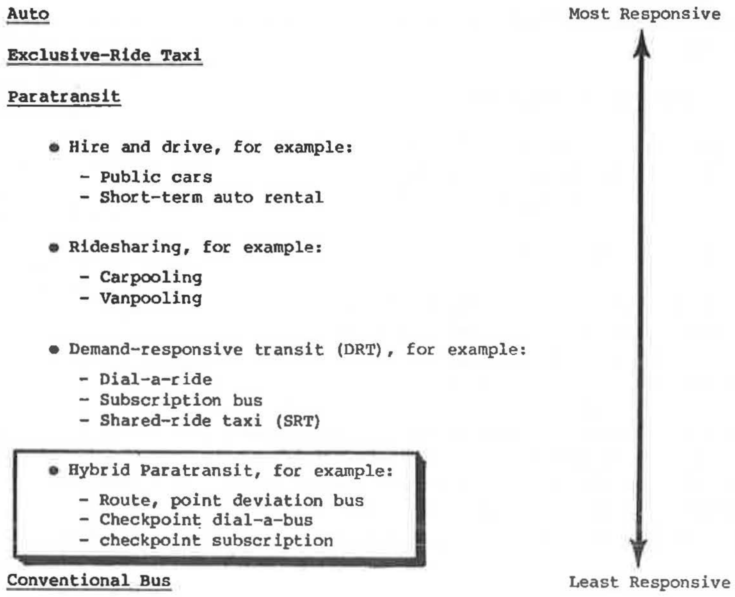
Hybrid paratransit, which combines features of conventional bus service and demand-responsive transportation, is examined. Hybrid paratransit sacrifices some of the flexibility of demand-responsive transportation to attain improved productivity and cost savings but retains some of that flexibility to achieve the levels of service necessary for adequate market penetration. One example of hybrid paratransit is checkpoint subscription service, a prearranged operation in which groups of passengers gather at common locations for collection and passengers are distributed only to those locations. Checkpoint and doorstep subscription service were analyzed and compared by applying models that predict cost and performance. The results show not only that the expected productivity increases accrue to the hybrid operation but also that, under many circumstances, the level of service of hybrid paratransit is superior. In addition, for any level of ridership, there may be a vehicle size that minimizes the operating costs of both subscription services. It is concluded that hybrid paratransit may offer service and cost characteristics that dominate demand-responsive transportation under a variety of conditions and may be the most appropriate option for service areas of moderate population density.

In most urban areas, transit alternatives that do not rely on fixed-guideway facilities are clearly the most appropriate service options. Until recently, as indicated by the appearance of such reports as that by Kirby and others (1), planners designing nonguideway public transportation systems typically restricted their attention to

Figure 1. Role of hybrid paratransit in spectrum of nonguideway transportation.



conventional fixed-route and fixed-schedule transit. In the current climate of increased awareness of paratransit modes, the range of alternatives now available for consideration is much broader than it was just a few years ago.

Paratransit has often been defined as the spectrum of transportation options that fall between exclusive-ride taxicab service and conventional fixed-route, fixed-schedule bus service. Various forms of demand-responsive transportation (DRT) rapidly emerged as among the most prevalent types of paratransit. Perhaps the most important DRT modes include (a) immediate-request, many-to-many dial-a-ride and (b) advance-request, many-to-one subscription bus. In sharp contrast to conventional bus service, which requires its patrons to tailor their travel needs to predetermined routes and schedules, these two DRT modes tailor both routes and schedules to the travel needs of their riders.

Recently, a new class of paratransit modes has earned an important place in the spectrum of nonguideway transportation options. Figure 1 shows the role of what is here defined as "hybrid paratransit". This term has been coined because the modes that fit into this category combine features of both DRT and conventional bus operations. For example, route- and point-deviation bus services are based on a predefined route but also make door-to-door passenger pickups and drop-offs. Checkpoint dial-a-ride and subscription bus combine the route and schedule flexibility of their DRT counterparts but, much like conventional service, require passengers to walk to a "bus stop".

The key distinguishing characteristic of a hybrid mode is that it offers demand responsiveness in relation to either space or time but not both or it discourages full responsiveness by charging its users additional fare for the option of purchasing additional responsiveness. Route- and point-deviation bus services do not offer temporal responsiveness since predetermined schedules are used, but they do provide spatial responsiveness since the buses will deviate to accommodate door-to-door travel requests (though at a higher fare in some operations). Checkpoint dial-a-ride and subscription bus make temporal responsiveness available to users since schedules are tailored to demand, but spatial responsiveness is limited in that door-to-door pickups and drop-offs are not made and, instead, passengers are required to use a predetermined set of dispersed checkpoints within walking distance of their doors.

