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# Patronage Estimate for Downtown People Movers

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**To provide some guidance in the early planning and conceptual design of downtown people movers, a rough, aggregate approach was developed for determining the effects on ridership of major downtown people movers design and policy decisions. The approach is an abstract, parametric analysis that uses aggregate relations and simplified assumptions to show how ridership of downtown people movers is influenced by (a) alternative downtown people movers design configurations (i.e., such factors as number of stations and station spacing), (b) operating characteristics and policies (i.e., such factors as speeds, headway, and fare), and (c) the size, density, and distribution of activities in the central business district. Trips in five categories are examined separately for possible diversion to downtown people movers: regional trips to the central business district by automobile and transit and internal central business district trips by automobile, transit, and walking. The many combinations of site, system, and service variables tested allow general implications to be drawn from the numerical results. Among the most important are the following: (a) station spacings below or above the 366-488-m (1200-1600-ft) range begin to be less efficient; (b) systems that interface with regional transit at a central business district fringe station divert more transit passengers than does a central delivery arrangement, except in large, spread central business districts; (c) parking fees and capacities at downtown people movers stations are major factors in potential diversion of automobile users to downtown people movers; and (d) downtown people movers service policies have less effect on ridership than fares, except where downtown people movers are in competition with the local central business district bus.**

Since no downtown people mover (DPM) systems have yet been built in this country, we have little experience to draw on in their plan, design, and implementation. Specifically, we have no basis for estimating their patronage. As part of its program for transportation planning support to urban areas, the Urban Mass Transportation Administration (UMTA) has developed several aids for planners of DPM systems, such as a DPM guideway-simulation model. Another of these is a report (1) that brings together the state of the art in planning data and methods for use in cities interested in DPM systems.

Before even the preliminary design of a DPM system is attempted for a specific downtown area, the planner must first determine whether or not a DPM is potentially suitable in the area. The planner must recognize the potential consequences of major design decisions about overall guideway length, number of stations, station spacing, and interfaces with the transit and highway systems. A chapter of the DPM planning methods report on aggregate analysis of system feasibility (1) presents a broad-brush parametric analysis by using aggregate relationships and simplified assumptions to examine the effects of alternative system configurations and service policies on potential DPM ridership. The planner can use the information in several ways: (a) a few basic pieces of data can be used to develop rough ridership estimates in a matter of minutes, by using the charts and tables; (b) more accurate patronage figures can be produced by using a worksheet technique, which is included to allow the use of more specific data; and (c) general implications and rules of thumb that can be used in initial considerations of policy and design can be derived from the results of the parametric analysis for several types of DPM use.

## GENERAL APPROACH

The procedure used to estimate demand for the DPM system requires neither detailed data on zones or individual trip making nor site-specific data on trip making. It relies on travel demand and transportation system characteristics typical, on the average, of various-sized downtowns in North America.

The method first develops aggregate relationships between travel in the central business district (CBD) and CBD activities measured by employment and floor space. These relationships are used to estimate five categories of existing CBD trips, each of which has a potential for diversion to a DPM system:

Regional CBD trips (one end outside CBD, one end inside)
1. Transit
2. Automobile

Internal CBD trips (both ends inside CBD)
3. Walk
4. Transit
5. Automobile

An abstraction of the CBD is assumed in that it is characterized by only three parameters: employment (or floor space), area size, and density gradient, where the gradient reflects either a spread or concentrated pattern of activities about the central point. Similarly, DPM system configurations analyzed in the CBD are described primarily by the number and spacing of stations, which are located for maximum CBD coverage.

To estimate possible diversions to DPM for each of the five trips listed above, a de facto "maxizone" structure is used in which each zone, in general, corresponds to each DPM station. Trips are allocated to each zone by use of the activity density gradient. Then the average non-DPM trip between each pair of stations is compared in terms of costs and travel times with that trip if taken by DPM. A percentage of the trip interchange volume for that pair, which corresponds to those portions of the zones for which the DPM holds an advantage, is then allocated to DPM.

Several other assumptions are used to simplify the analysis. Of particular importance are the assumed values of time that are used to convert trip times and costs to equivalent units for comparison of the impedances, or disutilities, of alternative modes. These were taken from the literature rather than derived from equations or models estimated for this study. The set of values used is given in the table below.

| | Walking Costs | | Automobile User Costs | |
|---|---|---|---|---|
| Mode | ($/min) | ($/h) | ($/min) | ($/h) |
| Transfer or ascend escalator | 0.05 | 3.00 | 0.08 | 4.80 |
| Wait | 0.03 | 1.80 | 0.05 | 3.00 |
| Ride | 0.02 | 1.20 | 0.03 | 1.80 |
| Walk | 0.05 | 3.00 | 0.08 | 4.80 |

Figure 1. Regional CBD trip ends.

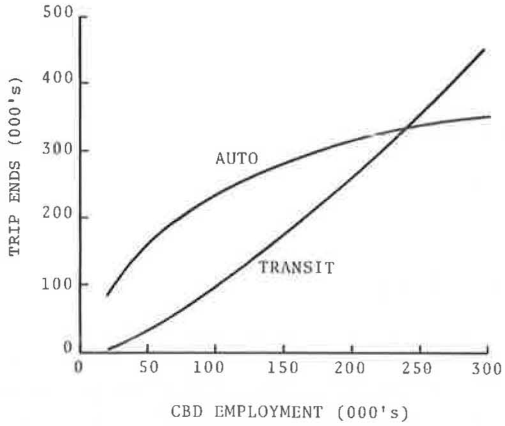


Figure 2. (a) CBD trip ends; (b) internal trip ends.

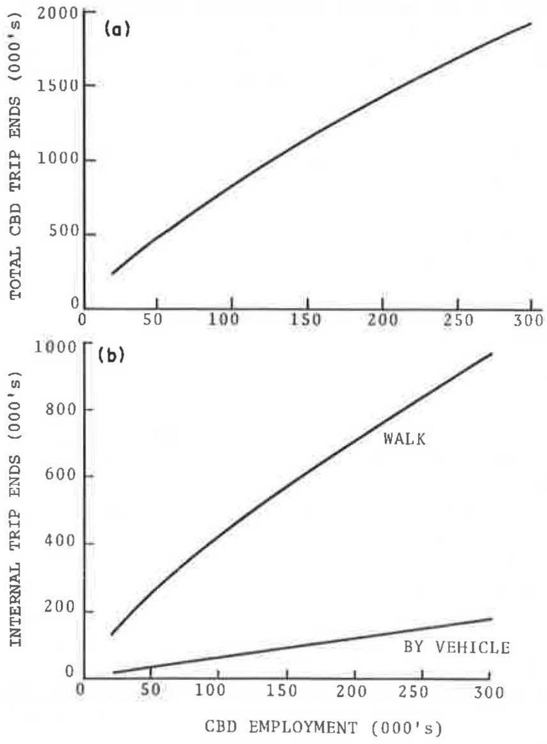
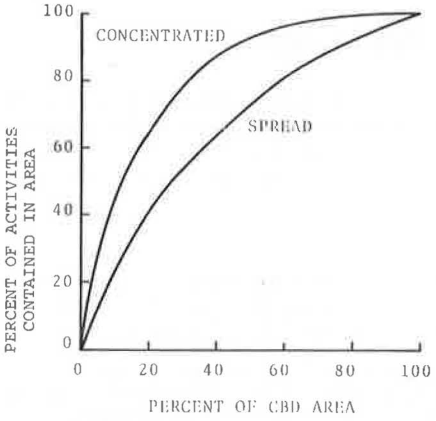


Figure 3. Activity estimation.



DPM daily ridership figures are calculated for different sized downtowns by parametrically varying the system configuration variables and three service variables—headway, vehicle speed, and fare. The estimates are unconstrained by any capacity considerations related to automobile parking or to the DPM system itself.

## TRIP GENERATION ESTIMATES

The trip generation estimation procedure was designed to yield trip volumes in the five trip categories listed above. The first step involved the estimation of regional CBD trips for automobile and transit, that is, trips that have one end external to the CBD and the other end inside the CBD. Several relations were developed by use of simple least squares regression techniques. These include (a) the use of CBD employment and floor space data, (b) the direct estimation of trip ends versus intermediate computations of transit mode shares, and (c) combinations of the data. Empirical data from about two dozen CBDs of widely varying characteristics were used to develop these relations. Estimates based on each yielded similar results; most correlation coefficients $(r^2)$ were in the 0.80-0.90 range. Figure 1 shows the regional CBD trip ends by automobile and transit for a range of CBD employment up to 300 000. The share of transit trip ends increases rapidly for larger CBDs.

