WHERE TRANSIT WORKS:
URBAN DENSITIES FOR PUBLIC TRANSPORTATION

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Introduction
Public policies favoring dispersal of urban settlement and the proliferation of the automobile have contributed to a decline of public transportation in the United States. Even in urban areas today, 96 percent of all motorized travel is by automobile; only 4 percent is on public transportation, compared to some 14 percent twenty-five years ago. And close to half the nation's transit travel is confined to the Tri-State New York Region—with less than one-tenth of the nation's population.

Yet political pressure for more and better transit remains firm to:
— enlarge the mobility of those who for reasons of health, age or income cannot drive.
— strengthen urban centers and reduce their need for highways.
— reduce pollution and conserve energy.

This study demonstrates that only changes in the nation's urban development pattern will achieve all of these goals effectively. Improvements in transit service and fare cuts will increase transit ridership, but they will not cut nationwide auto use much. Restraints on auto use will shift some trips to public transportation, but most of the foregone auto trips will simply not be made. By contrast, increasing the size and compactness of downtowns and other clusters of employment and increasing residential densities, particularly near downtowns, will cut auto trips without reducing people's mobility as much as when the auto is restrained directly: more auto trips will shift to public transportation, and there will also be more opportunities for trips on foot.

Of course, increasing the density of urban areas in America flies in the face of a long-term trend. The huge investment in spread-out development cannot be easily abandoned. Return to the older cities is further discouraged by poverty, crime, lack of amenities and high tax rates. Land development practices favor construction on vacant land over redevelopment. Nevertheless, with smaller households, for whom low density is not necessarily an asset, with more white-collar and service occupations suited to city environments, with a rising concern for preservation of agricultural and open land, a potential for reinforcing higher density areas does exist. It could lead to less mechanical travel, greater choice, and a more urban way of life.
This potential will have to be realized if the nation confronts the need to reduce its consumption of energy and other physical resources. With dwindling reserves of liquid fuels and with the inevitably higher cost of foreseeable substitutes, the long-term viability of an auto-dominated urban pattern is uncertain. Besides, higher densities save energy and materials not only in transportation but also in domestic and commercial consumption, and by preserving open land.

In addition to long-term considerations, there are more immediate considerations of efficiency. Both labor and other resource costs of public transportation depend on the level of its use; to keep these costs within reason, there must be substantial passenger demand, which in turn depends on the density of settlement. High quality transit service in areas of low density and low demand can easily exceed the costs of the automobile not only in dollars, but also in energy and materials consumption.

In this light, the study addresses two questions:
1. New urban facilities and housing are being built; what pattern of location and what density can support what type and quality of transit?
2. Transit systems are being extended and new ones built; what kind of transit service can be supported where, and at what cost?

Findings

The land-use policies which will do most for public transportation are those which will help cluster nonresidential floorspace in downtowns and other compact development patterns. The higher the density of a downtown and the larger its size, the more it will shift travel from auto to transit. Downtowns of 10 million square feet of nonresidential floorspace (the size of White Plains, New York or Stamford, Connecticut), if confined within less than one square mile, begin to make moderately frequent bus service possible and to attract an appreciable proportion of trips by transit. By contrast, downtowns of 5 million square feet (between Poughkeepsie, New York and Middletown, New York in size) can support only meager bus service. Spread suburban clusters of nonresidential use can only occasionally support meager bus service, i.e., if they contain shopping centers or if they are surrounded by fairly high residential densities.

Residential density is less important for transit use than proximity to a downtown of substantial size or proximity to a rail transit line. If greater transit use is the goal, it is more important to put housing close to a downtown than to make it high density. It is a fallacy to suppose that transit necessarily requires densities such as used to be found in the southern Bronx. In fact, residential densities in the range of 7 to 15 dwellings per acre (from Levittown, Long Island one-family houses to medium-density town houses) can support moderately convenient service by any transit mode if there is a place to go. Obviously, densities higher than that will support better service; Montreal, a strongly transit-oriented city, averages 35 dwellings per acre of land in residential use.

The approximate ranges of downtown size for which different transit modes and service levels appear worthy of consideration are summarized in Exhibit 1. The dashed bars suggest feasibility only under unusual conditions. The lower thresholds of residential density which can support a given transit service depend on numerous conditions, mostly proximity to a downtown and its size. These conditions are spelled out more fully in the text and are only briefly indicated in Exhibit 2.

Analysis of the individual modes leads to the following conclusions:
1. Dial-a-bus, a new mode that has received a lot of public and technical attention, appears to offer little promise, at least with present labor arrangements. Its application seems to be limited mostly to feeder service to other public transit and to pre-arranged subscription services. The densities it requires are higher than most new suburbs have. In many suburban situations, subsidizing taxicabs for particular groups of riders would be more effective than introducing new dial-a-bus systems.

2. The present generation of another new mode, automated light guideway transit, appears limited to special, small scale applications which lack sharp peaks in demand; it offers little promise for area-wide urban systems. The major development priority, which seems to receive no funding, is the perfection of a truly low-cost, visually unobtrusive light guideway, which could be justified for modest traffic volumes.

3. Express buses with access on foot require moderately high densities in the residential collection area, can provide only very infrequent service, and only to very large downtowns. By contrast, express buses with access by auto are broadly applicable to a wide range of medium-sized downtowns and can serve very low residential densities with moderate to good frequency.

4. The possibilities for building full-scale rapid transit systems seem to be limited to a handful of cities in the United States. Proposals for new rapid transit in several medium-sized cities appear questionable. Focusing rapid transit investment on the extension and upgrading of existing systems in the largest cities with heavy transit use would appear to be much more cost-effective.

5. By contrast, the possibilities for light rail (streetcar) systems with only partially grade-separated rights-of-way appear much wider than commonly assumed. There may be 30 or more urban areas in the United States where light rail could merit serious consideration. Whether or not it turns out to be feasible will strongly depend on local conditions, such as the shape of the city and the existence of conveniently located rights-of-way.
Exhibit 1
Transit Modes Suited to Downtown Size.
(approximate ranges)

Note: Downtown is defined as a contiguous cluster of nonresidential use and is larger than the more narrowly defined Central Business District.
6. The construction costs of new rail systems—whether light rail or rapid transit—are high in conventional transportation terms; but they are justifiable, up to a point, by long-term conservation of energy and other physical resources that will come about both from the use of the facilities themselves and from the more compact urban environment that they will make possible. To ensure that this result comes about, it behooves the public to see to it that land-use policy is made supportive of transportation policy.

Investigating the question of what transit mode can fit what pattern of development requires a look at three issues:
2. Ridership response to transit improvements.
3. The effect of density on transit ridership.
4. The cost of different transit services.

These issues lead to a number of policy conclusions in their own right. Subsequently, the findings are applied to investigate the feasibility of eight modes of public transportation in greater detail.