Examples of past and current hybrid paratransit services include the route-deviation bus system operated in Mansfield, Ohio (2, 3), and the point-deviation systems of Columbus, Ohio (4, 5), and Merrill, Wisconsin (6-10). Another version of hybrid paratransit—checkpoint many-to-many service—was suggested by the Transport Canada Research and Development Centre for operation in Ottawa (11).

PROMISE OF HYBRID PARATRANSIT

Hybrid paratransit systems, with their compromised characteristics of both DRT and conventional transit, have the potential of operating at significantly higher productivities (measured in passengers per vehicle hour) than DRT, a situation equivalent to lower-cost operations. Although by definition hybrid paratransit is not as responsive to the travel needs of passengers as DRT, the degree of responsiveness that it does retain is likely to make it significantly more attractive to users than a conventional bus system.

Productivity can be improved by shifting a DRT operation into a hybrid service because, by requiring travelers to partially accommodate the service, more efficient vehicle tours (in terms of the degree of ride sharing) can be designed and dispatched. This does not mean that all hybrid systems will exhibit productivities that are superior to those of all DRT systems. The density of demand also has a strong impact on the level of productivity that is actually achieved. Putting aside for the moment the question of what productivity will be achieved, the potential productivity of hybrid paratransit systems that share some of the characteristics of conventional transit far exceeds that of DRT. To illustrate this point, it is useful to consider the two ends of the responsiveness spectrum: conventional bus and exclusive-ride taxi. When demand densities are low, the productivities of conventional bus systems are similarly low; in corridors of high demand, conventional buses may exhibit productivities of 40-50 passengers/vehicle-h. In contrast, the productivity of a taxicab rarely exceeds 4 passengers/vehicle-h regardless of the density of demand.

Because the potential increase of productivity of a hybrid operation over a DRT system could be attained at little or no marginal (operating or capital) cost, the implication is the ability to significantly reduce cost per passenger trip by operating hybrid instead of DRT service. Thus, for a given subsidy level, hybrid fares can be considerably lower than DRT fares. In addition to lower costs and fares, hybrid systems are also likely to provide more reliable service—an often-cited area of weakness in many DRT systems—because restricting the responsiveness of service eliminates a degree of the randomness of passenger travel requests or at least allows the system operator to plan better for the randomness. Ewing and Wilson (12) present empirical evidence that confirms the superior reliability (and productivity) of a few hybrid services in comparison with comparable DRT systems.

Of course, it is not realistic to expect to increase productivity, lower costs, and improve reliability without giving up something in return. Level of passenger service can be expected to decline as a result of any shift from DRT to hybrid paratransit service because of the deliberate restrictions placed on responsiveness to passengers. Riders of route- or point-deviation bus systems would have to time their trips to match the fixed schedules of those services, and riders of checkpoint dial-a-ride or subscription bus systems would have to walk to the closest checkpoint to use the service. Both types of systems represent a reduced level of service in comparison with DRT, which picks up passengers at the their door as quickly as possible after their request for service. Nevertheless, the promise of hybrid paratransit depends on the hypothesis that improved reliability and potentially lower cost more than compensate for the resulting reduction in level of service. Although a full test of this hypothesis must await considerably more operating experience with hybrid paratransit, important inferences can be drawn from a comparison of the results of mathematical models of DRT and hybrid paratransit systems. The following sections of this paper describe such an experiment.

COMPARISON OF DRT AND HYBRID PARATRANSIT MODELS

Description of Services

As an example comparison of DRT and hybrid paratransit services, models of doorstep and checkpoint subscription-bus systems were developed and applied. Both types of operations require passengers to request service either well in advance or on a "standing-order" basis—e.g., monthly. Both services are usually oriented to a many-to-one trip pattern. Both services rarely schedule standees and may use vehicles that range in size from 5-passenger (taxi) sedans or 8-passenger vans to 50-passenger buses, depending on the expected density of demand. Finally, for both types of service, the afternoon distribution tours are usually the "mirror images" of the morning collection tours.

Doorstep and checkpoint subscription services differ in that a doorstep subscription bus will pick up passengers at home whereas a checkpoint subscription bus requires users to walk (or otherwise travel) to the closest of a set of checkpoints to be picked up. The locations of the checkpoints can be specified after passenger requests are known so that the lengths of passenger walking trips and vehicle tours can be minimized. Alternatively, the locations of the checkpoints can be predetermined so that all potential users of the checkpoint subscription service know in advance the location of their checkpoint if they request service. In that case, of course, only the checkpoints that are closest to passengers would be included in the vehicle tours; it is quite possible that a number of predetermined checkpoints would not be used by any subscription rider.

