the signal-controlled intersections have inadequate capacity to pass the traffic.

Speed and flow relationships for bus and nonbus traffic under priority and nonpriority conditions obtained by the use of the simulation model are shown in Figure 3. Figure 3 shows that (a) for a wide range of bus flows the travel time on the simulated section of highway may be regarded as constant with no interaction between vehicles and (b) for nonbus vehicles interaction occurs as the traffic volume increases because there is a marked increase in travel time as the traffic flow increases beyond 1000 vehicles/lane/h.

CONCLUSIONS

Use of these two speed and flow relationships allows overall passenger travel time savings to be calculated for various proportions of buses in the traffic flow as illustrated in Figure 4, in which we assumed a bus occupancy of 50 persons and a nonbus vehicle occupancy of 1.5 persons. When only 5 percent of the traffic is buses, the installation of a bus-priority scheme results in increases in passenger journey time at the traffic volumes studied. When the proportion of buses in the traffic flow is 10 percent, then the saving in passenger delay reaches a maximum at a total traffic flow of approximately 1050 vehicles/h. As would be expected when there is a high proportion of buses in the flow, then substantial reductions in passenger journey time can be expected; at a 20 percent proportion, a maximum saving of 43 passenger·h/h is reached when 1300 vehicles/h enter the section.

Since the introduction of the bus-priority scheme, field observations have verified, as far as possible, the validity of the model. The highway under consideration has, however, pronounced peaking characteristics, and the recent establishment of signal-controlled, pedestrian-crossing facilities has prevented the determination of comprehensive speed-flow relationships. Observations have shown, however, that the travel times of buses in the priority lane are in the region of 120 to 130 s when the flow is 50 to 60 buses/h. Travel times of nonbus vehicles are very variable, as would be expected, at flows producing such low levels of service.

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Abridgment

Evaluation of Bus-Priority Strategies on Northwest Seventh Avenue in Miami

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A 3½-year demonstration project was established in Miami in 1973 to develop more efficient people-moving capabilities in the I-95 and Northwest Seventh Avenue corridor that extends 16 km (10 miles) from the Golden Glades Interchange in north Dade County to Miami to the south. The basic transit concept was to provide fast, directional, line-haul, peak-period service by express buses that operated between a major residential area and four specific areas of major employment along Northwest Seventh Avenue (US-441), a major arterial street.

A park-and-ride facility located in the Golden Glades Interchange contained a bus terminal and a 967-space parking lot to accommodate the park-and-ride patrons. Some of the express buses were used to provide feeder route service in the residential market area. Provisions were made for kiss-and-ride and local bus interchanges. In addition, some car pools were formed and used the facility.

Various combinations of the following three bus-priority treatments were evaluated:

1. A reversible, exclusive bus lane;
2. A traffic signal preemption system that allowed express-bus drivers to preempt traffic signals to give themselves the green signal; and
3. A coordinated signal system designed to favor the movement of express buses in the peak-period direction.

Combinations of the three priority treatments were examined in the following five evaluation stages:

1. Stage 0—before condition, no priority treatment;
2. Stage 1—bus preemption of traffic signals, buses in mixed mode;
3. Stage 2—bus preemption of traffic signals, buses in reserved bus lane;
4. Stage 3—signal progression, buses in reserved bus lane; and
5. Stage 4—signal progression with bus preemption of traffic signals, buses in reserved lane.

The express-bus service was named the Orange Streaker and was operated by the Metropolitan Dade County Transit Agency (MTA). The bus-priority treatments were evaluated by considering their effects on bus operations, traffic signal performance, traffic stream,

and transit operations (1).

EFFECT OF BUS-PRIORITY TREATMENTS ON BUS OPERATIONS

All priority treatments were successful in reducing bus travel times and delay on the 16-km (10-mile) line-haul route equipped with the systems. The provision of a preemption capability (in mixed-mode operation) reduced the average travel time (during both morning and evening peak periods) by 22.5 percent from a before condition of 28.0 min. Adding the reserved lane resulted in the best overall travel times experienced in the project. The average travel time was 19.5 min, a 30.4 percent reduction. When signal progression was substituted for preemption, the travel time increased slightly to 20.9 min or 25.4 percent less than during stage 0. The combination of all priority treatments (stage 4) was only slightly better than treatments in stage 3 because average travel time was 20.6 min, only 26.4 percent lower than that in stage 0. These improvements were reflected proportionately in vehicle delay and other travel-related measures.

