by means of a specific policy is questionable.

Less Effective Policies

Toll surcharges, car-pool rebates, and programs to improve opportunities for midday transportation can all be categorized as poor performers. These policies falter because of the small group of commuters affected, their minor behavioral impact, or a combination of both factors. Such policies may still have potential in particular situations, but their effectiveness for most metropolitan areas is questionable.

Car-Pool Matching Programs

The study results with respect to policies to improve car-pool matching opportunities were not conclusive. The results of the trade-off model suggested very modest impacts on vehicle kilometers of travel for the two car-pool matching programs tested. However, for reasons that were previously cited, these results were not treated as completely reliable. Tabulation of attitude and perception responses suggested that the ease of finding someone with whom to share a ride to work was a moderately important factor in the decision on whether to car pool. Although car-pool matching programs are designed to address this problem, it is not clear that a conventional matching program can substantially improve the ease of finding an acceptable match. However, matching programs are incentive rather than disincentive in nature and do not generate much opposition.

General Market Considerations

The potential of any car-pooling policy is limited by the following general considerations:

1. Any policy based on surcharges or adjustments to existing parking rates will affect only about 10 percent of all commuters.
2. Nearly 75 percent of commuter parking is in employer-operated facilities. Only 9 to 17 percent of employees indicated that such parking, if supplied, was deficient. Thus, most employers lack a direct incentive to create some type of preferential parking policy.
3. In most cities, the percentage of commuters who pay tolls is very small. Toll surcharges will be ineffective except perhaps in cases where no alternative routes exist.
4. The perception of more than a third of commuters is that finding someone with whom to share a ride is impossible. This significantly limits the effectiveness of car-pool matching programs.
5. Commuters considered car pooling to be deficient for several reasons, including travel dependence, having to find a ride sharer, and the inability to make side trips on the way to and from work. Only the second deficiency can be significantly affected by public policy.

ACKNOWLEDGMENTS

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Transportation Efficiency and the Feasibility of Dynamic Ride Sharing

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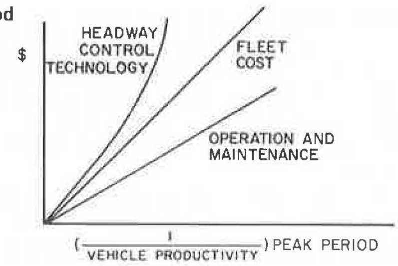
This paper defines the theoretical limits imposed on ride sharing by the spatial and temporal structure of urban travel demand. Differences in market potential between prearranged ride sharing as it is used in car pooling and dynamic ride sharing as it is used in, for example, shared taxi are given. The paper presents the results of the simulation of a hypothetical shared-ride transit system that used various operational policies of dynamic ride sharing and identifies the improvements in transportation efficiency and the economic and technological savings that result from ride sharing. Data on the dynamic ride-sharing taxi system operating at Union Station in Washington, D.C., establish the feasibility of implementing dynamic ride sharing.

As a result of the gasoline crisis of 1973 and the scarcity of federal funds for the construction of new urban transportation facilities, improved efficiency has become a primary focus of urban transportation policy. A recent transportation systems management directive issued jointly by the Urban Mass Transportation Administration and the Federal Highway Administration is aimed toward the efficient use of existing transportation facilities. The most obvious target for efficiency improvement is private transportation—the automobile and the taxi. Vanpooling and car-pooling programs are aimed at trying to increase the people-carrying capacity of street systems during peak demand hours without construction of additional physical facilities. Shared-taxi and jitney enabling legislation is also aimed at the people-carrying productivity and the economic efficiency of the taxicab and its driver.

Even analysts of futuristic automated transit systems

Figure 1. Peak-period vehicle productivity versus cost.



such as personal rapid transit (PRT) have begun to investigate the ramifications of measures that increase vehicle productivity and transportation efficiency. Fleet size, technological requirements of headway control systems, and per-passenger operating and maintenance costs are each inversely proportional to peak-period vehicle occupancy, as shown in Figure 1. Vast economic benefits could be gained by these new systems if they could effect higher peak-period vehicle productivity. The simplest and most effective way of increasing vehicle productivity is ride sharing.