The second step was to estimate the total number of internal trip ends, that is, trips that both begin and end in the CBD. This was done by use of trip-end rates for three types of CBD floor space (office, retail, and other) to first estimate all trips that have at least one end in the CBD. Average values of total floor space, percentage of floor space by type, and trip-end rates were used and, where data indicated, varied with CBD size. Trip ends are summed and plotted in Figure 2a. Internal trip ends were then derived by subtracting the regional CBD trip ends from the total CBD trip ends.

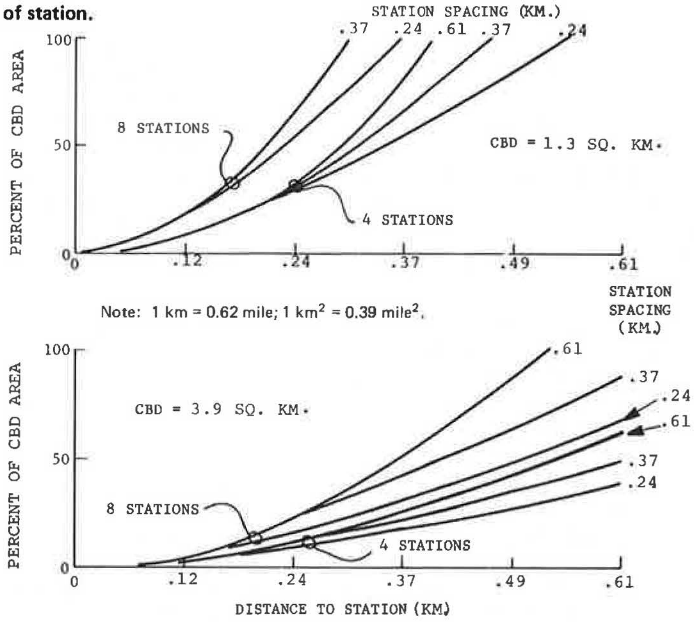
The final step in the trip generation process was to split the internal trip ends into trip ends by walking only, automobile, and transit. An apportionment was made first between walking trips and vehicle-mode trips, again by use of trip rates for floor space by type. These trip ends are shown in Figure 2b. The vehicle-mode trips were then split into automobile and transit modes by use of average transit mode shares by size of CBD based on data from about 10 cities. Transit shares ranged from about 60 percent for CBDs of 300 000 employees to about 10 percent for the smallest CBDs considered.

In this part of the study some of the weaker techniques of modeling are employed (2), namely, the use of long chains of calculations and the use of differences between numbers of the same order of magnitude. Nevertheless, the results seem reasonable, internally consistent, and appropriate for the intended effort.

## TRIP DISTRIBUTION PROCEDURE

The very simple procedure for allocation of trips to the DPM station maxizones is illustrated in Figures 3 and 4. Figure 3 describes, for two types of CBD density distributions, a cumulative distribution of activities for a given fraction of the CBD area. For example, the spread activity curves indicate that the densest 20 percent (in area) of the CBD contains 40 percent of the activities, and the next densest 20 percent contains about 20 percent of the activities in the CBD. The curves are based on small-area data from 10 cities where activities are measured variously by jobs, floor space, or trip destinations. These curves are used to estimate the

Figure 4. CBD area within given distance of station.



Note: 1 km = 0.62 mile; 1 km$^2$ = 0.39 mile$^2$.

share of CBD activities in a maxizone by the area of the maxizone and its density ranking compared to the other maxizones.

Figure 4 shows sample curves that describe, for two CBD area sizes, two sizes of DPM systems, three station spacings, and the percentage of the CBD area within a given distance of a DPM station. The coverage curves were derived geometrically, assuming that the stations are located to provide maximum area coverage, i.e., minimum overlap. The full set of coverage curves (given in the DPM planning report), and to some extent the samples of Figure 4, indicate graphically how the coverage can be increased by either increases in the number of stations or increases in the station spacing (the latter of which increases the total guideway length). The larger the number of stations in a given CBD area, the smaller is the range of potentially cost-effective station spacings available to choose from. This is because systems that have many stations may not physically fit into a given area if the station spacings are large. On the other hand, many stations spaced close together will result in substantial overlap in coverage.

Allocation of trips to the station maxizones involves use of the two figures as follows. If a 4.35 km$^2$ (1.7 mile$^2$) CBD has four stations at 366-m (1200-ft) spacing, each station, for simplicity, would have equal area coverage of about 12 percent of the CBD [within 610 m (2000 ft) of the station]. In the spread activity curve of Figure 4, the station located in the densest part of the CBD is assumed to have access from 26 percent of the CBD's activities, the station located in the next most dense maxizone, 21 percent (47-26), the third station 13 percent, and the last station 11 percent. The percentages of trips are assumed equivalent to the percentages of activities thus located.

## ESTIMATES OF DIVERSION TO DPM

Estimates of trips diverted from other modes to the DPM system are calculated separately for each of the five trip categories. All estimates are first developed in terms of percentages and then applied to the aggregate trip volumes to yield DPM trips. The diversion calculation procedures are similar in that each requires a comparison of the non-DPM (automobile, transit, or walking) trip with that of a DPM trip for the same origin-destination pair.

### Diversion of Regional Transit Trips

The knowledge of how trip ends are distributed about stations can be used to calculate the share of transit passengers likely to use the DPM if the destinations of the regional transit passengers are known. For example, the regional transit interface might be a central delivery point or it might be at one or more DPM stations at the fringe of the CBD. Also, walking is assumed to be the only alternative to DPM for the maxizone destinations, since any local CBD transit would be redesigned to avoid duplication with the DPM service.

The total DPM time and cost in dollars from a transit transfer station to a DPM destination station can be calculated by use of the values of time shown in the in-text table and a set of base DPM operating conditions and assumptions, such as headway (2 min), maximum vehicle speed [16 km/h (10 mph)], acceleration/deceleration [40 (km/h)/s (25 mph/s)], and no fare. This cost function does not include the access walk at the destination station.

The time cost for the walk-only trip can be calculated in a similar manner. Now the difference in the two cost functions represents the amount of walk at the destination DPM station of the DPM trip that would make the total costs of the DPM trip and walk-only trip equal. The data used to draw the curves of Figure 4 can be used to convert this break-even to the percentage of trip ends for which the DPM holds an advantage. If this procedure is performed for all relevant pairs of stations and all trips are added, the total number of transit diversions can be computed.

Figure 5 shows sample curves of transit diversions as a function of station spacing for two sizes of CBDs, two sizes of DPM systems, two-CBD density distributions, and alternative assumptions about where the transit system interfaces with the DPM system. A number of observations are suggested by the full set of curves (presented in the DPM planning report).

Short station spacings may be very inefficient. Spacing of 244 m (800 ft) generally attracts less than half the number of passengers of 366-m (1200-ft) spacings but requires two-thirds of the route length. However, if station spacing is increased beyond 366 m, the diversion rate begins to show diminishing returns. For systems that have many stations or in CBDs of small land areas, the diminishing returns become evident at shorter station spacings.

Similar route lengths produce similar diversion rates. More stations for the same route length produce only marginally more diversion.

In many cases, an increase in the number of stations may be desirable. For example, for a CBD land area of 2.6 km$^2$ (1 mile$^2$), eight stations achieve more than double the diversions of four stations, at least at lower station spacings. At the higher spacings, doubling the number of stations from four to eight remains efficient if regional transit users are delivered to a central point, but for the fringe delivery, returns diminish.

Delivery of all transit passengers to the fringe for transfer to the DPM will always produce greater diversions to the DPM than will a central delivery arrangement. In reality, it is exceedingly difficult to intercept all transit passengers at DPM stations since they arrive from many directions. Further, interception is not particularly desirable since many transit passengers may be forced to travel in a less direct manner. Nevertheless, the number of transit passengers who transfer to the DPM will be largely determined by the manner in which the existing line-haul transit system is modified to create the necessity for that transfer.

Comparison of the central delivery system to the more realistic 50 percent fringe delivery arrangement suggests that the former will work better for spread CBD distributions and for the larger systems.

The sensitivity of transit diversions to vehicle speed, headway, and fare was calculated. Representative results are plotted in Figure 6 for a CBD of 2.6 km$^2$ (1 mile$^2$), 8 stations, and a spread CBD. The following observations can be drawn from the sensitivity results.