The improved bus travel was more pronounced in the evening peak period. For example, the improvement of stage 2 over stage 0 was 20.4 min versus 29.7 min, but all travel times were somewhat higher in the evening peak period. The greater the traffic congestion was, the greater were the improvements.

There were three distinct geometric sections on Northwest Seventh Avenue. In a five-lane section the bus travel times increased between stage 1 and stage 2 (i.e., when the exclusive bus lane was added) in the evening peak period. In this five-lane section the bus lane was converted from the center left-turn lane and all left turns were prohibited, but the turning restrictions were widely violated. These violations point out a strong need for adequate enforcement of traffic regulations when bus-priority treatments are used and suggest that, unless a high degree of motorist cooperation can be anticipated, the benefits of bus-priority measures may not fully materialize.

In addition, two of the three bus-priority treatments produced an improvement in schedule adherence (i.e., arrival time of buses at the terminal compared to scheduled time); the combination of all three treatments produced the same improvement. The one treatment that demonstrated a lower degree of schedule adherence was the signal-preemption treatment. Drawing strong conclusions based on this observation is difficult; however, we may hypothesize that, because the preemption equipment allows the driver to proceed through the signal system at any desired speed, a greater variation in arrival times may be anticipated. Additional research would be required to support this theory.

EFFECT OF BUS-PRIORITY TREATMENTS ON TRAFFIC SIGNAL PERFORMANCE

Several observations were made from field studies of the traffic signal operations. Buses were able to clear the preempted intersection in nearly all cases within the maximum allowable preemption time of 120 s, and the bus-preemption signal produced a stable contact with the detection equipment at the intersection. No false preemption was evident during the off-peak period when buses were not operating, nor was there any indication of erratic preemption signals transmitted from the buses.

Slightly longer phase lengths were observed during cycles in which buses arrived. No differences from the normal timing were apparent on cycles immediately following bus departures. This lack of differences suggests that the disruption due to bus preemption is a short-lived phenomenon. More significant, the system control parameters (isolated versus interconnected, pretimed versus semiactuated, and so forth) exerted a more pronounced effect on the measures of effectiveness than did the bus-priority functions. Coordinated operation resulted in a vastly superior quality of progressive movement for through traffic, and semiactuated operation tended to favor the arterial route slightly, relative to pretimed operation.

The combination of coordination and signal preemption produced no evidence of incompatibility between these two functions. This conclusion applies only to the type of control system that was studied, i.e., central coordination of a system of traffic-actuated controllers. Other control equipment such as electromechanical, pretimed controllers may have led to different conclusions because of hardware constraints that create a greater potential for disruption of progression.

Bus-priority treatment required approximately twice the normal number of repair and maintenance calls to the 37 intersections; however, the result of 36.5 percent of these calls was that no problem was found and of the problems found only 10.5 percent related to the systems. This low percentage of problems suggests that such systems can be expected to increase the maintenance workload slightly, but public misunderstanding of the proper operation (particularly preemption) will result in a high incidence of nuisance calls.

EFFECT OF BUS-PRIORITY TREATMENTS ON TRAFFIC STREAM

Automobile travel time studies conducted along the bus route indicated that the average travel time decreased between successive stages until stage 3 (exclusive bus lane plus signal progression). During this stage automobile travel times were minimized; automobile travel times were increased when the bus-preemption feature was reactivated. The initiation of the bus-priority features actually reduced automobile travel time by almost 7 min (22.4 percent between stage 0 and stage 3).

Aerial photographic studies were conducted to determine the effect of the priority treatments on intersection delay at the signalized intersections on Northwest Seventh Avenue and on the cross streets (morning peak-period only). These data supported the results of the automobile travel time studies. Stage 3 was the best operational stage with relation to the Northwest Seventh Avenue traffic stream. In general, initiation of bus-priority treatments had little, if any, adverse effect on the traffic stream; considerable evidence showed that bus-priority treatments actually improved automobile movement in the traffic stream.

Perhaps the most significant measure of the effectiveness of bus-priority treatment on the traffic stream is the relative importance of the bus and automobile in moving people in the arterial. Generally, the Orange Streaker dramatically improved the people-moving capacity of the artery. Some variations between priority-treatment stages were apparent, but we felt that external factors such as construction on I-95 and changing demand had more influence on traffic stream than the priority treatment did. The Orange Streaker increased the total number of people moved by about 26.8 percent in the morning peak period even though the buses were only 2 percent of the traffic stream. This movement translated to an increase in equivalent automobiles of about 460 vehicles (28.3 percent).