### Exhibit 2
Transit Modes Related to Residential Density

<table>
<thead>
<tr>
<th>Mode</th>
<th>Service</th>
<th>Minimum Necessary Residential Density dwelling units per acre</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dial-a-bus</td>
<td>Many origins to many destinations</td>
<td>6</td>
<td>Only if labor costs are not more than twice those of taxis</td>
</tr>
<tr>
<td>Dial-a-bus</td>
<td>Fixed destination or subscription service</td>
<td>3.5 to 5</td>
<td>Lower figure if labor costs twice those of taxis; higher if thrice those of taxis</td>
</tr>
<tr>
<td>Local bus</td>
<td>“Minimum,” ¼ mile route spacing, 20 buses per day</td>
<td>4</td>
<td>Average, varies as a function of downtown size and distance from residential area to downtown</td>
</tr>
<tr>
<td>Local bus</td>
<td>“Intermediate,” ½ mile route spacing, 40 buses per day</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Local bus</td>
<td>“Frequent,” ½ mile route spacing, 120 buses per day</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Express bus—reached on foot</td>
<td>Five buses during two hour peak period</td>
<td>15 Average density over two square mile tributary area</td>
<td>From 10 to 15 miles away to largest downtowns only</td>
</tr>
<tr>
<td>Express bus—reached by auto</td>
<td>Five to ten buses during two hour peak period</td>
<td>3 Average density over 20 square mile tributary area</td>
<td>From 10 to 20 miles away to downtowns larger than 20 million square feet of nonresidential floor space</td>
</tr>
<tr>
<td>Light rail</td>
<td>Five minute headways or better during peak hour.</td>
<td>9 Average density for a corridor of 25 to 100 square miles</td>
<td>To downtowns of 20 to 50 million square feet of nonresidential floor space</td>
</tr>
<tr>
<td>Rapid transit</td>
<td>Five minute headways or better during peak hour.</td>
<td>12 Average density for a corridor of 100 to 150 square miles</td>
<td>To downtowns larger than 50 million square feet of nonresidential floor space</td>
</tr>
<tr>
<td>Commuter rail</td>
<td>Twenty trains a day</td>
<td>1 to 2</td>
<td>Only to largest downtowns, if rail line exists</td>
</tr>
</tbody>
</table>
The Standard Light Rail Vehicle—the new streetcar produced to United States Urban Mass Transportation Administration specifications—promises reduced operating costs compared to its predecessors and if on its own right-of-way, faster speeds than buses. Generally applicable for downtowns ranging from under 35 to over 50 million square feet of nonresidential floorspace.

The automated light guideway transit system connecting the dispersed campus of the University of West Virginia in Morgantown. High capital costs and relatively low hourly capacity presently make such systems applicable only for situations without high commuter peaks. Fitting the bulky structures into an existing urban fabric presents added difficulties.

The Washington Metro—a full scale rapid transit system to include nearly 100 miles of route when completed, in scale with approximately 100 million square feet of nonresidential floorspace of downtown Washington.
Ridership Response to Transit Improvements

So far, efforts to expand transit use have focused on making public transportation more appealing—with lower fares, more frequent and faster service, better amenities and new technology.

Fare reductions. Cutting fares by 50 percent tends to increase the number of transit riders anywhere from 7 to 45 percent, depending on the type of trip and on the size of the urban area. Non-work trips are more sensitive to fares than work trips, and small places with sparse transit use are more sensitive than large cities. However, this does not mean that fare subsidies are better spent in small, low-density places. Riders are concentrated in large and dense cities to such an extent that, with an equal subsidy per rider, the absolute gain in ridership will be much greater there.

Reductions in travel time. Cutting running time by 50 percent tends to increase ridership by 14 to 20 percent, while doubling service frequency (thereby cutting waiting time by 50 percent) tends to increase ridership by 24 to 77 percent, depending on existing service frequency. Cutting walking time is also very important. On the whole, passengers are more responsive to travel time reductions than to fare reductions. However, this does not mean that money is necessarily better spent on service improvements than on fare reductions. For example, if the cost of service improvements is high, situations can arise when more riders per dollar of subsidy can be attracted by lowering fares.

Improved amenity. Ridership response to improved amenity is not well quantified, but both the assurance of a seat and air conditioning appear important. Also, evidence suggests that fixed rail systems do attract more riders than buses under comparable conditions.

Costs vs. increased use. Whether a transit agency attracts extra riders by lowering fares or by more frequent service, it will as a rule lose more money. Lowering fares has the advantage that the total cost per rider (fare plus subsidy) is lowered. More frequent service means—other things being equal—higher total cost per rider. Only higher operating speed offers the intriguing possibility of both greater ridership and greater revenue. Yet, attaining higher speed often requires large capital investment, as does replacing buses with a new rail line. Thus lowering fares and, especially, expanding service are rather expensive ways of gaining riders.

Diversion from the automobile. In practice, new bus and rapid transit systems have increased transit ridership in the affected areas by 50 to 100 percent, rarely more. Typically, about half the new trips represented trips not made before, indicating that the systems did indeed expand mobility. The other half were trips diverted from the automobile. This is significant from the transit viewpoint, but from the viewpoint of overall auto use, the reductions were small. Given the preponderance of auto travel, even a 50 percent increase in transit use nationwide would cut urban auto travel about one percent. Of course, in specific places, such as entrances to a downtown, the reduction can be much greater and forestall the need for building new freeways.

Auto restraints. Depending on how severe they are, auto restraints can have more of an effect on both reducing auto use and increasing transit use. For example, gasoline rationing in World War II cut urban auto travel as much as 25 percent; about one-third of the foregone auto travel showed up on public transportation, raising its use about 55 percent. On a much smaller scale, the 1974 gasoline shortage had a similar effect.

The Effect of Density on Transit Ridership

Higher density of urban development acts both to restrain auto use and to encourage the use of public transportation. Highe: density has two related aspects—greater downtown size and greater residential density. Data from urban areas with large downtowns suggest that, keeping income characteristics the same, neighborhoods with 15 dwellings per acre produce about 30 percent fewer auto trips per person than those with five dwellings per acre. Meanwhile, public transit use is over 100 percent greater. More than half the foregone auto trips show up on public transportation, meaning that mobility is sacrificed less than with auto restraints alone.

To illustrate, about five dwellings per acre appeared to be the average density of urban areas in the United States around 1970; 15 dwellings per acre is typified by attached one-family houses on 30 x 100 foot lots—still only one-thirtieth the residential density of Manhattan. This relatively moderate difference in density has a greater effect on the balance between auto and transit than the rather severe curtailment of auto travel in World War II.

Average relationships between residential density and transit use can be summarized as follows:

- At densities between 1 and 7 dwellings per acre, transit use is minimal.
- A density of 7 dwellings per acre appears to be a threshold above which transit use increases sharply.
- At densities above 60 dwellings per acre, more than half the trips are made by public transportation.
- The reduction in auto trips (and total trips) per person and the increase in transit trips with higher density is most pronounced among middle-income households. It is somewhat less pronounced among upper-income households, who buy more transportation at any density. Low-income households make only the most essential trips to begin with, so that rising density affects their total travel least of all; but they do substitute transit trips for auto trips more than others.

Reasons for rising transit use with rising density. The number of cars owned by a household makes by far the greatest difference in its transit use. However, the num-
ber of autos per household, in turn, depends not only on income and the number of persons of driving age but also on several aspects of development density and transit service, namely:

- **Higher residential density tends to cut auto ownership.** Comparing households of the same income and size, a tenfold increase in residential density reduces ownership by about 0.43 autos per household. This is so because at higher densities, auto storage and use are less convenient and more costly, and alternative means of travel, including walking, are available.

- **The presence of rail transit suppresses auto ownership.** A nearby rapid transit station can have an effect equivalent to more than a tenfold increase in residential density. Proximity to commuter rail in upper-income low-density areas also has an effect, though much smaller.

- **Auto ownership is further influenced by the habitual destination of the trips a household makes.** Two households residing at the same density will own different numbers of autos depending on whether their workplace is in a downtown or in a spread suburban development.

Then, among auto owners, transit use is further affected by two factors:

- **The density of the nonresidential destination—the higher it is, the more likelihood that auto owners will use transit.**

- **The quality of transit service—availability of commuter rail, proximity to a rapid transit station, and the frequency of bus service attract auto owners to transit.**

In brief, transit use at high residential densities tends to be high because auto ownership is low, transit service is good, but most importantly because many trips are destined to nonresidential places of high density, such as downtowns, which have an auto-suppressing and transit-attracting power of their own.