Under any conditions, increase in maximum DPM vehicle speeds from 16 to 32 km/h (10 to 20 mph) diverts very few additional passengers to the DPM. This occurs because maximum speeds affect only the in-vehicle portion of the total DPM trip, which is a small share of its price to the user. Furthermore, the higher maximum speeds are diminished by frequent stopping and starting of the system.

The impact of more frequent service also has a limited effect. Doubling of frequencies [i.e., reductions in headways by half from 2 min (base condition) to 1 min] decreases the waiting time for the DPM passenger by only 30 s, again only a small portion of the total price of the DPM trip. Reductions in service frequency by half (i.e., doubling of headways from 2 min to 4 min), also produce quite modest differences in the diversion rate.

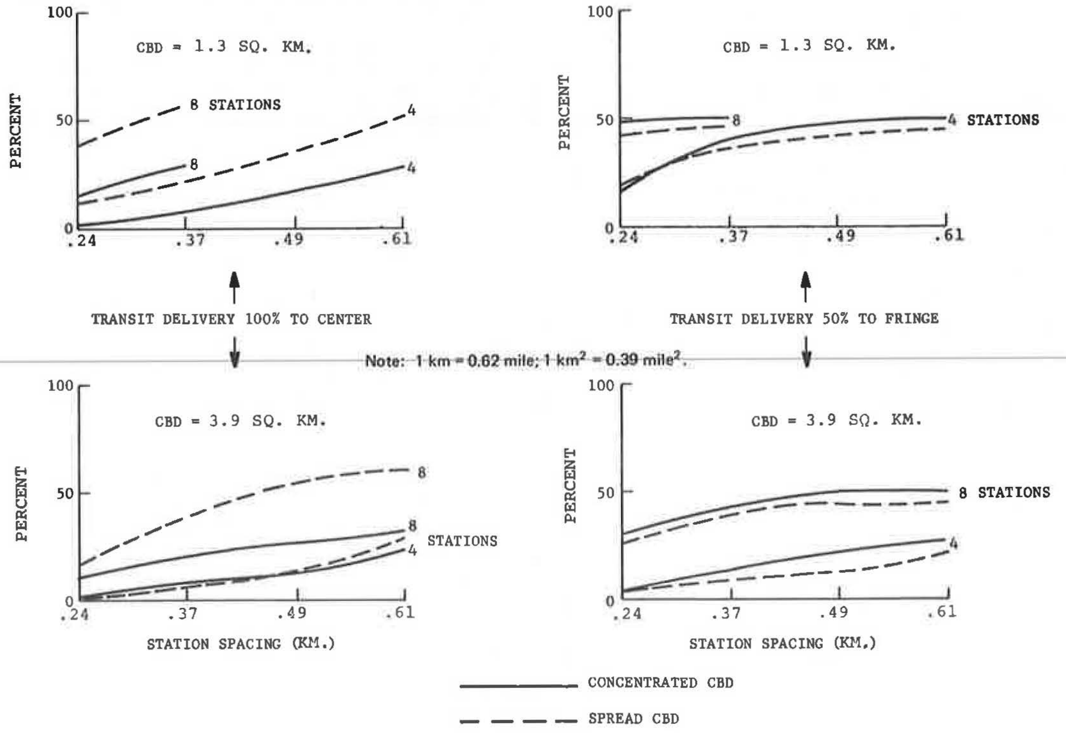
The imposition of fares has a sizable effect on diversion to the DPM. The percentage of reductions in ridership if the $0.25 fare were imposed appears to be greater for the smaller systems. Since smaller systems are more likely to be planned for smaller CBDs, this tends to confirm the finding reported elsewhere that fare elasticities tend to be larger in smaller metropolitan areas. The magnitudes of differences between no-fare and fare systems also conforms to the evidence that ridership doubles for CBD systems when fares are eliminated.

Operating changes generally have more impact on the central delivery arrangement than on the fringe delivery arrangement. This apparently occurs because most transit users delivered to the fringe are sufficiently far away from their trip end locations to require another mode. Those delivered to the center will be more sensitive to the characteristics of the DPM because they have generally shorter walks to their final destinations.

## Diversion of Regional Automobile Trips

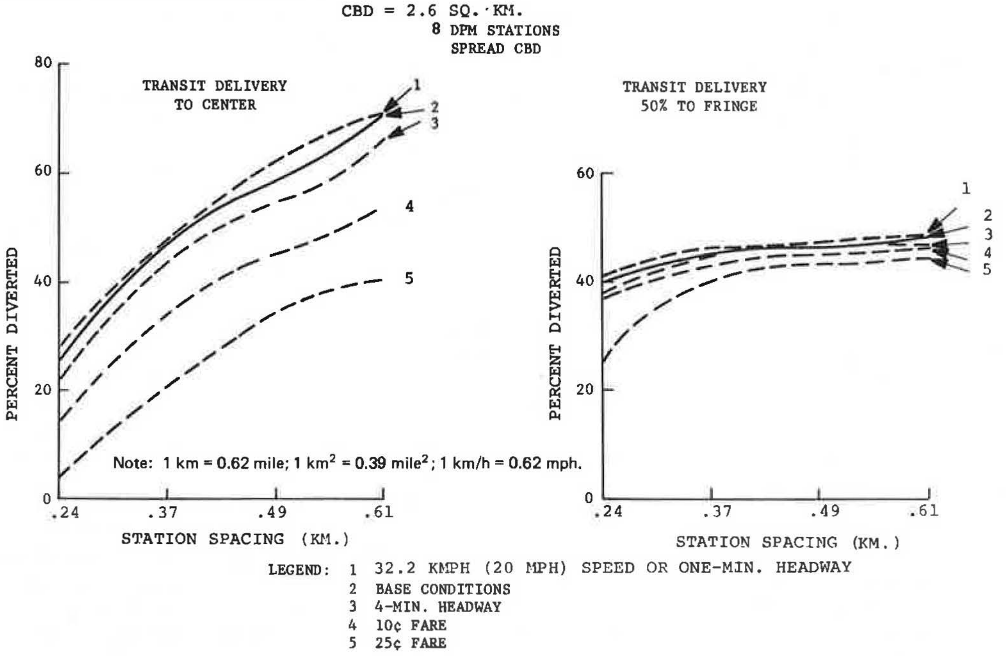
The methodology for determination of diversion of regional automobile trips is similar to that used for regional transit diversion. Several other variables per-

**Figure 5. Regional transit users diverted to DPM.**



Note: 1 km = 0.62 mile; 1 km$^2$ = 0.39 mile$^2$.

Figure 6. Transit diversion sensitivity to operating assumptions.



Note: 1 km = 0.62 mile; 1 km$^2$ = 0.39 mile$^2$; 1 km/h = 0.62 mph.

tinent to the automobile trip, such as CBD and DPM parking charges and automobile speeds in the CBD, are derived for the analysis on the basis of CBD size. Other assumptions relate to those automobile users whose parking is subsidized (assumed to be 20 percent of all automobile users), and how accessible the highway system is to DPM stations (assumed variable).

The complex interplay of the relationships that contribute to the diversion of automobile users suggests a number of observations relevant to the planning of a DPM system.

Each CBD configuration (jobs-area-distribution combination) appears to have a DPM configuration that can maximize diversion of automobile users to a DPM. This occurs because systems that are too small may not capture travel to a high proportion of CBD activities, and ambitious systems that have many stations and longer station spacings may lose riders who would have to spend excessive amounts of time on the system.

A CBD that covers a large area will require a larger system to reach the same diversion rates as a CBD of small area, but with the same overall amount of activities. For example, the 300 000-job, 8.9-km$^2$ (96-million ft$^2$) CBD could conceivably divert over 70 percent of automobile users to a four-station system if the CBD is contained in 1.3 km$^2$ (0.5 mile$^2$). However, if the area of the CBD is 3.9 km$^2$ (1.5 miles$^2$), eight or more stations that have longer spacings are required to achieve the same diversion rate.

A more concentrated CBD generally diverts more automobile users to the smaller DPM systems (4 stations). The reverse seems to be the case for larger systems (12 stations). This occurs because a small system can more efficiently service the fewer centers of activity in a concentrated CBD, but a spread CBD requires a more extensive system to service its more scattered locations.