Figure 2 shows the type of collection tours that would be developed for both doorstep and checkpoint subscription-bus operations for the same set of passengers. The models that were developed and applied to compare these examples of DRT and hybrid paratransit are designed to yield the following output: required fleet size, productivity, cost per passenger, and passenger travel time (including walk time for checkpoint service). As input, they require a description of the service area, the type of service to be offered (including vehicle size), and the passenger demand density to be tested. Because demand is an input, these models are properly considered supply or performance models.

Analysis and Results

The development of the models of doorstep and checkpoint subscription services can be traced back a number of years through an evolutionary process that involved a number of researchers. A key, and common, element of the current models is the calculation of the length of tour a vehicle would traverse in order to visit a given number of points in an area of given size with a given aspect ratio (ratio of the area length to width). This part of the models was first developed by Mason and Mumford (13) in an effort to model dial-a-ride service. Ward (14) borrowed the Mason and Mumford tour-length model and used it in a fairly restrictive model of doorstep subscription service. Working from the Ward model, Batchelder and others (15) and Englisher and Sobel (16) relaxed many of the restrictions of the formulation and added the capability of representing checkpoint subscription service. In a parallel effort, Billheimer and others (17) also used the work of Ward to develop models of both doorstep dial-a-ride and doorstep subscription service. Finally, Menhard and others (18) further modified the work of Englisher and Sobel to improve the models' realism and accuracy.

The models presented here fall midway between the models of Englisher and Sobel (16) and Menhard and others (18). A vehicle round trip is disaggregated into three or four main components and analyzed piecemeal. Figure 3 shows these components, which include an external line-haul segment, a zonal line-haul trip segment, either of two types of collection-distribution tours (called simultaneous and sequential tours), and a sector line-haul segment for use with simultaneous collection-distribution tours.

A sequential collection-distribution tour is one in which all distribution passengers are dropped off before the collection passengers are picked up. This type of tour helps to avoid possible problems with vehicle capacity constraints but can potentially pass close to collection passengers who are waiting for service and not pick them up. The doorstep subscription service is modeled with sequential collection-distribution tours. A simultaneous collection-distribution tour entails the picking up and discharging of passengers in a single "sweep" without regard to the order of passengers entering or leaving the vehicle. This type of tour was selected for checkpoint subscription service to avoid the necessity of visiting the same checkpoint twice in a single tour when distribution and collection passengers both live near the same checkpoint.

The zone in Figure 3 corresponds to the service area being analyzed, and the sectors represent the area served by a single vehicle. Clearly, sector size depends, in part, on the density of demand.

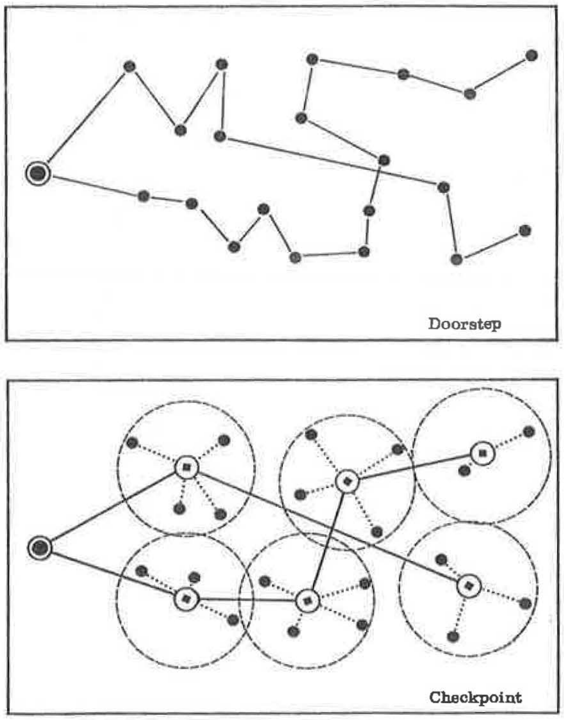
The fundamental equations for the models are the following:

$$d = V/A \quad (1)$$

$$a = 60n/dT \quad (2)$$

$$D_L = \pi(\sqrt{A}/4)[1 - (\sqrt{a}/\sqrt{A})] \quad (3)$$

Figure 2. Configuration of doorstep and checkpoint collection-distribution tours.