What evidence is there that vehicle productivity can be improved through ride sharing? Some ride sharing does exist in urban areas; it occurs almost exclusively on conventional fixed-route transit systems during peak hours, in automobiles for trips involving families, and among car and van poolers. On a metropolitanwide basis, relatively little ride sharing occurs except for trips involving families. Average automobile occupancy during peak hours is less than 1.5 persons. In most urban areas, the transit share of the peak-hour mode split is less than 25 percent. Even if these transit riders were accommodated by existing automobile trips, automobile occupancy would increase by less than 0.5 persons/automobile. [Several vehicle-productivity measures can be used; each is important for different reasons. For alleviating congestion at a bottleneck (e.g., a freeway or a parking lot), only vehicle occupancy at the bottleneck is important. For energy and pollution, the measures that should be used are (a) the ratio of hypothetical energy consumption (for a vehicle occupancy of 1.0) to actual energy consumption, which penalizes long-distance, single-occupancy trips; (b) the circuity of ride sharing; and (c) the tendency toward larger automobiles for car poolers.]

Although car-pool and van-pool incentive programs have been successful in isolated applications, the impact of these programs on urban-area peak-hour vehicle occupancy has been negligible. Dial-a-ride experiments have experienced a peak-hour vehicle productivity of less than 20 trips/h. Jitneys operate legally only in Atlantic City, New Jersey. Washington, D.C., is the only major urban area in the United States in which shared-ride taxi regulations have been enacted.

To what extent does the fundamental structure of urban travel demand in terms of origin, destination, and time of travel allow for ride sharing? What sacrifices in travel time or changes in operational structure are required to increase the potential for ride sharing? How well do automobile-size vehicles serve extremely high surges in demand?

The simulation results presented in this paper define the ride-sharing potential for one urban area but may be representative of many other urban areas. The study differentiates between the operational aspects of prearranged ride sharing, such as car pooling, and dynamic ride sharing where the matching of demand and supply is accomplished on a demand-responsive, dynamic basis. A discussion of the benefits of dynamic ride sharing is presented here for a simulated automated guideway transit (AGT) system. The feasibility of its implementation from the point of view of passenger acceptance under peak and off-peak demand conditions was investigated by studying the dynamic shared-ride taxi operation at Union Station in Washington, D.C.

POTENTIAL OF RIDE SHARING

Urban travel is many individual trip makers wishing to travel from specific origins to specific destinations at precise times. The degree of specificity of the geographic location of origin and destination and the departure time are very sensitive to an analysis that attempts to find the degree of commonality in trip making. Insisting on too much specificity can lead to zero commonality, and too little can lead to a condition that is unacceptable to trip makers. In this study, the smallest element of geographic specificity is defined by the 0.4-km (0.25-mile) walking radius or approximately 0.5 km^2 (0.2 $mile^2$), and the departure-time indifference is taken to be on the order of 10 min.

Ride-sharing potential can then be defined as the degree to which there is commonality in trip making. In addition to geographic and time-related commonality, the operational characteristics of the transportation system can either expand or limit the degree of trip commonality. These operational characteristics, which are defined by the number of specific origins and destinations that can be served by a vehicle at any one time, are as follows:

1. One-to-one (O-O)—single origin to single destination (SO-SD), e.g., car pooling, personal rapid transit (PRT), and shared taxi;
2. One-to-many (O-M) or many-to-one (M-O)—single origin to multiple destination (SO-MS or MO-SD), e.g., car pooling, van pooling, PRT, shared taxi, subscription bus, and dial-a-ride; and
3. Many-to-many (M-M)—e.g., jitney, fixed-route transit, PRT, shared taxi, subscription bus, route-deviation bus, and dial-a-ride.

The commonality of trips for the SO-SD mode is constrained by the size of the walking neighborhood and by time. Commonality for the O-M and M-M forms of ride sharing should be further constrained by a circuity measure of order of tens (rather than one or hundreds) of percents for the longest trip being served. Therefore, the potential for ride sharing on an SO-SD system, for example, is simply

$$AVO_{ijk} = \sum_{n=1}^{\infty} n \cdot P_{n_{ijk}} \qquad (1)$$

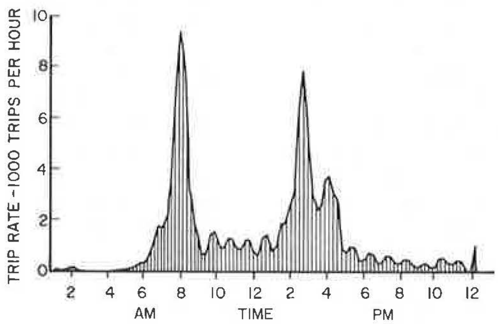
where

AVO = average vehicle occupancy,
i = origin neighborhood,
j = destination neighborhood,
k = time interval, and
P_n = probability that exactly n people request service from i to j within a specified k.