Downtowns discourage autos and stimulate transit riding compared to spread out offices and shopping along the highways, because space in a compact business area is limited. Autos require a great deal of space. On a local street during the peak hour, a person in a car needs 20 times more space than a transit rider at comparable speed, and on a freeway about 10 times more. The loss of time in a congested area becomes great and so does the price of parking. These factors ration scarce downtown space by shifting those to transit who can most readily use it or who can least afford to use their car. Furthermore, more people can use transit conveniently because they are going to a compact area. The high demand can support a high-quality service, and walking distances are short.

**The cumulative effect of these interrelated factors** explains the proportion of travellers who will choose transit between a particular residential area and a nonresidential destination. However, in assessing the total number of trips—which, after all, determines the feasibility of transit—the distance between these two places is of key importance. The willingness to make trips falls off very sharply with distance. As a result, trips to a downtown, for example, will be found in very large numbers only from fairly close proximity to that downtown. In sum, residents will be more likely to use public transportation:

1. The higher the density and the larger the size of a downtown or another cluster of nonresidential activity;
2. the closer their neighborhood is to that nonresidential concentration;
3. the higher the residential density of their neighborhood;
4. the better the transit service.

The density (which is usually related to size) of the nonresidential concentration is most important. The distance is second in importance. High residential density by itself will do little for transit if there is no dominant place to go.

**Examples of Land Use Policies Affecting Transit Use**

The relationships outlined make it possible to estimate the effect of different land use policies on transit use. The figures should not be taken as very precise but indicative of the scale of the changes needed. Four examples will illustrate.

1. **Clustering or dividing nonresidential space.** Say 10 million square feet are to be added to a growing urban area. One option is to put the nonresidential floor-space into two spread clusters, each five million square feet in size. Another is to create a new downtown of 10 million square feet. In the second case, per capita trips by transit within a 3 to 5 mile radius will be **50 to 70 percent higher** than in the first case, keeping residential density the same.

2. **Enlarging downtown size or raising nearby residential density.** Say the options are to double the size of a downtown from 10 to 20 million square feet, or to double the residential density within a few miles of it from 15 to 30 dwellings per acre. The former will increase per capita trips by transit in the vicinity of that downtown **three to four times more** than the latter.

3. **Increasing residential density near downtown or farther away.** Say the options are to double residential density from 5 to 10 dwellings per acre either within one mile of a downtown of 10 million square feet or at a distance of 10 miles from it. In the first case, public transit trips per capita in the affected area will increase **seventeen times as much** as in the second case.

4. **Scattering apartments or concentrating them near transit.** Say a rapid transit station is located five miles from a downtown of 50 million square feet of nonresidential floorspace (the size of Newark, New Jersey). At a density of 15 dwellings per acre, the square mile surrounding the station will send about 620 trips a day to the downtown by transit. Suppose speculative devel-
Newark, New Jersey, a downtown of 50 million square feet of nonresidential floorspace, of sufficient size for extensive and frequent local bus service, express bus park-and-ride and a light rail operation.

Bridgeport, Connecticut, a downtown of almost 20 million square feet of nonresidential floorspace, enough for frequent (every 10 minutes) local bus service. Express bus park-and-ride and light rail transit are highly questionable.

White Plains, New York, a downtown of over 10 million square feet of nonresidential floorspace. Adequate in size for only intermediate (half-hourly) local bus service.

Paramus, New Jersey, a loose string of highway-oriented shopping centers totaling about 9 million square feet, only partially shown here. Such clusters can support half-hourly local bus service if they are as large as Paramus and hourly service if half as large.
Two views of low density single-family housing of under three dwelling units per acre—a residential density too low generally to support any transit except taxicabs and commuter rail or park-and-ride express bus to very large downtowns.

Seven dwelling units per acre—60 by 100 foot lots—can generally support an intermediate (half-hourly) local bus service.

Ten dwelling units per acre—shown here as either detached houses on 40 by 100 foot lots or attached units with pooled open space—can generally support an intermediate (half-hourly) local bus service. If these densities exist over a wide tributary area in a corridor leading to a major downtown, a light rail or rapid transit line may be supported.
Fifteen dwelling units per acre—either attached units or garden apartments on two floors with pooled open space—can support a wide array of transit service, if there is a downtown to go to.

Yet even high-rise apartment houses will not support transit if they are isolated, far from a nonresidential concentration as shown here in rural Dutchess County. Neighboring units of 20 to 30 dwellings per acre begin to provide sufficient ridership for walk-to-rapid transit service, as shown in outer Queens. Better still is an arrangement of highs and lows that relate directly to the bus routes and rapid transit stations while offering a choice of housing types, as shown in Toronto.
opment scatters apartments throughout the square mile, raising its density by 20 percent. That will increase transit ridership at the station by about 24 percent. But if the apartments are clustered within 2,000 feet of the station, preserving the rest of the neighborhood intact, transit ridership will increase by 34 percent or more; at least a carload of 62 people a day will be added from any increase in average density but only from a different arrangement of the new development within the square mile.

The Costs of Public Transportation

Analyses such as those above can provide rough estimates of the demand for public transportation in various settlement patterns, which can be modified depending on assumptions about fare and service levels. To know what it takes to meet the demand, one must know the costs of supplying public transportation by different modes.

Public transit costs have risen notoriously of late: between 1965 and 1975, the operating cost per passenger nationwide rose 85 percent in constant dollars. The reasons have more to do with broad social policies than with the technology or management of the transit systems themselves. A major cause was the rise in auto ownership with a resulting decline in transit use. As revenue passengers in the nation dropped by 17 percent over the decade, transit service was cut only by one percent so as not to cause still larger ridership declines. In fact, considerable expansion of service in many areas since 1972 helped to arrest the decline in riders. But, the result was a sharp drop in productivity—fewer passengers carried per vehicle or per employee. At the same time, wages and fringe benefits in the highly-organized transit industry were allowed to rise much faster than in the economy as a whole. Fares were kept stable in constant dollars (they rose in some places, like New York City, but dropped in others) and the difference was covered by public subsidy. In 1975, subsidies amounted to 46 percent of nationwide transit operating expenses. About half this subsidy covered increased real wages and fringe benefits per worker. While any projection of transit operating costs is highly conjectural (New York City succeeded in freezing wages in 1976), an allocation of the costs and comparisons among modes can be studied at one point in time, in this case 1974.

Operating and maintenance costs in dollars. Generally, between 70 and 85 percent of the operating and maintenance cost of public transportation is labor cost. The remainder is split about evenly among three categories: energy, materials and miscellaneous, which includes insurance and non-labor related taxes.

The all-important labor cost varies widely both geographically and among transit modes. Bus driver wages on the larger systems in the Tri-State New York Region were twice as high as on some small operations. Earnings of railroad employees were two to four times higher than those of taxi drivers. Often, the cost advantage of a particular mode, such as taxicab versus dial-a-bus or rapid transit versus commuter rail, results not from the technology of the system but from the labor arrangements peculiar to it.

Automation is often advanced as a way of reducing labor costs. In fact, the number of employees per vehicle on automated systems is not much lower than on similar manual ones. Savings in on-board personnel tend to be cancelled by the more demanding maintenance of the complex equipment. However, the automated vehicles do work harder and with the same labor produce more vehicle-miles than manually operated ones, once their various "bugs" are worked out. Still, manpower savings much greater than those of complete automation can be attained on some overstaffed commuter railroads by changing labor agreements and by automating fare collection alone.

Looking first at the cost of providing space on a vehicle per hour of operation, buses, rapid transit, light rail, and automated guideway cars all fall in the same range—between 32¢ and 42¢ per hour to operate a space necessary to carry one passenger comfortably (about six square feet). On the average, rapid transit tends to be slightly cheaper than bus, and both light guideway cars and light rail with old equipment tend to be slightly more expensive. The important point is that the differences are marginal. The three modes which stand out above this range are commuter rail (one-and-one-half times as expensive), dial-a-bus (two times as expensive) and taxicab (over three times as expensive).