High-activity CBDs can divert a substantial portion of all automobile users; low-activity CBDs can divert relatively few. This occurs largely because parking costs are usually sufficiently low in low-activity CBDs that there is little incentive to avoid them.

The most dramatic differences in diversion rates for automobile users occur as a result of the placement of sufficient parking areas at fringe DPM stations. Four well-placed stations around the fringe of the CBD that have good highway access may produce diversions several times as great as will one such station.

Sensitivities of automobile diversions to varying operating assumptions were tested. General observations from sensitivity testing showed that very high-activity CBDs show only minor changes in diversion rates for variations of operating conditions. This occurs because most automobile users found use of the DPM system overwhelmingly advantageous and the changes postulated made little difference. For very low-activity CBDs, the diversion rates also change very little. This is so because these automobile users found use of the DPM system overwhelmingly disadvantageous and the postulated changes made little difference.

CBDs in the middle range of activity show greater variation in diversion rates. This occurs because the choice of using the DPM is often not that clear-cut and small differences can tip the potential rider's decision in one direction or another.

As with transit users, automobile users will be most influenced by changes in fare; a $0.10 change in fare has considerably more impact than doubling speeds or doubling or halving headways.

## Diversion of Walking Trips

The same procedure was used to determine diversions of walking trips to DPM as was used for regional trips. A major consideration in the walking trip analysis is the variation of trip lengths with CBD size: the larger the CBD, the greater proportion of long walking trips. The walking trip-diversion analysis yields the following suggestions.

A DPM seldom attracts more than one-third of all walking trips. This occurs because a large share of such trips are for very short distances when the savings in time and convenience of using the DPM cannot be realized.

CBDs that have more activities will attract a larger share of walking trips to a DPM. This occurs because walking trip lengths are generally longer in such CBDs, so the choice of a DPM is relatively more attractive. CBDs where activities are concentrated will attract a larger share of walkers to the DPM than will spread CBDs. This occurs because a concentrated CBD is more likely to have a larger share of its trip ends located near a DPM station, which results in short walking links to the station. The concentrated CBDs, in general, have diversion rates that are at least one-third higher.

CBDs small in area divert walkers at a greater rate than CBDs of larger size but with the same amount of activity. This finding is intuitively logical because a larger share of trip ends is likely to be within a short walk of a DPM station if the CBD is small in area. Diversion rates generally increase at least in direct proportion to the increase in the number of DPM stations.

As the spacing between stations increases, diversion rates for a fixed number of stations increase, up to a point. In most cases, maximum diversion appears to take place at a station spacing of about 487 m (1600 ft). This occurs because at very short station spacings the DPM will be unable to reach a large share of activities, and at very long station spacings potential users will find the access walk to or from the DPM station excessive.

A sensitivity analysis of operating characteristics on walking trip-diversion rates produced the following observations. Variation of service characteristics of speed and headways within the range tested do not alter the diversion rates dramatically. They do, however, result in modest but significant shifts in relative terms. The increase of speed to 32 km/h (20 mph) adds 1 or 2 percentage points to the diversion. In effect this would increase ridership among walkers up to at least 20 percent. The reduction of headways to 1 min has slightly less impact, but an increase in headways to 4 min lowers the diversion rates in more or less an equal but opposite direction. The imposition of a fare causes a dramatic drop in the diversion rates. A $0.10 fare tends to lower the diversion rates up to half; a $0.25 fare lowers the rate by two-thirds or more in every case.

## Diversion From Local Transit

To determine the extent to which the DPM can divert trips from the local bus system, we assumed that the DPM system replaces bus routes that run on the same street, and that, at least in the central portion of the CBD, the existing bus routes operate in a tight grid pattern, run on every street, and stop every 122 m (400 ft).

General conclusions of the local transit diversion analysis were similar to those of walking trips:

1. CBDs of greater activity divert a larger share of trips,
2. CBDs of larger land area divert a smaller share of trips,
3. Concentrated CBDs divert a larger share of trips than do spread CBDs,
4. DPMs attract trips in direct proportion to the number of stations, and
5. Diversion rates increase when spacing between stations is longer but returns are greatly diminished.

Of more interest is that the diversion of internal transit trips to a DPM is very sensitive to the operating policies assumed. This is because the competition in this case, the local bus, has similar, directly comparable features. Small changes can easily tip the scales toward one mode or the other. That was not the case for diversion of regional automobile trips, where the cost of parking in the central CBD and the availability of fringe parking near a DPM station weighed more heavily than DPM system's operating characteristics. And this was not the case for walking trips, where trip length largely determined diversion rates.

Eight combinations of operating variations, which represent different advantages of the DPM over local bus service, were tested. It was determined that the DPM will attract no internal transit trips when the only advantage is headway or when speeds are only 32 km/h (20 mph). In fact, the headway advantage and a high-speed system together will not attract passengers under most circumstances. A fare differential is required to attract local bus trips and to attract more and more passengers as the system becomes larger. Furthermore, with a fare differential, the other DPM advantages begin to have an impact; the fare advantage combined with either higher speed or closer headways increases the DPM diversion rates by almost two times. The combination of all three advantages produces a still more potent impact and diversion rates of about three times are achieved.

The synergistic effect that the relative headway and speed improvements can have when combined with the fare differential requires some explanation. Without the fare difference, the other advantages can barely, if at all, overcome the negative impact of the pedestrian change in grades of an elevated DPM. Consequently, the break-even walking distances around the DPM stations are minuscule, and few trips are captured. When the fare differential is $0.25 and the break-even walking distances are longer and cover a wider area, any further improvement (headways or speeds) expands the covered area as the square of distance and the diversion rate is consequently increased.

## Diversion of Internal Automobile Trips

The diversion to DPM of internal automobile users is determined by assuming that this group is composed of three types of trip makers:

1. The regional automobile user who diverts to a DPM at the fringe and then behaves like a transit user for the internal trip;
2. The nondiverted regional automobile user who pays for parking but who values comfort and convenience highly; and
3. The regional automobile user who is assumed to be nondivertible because parking costs are reimbursed or because the use of automobile for multistop shopping or business provides an overwhelming convenience over every form of public transit.

The first group is handled in the same manner as local transit users. The second group's diversion is determined by the usual trip time and cost comparison method, which yields the break-even walk distances for DPM use. The third (nondivertible) group is simply assumed to represent 20 percent of the total.

The implications of the local automobile diversion analysis are similar to those of other trip-making categories. An important point is that the vast majority of diverted automobile trips comprise those who left their automobiles at the fringe and become captive transit riders for their internal trips. This diversion, then, depends on constraints of fringe parking location and capacity.

## Induced DPM Demand

Up to this point, the only DPM demand explicitly considered is that generated by existing land use and diverted to the DPM. New development activity at particular sites would, of course, generate potential DPM trips that should be considered in forecasts. These induced trips will occur if the DPM enables a trip to be made that was very difficult via existing modes, such as trips that require either excessive time unavailable to the potential trip maker (lunch hour shopping trips) or high costs and great inconvenience. Most of these trips will probably be internal CBD trips; regional CBD trips are less spontaneous because of their greater length. Also, since the DPM represents a small portion of a longer trip, regional CBD trips are less likely to be induced by a new DPM that serves a small segment of the total trip.

## IMPLICATIONS FOR PLANNING

DPM ridership potential will be greatest in CBDs that have the greatest activities for three reasons:

1. In larger CBDs, a greater share of those traveling to the CBD are already transit users and divertible to the DPM;
2. The contrast in the cost of parking in the CBD core and the cost of parking at the DPM fringe stations will be greater in the larger CBDs, thus providing more incentive to divert to the DPM; and
3. The number of walking trips is significantly greater in larger CBDs and the lengths of those trips are longer there.

Thus, the DPM would provide greater benefits for a larger number of walkers in larger CBDs. The full potential of the DPM in any CBD, whatever the size, depends on a number of factors. To divert regional transit passengers, the transit system must be arranged to feed the DPM at the fringe of the CBD. For existing transit systems that are fixed, the interface between their CBD stations and the DPM are also critical. Diversion of substantial numbers of regional automobile users depends on the provision of sufficiently large parking areas at fringe DPM stations, which are located strategically near the highway network. Finally, the operating characteristics and policy of both the DPM and existing internal transit systems, usually bus, is critical. Ridership will be especially sensitive to the DPM fare. If the fare is set low, many passengers will be attracted, particularly if fare levels are kept higher on the preexisting transit mode. Considerably less important in attracting more DPM riders are very high DPM speeds or very low DPM headways. This finding suggests that the DPM need not be highly sophisticated technologically to be a constructive addition to the urban scene.