Implicit to the equation is that $\sum_{n=1}^{\infty} P_{n_{ijk}} = 1$.

Relations similar to Equation 1 are appropriate for the other operational conditions of O-M and M-M but include the additional constraints that the feasible sequence of multiple pickup or discharge points lies along a fixed route or results in a travel circuity that does not violate

Figure 2. Total travel-demand rate for Trenton (automobile plus transit) as function of time of day.



some upper bound. From Equation 1 it is obvious that AVO may be increased independently by increasing the specified time interval, the neighborhood area at trip ends, the number of access points, or the circuity limit.

One difficulty with the equation is that its full potential is constrained by the operational limitations of prearranged car pooling and van pooling because (a) prearrangement requires that there be little or no variance in origin, destination, or time of travel from day to day and (b) riders usually share the same vehicle for a round trip rather than a one-way trip. The match of departure times at both ends of the trip effectively restricts car pooling to persons who have proximate destination points. The problem of day-to-day variance in O-D location and departure time has been expressed qualitatively for car pooling. Further study is required to determine the extent to which the round-trip matching requirement restricts the potential for prearranged car pooling.

A much greater ride-sharing potential exists for one-way trips. Dynamic ride sharing removes constraints such as passengers having to share the same vehicle every day; it is simply a grouping of persons with common travel-demand characteristics in terms of origin, destination, and time of travel on a trip-by-trip basis.

Quantitative estimates of the probabilities (P_n) for dynamic ride sharing are difficult to make because the demand data on which to base the estimates must be precise as to O-D locations and times of travel. Moreover, the surveys that would be most useful for this purpose are those that capture all trips at least for some origin. Only then can P_n be estimated for the sampled origin areas and expanded to the entire urban area. No such survey seems to have been made. At some cost in accuracy, spatially and temporally precise total urban travel-demand data can be reconstructed from random samples that contain a large percentage of total trips. This was done in the case of the data base constructed for Trenton, New Jersey, by Princeton University (1). The reconstruction was accomplished by developing temporal and spatial distribution models to expand the survey data (2). The operation of a hypothetical AGT network in Trenton was simulated. The resulting estimates of the potential for dynamic ride sharing are presented below.

QUANTITATIVE ESTIMATES OF DYNAMIC RIDE-SHARING POTENTIAL

In an attempt to estimate the productivity potential of alternative dynamic ride-sharing strategies, a simulation model and a demand data base were developed. The simulation model has the potential of modeling SO-SO, SO-MD, and MD-SO routing strategies (3). The simulation was implemented on a hypothetical automated guideway transit network designed for Trenton, New Jersey. Although the motivation of this simulation was to assess the productivity potential of such systems, its results are transferable to any system that could operate in a dynamic ride-sharing manner in either an SO-SD, SO-MD, or MO-SD operational mode, e.g., a system of taxicabs running between taxicab stands over the routes established for the AGT system.

The travel-demand data that are the "forcing function" to the simulation were developed from a home interview travel-demand survey of 14.7 percent of the residents of Trenton, New Jersey (4). The origins in this data base were coded to specific census blocks and then aggregated to traffic-assignment zones ~0.25 km^2 (~0.1 mile^2) in area. Recorded departure times were coded to the minute but aggregated to 15-min time increments centered about the quarter hour. Survey data were available for a complete 24-h day with an aggregate trip rate per 15-min interval, as shown in Figure 2.

The travel data were expanded to represent a record of every trip made during a 24-h period by assuming that

1. For each origin the attractiveness of destinations was constant over each of four time blocks—a.m. peak, midday, p.m. peak, and night (sufficient statistics were thus available from the survey data to establish the relative attractiveness of each destination zone for each origin zone); and
2. Continuity in the trip rate existed between 15-min time blocks.