The cost at which these different modes deliver capacity-unit miles of travel (as distinguished from capacity-unit hours above) depends on their speed. At higher speed, more miles per hour are produced and cost per mile is lowered. Speed depends on the density of the surrounding development and on availability of an exclusive right-of-way. Thus New York City buses in Manhattan operate at 5.7 mph while those on Staten Island run at 11.7 mph and therefore cost only half as much per mile travelled. Commuter railroads, averaging 30 mph, deliver capacity-unit miles at an even lower cost, despite their high labor intensity and high wages.

The cost per passenger-mile depends on the extent to which the capacity-units of rolling stock are occupied by passengers. Average transit occupancies are low because of much idle capacity in the reverse direction during peak hours and in both directions during off-peak hours. Only about 15 percent of the space (of the capacity-units) is used on the average on taxicabs and on some local buses, while 26 to 28 percent is used on some rapid transit and commuter rail lines. Obviously, the chances of attaining higher occupancy are better as development density increases.

With speed and occupancy related to density in opposite ways, the ultimate cost at which a transit system delivers passenger-miles depends not just on the
system but on the urban environment in which it is used. In the three-state area of New York, New Jersey and Connecticut in 1974, the operating cost per passenger-mile stacked up about as follows: taxicabs—about 75¢; local buses—14¢ to 26¢; light rail—19¢; rapid transit—6¢ to 14¢; express bus—about 8¢; commuter rail—8¢ to 10¢. Of course, such cost ranges are affected by local circumstances and can quickly change in an inflationary period.

**Costs in resources.** The dollar cost of the basic resources used for public transportation varies by geography and is extremely volatile over time. Therefore, Exhibit 3 portrays selected costs in units of labor, energy, materials and space. These are mostly based on operating conditions and passenger use typical of the three-state area.

It is evident that taxi and dial-a-bus are extremely labor intensive. To produce 1,000 passenger-miles of travel, they require 20 to 30 calendar man-days (i.e., man-days including days off) of operating and maintenance personnel, compared to 2.5 to 4.0 man-days on local buses and only 1.0 to 2.5 on rapid transit and commuter rail. Because workers on the more productive systems get paid more, the contrast is not so stark when costs are measured in dollars.

Second, direct energy consumption for 1,000 passenger-miles travelled by taxicab or dial-a-bus is about twice as high as by auto; by the mass transit modes, it is only half as high as by auto. The bus is somewhat more energy-efficient than present-day electric modes because it does not have the handicap of thermal energy loss in the production of electricity. With equipment to recover energy losses in braking (being tested on New York City subways), efficiency of the electric modes can be improved.

The third set of bars in Exhibit 3 shows materials consumption for the replacement of vehicles. Again, the taxicab has the highest cost, much above the auto. The bus consumes about one quarter the material used by the auto to produce 1,000 passenger-miles. The more durable vehicles of rapid transit and commuter rail use about one quarter the material needed for bus replacement.

The fourth set of bars shows space consumption. The space that is occupied by roadway pavement or by tracks and excludes pavement for off-street auto parking and space in bus garages or rail yards; no distinction is made between space at grade, above grade or underground. The figures reflect actual land use in the Tri-State Region, not space needs at maximum capacity, which are much smaller; the space is allocated to exclude freight use of highways and railroads. Once again, the taxicab leads the list with 1.7 acres of pavement used to produce 1,000 passenger-miles per weekday. The auto uses just under one acre, commuter rail about one-third of an acre, the bus about one-sixth, and rapid transit only one-twentieth. Light rail, represented by the Newark subway, does worse than other mass transit modes in this instance because of the sparse use of that facility.

Generally, the modes suitable for areas of low density and low demand, namely taxi and dial-a-bus, are very costly in terms of manpower and tend to be actually costlier than the auto in environmental terms of energy and materials, at least at currently attainable occupancies. The case for them in preference to the auto must be made on social grounds, i.e., serving passengers who cannot drive.

By contrast, large-scale systems such as rapid transit and commuter rail tend to be extremely efficient in the use of manpower and materials for vehicles, and quite efficient in the use of energy and space. Yet, for this efficiency to be used, high passenger demand must be present, which requires high density. Where public pressure achieves transit service in low-density areas, it is quite likely that resources will be wasted, compared to complete reliance on the auto.

**Evaluating capital investment.** To determine the full money costs of different modes of transportation, the capital cost of vehicles and guideways must be added to the operating cost. Particularly for long-lived equipment, this capital cost will vary greatly depending on the interest rate. Interest rates of 8 to 10 percent, widely used at present, incline a hedge against future inflation. In dollars of constant value, the long-term cost of capital is closer to 3 percent, or 4 to 5 percent if a risk that the investment will be abandoned prematurely is accounted for. Yet, inflation affects not only the money with which loans will be repaid but, so far even more strongly, the transit operating costs. Therefore, if the interest rate is to account for inflation, inflation in operating costs over the lifetime of the investment would have to be accounted for as well. This kind of a calculation is highly conjectural, and it is simpler to work in dollars of constant value: take operating costs at a point in time as being fixed and add capital costs at an interest rate that does not include future inflation.

**Capital cost of vehicles.** Adjusted for a unit of capacity and for length of use, the difference in dollar costs between different types of transit vehicles is not too great. Generally, the capital cost of rolling stock adds about one-tenth to the operating cost per mile of taxis, dial-a-buses and local buses. For equipment running at high speeds, which has a low operating cost per mile, the capital cost per mile becomes relatively more important; it may add one-third to operating cost if a 4 to 5 percent interest rate is assumed. However, these additions essentially leave unchanged the ranking of the different modes based on operating costs alone.

**Capital cost of guideways.** The critical difference in capital costs is in the cost of building new guideways for systems which run on exclusive rights-of-way. If that cost is very high and passenger use very low, such systems can become by far the most costly per passenger-mile. Therefore, capital investment in guideways must be related to prospective passenger use and so to development density.
Exhibit 3
Resource Use of Transportation Systems

Exhibit assumes the following average occupancies (persons per vehicle):
Auto, 1.5; Taxicab, 0.7; Dial-A-Bus, 1.2; Bus, 11; Light Rail, 10; Rapid Transit, 24; Commuter Rail, 31.
One way of doing that is benefit-cost analysis. However, it can quantify only some of the more obvious transportation-related benefits. Even there, different assumptions about the value of time (a highly subjective figure) and about interest rates can lead to widely different conclusions. Broader community-related benefits such as result from tunnels are difficult to quantify. One can argue that the large added cost of tunneling is not a transportation investment but an urban design investment and not subject to analysis in transportation benefit-cost terms much as an urban park, which might not withstand such analysis in recreation terms alone. Also, long-term benefits, such as enabling the eventual development of a higher-density, resource-conserving urban environment, are beyond the reach of benefit-cost analysis in today's dollars.

To avoid the issues of interest rates and hard-to-quantify benefits, one can compare cost-effectiveness of capital investment among different systems simply by relating it to daily passenger use expected or attained after completion of the project. A sampling of fixed guideway projects recently completed or underway in the United States shows their capital cost (in 1974 dollars) to range from $240 to $3,200 per daily passenger-mile. Assuming present ridership levels, New York City subway construction is in the range of $800 to $1,800; BART in San Francisco cost about $1,500 converted into 1974 dollars. This can be a helpful reference for investment elsewhere; presumably the various benefits of the projects have been weighed in the process of political and design decisions.