## ACKNOWLEDGMENT

The study from which the material in this paper was taken was sponsored by the Urban Mass Transportation Administration under grant funding to the Regional Plan Association from the Office of Policy Research and under project funding to the Transportation Systems Center from the Office of Planning Methods and Support. The conclusions discussed in this paper are our own and, of course, do not necessarily represent the views of the U.S. Department of Transportation.

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1. Planning for Downtown People Movers. Transportation Systems Center, U.S. Department of Transportation, Cambridge, MA, Draft Rept., Feb. 1979.
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# Discussion

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The paper represents an important attempt to quantify the potential ridership of a DPM system that must compete with other modes. However, the authors appear to have made some implicit geometric assumptions that are so strong as to make their results difficult to believe. Moreover, some of these results are presented in a form that is likely to lead the reader to draw unwarranted conclusions.

The authors' description of a DPM system includes the number of stations and the station spacing as the principal independent variables. The DPM system's area of coverage (fraction of CBD within a specified allowable walk-access distance) was derived by assuming that the stations are located so as to provide maximum area coverage and no overlap. However, neither the geometry of the station service areas, the relative locations of the stations, nor the guideway alignments were specified. This is a serious oversimplification, particularly when the DPM system is designed to contain more than a very few stations. In order to produce realistic estimates of passenger travel and wait times (number of intermediate station stops), explicit assumptions must be made about guideway alignment, network topology, and service policies. The authors' implicit assumptions unfairly penalize systems that have a larger number of stations, which could be expected to offer more sophisticated service policies on more highly connected networks (such as skip-stop or alternate routes). The conclusion that increasing the number of stations reduces the DPM modal split without qualifying that observation by the simplifying assumptions they have made is thus misleading.

A highly aggregate analysis, such as that presented by the authors, produces some very strange implicit assumptions about service area geometry and network topology, especially if all stations are assumed to be located on a single closed loop or extended shuttle. Indeed, it appears (based on the final paragraph of the section entitled Trip Distribution Procedure) that the authors have implicitly assumed their station maxizones to be annular. This would produce some rather odd walk-access trips. The minimum-walking-distance station service areas, in a CBD having a rectilinear street grid, should be diamond-shaped, as I have demonstrated (3), which incorporates an explicit geometric representation of a DPM-like network.

The results and conclusions presented in the paper did not clearly distinguish among the effects produced by changes in the different independent variables. Particular problems were in distinguishing among the effects attributable to station spacing, number of stations, and area coverage. The authors drew very different conclusions about the effect of the number of stations on diversions of walking trips and transit trips without explaining the source of the difference. In the discussion of walk-trip diversion, the authors note that diversion rates increase (up to a point) as the spacing between stations increases, for a fixed number of stations. The increase they observe could be just as easily (and probably more justifiably) attributed to the increased length of the system, which will provide walking accessibility to more of the CBD. Had the guideway length been held constant, and the spacings and number of stations varied, the effect of station spacing on trip diversions would have appeared to be reversed.

The same problem of choosing which parameters to hold constant is the source of the intuitively unappealing trend of increasing diversions with increased station spacings shown in Figure 5. A reader could easily conclude from that figure that the best way to increase DPM ridership is to locate stations as far apart as possible, since the increasing ridership trend on that figure is the strongest of any presented in the paper. This, of course, disregards travelers' willingness to walk and walk-refusal distances. Would it not be less potentially misleading to present that figure with guideway length as the independent variable, or to replot the results for constant guideway length, with station spacings and number of stations varying?

There is a very real need for the development of planning tools that can be used to design DPM systems. The demand-related aspect of the work reported in the paper appears to be a worthy contribution toward filling this need, but the supply modeling seems to have suffered from some overly generalized geometric assumptions. Combination of the demand analysis reported here with a more geometrically specific supply analysis such as I suggested in another article (3) would produce a significantly more powerful DPM design tool. The results derived by use of such a DPM design tool need to be presented so that the significance of the respective independent and dependent variables is made unmistakably clear to avoid possible misinterpretations.

REFERENCE

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## Authors' Closure

The discussion is useful on two grounds: It ventilates some of the problems associated with the complexity of DPM system design and it provides the opportunity for us to clarify the possible misconceptions arising from the paper and omissions therein.

Let us handle the omissions and misconceptions first. Our analysis assumes that (a) the station coverage areas are diamond-shaped, not annular, which is indeed a necessary assumption for a grid street pattern; (b) stations are spaced equally, for to do otherwise would be unnecessarily complex and unmanageable; (c) guideways are aligned either as a loop or a shuttle; (d) stations are located to maximize coverage, which could, nevertheless, lead to overlap, particularly if there are a large number of stations, spaced close together; and (e) service is provided without skip stops, alternate routes, or other sophisticated arrangements, a reasonable assumption for the first wave of DPMs.

The explanation for the very different patterns of DPM diversions among walking trips and line-haul transit trips with respect to station spacing, number of stations, and coverage, lies in the fact that the walking trips diverted to the DPM involve two new walk links, access and egress, but the transit trips diverted involve only one. This occurs because the transit station and DPM station are located at the same point.

The discussant is quite right that the use of the system length as a variable in the graphics would add another valuable dimension to the paper. Indeed, longer system length would provide added DPM accessibility for walk trips, albeit with the danger of diminishing effectiveness. Unfortunately, in the interest of brevity, only a sampling of the derived relationships are shown.

The full report, which this paper summarizes, provides an estimate of DPM demand for 504 explicit combinations of DPM and CBD characteristics, including system length, for each of five categories of demand. From these, serious evaluation of alternative DPM configurations can take place. In addition, six DPM service alternatives, two line-haul transit arrangements, and a spectrum of highway configurations are treated in the analysis. We hope that a reading of the full report will remove any unintended misinterpretations that emanated from the necessarily telescoped version presented here.

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# Development of Efficient Central Management Strategies for Advanced Group Rapid Transit Systems

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**This paper presents a summary of a computer-aided method for developing efficient central management system strategies for advanced group rapid transit systems by use of medium-sized, automatically controlled vehicles that travel on dedicated guideways. Some efficient central man-**

agement system strategies developed for a test network that uses the method are presented and discussed in detail. The method consists of an iterative process in which experienced transit system operators make complex, judgmental decisions and a computer performs extensive and repetitive computations. This computer-aided method allows transit system operators to compare the consequences of various central management system strategies in terms of such measures as passenger wait times, number of passenger intermediate stops, vehicle fleet size, vehicle load factor, and vehicle flows in various guideway sections and at various passenger stations. After studying such measures, operators can develop a set of efficient and realistic central management system strategies. The computer-aided method and the associated computer simulation program are general in nature and can be used to develop central management system strategies for a variety of network configurations and trip demand data.

As part of a feasibility study of an advanced group rapid transit (AGRT) system in an urban environment, which was undertaken for the Urban Mass Transportation Administration (UMTA) (1, 2), we developed a powerful simulation program to test various central management system (CMS) strategies for the AGRT system proposed by Rohr Industries. The AGRT system uses medium-sized, automatically controlled vehicles that have a typical capacity of 12 passenger vehicles. Rohr's CMS is based on the nonsynchronous mode of vehicle control. Typical headways are 4-6 s; the minimum allowable headway is 3.1 s.

AGRT systems typically will be used in urban environments where the network to be served has a grid pattern. Furthermore, for AGRT systems that use relatively small vehicles to provide personalized service, demand-responsive service is more desirable than fixed-schedule service, particularly during off-peak periods. Even during peak periods, fixed-schedule strategies do not necessarily provide efficient service and a high vehicle-load factor. When a route network is even moderately complex and vehicle size is small, numerous routing and scheduling strategies between various origin-destination (O/D) pairs become possible. Therefore, a sufficiently detailed CMS simulation program was developed to test several strategies for a variety of networks and trip demand data.

This paper presents the basic functional details for the CMS simulation program and the results of the application of the program to a test network. The methodology and the simulation program developed are essentially independent of the design details of the AGRT system.

## THE PROBLEM

Central management of an AGRT system requires the development of an efficient strategy of operations to serve a specified demand given (a) a guideway network in terms of the O/D nodes (passenger stations) and connecting links (guideway tracks), (b) the O/D demand data of passengers, and (c) the capacity of AGRT vehicles. Unfortunately, no single criterion of efficiency can be defined realistically. However, the following performance measures can be used to compare various alternatives:

1. Wait and trip times of passengers,
2. Number of intermediate stops between various O/D pairs,
3. Deviations from shortest distance routes between O/D pairs,
4. Vehicle fleet size required,
5. Vehicle flows on links and in stations,
6. Delays under failure conditions, and
7. Capital and operating costs.