$$D_{CD\text{-}SEQ} = f_a \sqrt{a/2}(2.96 + 0.16\ NS_c + 0.2\ NS_d) \quad (4)$$

$$D_{CD\text{-}SIM} = f_a \sqrt{a/2}\ \{2 + [NS/(NS + 1)] + (1.2 + 0.2\ NS)\} \quad (5)$$

$$T = f(D_{EX}, D_L, D_{CD}, LYOV, TPD, NS, V_{EL}) \quad (6)$$

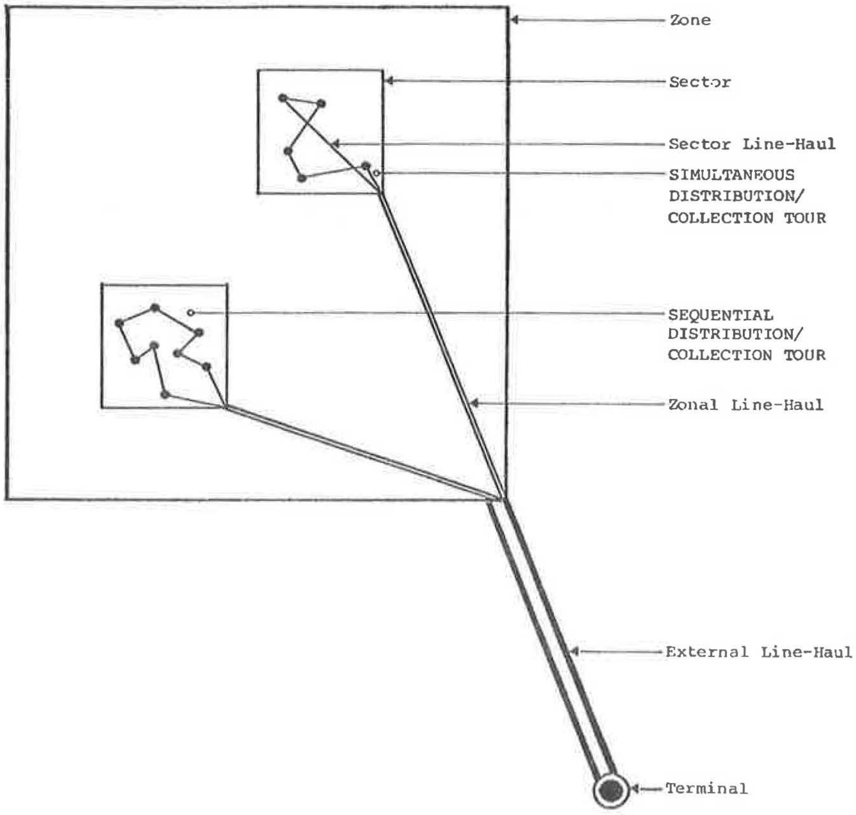
$$FLT = A/a \quad (7)$$

where

d = demand density (trips/km^2/h);
V = design volume (passengers/h);
A = service or zone area (km^2);
a = sector area (km^2);
n = vehicle size (number of seats);
T = vehicle round-trip travel time (min);
D_L = zonal line-haul distance (km);
$D_{CD\text{-}SEQ}$ = distance of sequential collection-distribution tour (km);
f_a = street adjustment factor, relating rectangular distance to straight-line distance, usually equal to $4/\pi$ (19);
NS_c = number of collection stops in a tour;
NS_d = number of distribution stops in a tour;
$D_{CD\text{-}SIM}$ = distance of simultaneous collection-distribution tour, including sector line-haul (km);
NS = total number of stops in a tour;
D_{EX} = extensional line-haul distance (km);
$LYOV$ = layover time between tours (min);
TPD = time to pick up or drop off a passenger (min);
V_{EL} = "cruising" velocity of subscription vehicles (km/h); and
FLT = fleet size (number of vehicles).

Equations 2-6 are applied iteratively until the value of T in Equations 2 and 6 is tolerably equivalent. Note that any reasonable estimate of T will suffice for the

Figure 3. Structure of subscription-service model.



initial application of Equation 2. Computational experience indicates that convergence is quite rapid—usually in fewer than 10 iterations—for tolerances in the range of 90 s in 30 min. The converged value of T is then used to calculate average passenger travel times. Other outputs of interest include the productivity of the services (passengers per vehicle hour), cost per passenger and per passenger kilometer, and vehicle kilometers and vehicle hours traveled.

Figure 4. Cost per passenger versus travel time for volume of 120 passengers/h.