To get a feel for what investment might be excessive, one can check if a particular route would use more energy indirectly (for construction) and directly (for operation) than would be used if all prospective passengers travelled by auto. Both the energy use per dollar of heavy construction and the direct and indirect energy costs of the auto are known approximately. One can estimate that if guideway construction cost exceeds about $2,000 per daily passenger-mile in constant 1974 dollars, the route will be less energy-efficient than the auto over a 50-year period. Apportioned among travellers over the 50-year period, and assuming a four percent interest rate, the $2,000 works out to about 30¢ per passenger-mile, a yardstick that might seem high until the full energy cost of transit is compared to the full energy cost of the automobile. Obviously, both future cost estimates and future patronage estimates can be wrong by a large margin, and decisions cannot be based on cost-effectiveness yardsticks alone; still, they can help enlighten decisions.

**What Density for What Transit Service**

Knowing passenger demand for transit at any development density and service level as well as the costs of supplying the service by different modes, it should be an easy matter to calculate cost per passenger for different levels of service at different densities. Based on the cost per passenger (or per passenger-mile) one could then judge what transit service is feasible where. However, the calculation is complicated by many additional factors.

On the demand side, development density cannot be represented by a single figure. Rather, one must take into account the residential density at the origin, the distance to one or several nearby nonresidential concentrations, their size or density, and their character: are they downtowns or suburban shopping centers, surrounded by scattered nonresidential development, or other spread clusters with industrial and commercial use? At the residential end, the share of total land area devoted to residential use and population characteristics such as income, household size and labor force participation are also important. Aspects of transit supply which affect demand are the presence or absence of commuter rail in an area, the proximity of a rapid transit station, the frequency of bus service, and the level of fares.

On the supply side, the quality of service must be defined in terms of service frequency, service span, and route spacing for fixed route systems. For demand-responsive systems such as taxi and dial-a-bus, defining service level is more difficult and involves such indicators as waiting time and detour time. Knowing operating speed (which, for transit systems that operate on streets, is closely linked to development density), the quality of service at any density can be expressed in vehicle-hours per square mile. For each mode, the cost per vehicle-hour falls into a fairly predictable range, except that it does vary from place to place depending on local labor agreements. Moreover, neither labor nor rolling stock can be added incrementally but only in discrete chunks: one entire eight-hour workday (which may be in two separate shifts if the labor agreement permits), one entire vehicle or one train. The number of vehicles needed, in turn, depends partly on the length of the route: a short route allows the same vehicle to make several runs during the peak period while a long one may mean that each peak period run requires a separate vehicle.

Further, characteristics of demand also influence the costs of supplying transit. How far people are willing to travel to get to a station and whether they walk or drive is very important. The farther people are willing to travel to stations, the farther the routes can be spaced; for the same cost, more frequent service can be provided on each route. Of course, people's willingness to travel to stations is in turn affected by the quality of service: for example, half the walk trips to local buses rarely exceed one-seventh of a mile, while half the walk trips to rapid transit exceed one-third of a mile. Another important characteristic is the peaking of demand: the size of the vehicle fleet is determined by peak-hour demand at the highest load point.
Lastly, the distribution of the demand in space will also affect the cost of service. It is often neither desirable nor possible to balance supply and demand in each square mile. Having high-demand square miles subsidize low-demand square miles will tend to maximize ridership. This can be true on a particular route or on an entire system. Thus, the feasibility of transit service in one particular square mile with a given density is a function not just of the density of that square mile but also of the density of other, neighboring areas.

In sum, the question "what density of service can be supported by what density of development" cannot be answered in general terms but only after a large number of variables defining the particular context have been specified. Nevertheless, one can construct more or less average hypothetical situations and calculate what transit mode and what level of service fit what density under specified assumptions. One can also compare these to real-life examples. The answers are not precise, but they do show relationships that are useful. The methodology underlying the study allows the reader to investigate specific situations on his own.

**Taxicab and Dial-a-Bus**

The taxicab provides individualized, door-to-door service on call over the full range of city and suburban densities. While taxis are most conspicuous in dense urban areas where they in large part compete with other public transportation, their services are more essential in low density areas and small communities, where they often represent the only feasible form of public transit. Yet, they can serve only a very small share of total travel because of their high cost, which results from low passenger occupancy.

The dial-a-bus represents an effort to lower the per-passenger cost of a taxicab by encouraging group riding. This presupposes a density sufficiently high so that several people with similar origins and destinations can be found at any one place and time. As density declines, either the waiting times and detours necessary to serve several people door-to-door with the same vehicle increase so much that service is no longer attractive or the vehicle occupancy shrinks so much that it is no longer higher than a taxicab's.

In practice, dial-a-buses operated in the manner of taxicabs, i.e., between many random origins and destinations, have attained occupancies only moderately higher than taxis. By contrast, service from many origins to a fixed destination (such as a railroad station or a shopping center), or subscription service (where a predictable pattern of trips is served each day) can attain occupancies that begin to come close to those of fixed-route buses.

On the cost side, the wage rates are critical. Even if dial-a-bus attains twice the occupancy of a taxi, but higher wages and benefits make its operating cost twice as high, cost per passenger is no lower than on a taxi. On a number of experimental services, this is what happened. Costs often exceed those of taxis, and with a low fare, the subsidy alone averaged over $2 per ride in 1974 prices, more than the average taxi fare.

Based on existing experience, **dial-a-bus in service between many origins and many destinations** can carry passengers at a cost lower than the taxi only if the wage rates are such that the cost per vehicle-hour is less than twice that of local taxis. In that case, such dial-a-bus service may be applicable at densities between about 6 and 12 dwellings per acre. If wage rates are higher, then the social purpose of dial-a-bus (providing mobility to transit-dependent areas where other public transit is inadequate) could be served at a lower cost by offering subsidized rides on local taxis. Allowing ride-sharing on taxis in many-to-many service will not lower taxi costs appreciably, because the probability of shared rides is low.

Conditions are quite different for **fixed-destination and subscription services**; at costs per vehicle-hour twice those of taxicabs, these appear to be competitive with taxis in cost per passenger at densities above 3.5 dwellings per acre; at operating costs twice those of taxis, above about 5 dwellings per acre. Also, allowing ride sharing on taxicabs in situations where many people are going to the same destination can lower their cost appreciably.

Empirically, dial-a-bus systems have served suburban areas with densities between 4.6 and 11 dwellings per acre and urban poverty areas with up to 27 dwellings per acre. Their service areas have typically been small (less than 10 square miles), their daily service spans mostly less than 24 hours (sometimes only 12 hours), and waiting times between 10 and 30 minutes.

**Jitney service**, a nonscheduled operation along a fixed route, is not investigated in this study. Conceptually, however, jitneys are not a mode for low-density areas. They require densities similar to those of local buses with a rather frequent schedule, otherwise the waiting time becomes excessive. Surviving jitneys in the United States operate in such higher density environments as downtown San Francisco, Pittsburgh and Atlantic City.

**Local Bus**

In contrast to demand-responsive modes, local buses operate according to a schedule along fixed routes; their service level is defined by the spacing of routes, the frequency of service, the hours of service and their speed. Assuming that parallel bus routes are spaced one-half mile apart (or routes forming a grid are spaced one mile apart), three service frequencies are examined here: "minimum service" (20 bus runs per direction per day), "intermediate service" (40 runs), and "frequent service" (120 runs).

Exhibit 4 displays the dollar costs of providing these levels of service at different densities. Speeds encountered on the average at these densities are assumed, as
is an operating cost of $15 per bus-hour, corresponding to wage rates in the lower range as of 1974. Reading along the right-hand scale one can find, for example, that an “intermediate” service would cost $120 per square mile at 2 dwellings per acre, $160 at 5 dwellings per acre, and $230 at 15 dwellings per acre; the increase in cost reflects a decline in operating speed.

Along the left-hand scale of the exhibit, the costs per square mile are converted into daily costs per resident, assuming neighborhoods that have an average share of land area devoted to residential use. Providing the “intermediate” service (half-hourly over 20 hours, on the average) would cost about 12c per resident per day at a density of 2 dwellings per acre, 5c at 5 dwellings per acre, but only about 2c at 15 dwellings per acre.