Each trip was reconstructed by using a random selection process from cumulative density functions. Destination was selected from the relative attractiveness functions and departure time from the trip-rate density function; totals were controlled for each origin over each of the four daily time intervals.

In the actual simulation assigning demand to vehicles to determine ride-sharing potential, the demand records were ordered in ascending order of time of departure and a mode-split analysis that eliminated all nontransit trips and assigned transit trips to origin station and destination station on the transit system was performed on the data. Some liberty was exercised in assigning times of travel to the origin data; these times were therefore assumed to be desired departure times at the departure transit station. The simulation dealt with the demand records in sequence. The following procedures were applied for each trip demand:

1. All departure demands were dispatched as soon as the maximum wait time for departure had been exceeded. The occupancy of each dispatched vehicle was recorded.
2. A search for a commonality of demand was made for each vehicle awaiting departure. If commonality was found, the demand was added to the common vehicle. If not, the demand was assigned to an empty vehicle and dispatch was programmed for maximum wait time in the future.

The process was continued for each demand record. For multiple origin or destination service, commonality was defined as applying to stations along the minimum path between assigned vehicles, and a search was made of the minimum-path tree beyond the most distant destination (in the case of multiple destinations) or before the origin (in the case of multiple origins).

Quantitative estimates of ride-sharing potential depend on the topology of the network and the nature of the demand input. Precise details of the spatial and temporal distribution of transit demand as well as the network configuration (station and guideway locations) affect the estimates. The numerical results reported here are for an areawide network serving the 20-km^2 (7.8-mile^2) area of Trenton, New Jersey. The city has a population of 100 000 and is considered to be typical of a large number of older, medium-size industrial cities in the Northeast and the Midwest. The simulated transit network (Figure 3) consisted of 46 stations interconnected by 34 km (21 miles) of one-way guideway. The results of the simulation of dynamic ride-sharing potential are shown in Figures 4 through 10.

Figure 4 shows vehicle productivity in terms of daily average vehicle occupancy over a 14-h operating period (from 6:00 a.m. to 8:00 p.m.) as a function of level of service in terms of maximum wait time for the first occupant. Curves are presented for each of three shared-ride service policies: single origin to single destination (SO-SD), single origin to multiple destination (SO-MD), and multiple origin to single destination (MO-SD). Note that, for the multiple origin or destination service policies, average vehicle occupancy is actually the ratio of passenger kilometers to vehicle kilometers for each trip. The figure shows that, for a maximum wait of 2 min, a 60 percent improvement in daily AVO is possible for SO-SD service and a wait of 5 min improved daily AVO by 120 percent over purely non-shared-ride operation. The addition of more elaborate multiple-stop policies can improve vehicle productivity by 85 to 190 percent depending on the acceptable level of service. These results indicate that significant economies in variable expenses (accompanied by small reductions in level of ser-

Figure 3. Simulated automated guideway transit network.

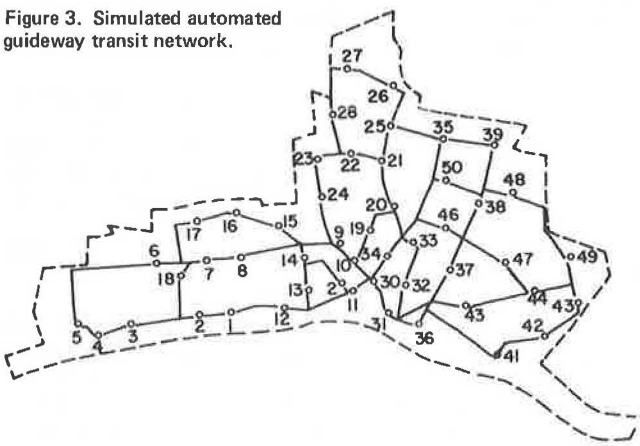


Figure 4. Vehicle occupancy versus wait time.

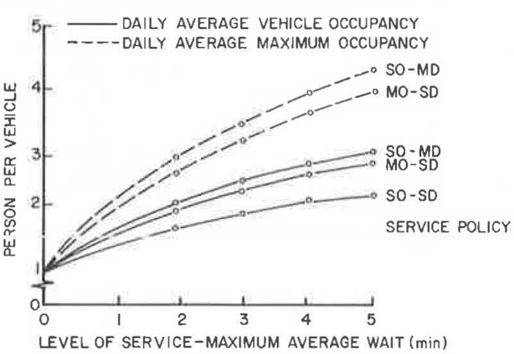


Figure 5. Cumulative distribution of maximum occupancy per vehicle.