One adverse outcome of the priority strategies concerned bus accidents. The bus accident rate was sub-

stantially higher on Northwest Seventh Avenue during the stages that included a reserved lane. Most of the bus accidents involved automobiles making illegal left turns; e.g., 72 percent of the bus accidents happened because buses were cut off by automobiles, and 22 percent of the bus accidents were caused when buses were sideswiped by automobiles—all illegal maneuvers by automobiles. Thus, illegal use of the exclusive lane by automobiles was the major source of bus accidents.

EVALUATION OF THE TRANSIT SERVICE

One of the most important measures of the effectiveness of the transit service is patronage. Total ridership increased from approximately 1050 passengers/d at the beginning of the project to approximately 1450. The net ridership increase during the project was 37.3 percent, which represents an annual increase of 20.3 percent. In the same time period, MTA total ridership increased by 14.6 percent; therefore growth of Orange Streaker ridership was greater than overall growth of transit ridership in the Miami area. Except for a few months at the beginning of the Orange Streaker service, the average load factor was slightly over 60 percent.

Another indicator is the percentage of tripmakers using the transit service. In this analysis only persons making project trips (i.e., from the Orange Streaker market area to its service areas) were considered. Trips on the Orange Streaker averaged 17 percent of the trips during the demonstration project (with a high of 19.4 percent) compared to 5.1 percent for comparable routes that existed prior to the Orange Streaker service.

To assess public reaction three surveys were conducted.

1. An on-board survey was conducted of all bus riders.
2. A handout, mail-back survey was conducted of car poolers forming at the park-and-ride facility.
3. A telephone home-interview survey was conducted of the general public in the market area.

One of the most interesting findings of the bus survey was that most of the Orange Streaker passengers were choice riders. Almost three-fourths of the passengers had an automobile available to them but chose to ride the bus. Of the passengers who made the same trip before the Orange Streaker service, 55.6 percent made the trip in a single-occupant vehicle. Another 18 percent had previously made the trip in multiple-occupant vehicles, and 25.4 percent had ridden another bus. Thus, the Orange Streaker service did replace a large number of automobiles in the traffic stream. The passengers were generally favorable toward the service (93.8 percent gave it a positive rating and only 2.6 percent gave it a negative rating).

Most of the nonusers of the service cited bus-service-related reasons for not using the service: 32 percent cited inconvenience of bus routes, 25 percent cited schedule difficulties, 8 percent cited preference for automobile, and 5 percent cited bus travel time. The attitude toward transit service, therefore, appeared to be positive among the nonusers, and apparently a high percentage of the nonusers would use a transit system if it serviced them more directly.

The Golden Glades park-and-ride facility provided the opportunity for intermodal transfers. Parking lot use was approximately 440 vehicles near the end of stage 1, and car-pool formation was estimated to be between 30 and 40/d. The relatively low car-pool formation was not too surprising since car pooling was not stressed in this stage and other locations were more accessible.

Approximately two-thirds of the vehicles that entered the lot parked there (i.e., park-and-ride vehicles). About 26 percent of the entering vehicles were kiss-and-ride vehicles and 7 percent were car-pool vehicles. A study of the access modes used by express-bus passengers indicated that approximately 25 percent of the bus passengers used the feeder-bus service to reach the bus terminal, approximately 55 percent used the park-and-ride mode, and approximately 20 percent used the kiss-and-ride mode.

We concluded that the park-and-ride facility was an important element of the express-bus service. We estimated that if the park-and-ride and kiss-and-ride capabilities had not been provided, approximately 60 percent of the express-bus passengers would have been lost to the automobile.

Another important measure of effectiveness is the economic viability of transit operations. We determined that the total cost of operating the Orange Streaker service in the Northwest Seventh Avenue stages of the project was \$903 698 (\$1.70/passenger); revenues, however, accounted for only \$320 836 (\$0.60/passenger). This deficit resulted in a total deficit of \$1.10/passenger (or \$2.20/passenger/d). There were five primary reasons for this deficit.