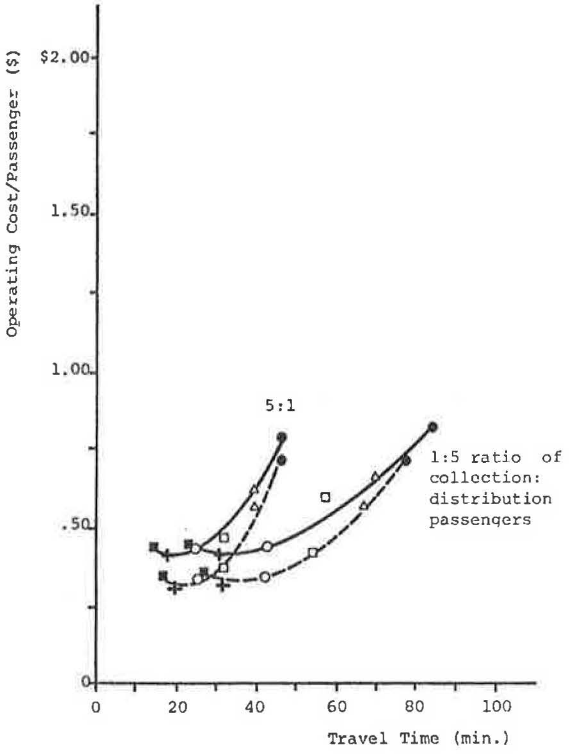
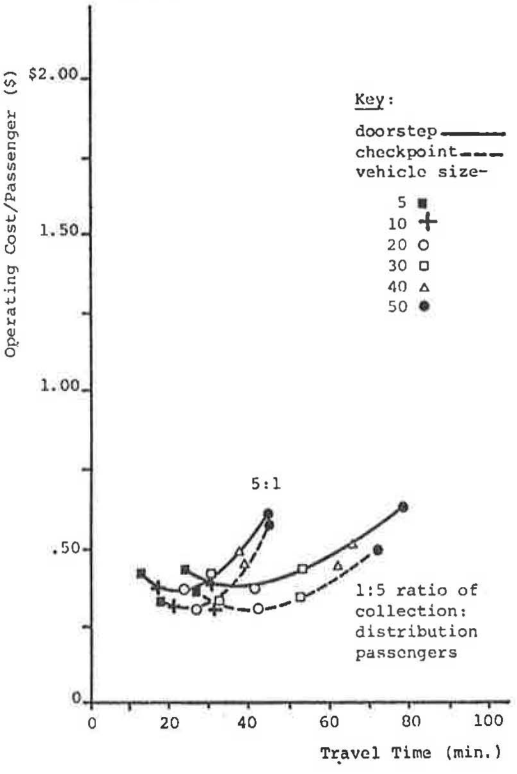


Figure 5. Cost per passenger versus travel time for volume of 240 passengers/h.



The models were applied to test and compare doorstep and checkpoint subscription services in a hypothetical area of 15.5 km^2 (6 mile^2), the closest point of which is 2.4 km (1.5 miles) from the subscription terminal. Layover time was assumed to be 5 min, and vehicle cruising speed was taken as 48.3 km/h (30 mph). Time to pick up and drop off passengers at a stop was set at 1 min, maximum walk distance was set at 0.4 km (0.25 mile), and walk speed was assumed to be 4.8 km/h (3 mph). A cost per vehicle hour of $5.50 was specified (primarily to cover labor costs); cost per unit of distance traveled ranged from $0.16/km ($0.25/mile) for a taxi-like sedan to $0.40/km ($0.64/mile) for a 50-passenger bus. Volumes of 30-300 passengers/h were tested in travel patterns representative of a morning peak period, an afternoon peak period, and a midday (balanced) period. Vehicle sizes of 5, 10, 20, 30, 40, and 50 passenger seats/vehicle were tested for each ridership level and travel-pattern run.

Results of the tests are shown in Figures 4-9. Figures 4 and 5 compare average cost per passenger versus average passenger travel time for doorstep and checkpoint subscription service for volumes of 120 and 240 passengers/h, respectively [these volumes correspond to demand densities of 7.7 and 15.5 passengers/km^2/h (20 and 40 passengers/mile^2/h)]. Results are shown for all six vehicle sizes tested. In addition, the pattern of passenger demands is varied so that the ratio of collection passengers to distribution passengers is tested at 5:1 and 1:5.