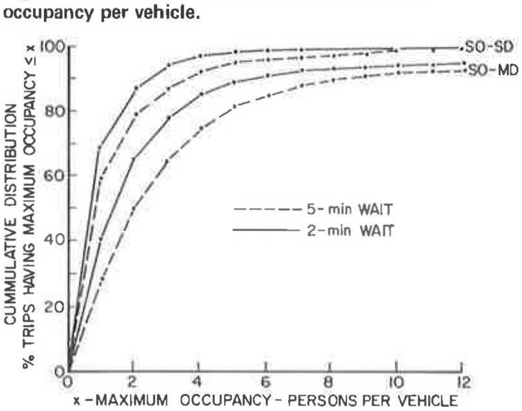


Figure 6. Peak-period vehicle productivity.

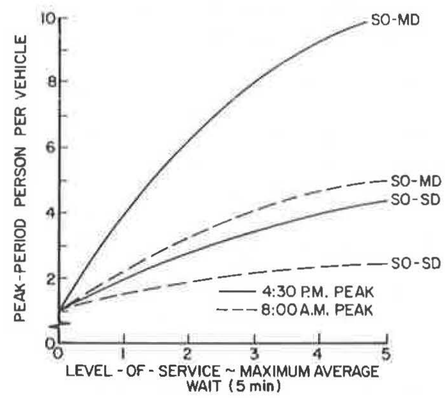


Figure 7. Taxi demand rate at Union Station.

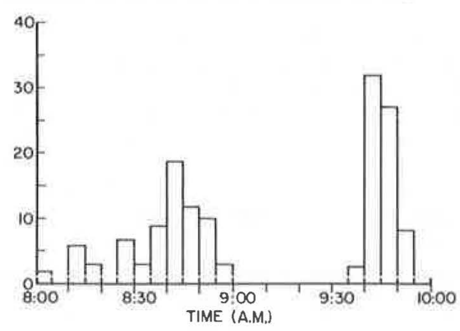


Figure 8. Computer display of passenger destinations for three Union Station taxis.

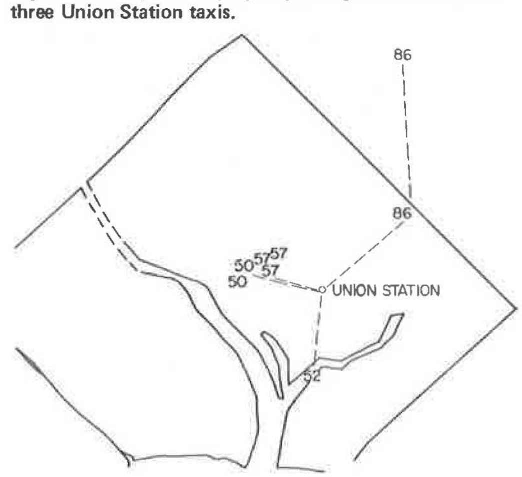


Figure 9. Cumulative distribution of shared-ride taxi passengers served.

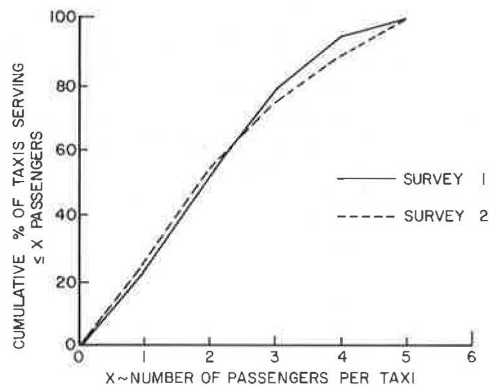
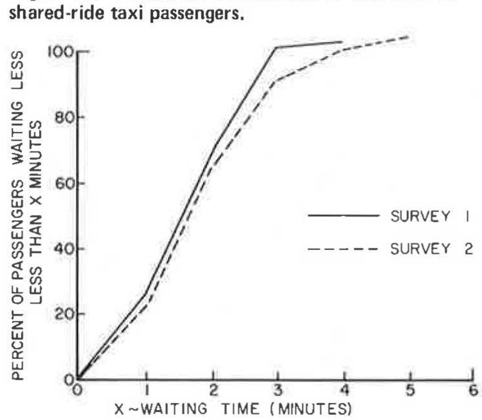


Figure 10. Cumulative distribution of wait time for shared-ride taxi passengers.



vice) are attained if shared ridership is encouraged.