More pertinent, of course, are costs per passenger, i.e., the cost of service per square mile divided by twice the number of passengers originating in the square mile (to cover round trips).

With per capita bus trip rates characteristic, on the average, of different densities in the New York Region, with operating costs between $15 and $20 per bus-hour and costs per passenger of 50c to 75c, also typical of the Region in 1974, enough bus passengers can be found to provide “minimum” bus service at a density of 4 dwellings per acre; “intermediate” bus service at 7 dwellings per acre; and “frequent” bus service at 15 dwellings per acre. The fare in these cases covered 70 to 95 percent of the operating cost.

In any particular municipality, conditions may depart significantly from region-wide averages. For example, the town of Westport, Connecticut, was able to provide about the equivalent of “minimum” service (half-hourly over 14 hours with 1.5 route-miles per square mile) at a density of just under two dwellings per acre. Demand in Westport is far above expected levels for a number of reasons, including a service level unusual for the low density and a very low fare, paid mostly through pre-purchased annual passes. While the subsidy at 50c per ride on the “minny-buses” was high, it is much less than for most dial-a-bus services, which operate in areas of considerably higher density.

By contrast, Poughkeepsie, New York, supported about “minimum” service (half-hourly over 12 hours with 2.4 route-miles per square mile) at a density of 11 dwellings per acre and at a cost lower than Westport only because of lower wage rates. Yet the demand in Poughkeepsie is only moderately below region-wide levels, considering that it is outside the Manhattan commutershed and that its downtown is small.

At any particular residential density, the demand will vary depending on the area’s distance from a nonresidential concentration, the size of that concentration and its character (whether a downtown, a suburban shopping-oriented cluster, or one with mixed use). Exhibit 5 separates some of these major factors influencing demand. It shows the maximum distance at which an area of a given residential density can be from a downtown cluster of a given size (measured in square feet of gross nonresidential floorspace) and produce enough bus trips at three selected service frequencies to keep the cost per passenger within reason, i.e., have 30 passenger boardings per bus-hour, a standard that was maintained in the preceding examples. Only trips from the residential area to the nonresidential cluster in question are considered in the exhibit. In real life, a number of different nonresidential clusters might well be within reach of a residential area, and its bus service would be appropriately enhanced.

Exhibit 5 shows, for example, that to support “intermediate” service, an area with seven dwellings per acre must be at most two miles from a downtown of eight million square feet (the size of Elizabeth, New Jersey) or four miles from a downtown of 20 million square feet (somewhat larger than Bridgeport, Connecticut) or seven miles from a downtown of 50 million square feet (the size of Newark, New Jersey). It also can be seen that given, say, a downtown of 20 million square feet and a location five miles away from it, the density must be five dwellings per acre to support “minimum” bus service (upper chart), and eleven dwellings per acre to support “intermediate” service; “frequent” service would require a density of 45 dwellings per acre, which is unrealistic for that density as indicated by the dashed curve. Generally, knowing any three of the four factors, net residential density, downtown size, the distance between them and the service frequency, the fourth factor can be found from the charts.

Exhibit 5 deals with downtown-type nonresidential clusters. The ability of shopping-oriented spread suburban clusters to support transit does not differ much from that of small downtowns (generally below five million square feet of nonresidential floorspace). By contrast, highway-oriented spread clusters with mixed use (offices, factories, retailing and wholesaling) attract only about half as many transit trips as downtowns do and therefore cannot support any bus service on their own, unless they are surrounded by densities in excess of seven dwellings per acre. They can, of course, receive some service from routes leading to a nearby downtown.

Exhibit 5 deals with the ability of an average square mile to support bus service. Bus routes, however, typically traverse several square miles which vary in density. Those closer to a downtown, with a higher density and hence more than the assumed 30 passenger boardings per bus-hour at each of the service levels, may generate surplus revenue to subsidize the route considerably beyond the distances indicated. The distances in the exhibit hold true only if density does not change with distance. If there is a density gradient, average density over the entire tributary area of a route must be taken into account, and each route must be examined individually.
The costs of providing a given level of bus service per square mile (shown along the right scale of this chart) are easily calculated. They go up somewhat with rising density because of slower speed. However, calculated per resident of the area served (left scale) costs drop very sharply. Costs per passenger drop even more sharply, because at higher densities each resident makes more bus trips. Costs per passenger are not shown because the number of trips per resident depends on many factors other than residential density in the area.
Bus routes to each downtown size tend to have an optimum service frequency, one that results in the lowest cost per passenger-mile. (Passenger-miles are used because cost per passenger at different downtown sizes is likely to conceal differences in average trip length).

Thus the “minimum” frequency (20 runs per day with half-mile route spacing or its equivalent) appears to provide service at the lowest cost to a downtown of about 10 million square feet (White Plains, New York). Smaller downtowns have insufficient demand to fill the buses at that frequency, so cost rises, though it is still within reason for a downtown of five million square feet.

As downtown size rises above 10 million square feet, “minimum” service becomes insufficient to satisfy peak hour demand; more buses must be added, until the service becomes an “intermediate” one. At about 35 million square feet (Hartford, Connecticut), “frequent” service becomes necessary.

With rising downtown size, the surrounding residential density rises, so bus operating speed declines, making local bus operations to the larger downtowns more costly. This rise in local bus costs to downtowns above about 20 million, and particularly those above 50 million square feet, leads to the consideration of other transit modes for the larger downtowns.

Express Bus

The express bus differs from the local bus in its manner of operation. Rather than picking up and discharging passengers continuously, it travels non-stop over a major portion of the route, making use of freeways whenever possible. Preferential treatment or even exclusive bus lanes may be provided. Therefore, express bus speed is not neatly related to density as local bus speed is but must be ascertained case by case. Also, the length of the route is critical to know how many bus-hours will be needed to provide a given service frequency; the bus-hours will include largely empty return runs. Lastly, the tributary area from which the express bus collects its passengers must be known: it will be quite different depending on whether most patrons will walk or arrive by auto. For these reasons, the feasibility of express bus service can only by analyzed by way of examples under assumed conditions.

Two types of service are examined: pedestrian collection from a two square mile residential area (in which the bus is assumed to circulate for 15 minutes before it begins the non-stop run), and park-and-ride collection (in which passengers drive or are driven from an area assumed to be 20 square miles). For both cases, a cost of $15 per bus-hour is assumed as before, and the bus-hours are added in four-hour increments, assuming that a split shift is allowed by the labor contract. On the demand side, all trips are assumed to be for work purpose only, occurring over a two-hour period inbound and a two-hour period outbound.
Exhibit 6 relates downtown size and the average residential density of the collection area to express bus routes of stated length and service frequency. Pedestrian collection and park-and-ride services are shown separately; the speed on the express run is assumed to be 25 mph.

If a cost limit of 10¢ per passenger-mile is used as a measure of supportable service (in scale with both existing express bus service and potential rail competition), then the pedestrian collection service can be supported only for the minimal frequency of five buses over a two-hour period in a limited number of circumstances: residential densities of 15 dwellings per acre or more at a distance of 10 miles or less from a downtown of 50 million square feet, for example. In reality, such density over a two square mile area at this distance is likely to be associated with downtowns much larger than 50 million square feet.

If instead of 10¢, a limit of 20¢ per passenger-mile is assumed (in scale with local bus service that the express bus might replace), the potential range of an express bus with pedestrian collection enlarges considerably, as seen in Exhibit 6. One should remember though, that at 20¢ per passenger-mile, the 10-mile express bus trip will cost $2 per passenger, even with the low driver wages subsumed in the $15 cost per hour.