Figure 6 compares doorstep and checkpoint cost per passenger as a function of ridership for two vehicle sizes and a 5:1 ratio of collection to distribution passengers. Figure 7 plots doorstep and checkpoint vehicle kilometers of travel for two different demand levels, at a 1:1 ratio of collection to distribution passengers, versus the size of vehicle used to provide the service. Figure 8 shows doorstep and checkpoint passenger travel time versus ridership for two vehicle sizes and a 5:1 ratio of collection to distribution passengers. Finally, Figure 9 compares doorstep and checkpoint passenger travel time at one level of demand versus the size of the vehicle used for a 5:1 ratio of collection to distribution passengers.

A number of interesting results can be inferred from the graphs. For example, Figures 4 and 5 show that, when checkpoint service operates with larger vehicles, it provides not only lower-cost service, as expected (because of higher potential productivities), but also shorter travel times than doorstep subscription service. This can be seen by comparing the data points that form the doorstep and checkpoint curves: The checkpoint-service points that denote large vehicles (30, 40, and 50 passengers, for example) are not only below the corresponding doorstep data points (less expensive) but also fall to the left of the doorstep points (lower travel time). This apparently counterintuitive result is actually quite reasonable. Although passengers of checkpoint subscription bus must walk to gain access to the service, this travel-time degradation is more than compensated for by the reduction in the length of the collection-distribution tour that results from the multiple pickups at each visited checkpoint. This impact is not apparent for small vehicles because the maximum potential reduction in the number of stops on a collection-distribution tour is small (perhaps 2 or 3 stops for a five-passenger vehicle); in contrast, large vehicles that operate in the checkpoint hybrid mode might reduce the number of stops on their collection-distribution tours by as many as 20 or 30. Of course, the increase in travel time attributable to the walk requirement is the same for checkpoint subscription passengers regardless of the size of the vehicle that will carry them.

Figures 4 and 5 also show that, for any vehicle size, checkpoint subscription service will always be less expensive to operate than doorstep service as a direct result of its superior productivity (the dashed lines con-

Figure 6. Cost per passenger versus ridership.

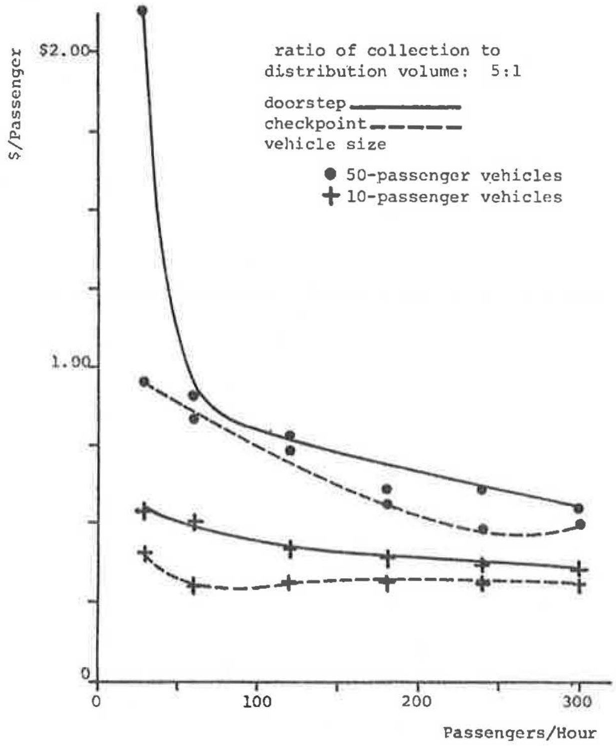


Figure 7. Vehicle kilometers of travel versus seating capacity.

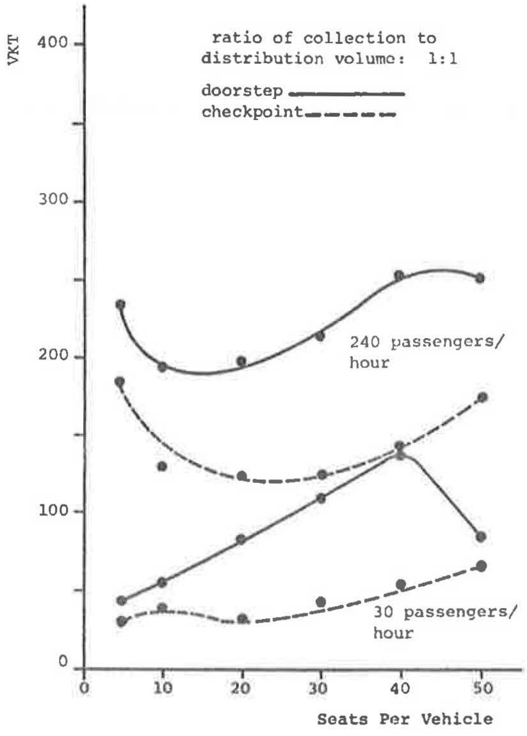


Figure 8. Travel time versus ridership.