Figure 5 shows the cumulative distribution of vehicle occupancy over the daily period for the two service policies and maximum waits of 2 and 5 min. Note that more than 50 percent of the trips for the SO-SD service policy were private trips and that only for the SO-MD service policy was there a significant need for vehicles of more than 12-passenger capacity. If only 6-passenger vehicles were provided, additional capacity could have been used in only 49 percent of the vehicle departures in the case of the SO-SD mode with a 5-min wait. The appropriate vehicle capacity can be determined from the results shown in Figure 5 once the service policy is established.

The results presented so far have focused on daily vehicle productivity. Peak-hour productivity is probably as important if not more so. Peak-period vehicle occupancy defines the fleet size and the guideway and station vehicle-capacity requirements. Not only is the level of demand higher; it is also more spatially directed so that both the potential and the benefits of dynamic ride sharing are highest. Peak 15-min demand on the Trenton network occurred at 8:00 a.m. and 4:30 p.m. where 2300 and 3500 passengers respectively were served every 15 min. It is interesting that, whereas 4:30 p.m. represented the peak passenger demand period, 8:00 a.m. was the peak vehicle demand period for each of the shared-ride policies. Data for peak-period AVO are shown in Figure 6 for each shared-ride service policy. The figure shows peak-period vehicle dispatches as a function of maximum wait time. The assumption that each vehicle can serve only one dispatch every 15 min during peak periods implies that the fleet size is defined by the maximum of the 8:00 a.m. and 4:30 p.m. curves for each shared-ride policy in Figure 6. Therefore, the SO-DS policy with a 2-min wait results in a 63 percent reduction in the size of the vehicle fleet normally required under a non-shared-ride policy. For the SO-MD policy with a 5-min wait, the reduction in fleet size is 88 percent. These results indicate that dynamic ride sharing does produce significant benefits.

Benefits of equal magnitude, though more difficult to quantify, would accrue from the increase in minimum headway requirements if ride sharing were encouraged in an AGT application. The reduced fleet size implies an inversely proportional reduction in minimum headway; therefore, the 63 percent reduction in fleet size for the SO-SD policy with a 2-min wait implies an increase in minimum headway by a factor of 2.7 (3.1 for a 3-min wait). Therefore, if nonshared vehicles require a 1-s minimum headway, a comparable, nonstop, single-origin to single-destination service could be offered that uses 3-s minimum headway technology (if the maximum wait time in stations is 3 min). This saving goes beyond economic benefits to technological feasibility.

DYNAMIC RIDE-SHARING TAXI SYSTEM

The computer simulations described in the previous section considered a wait-time penalty in the mode-split analysis, which meant that only those persons who would tolerate the maximum wait were considered in the analysis. Questions remain as to whether people would indeed share rides. To answer this, one could propose a demonstration project to determine the feasibility of dynamic ride sharing and examine trade-offs among various ride-sharing policies. Another way is to see if such a demonstration already exists. For most practical purposes, the shared-ride taxi operation at Union Station in Washington, D.C., can serve as an analogous demonstration of a shared-ride transportation system that employs either SO-SD or SO-MD dynamic shared-ride policies.

At Union Station, taxis diverge from Massachusetts Avenue into a passenger boarding area. Passengers approach and are marshalled into waiting taxis. The first passenger establishes the destination of the taxi, and subsequent taxi sharers either have common destinations or destinations en route. After a period of waiting, or as the taxis are filled, the vehicle is dispatched from the boarding area. When demand is low, the taxis provide private service. However, when the demand is high (for example, shortly after the arrival of the 9:34 a.m. Metroliner from New York), rides are shared to increase the productivity of the system.