The study of such measures will enable experienced transit system planners and operators to develop efficient CMS strategies after a few iterations.

## METHOD OF APPROACH

The central management of an AGRT system has the following major functional requirements:

1. Vehicle assignment in response to a trip request,
2. Route designation of vehicles,
3. Empty vehicle management, and
4. Suitable contingency plans for failure conditions.

The alternatives available to the designer of a CMS essentially consist of two types of design variables:

1. Planning variables—variables that must be defined early in the design process (e.g., station sizes, turnarounds, bypasses, storage and maintenance areas, and fleet size), and
2. Operating variables—variables that can be adjusted dynamically once the AGRT system has been put in place (e.g., stopping policies, vehicle assignment policies, vehicle routing policies, and operating fleet size).

These design variables can be combined in a number of ways, and their combination requires considerable human judgment; however, the manual calculation of various performance measures for various combinations of design variables is a difficult and laborious process. In view of these considerations, the study team developed a method whereby complex judgmental decisions (such as the definition of alternative stopping policies) could be made by experienced transit system operators, and the extensive and repetitive computations needed to calculate various performance measures could be performed by a computer. A simulation program was developed to test various combinations of design variables, study their consequences in terms of relevant performance measures, and eventually develop a set of efficient CMS strategies. Figure 1 shows the overall human/machine iterative process by which suitable CMS strategies can be developed.

Figure 1. Man-machine iterative process associated with the development of CMS strategies.

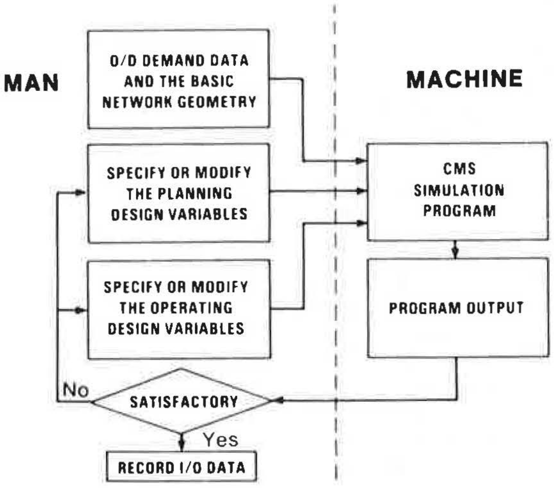


Table 1. Overview of the principal functional models of the CMS simulation program.

| Functional Model | Purpose |
|---|---|
| Passenger-station interface | To generate random numbers of trip requests of varying party sizes and with varying O/D basis. |
| Gate operations | To calculate the dwell time a vehicle spends in a station on the basis of boarding and deboarding. |
| Vehicle-station interface | To calculate the time a vehicle spends in a station in addition to dwell time, as a function of station configuration. |
| Station capacity | To determine whether vehicles can enter a station based on a prespecified capacity. |
| Trip assignment | To locate a vehicle within a prespecified vicinity of trip requesting station, test its acceptability, and assign it to the request. |
| Routing | To route the vehicle on a switch-by-switch basis based on prespecified switching tables. |
| Empty vehicle distribution | To route empty vehicles based on prespecified algorithms. The algorithm will be developed offline. |
| Training vehicles | To study the possibilities and consequences of entraining the vehicles. |
| Scheduled vehicles | To model the operations of scheduled vehicles. |
| Zone management | To model the effects of zone congestion and the strategy for relieving this congestion. |
| Central scan | To model the central scan functions of the CMS. |
| Longitudinal/headway control | To ensure, in a simplified manner, that headway between vehicles is sufficient on the guideway based on average vehicle velocity and allowable number of vehicles. |
| Merge/demerge switch control | To calculate switch delay and sequence for a vehicle approaching a merge switch. |
| Vehicle position and velocity control | To describe the link position and link transit time of vehicles. |
| Network configuration | To describe and specify a network with links and switch points. |
| Link congestion | To model the effects of link congestion and the strategy for dealing with congestion. |
| Network status | To provide a report on link, zone, and station loading for purposes of vehicle management. |
| Alarm | To generate the time, type, and location of an emergency (i.e., failure conditions) based on a prespecified algorithm. |
| Failure management | To model failure management procedures for failures of a vehicle, link, station, and zone. |
| Performance measures and statistics generation | To generate the specified performance measures in the specified formats. |

## SUMMARY OF THE CMS SIMULATION PROGRAM

A dominant consideration in the development of the CMS simulation program was to provide an efficient, cost-effective tool for testing CMS implementation concepts. Thus, a program was designed whose running time and costs per run were not excessive. This was accomplished by using sufficiently detailed models of the following basic CMS functions:

1. Trip assignment,
2. Empty vehicle management,
3. Failure management (e.g., vehicle, link, zone, and station), and
4. Performance measures and statistics.

Models associated with functions not directly related to central management (e.g., longitudinal-headway control) were relatively simple to model. Table 1 presents an overview of the functional models associated with the CMS simulation program.

## SUMMARY OF PROGRAM INPUTS AND OUTPUTS

The input data for the CMS simulation program can be grouped according to

1. Network geometry,
2. Demand,
3. Parameters associated with certain models,
4. CMS strategies, and
5. Simulation run options.

Data related to network geometry typically consist of various link numbers, their lengths, connectivity, the location of stations and storages, and their relation to main-line links.

Data related to demand are generated by use of a random trip generation program based on the given or assumed average hourly O/D matrices for various hours of the day and certain specified parameters. The designer can select any period of a day (e.g., 6:00-9:00 a.m.) or an entire 24-h period to test various CMS strategies for that period.

The CMS simulation program contains certain models, such as vehicle movement in links and dwell time of vehicles at berths, that require specification of some parameters. For example, the velocity-headway curve is used to model vehicle movement in the links. The velocity-headway curve was modeled as a second-order equation of the form:

$$H = K_1/v + K_2 + K_3 v \qquad (1)$$

where H = the headway in seconds and v = the velocity in miles per second. The program user has to specify the values of the coefficients $K_1$, $K_2$, and $K_3$.

Input data that specify the major elements of a CMS strategy under normal conditions consist of

1. Vehicle search regions associated with each station,
2. Vehicle type search priority,
3. Allowable en route stations between various O/D pairs,
4. Allowable number of stops between various O/D pairs, and
5. Route specification between various O/D pairs.

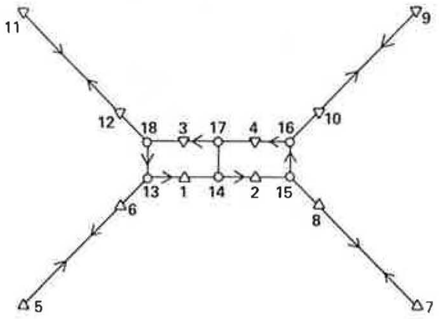
Vehicle search regions for various stations are specified in terms of links, other stations, and the storage and maintenance areas. The CMS simulation program is designed to search for vehicles sequentially in links, stations, and storages, in the order specified. Other elements of the strategy have to be specified in a similar way.

The program user can specify certain data associated with simulation run options. These data include the times at which the outputs are to be printed or the times at which network statistics are to be set to zero (e.g., at 8:00 a.m., 9:00 a.m., or 10:00 a.m.). A complete list of data related to simulation run options is included in the technical specifications for the AGRT-CMS simulation program (3, 4).

The CMS-simulation program was used to develop various efficient CMS strategies for a test network provided by UMTA. The basic geometric configuration of the test network is shown in Figure 2. Basic data about the network are given below (note 1 km = 0.6 mile).

| Item | Information |
|---|---|
| Number of stations | 12 |
| Total length of one-way guideway | 41.8 km |
| Number of passengers to be served during peak hours | ~10 000/h |
| Total number of trips per day | ~80 000 |
| AGRT vehicle capacity | 12 passengers |

Figure 2. Test network provided by UTMA.



The CMS-simulation program provides a capsule report, for quick analysis, as well as detailed information associated with various performance measures, for detailed analysis. Typical output data from an actual run are presented in Figures 3-5. (The models were designed for U.S. customary units only; therefore, values in Figures 3-5 are not given in SI units.)