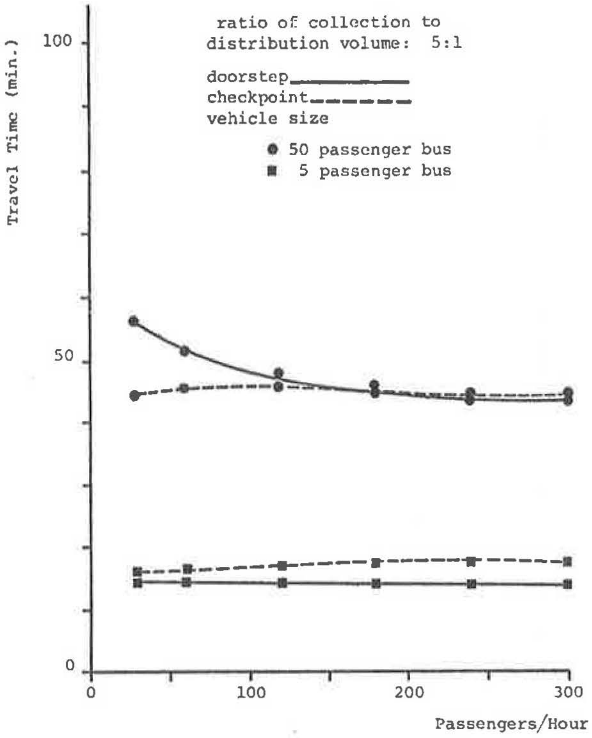
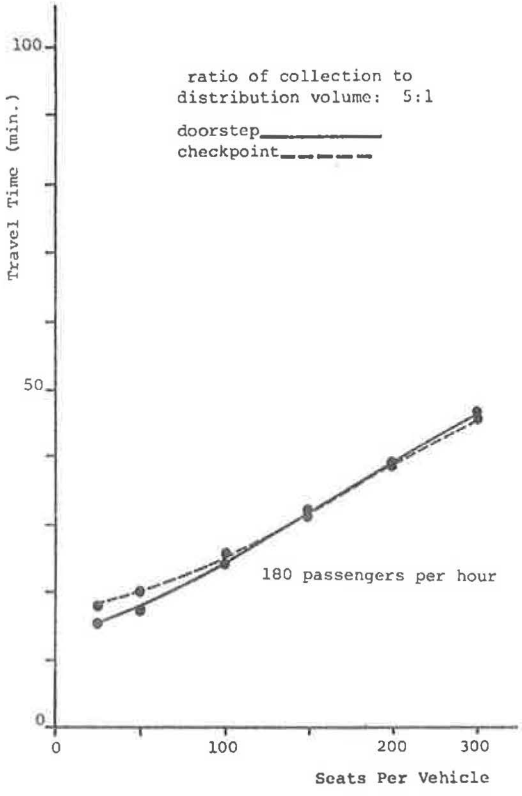


Figure 9. Travel time versus seating capacity.



sistently fall below the solid lines). In correspondence with its improved productivity, checkpoint service typically requires a smaller fleet of vehicles to carry a given passenger load and consequently also uses fewer vehicle kilometers and vehicle hours of service. These reductions translate into savings in total operating costs, which compounds the impact of improved productivity for reducing costs on a per-passenger basis.

An interesting corollary to the examination of costs is that, for each of the DRT and hybrid operations, there is a particular vehicle size (different for the two modes) that, if selected, will minimize the cost of providing service. This minimal-cost vehicle size is a function of passenger volume and its distribution and generally appears to be about 15-18 seats/vehicle (results for the "balanced" services of 1:1 ratio of collection to distribution passengers, which are not shown, are closer to 10 or 12 seats/vehicle). Of course, a more detailed cost model, including capital acquisition costs, would have to be developed and tested before confidence could be placed in the values of "design decision" results of this type. It should be noted here that the minimal-cost solution for a checkpoint operation usually results in slightly greater travel time than that for doorstep service. This indicates that the minimal-cost vehicle size for checkpoint service is below the size required to significantly reduce the collection-distribution tour and thereby compensate for the added walk time of checkpoint service versus doorstep subscription bus.