In an attempt to quantify the productivity gains attributable to dynamic ride sharing, Princeton University's transportation program observed the Union Station shared-ride taxi operation. Surveys were conducted on two mornings during a 2-h period that included the arrival of some local commuter trains and the surge in demand caused by the arrival of a Metroliner. Goals of the survey included (a) recording the magnitude and variation in ride sharing over the 2-h period, (b) obtaining estimates of the distribution of time spent by taxis waiting for additional riders, and (c) obtaining measures of the degree of commonality of destinations among the passengers in each taxi. Data collected for each taxi dispatched during the survey period were (a) time and destination (street corner) of each rider and (b) the time the taxi left the boarding area.

Demand for service was recorded as a function of the time service was requested (Figure 7). Note the extremely sharp peaks in demand over very short periods

Table 1. Results of two surveys of shared-ride taxi operations at Union Station.

Time	AVO Effective	AVO Maximum	Average Passenger-Trip Distance (straight-line km)	Average Wait Time per Passenger (min)
2-h average	2.19	2.53	2.24	1.9
	2.17	2.47	2.15	2.1
Metroliner peak	2.26	2.74	2.17	2.2
	2.31	2.77	2.15	2.4

Note: 1 km = 0.62 mile.

of time. The Metroliner peak represents an hourly demand rate of 800.

Air-line travel distance for each passenger was computed from digitized geographic locations of destinations, and computer graphic maps of trip destinations were produced for each taxi and various groups of taxis. An example is shown in Figure 8. These maps reveal that the apportioning among taxis of patrons with compatible destinations was efficient. Most taxis used an SO-MD type of ride-sharing policy.

Effective average vehicle occupancy for each taxi was computed from the ratio of passenger straight-line distance to maximum straight-line distance (circuity was neglected). Table 1 gives a summary of the performance measures that were assessed in the two surveys at Union Station. Note that the large difference between effective AVO and maximum AVO implies that the ride-sharing policy is serving multiple destinations to a significant extent. Figure 9 shows the distribution of the number of taxis as a function of the maximum number of passengers. Figure 10 shows the cumulative distribution of passenger waiting time. Note that 22 percent of the users received immediate service and 98 percent were served within 5 min.

CONCLUSIONS

The Union Station dynamic ride-sharing taxi operation results in substantial improvements in vehicle productivity. The a.m. peak-period ride sharing results in services being provided by 60 percent fewer taxis that consume 55 percent less energy than if the service were offered by non-ride-sharing taxis. In addition, the cost of the taxi is distributed among the ride sharers, which results in reduced fares per passenger. The reduction in level of service was found to be minimal when it was compared to the additional benefits derived from ride sharing.

The implications of the Union Station demonstration for the operating feasibility of a dynamic shared-ride AGT system are substantial. They may be the determining factor in the economic feasibility of AGT systems. What is certain is that the implications were obtained from a cost-effective demonstration; it cost less than $500 to conduct the study and analyze the results.

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Car-Pooling Programs: Solution to a Problem?

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Information from 26 car-pool programs is reported that suggests that appeals to self-interest made through work organizations are more effective than other means of encouraging car pooling because employees of work organizations form a known population with a common destination and, typically, a similar work schedule. It is proposed that such appeals should focus on the benefits of car pooling for the individual rather than on general values such as patriotism. Interviews of selected long-term car-pool participants (2 or more years) indicated that work organizations provide a setting in which personal information about potential participants can be obtained and that this information facilitates the formation of car pools. These interviews further suggested that the intimacy of the private automobile may limit the size of car pools as well as the willingness of some individuals to participate in them. Ride-sharing programs that present alternative transportation modes may be more effective than car-pool matching programs in changing current patterns of work travel.

In the 1970s, with the advent of the energy crisis, transportation patterns became a national issue. Rising U.S. consumption of petroleum involved increasing energy-related dependence on foreign countries. In late 1973, attention focused on changes in the policies of major oil-producing nations. Automobile gasoline consumption was recognized as inefficient. The U.S. Department of Transportation proposed saving gasoline by increasing the number of car pools. In December 1973, federal legislation was enacted that provided funds for car-pooling programs. Programs were instituted in many places in January 1974, e.g., Austin, Texas; Charlotte, North Carolina; Norfolk, Virginia; and Phoenix. Mass-media campaigns tried to mobilize voluntary energy-conservation behavior, i.e., car pooling to work.

The success of specific programs and general media promotions is difficult to measure because of the lack of local baseline data, unspecified definitions of car pools, and inconsistent measures of car-pooling levels. In this