1. Costs attributed to vehicle-hours represented 53 percent of the total cost, primarily because of drivers' wages and related expense items. Because the express service was strictly a peak-period service and drivers had to be paid a minimum of 8 h/d, an extremely high percentage of non-revenue-producing hours resulted (63 percent of the total).
2. A relatively large number of buses were only able to make one revenue trip since the service was offered only in the peak period. The average number of trips per bus was less than 1.5 trips/peak period. Costs due to these vehicles (which relate to expenses of yards, garage facilities, and administrative overhead) amounted to 30.4 percent of the total cost.
3. The peak-period, unidirectional nature of the express service produced a high percentage of deadhead travel. Over 46 percent of the Orange Streaker bus travel was nonrevenue producing; the comparable figure for MTA systemwide, however, was 13.3 percent. This variable contributed 14.5 percent of the total cost and relates to fuel, lubrication, and maintenance costs.
4. The Orange Streaker service included some feeder routes in the market area. These routes returned only 10.5 percent of their cost, although the line-haul portion returned 39.1 percent of its cost.
5. Service to each of the four employment areas was investigated, and we found that the downtown and Civic Center routes were the most productive and collected about 41 percent of their costs. The airport employment area was less productive, returning 36 percent of its cost; but the airport terminal and Coral Gables route was extremely inefficient, returning only 11.9 percent of its cost.

In summary, the extremely high-quality service and low-fare structure, coupled with some relatively inefficient routes (airport area and the feeder segments), produced costs that greatly exceeded the collected fares.

CONCLUSIONS

1. The project was successful in demonstrating that express buses can be given priority treatment on urban arterial streets and cause little or no adverse effect on

the general traffic stream. Indeed, positive benefits can accrue to the automobile traffic.

2. A park-and-ride express-bus combination that provides a high level of service can attract automobile riders although such high-level service is extremely expensive for the public to support. This observation suggests that a service oriented to a relatively small market requires a carefully established fare and route structure to ensure that revenues offset a realistic portion of the operational costs.

3. Increases in bus accidents appear to be a problem when a reversible exclusive center bus lane is used.

4. The bus-preemption system did not appear to have an adverse effect on traffic signal operation but did increase the required service calls.

5. The new bus service and the bus-priority treatment greatly increased the number of persons moved on Northwest Seventh Avenue. Between 20 and 30 percent of the persons moved on Northwest Seventh Avenue were moved by bus although buses constituted less than 2 percent of the traffic stream.

6. The park-and-ride facility was an essential element of the transit service, and a majority of the bus passengers would have been lost to the automobile if the facility had not been provided.

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Where Express Buses Work

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Densities of residential areas and sizes of central business districts necessary to generate sufficient demand to support express buses for given frequencies of service at a reasonable cost are estimated. Two types of express-bus operations are considered. In the first case, patrons are picked up by buses circulating in a residential area before the bus travels express to the central business district. In the second, commuters arrive by automobile at a park-and-ride lot before continuing their trips by express bus. We found that, for express-bus operations with pedestrian access, a cost of 6 cents/passenger·km (10 cents/passenger-mile) is attainable for only a narrow range of residential densities and only to rather large central business districts. If 12 cents/passenger·km (20 cents/passenger-mile) is an acceptable cost standard, a wider range of supporting conditions is possible. Express-bus operations that provide park-and-ride facilities are more broadly applicable at the 6 cents/passenger·km (10 cents/passenger-mile) standard. Residential densities as low as 7 dwelling units/hm² (3 dwelling units/acre) and central business districts of moderate size can in some cases support express-bus service. These findings match reasonably well with empirical data from 11 express-bus operations in two Connecticut cities. The achievement of more express-bus operations is possible by higher residential densities over a larger area and by growth of central business districts in medium- to large-sized cities.

This paper is part of a larger study to determine the land use densities suitable for a variety of public transit modes and service levels. The express bus is only one of eight modes considered. The measure of demand for public transit in an urban setting and the cost of supplying the service to meet that demand, developed as part of this effort, will not be fully described here. Nevertheless, outlining the relevant variables involved is necessary before the focus of this paper—matching demand and supply for express-bus service—is discussed.

A set of models was created that estimate the number of public-transit trips from a residential area to a nonresidential concentration or cluster. One model estimates the total number of trips between two places; the other model divides those trips into trips by transit and trips by automobile. The models further record the distinction between work trips and nonwork trips and the distinction between travel to CBDs or spread highway-oriented clusters.

The model developed to estimate total trips between a residential area and a nonresidential cluster shows that such trips are a direct function of the size of the nonresidential cluster measured by square meters (square feet) of nonresidential floor space, the number of workers (for work trips) and number of people (for nonwork trips) in the residential area, and an inverse function of the distance between the residential and nonresidential areas. Since the model was calibrated with data from the New York urban region, the competing influence of Manhattan as an attractor of trips is also accounted for.

The modal-choice model distinguishes among travelers with zero, one, or two or more automobiles available in their households. Automobile ownership is shown to be a function of residential density, income, transit service available, and number of drivers in the