## EXAMPLES OF CMS STRATEGIES FOR A TEST NETWORK

To demonstrate the effectiveness and performance of the CMS-simulation program, UMTA provided the study team with a test network and O/D demand data. The basic geometric configuration of the test network is shown in Figure 2. An initial detailed network layout was prepared by the study team based on the basic test network. The detailed network includes certain turnarounds to allow for one-sided stations and to provide an alternative path in case of failures of certain links. The network also includes six storage areas for vehicles that can be called on either a demand-responsive or fixed-schedule basis.

Figure 3. Sample of capsule report.

```
        CAPSULE REPORT

A. USER RELATED MEASURES

   1. STATION WAIT TIME
      MEAN WAIT TIME =        2.95 MINUTES
      MAXIMUM WAIT TIME =        7.52 MINUTES
      TRIPS WITH A WAIT .LE. 5 MINUTES =      82.19 PERCENT
      TRIPS WITH A WAIT .LE. 10 MINUTES =     100.00 PERCENT

   2. INTERMEDIATE STOPS
      PERCENTAGE OF TRIPS WITH NO STOPS =      88.83
      PERCENTAGE OF TRIPS WITH 1 STOP =     11.17
      PERCENTAGE OF TRIPS WITH 2 OR 3 STOPS =       0.00

   3. AVERAGE SYSTEM TRAVEL SPEED =    29.86 MPH

B. OPERATIONS RELATED MEASURES

   1.          2470 PASSENGERS BOARDED VEHICLES, AND          1853 PASSENGERS DISEMBARKED


   2. FLEET SIZE OF ACTIVE VEHICLES ON GUIDEWAY OR IN STATIONS
      TIME WEIGHTED AVERAGE FLEET =    123.55 VEHICLES
      MAXIMUM FLEET =     175 VEHICLES

   3. VEHICLE ARRIVAL RATE AT STATIONS
      SYSTEMWIDE TOTAL =     1019.00 VEHICLES/HOUR
      MAXIMUM ARRIVAL RATE =         98.00 VEHICLES/HOUR AT STATION      2

   4. PASSENGER QUEUE LENGTH IN STATIONS
      SYSTEM AVERAGE =         10.67 PASSENGERS
      MAXIMUM AVERAGE QUEUE =         20.74 PASSENGERS IN STATION    8

   5. MAXIMUM LINK FLOW =    314.00 VEHICLES/HOUR ON LINK  30

   6. VEHICLE REJECTIONS FROM FULL STATIONS
      TOTAL FOR ALL STATIONS =              0 VEHICLES
      REJECTIONS AS A PERCENT OF ALL ATTEMPTS TO ENTER STATIONS =         0.00

   7. SYSTEMWIDE VEHICLE LOAD FACTOR =     19.14
   8. MILES TRAVELLED
      TOTAL VEHICLE MILES =     3678.72 MILES
      TOTAL PASSENGER MILES =     8006.89 MILES
```

Figure 4. Sample of link loading data.

```
B. MEASURES RELATED TO NETWORK MANAGEMENT.

1. VEHICLE LOADING BY LINK.

                    HIGHEST         TIME-WEIGHTED     PERCENT TIME
                    VEHICLE           AVERAGE      LINK ABOVE MINIMUM    VEHICLE FLOW
    LINK NUMBER  DENSITY/MILE      DENSITY/MILE     HEADWAY DENSITY       PER HOUR

          1           9.89              3.14              0.00             124.00
          2          14.23              4.55              0.00             179.00
          3          17.86              6.21               .26             145.00
          4          20.92              7.86             14.28             297.00
          5          24.24              5.60              6.60             204.00
          6          24.39              7.81              8.22             292.00
          7          21.23              5.15              1.41             186.00
          8          24.39              7.58              2.73             290.00
          9          24.24              5.14              4.12             190.00
```

Figure 5. Sample of O/D data.

```
                    FINAL REPORT

ORIGIN-DESTINATION DATA FOR DEMAND TRIPS



FOR PASSENGERS TRAVELING FROM ORIGIN STATION  1

                                AVG. NET                                                        MEAN WAIT TIME
                                 TRAVEL              WAITING TIME                 TRIP TIME      AS PERCENT
DESTINATION    NUMBER  OF        SPEED                (MINUTES)                   (MINUTES)        OF MEAN
  STATION      PASSENGERS        (MPH)       MAXIMUM    MEAN     STD DEV      MEAN     ST DEV     TRIP TIME

      2              3           29.43        4.73      3.48       1.22       5.51      1.29         63.11
      3              5           24.63        5.65      3.36       1.63       6.62      1.61         50.70
      4              6           28.18        5.03      4.22       1.49       8.79      1.65         48.03
      5              3           28.82        4.42      4.36        .04      14.70       .06         29.68
      7             11           30.63        5.72      3.65       1.84      12.22      1.82         29.89
      8              5           28.82        5.44      4.04       1.29       8.33      1.16         48.53
     10              2           28.15        4.59      4.45        .14       9.37       .42         47.48
     12              7           25.28        5.65      3.71       1.58       9.44      1.44         39.29
TOTALS FOR
   ORIGIN
      1             42           28.13        5.72      3.83       1.53       9.70      2.90         39.49
```

Table 2. O/D demand data for the morning peak period.

| Origin Station Number | Destination Station Number | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | RSUM |
| 1 | 0 | 3 | 10 | 12 | 7 | 0 | 3 | 3 | 0 | 5 | 0 | 12 | 55 |
| 2 | 2 | 0 | 7 | 2 | 6 | 11 | 10 | 11 | 0 | 3 | 8 | 13 | 73 |
| 3 | 11 | 11 | 0 | 1 | 13 | 14 | 10 | 15 | 4 | 14 | 3 | 38 | 134 |
| 4 | 1 | 7 | 12 | 0 | 9 | 3 | 2 | 7 | 0 | 9 | 0 | 12 | 62 |
| 5 | 133 | 118 | 121 | 117 | 0 | 51 | 7 | 51 | 42 | 5 | 47 | 20 | 712 |
| 6 | 48 | 35 | 51 | 46 | 85 | 0 | 20 | 22 | 22 | 39 | 18 | 36 | 422 |
| 7 | 100 | 120 | 82 | 112 | 52 | 39 | 0 | 25 | 14 | 13 | 9 | 0 | 566 |
| 8 | 153 | 186 | 56 | 142 | 59 | 62 | 47 | 0 | 56 | 51 | 9 | 61 | 882 |
| 9 | 103 | 98 | 41 | 80 | 0 | 3 | 0 | 43 | 0 | 21 | 0 | 31 | 420 |
| 10 | 39 | 33 | 20 | 31 | 12 | 17 | 0 | 13 | 0 | 0 | 0 | 38 | 203 |
| 11 | 124 | 110 | 156 | 88 | 51 | 61 | 0 | 0 | 0 | 2 | 0 | 41 | 633 |
| 12 | 38 | 52 | 27 | 34 | 0 | 13 | 0 | 14 | 0 | 9 | 8 | 0 | 195 |
| CSUM | 752 | 773 | 583 | 665 | 294 | 274 | 99 | 204 | 138 | 171 | 102 | 302 | 4357 |

Note: The numbers given are baseline numbers of trips. To calculate the passenger demand during morning peak hour (8:00-9:00 a.m.) numbers should be multiplied first by a factor of 2 to reflect the peak effect and then by a factor of 1.175 to reflect average party size. These factors were specified by UMTA.

Basic O/D demand data for the morning peak demand period are shown in Table 2. Similar tables were provided for off-peak and evening-peak periods. By use of these basic hourly demand data and certain specifications, we generated a random trip demand file for the entire 24-h period, during which approximately 80 000 trips were requested.

## Experiments for Morning Peak Period

The following five strategies were tested for the morning peak period:

1. All en route stations eligible for stops, and no limit on number of intermediate stops;
2. All O/D pairs served nonstop;
3. Same as for strategy 1, but only one intermediate stop allowed;
4. Nonstop service for high-demand O/D pairs, one intermediate stop allowed for medium-demand O/D pairs, and no limit on stops for low-demand O/D pairs; and
5. Same as for strategy 3, but 20 special service routes used for highest demand O/D pairs (e.g., station 5 to station 1, special service vehicles every 2 min; station 5 to station 2, special service vehicles every 2.5 min).