In sum, express buses with pedestrian access will work mostly in the vicinity of very large cities and can operate only at very low frequencies. The major existing walk-to-express-bus services are located in the Washington area, in New Jersey, and in New York City.

The park-and-ride express bus operation, by contrast, collects passengers from a large tributary area, and so can be supported in a variety of situations. At a cost of 10¢ per passenger-mile the minimum frequency of five buses in two hours will work for residential densities around four dwellings per acre up to 20 miles distant from a downtown of 50 million square feet (the size of Newark), 15 miles from a downtown of

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**Exhibit 6**

Downtown Size, Residential Density and Distance by Express Bus Service Frequency at Given Cost Per Passenger-Mile

**EXPRESS BUS PEDESTRIAN ACCESS**

**MINIMUM SERVICE**

5 buses in two-hour peak period

$0.10 per passenger-mile

$0.20 per passenger-mile

5 miles from downtown

**INTERMEDIATE SERVICE**

10 buses in two-hour peak period

$0.10 per passenger-mile

$0.20 per passenger-mile

5 miles from downtown

**EXPRESS BUS PARK-AND-RISE**

$0.10 per passenger-mile only

**MINIMUM SERVICE**

5 buses in two-hour peak period

20

15

10

5 miles from downtown

**INTERMEDIATE SERVICE**

10 buses in two-hour peak period

$0.10 per passenger-mile

$0.20 per passenger-mile

5 miles from downtown

**Note:** Dashed lines indicate unlikely average residential densities in tributary area at given distance from downtown of given size.
35 million square feet (Hartford) or five miles from a downtown of 20 million square feet (Bridgeport), as shown in Exhibit 6. The higher frequency of 10 buses in two hours can be supported over shorter distances (five miles) by downtowns in the 20 to 50 million square foot range if densities of 3 to 6 dwellings per acre are found on the average within the 20 square mile tributary area assumed. Of course, park-and-ride service over a distance as short as five miles may not be too attractive to motorists if auto access to a downtown is easy. If a cost of 20¢ per passenger-mile is acceptable, then park-and-ride service can cover an even wider range of conditions than shown in Exhibit 6, including slower speed and more frequent service.

In sum, park-and-ride express bus service can provide low and intermediate service frequency (5 to 10 buses in a two-hour period) to downtowns in the 20 to 50 million square foot range or larger, for distances up to about 15 miles, from residential areas with densities above three dwellings per acre. It is broadly applicable to medium-sized cities but becomes difficult for downtown sizes of 20 million square feet or less.

Empirical evidence in Connecticut supports these conclusions. Hartford, with a downtown of some 35 million square feet (including 7.4 million square feet of office space) supports a healthy array of park-and-ride express bus routes; by contrast, in New Haven, with 26 million square feet of nonresidential floorspace (of which 3.6 million square feet are offices) only one of two express bus routes has developed reasonable patronage. Other Connecticut downtowns, with fewer than 20 million square feet of nonresidential space, do not have express bus service.

Light Rail

Light rail vehicles, better known as streetcars, were for a time the dominant mode of urban public transportation. But they had to bear track and power maintenance costs which buses did not and were hampered by street traffic, in which buses could maneuver with greater ease; this contributed to their demise. Significantly, most surviving light rail operations in North America have reserved rights-of-way. If able to attain higher speed than the bus on a comparable route, light rail can be less expensive to operate, even today. This advantage is expected to increase with the introduction of new, larger vehicles.

The promise of reduced operating cost and the amenity of tracked, electric vehicles led to a renewed interest in light rail. One possible application is the substitution of light rail cars for ordinary railroad equipment on some lightly used commuter rail lines. With their much lower operating cost (due largely to different labor arrangements), light rail cars on such routes could attain greater service frequency and attract more passengers. The conversion of the Riverside Line in Boston in 1959 is often cited as a prototype: it increased ridership on the line tenfold.

More broadly, light rail on reserved rights-of-way is viewed as junior rapid transit for medium-sized downtowns. Full grade separation is not necessary: grade crossings with intersecting streets can be controlled by signals assuring priority, and slower speed allows sharper curves, steeper grades, and less elaborate stations, resulting in savings compared to full rapid transit. Compared to buses, light rail vehicles have the advantage of operating through tunnels without costly ventilation. Or, if the attitude toward allowing the auto anywhere in downtown changes, streets can be dedicated to pedestrians and streetcars only, minimizing the conflicts of mixed traffic without the expense of tunneling. However, since most of the cost advantage of light rail over buses is expected to come from larger vehicle size, such a substitution can lead to lower service frequency; it therefore makes sense primarily on heavily travelled routes.

To explore such relationships, hypothetical light rail corridors are examined for downtowns of 20, 35, 50 and 100 million square feet. A residential density gradient is assumed for each downtown size, as is the length of the route and its tributary area, which covers one-seventh of a city assumed to be circular in shape. It is further assumed that within a one-mile band centered on the light rail route, its influence on the choice of mode is the same as that of rapid transit; beyond that band, the same as in bus territory with sparse service. It is assumed that all public transit trips to downtown from the tributary area use the route (except for some in the immediate downtown vicinity) and that 30 percent of the one-directional flow occurs in the peak hour.

Under these assumptions, even a downtown of 20 million square feet (somewhat smaller than New Haven, Connecticut) can support a respectable service frequency, i.e., 12 runs in the peak hour of the new Standard Light Rail Vehicles. A downtown of 50 million square feet would require 24 two-car trains during the peak hour. Thus, even with vehicles twice as large as buses, insufficient frequency does not seem to be a problem for light rail at any of the downtown sizes tested.

Assuming stations spaced half a mile apart, speeds (including an allowance for layover time) in the 15 to 20 mph range, and a cost per vehicle-hour of $28.50 in 1974 prices, the cost per passenger on the hypothetical routes is found to be in the 31¢ to 34¢ range and the cost per passenger-mile in the 7¢ to 10¢ range. These results, much superior to those of local buses, stem from a large number of passenger boardings per vehicle-hour, attained by a combination of high speed and a large tributary area of the assumed route, which ranges from 25 square miles for the smallest downtown to 100 square miles for the largest. Roughly one-third of the patrons arrive from beyond the one-mile band within which access to stations on foot is possible.
The high performance of light rail hinges on a reserved and perhaps partially grade-separated right-of-way, the provision of which requires capital expenditures. Using a rough investment yardstick of $1,500 per daily passenger-mile, related earlier to the construction of BART, a 6-mile light rail route to a downtown of 20 million square feet would on the basis of its passenger use, warrant an investment of $38.5 million in 1974 prices; this might be enough to equip the line only if a fully prepared right-of-way exists in the right place. By the same reckoning, a downtown of 35 million square feet might warrant spending $102 million for a 9-mile route, or $11 million a mile. This does leave some money for heavy construction. A downtown of 50 million square feet might warrant spending $212 million on a 12-mile route; at $17.5 million a mile on the average, this allows a short tunnel for downtown access and some other grade separation.

In sum, the calculations suggest that light rail seems promising for downtowns in the 35 to 50 million square foot range, generally found in metropolitan areas with more than three-quarter million inhabitants; under fortuitous circumstances of existing rights-of-way, individual lines may be workable to downtowns as small as 20 million square feet. Averaged over the length of the route, residential densities of 9 to 12 dwellings per acre or more can be served.

**Light Guideway Transit**

Light guideway transit is a new, usually automated mode, limited so far to fairly small installations but sometimes advocated for area-wide urban systems. Comparing the larger of the automated systems with manned light rail, it appears that their hourly operating costs per rider space are similar; but the speed of the automated systems is lower as are passenger occupancies. This suggests higher cost per passenger-mile. The advantage of automated vehicles is that they can provide frequent service even for low traffic volumes, especially in off-peak hours.