Figures 6-9 provide some different types of insights that are not directly available from the cost versus travel time format of Figures 4 and 5. For example, it is apparent in Figure 6 that, with the exception of 50-passenger vehicles operated in the doorstep mode, only very modest economies of scale are inherent in subscription service. However, although cost per passenger is not very sensitive to passenger volume, it is quite sensitive to the vehicle size used. Figure 7 shows the discontinuities in vehicle kilometers of travel as different vehicle sizes are tested in response to changing fleet requirements (a factor strongly influenced by selected vehicle size). Checkpoint service often requires fewer vehicles than doorstep subscription service, especially when large vehicles are used, because the lower travel times for checkpoint operation allow each vehicle to make additional round trips for a given period of time. Finally, Figures 8 and 9 show that, although travel time is reasonably insensitive to passenger volume, it is strongly affected by the selected vehicle size.

CONCLUSIONS

As a result of the above discussion of hybrid paratransit, two basic types of conclusions can be reached: One concerns operational lessons that can be learned from the study comparison of doorstep and checkpoint subscription bus service, and the other deals with the policy implications for the planning and provision of paratransit.

For subscription service, if vehicle sizes have not been predetermined, it appears that significant savings in operating costs can be achieved simply by making a judicious selection of vehicle size after a reasonable analysis. Even if vehicle size is a given constraint, important cost savings will accrue if the service operates in a checkpoint instead of a doorstep mode. Under some circumstances (e.g., with large vehicles), such cost savings would also be accompanied by superior levels of service offered to subscription bus users. Better service at lower cost is a possibility too attractive to ignore.

From the perspective of paratransit service policy, hybrid paratransit should clearly be given at least as much emphasis as DRT. Compromises between two extremes often combine the "worst of both worlds", but this is not the case for hybrid paratransit. This paper has shown that under some circumstances hybrid paratransit displays the best features of DRT and conventional fixed-route, fixed-schedule bus: low cost and high level of service. Hybrid paratransit options may make the most sense in areas of moderate population density, where population is too sparse to economically support conventional bus service but where requests for DRT service would overload system capacity. Of course, for a number of reasons, it may be preferable to retain in the system design the ability to "sell" DRT-like responsiveness to users for additional fare—e.g., a checkpoint subscription that will pick up riders at their homes for an extra 25 cents/trip. Such a premium service-fare combination is likely to be attractive or necessary to users such as shoppers and the elderly and the handicapped and can be equitably provided with flexible (e.g., user-side) subsidy schemes.

In summary, hybrid paratransit should be given full and serious attention as an alternative in a broad range of service options available for implementation.

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**K. L. Sobel was with Multisystems, Inc., when this research was performed.*

Integrated Paratransit: Myths and Realities

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A study that involved a systematic attempt to estimate all of the potential impacts of a range of integrated transit-paratransit options in a variety of settings is reported. The study concluded that, in some but not all instances, the benefits of integrated paratransit—in terms of improved service levels and mobility, reduced automobile expenditures, and other impacts—may justify system deficits. Necessary conditions for this include (a) high paratransit productivity, which could possibly be achieved by implementing hybrid fixed-route and demand-responsive service (such as checkpoint many-to-many), and (b) low operating costs, which might be achieved by contracting with private operators. Integrated paratransit was found to have a positive but insignificant impact on automobile use and ownership and no measurable impact on vehicle kilometers of travel, fuel consumption, or emissions. Areas that have population densities of 1160-2300 persons/km^2 (3000-6000 persons/mile^2) and limited existing transit service are promising locations for implementation of integrated paratransit service.

Paratransit, the family of transportation services that falls between exclusive-ride automobile and conventional fixed-route transit, has been the center of considerable analysis and discussion in recent years. A number of national conferences have been held on the general subject of paratransit, and other conferences have been held to discuss individual paratransit services such as vanpool, dial-a-ride, taxi, and services for the elderly and the handicapped. Many research and demonstration projects on paratransit have been initiated at the federal, state, and local levels.

Despite these analyses, or perhaps as a result of the level of analysis, there has been a fair amount of confusion and disagreement about paratransit. The ways in which it can or should be integrated with fixed-route service and the potential impacts of such "integrated paratransit" service have been the subjects of a debate in which the overall concept has gained both proponents and opponents. For example, some researchers point to integrated paratransit as the future of metropolitan area transportation (1), whereas other researchers cite the failures of paratransit or claim that such services are too costly (2-4). Some studies advocate paratransit as a means for energy conservation (5), whereas others cite paratransit as among the most energy-consuming transportation modes (6, 7).

To help settle some of these controversies and to begin to sort through and integrate the wealth of paratransit experience that already exists, the Urban Mass