The key difficulty is that the capital cost of automated light guideways is inherently much higher than that of light rail because of the need for complete grade separation, elaborate stations, and complex control equipment. It cost about $7 million a mile to build the Dallas Airport system and $27 million a mile for the Morgantown system. The latter is closer to what would be needed to insert a new guideway into an existing urban area. At low traffic volumes, where the capability of small automated vehicles for frequent service would be most useful, the investment per daily passenger-mile can easily exceed $3,000—about twice the cost of BART and three times that of the Second Avenue subway in Manhattan. On the other hand, serving traffic volumes sufficiently large to keep capital cost per passenger-mile within reason would mean, with urban peaking patterns, peak volumes of a magnitude that single small vehicles cannot handle. Some light guideway systems are equipped to operate in trains, but such systems are more akin to traditional rapid transit than to “personal rapid transit”—with demand-responsive operation where stops are skipped when no one gets on or off and “vehicles wait for passengers instead of vice versa”—what many light guideway designers initially envisaged.

In short, in those line-haul applications where the unique attributes of automated light guideways would be most useful, the capital cost per passenger-mile of the present technology is far above a reasonable range. Where passenger volume could justify the high capital cost, traditional transit, such as light rail, seems able to provide satisfactory service frequency at a lower capital cost and at a similar or lower operating cost. The present generation of light guideways seems limited to special applications, not to line-haul use with its high peaks. Morgantown appears to be an appropriate special application: use throughout the day on a university campus results in high passenger-miles per mile of route, despite a relatively low peak period capacity.

Much research in light guideways is directed toward attaining shorter headways between the small vehicles and hence peak period capacity competitive with traditional rail systems. A more promising research thrust would be to greatly simplify the design of the guideways and of the appurtenant hardware so that capital cost can be reduced to a level where light guideways could economically serve modest traffic volumes, below the reach of traditional transit. A related aim would be to reduce the visual bulk of the elevated guideways, to improve their community acceptance.

**Standard Rapid Transit**

Standard rapid transit comes into its own where travel volumes are sufficiently high so that vehicle operation in trains, rather than singly, can still provide reasonably high frequency, and where travel distances are such as to require speeds higher than those which light rail or light guideway transit can provide. It becomes necessary when travel volumes exceed the capacity of light rail.

Thus rapid transit appears inappropriate for downtowns of less than 50 million square feet, mostly because the economies of train operation cannot be adequately realized without sacrificing service frequency. On the other hand, to a downtown above 100 million square feet, the travel volume on a tramline just about reaches the practical capacity of light rail, making rapid transit necessary above that point. Just as with light rail, as long as the attraction of a large downtown is present and as long as access to stations by feeder modes exists, moderate residential densities, averaging perhaps 12 dwellings per acre over the tributary area, can support rapid transit.

Scaling capital costs against the illustrative yardstick of $1,500 per daily passenger-mile, it was shown before that for a downtown of 50 million square feet, $17.5 million a mile could be spent. This would buy a 12-mile light rail route of a high standard but would
not build rapid transit. Cutting the route to six miles might cut passengers less than 20 percent but reduce passenger-miles about 40 percent, allowing an investment of perhaps $22 million a mile, which might suffice only if existing rights-of-way are available. By contrast, for a downtown of 100 million square feet, $40 million a mile could be spent on a 15-mile route. This would buy rapid transit. Both the Washington and the Atlanta rapid transit systems cost about $40 million a mile in 1974-75 prices. In both the light rail and rapid transit examples, the possibility of 6 to 7 radial trunks was assumed. This implies most a 40-mile system for a downtown of 50 million square feet and one of about 100 miles for a downtown of 100 million square feet.

On operating grounds as well as on the grounds of capital cost, rapid transit to a downtown of 50 million square feet of total nonresidential floorspace appears to be a touch-and-go proposition. Generally speaking, a downtown size larger than that—closer to 100 million square feet—seems to be needed both to attain frequent service with reasonably long trains and to make the capital investment in guideways cost-effective. Among North American downtowns served by rapid transit, Chicago has over 280 million, Washington about 95 million, Montreal 91 million and Toronto over 75 million square feet of nonresidential floorspace.

Because total nonresidential floorspace figures for many downtowns are not readily available, and because transit ridership may be more closely related to office floorspace than to total nonresidential floorspace, empirical comparisons of rapid transit ridership and office floorspace in central business districts can be useful. Downtown, as defined in this study, represents a contiguous area of nonresidential use; central business districts are typically smaller and represent the core of downtown. Under existing conditions, central business districts with less than 15 million square feet of office floorspace tend to generate rather meager rapid transit use, i.e., about 80,000 daily riders or less, which is enough to fill two rather lightly used transit spkes. As of 1970, there were only about half a dozen central business districts in North America which had more than 15 million square feet of office space and which did not have rapid transit in operation or under construction. One of them was Atlanta, which started construction in 1975; the others were Los Angeles, Detroit, Pittsburgh, Dallas and Houston; Baltimore was on the borderline.

One should add that while downtown size is a much better criterion of transit feasibility than population size, it is by no means the only one. The shape of the urbanized area plays a very important role. If topography squeezes settlement and travel into a few narrow corridors, the chances for rapid transit are much better than when development is spread over a featureless plain, which was assumed in the examples investigated.

**Commuter Rail**

Commuter rail is a highly specialized mode of public transit; significant use in North America is limited to only seven urban areas: New York, Chicago, Philadelphia, Montreal, Boston, Toronto and San Francisco. All have more than 25 million square feet of office space in their central business districts. Washington, with 54 million square feet of office space, had only modest service. Detroit, with 23 million square feet was expanding its fledgling commuter service in 1976.

Inflated by labor arrangements, commuter rail operating costs are high. However, because of high speed and fairly high passenger occupancy, the operating cost per passenger-mile is not out of line with rapid transit and often is similar to express bus. Generally, commuter rail appears able to attract more passengers than buses under comparable conditions.

Opportunities for the expansion of commuter rail into presently unserved territory depend on the presence of existing rail lines which can be upgraded at moderate capital expenditure and which lead to a very large downtown. Where such lines can be found, the residential density needed to support a commuter rail line is very low, because of dependence on auto access to stations and of the relatively infrequent nature of the service.

For example, 128 passengers a day boarding trains for each mile of rail route can support a rather good frequency of 20 six-car trains a day, paying an average of $1.80 to $2.50 for a trip that averages 25 miles. The residential density would have to be fairly high if all of the 128 passengers were to live within walking distance of stations. In reality, they do not. In the New York Region, they may come from an area of seven square miles if the density is two dwellings per acre, and 12 square miles if the density is one dwelling per acre. As a result, residential densities as low as 1 to 2 dwellings per acre can support commuter rail if about 10 to 20 trips per day can be found originating in a square mile and destined for a very large downtown.
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| World Total | 67.2 242.1 627.3 931.2 1,117.4 1,567.4 1,900.8 | 144.8 13.2 |
| U.S. Total  | 32.2 100.1 323.5 430.7 428.7 466.5 549.1 | 25.2 21.2 |

Route-miles without duplication (for first-track miles) of grade-separated urban rapid transit; excludes commuter or suburban railroads, and portions of them which may operate in tunnels in inner urban areas; includes those portions of light rail or streetcar lines which operate in tunnels and are sometimes known as pre-metro (marked PM). Not all miles conform exactly to years shown.


*Includes NYCTA 230.6 mi, SHRTA 14.3 mi, PATH 13.9 mi, and Newark Subway 4.3 mi.
**Includes 18 miles of streetcar routes in tunnel or on grade-separated right-of-way.
***Includes 3.1 miles which are inoperative due to partition of the city.
****Includes SEPTA subway-elevated 22.1 mi, SEPTA Norristown line 13.5 mi, PATCO Lindenwold 14.0 mi.

Metric conversion: 1 mile = 1,609 Km.
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