Comparative summaries of several performance measures for these five strategies are given in Table 3. Strategies 1 and 2 generate some unacceptable situations. For strategy 1, the average effective travel speed becomes very low, 40 km/h (25 mph); only 55 percent of the trips are served within a mean wait time of 5 min; the vehicle arrival rate at station 4 is excessive, and total station rejections are very high. For strategy 2, the needed vehicle fleet and link flows are quite high compared to other strategies. The philosophies of strategies 3, 4, and 5 appeared promising and were improved by use of later versions of the program, by modifications of the capture regions, and by improvements in selection of allowable stops.

## Experiments for Midday Period

The following strategies were tested for the midday period (12:00 n.-1:00 p.m.):

1. All en route stations eligible for stops, and no limit on number of intermediate stops;
2. All O/D pairs served nonstop; and
3. Same as in strategy 1, but only one intermediate stop allowed at most.

None of the three strategies creates any unacceptable situations, and each one is a reasonably good candidate strategy. Strategy 1 requires the fewest number of vehicles, but only 32 percent of the trips are served nonstop; the other trips served have one or more intermediate stops. Strategy 2 is the best from the passengers' point of view, but it requires a larger fleet

Table 3. Comparison of five CMS strategies for the morning peak period.

| Performance Measure | Strategy 1 | 2 | 3 | 4 | 5[a] |
|---|---|---|---|---|---|
| Number of passengers | | | | | |
| Boarded | 10 213 | 10 276 | 10 383 | 10 319 | 10 369 |
| Disembarked | 9 954 | 10 174 | 10 214 | 10 180 | 10 279 |
| Station wait time | | | | | |
| Mean wait time (min) | 4.08 | 3.59 | 4.44 | 3.25 | 2.62 |
| Maximum wait time (min) | 22.92 | 15.17 | 13.87 | 10.95 | 16.25 |
| Trips, ≤5-min wait (%) | ~55 | ~73 | ~57 | ~80 | ~90 |
| Trips, ≤10-min wait (%) | ~89 | ~100 | ~99 | ~100 | ~100 |
| Stops (%) | | | | | |
| Trips, nonstop | ~34 | 100 | ~56 | ~91 | ~90 |
| Trips, one stop | ~36 | - | ~44 | ~9 | ~10 |
| Trips, two or three stops | ~30 | - | - | 0 | - |
| Average system travel speed (km/h) | ~40 | ~54 | ~52 | ~56 | ~56 |
| Time-weighted fleet | 262 | 308 | 244 | 267 | 311 |
| Vehicle arrival/departure (vehicle/h) | | | | | |
| Systemwide | 3 245 | 2 432 | 2 760 | 2 507 | 2 771 |
| Maximum | 405 | 264 | 343 | 271 | 323 |
| Station number | 4 | 2 | 1 | 8 | 8 |
| Passenger queue | | | | | |
| System average | 62 | 51 | 63 | 46 | 37 |
| Highest average | 155 | 133 | 178 | 116 | 88 |
| Station number | 11 | 5 | 5 | 5 | 5 |
| Maximum link flow (vehicle/h) | 734 | 865 | 709 | 788 | 837 |
| Link number | 32 | 4 | 34 | 6 | 8 |
| Rejections | | | | | |
| Total | 362 | 12 | 55 | 9 | 15 |
| Percent | 11.5 | 0.5 | 2 | 0.4 | 0.55 |
| Systemwide vehicle load factor | 0.55 | 0.36 | 0.46 | 0.39 | 0.35 |

Note: 1 km/h = 0.6 mph.

[a] 20 special routes.

size and generates higher link flows than either strategy 1 or 3. Strategy 3 offers a good combination of attractive user-related performance measures (54 percent of the trips are nonstop; 46 percent have only one intermediate stop) and a medium-sized fleet. Only a minor fraction of passengers waits the maximum of 10 min. This could be rectified easily by improvements to the search sequence of links in the vehicle search region.

During periods of low or medium demand it is possible to implement several policy variations with acceptable operations and user-related performance measures. Thus, one could use a large number of vehicles and provide nonstop service or use relatively fewer vehicles and provide service with at most one stop.

## Experiments for Evening Peak Period

Results of the morning peak period simulation runs indicated that the two extreme strategies of allowing all stops (strategy 1) or serving all O/D pairs nonstop (strategy 2) create certain unacceptable situations. Since the traffic volumes in the evening peak period are the same as those in the morning peak period (reverse direction), we did not test the two extreme policies for the evening peak period. Strategy 4, tested for the morning peak period, appeared to be a good candidate for the first test experiment for the evening peak period. Thus strategy 4 was tested after appropriate adjustments in the directionality of high-demand O/D pairs and stations to be stopped at and some modifications in capture regions to account for the reverse flows. The results of this experiment are comparable to the results of the strategy 4 experiment for the morning peak. This strategy was refined later by use of the final version of the program.

## Some Conclusions Related to Peak and Off-Peak Period Strategies

After we conducted experiments for the morning peak, midday, and evening peak periods and established that the two extreme strategies of allowing all en route stops (strategy 1) and no en route stops for all O/D pairs (strategy 2) produced certain unacceptable phenomena (e.g., high link flows and excessive station rejections), we concentrated on refining strategies that use a combination of nonstop, fixed route (both one-way and closed loop), and one intermediate stop strategies for various O/D pairs. Several combinations were tested. Based on the results of these tests we concluded that

1. For both the morning and evening peak periods, a demand-responsive strategy that provides nonstop service for high-demand O/D pairs and (at most) one intermediate stop service for medium- and low-demand O/D pairs gives the best overall combination of passenger- and operation-related performance measures. Other strategies result either in high link flows, excessive wait times, or excessive station arrival and departure rates.
2. For medium-demand periods (i.e., 11:00 a.m.-3:00 p.m.) a variety of strategies is possible. Even the two extreme strategies of serving all O/D pairs nonstop or allowing all en route stops between each O/D pair result in service that is acceptable and do not cause any excessive link flows or station arrival and departure rates.
3. For very low-demand periods, no significant operational advantage results, even if en route stops are allowed, unless very long wait times (greater than 10 min) are tolerated. Most passengers dislike long wait times or intermediate stops, particularly at night. Thus it was concluded that nonstop, demand-responsive service is most appropriate for very low-demand periods during nighttime (e.g., from 10:00 p.m. to 6:00 a.m.).

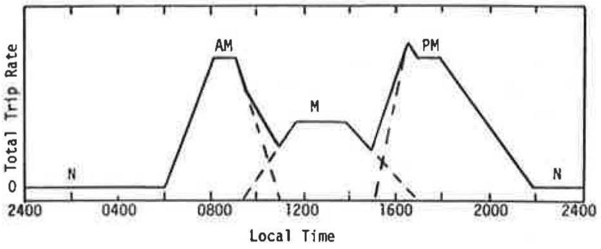
### Experiments to Develop CMS Strategies for the 24-h Period

A final set of experiments was conducted to develop composite CMS strategies for various periods of the day. The overall pattern of the demand level at various periods of the day as specified by UMTA is shown in Figure 6. Between 10:00 p.m. and 6:00 a.m. the demand level is very low—approximately 300 passengers/h. On the other hand, the demand during the 8:00-9:00 a.m. and 4:00-8:00 p.m. periods is substantially high—approximately 10 000 passengers/h. During the midday period, the demand is medium—about 5000 passengers/h.

The general strategies used for various periods of the day are shown below.

| Period | Strategy |
|---|---|
| 12:00 m.n.-6:00 a.m. | All O/D pairs served nonstop |
| 6:00-11:00 a.m. | High-demand O/D pairs served nonstop; medium- and low-demand O/D pairs served with one intermediate stop allowed |
| 11:00 a.m.-3:00 p.m. | All O/D pairs served nonstop |
| 3:00-10:00 p.m. | High-demand O/D pairs served nonstop; medium- and low-demand O/D pairs served with one intermediate stop allowed |
| 10:00 p.m.-12:00 m.n. | All O/D pairs served nonstop |

Figure 6. Diurnal variations of demand for UMTA's test network.



Vehicle search regions were also adjusted to suit the demand and empty vehicle availability patterns. A summary of hourly performance during various periods of the day is shown in Table 4. Variations of some important performance measures at various hours of the day are shown graphically in Figures 7 and 8.

## SUMMARY OF RESULTS

During morning and evening peak periods, a demand-responsive strategy that serves high-demand O/D pairs nonstop and makes at most one intermediate stop between medium- and low-demand O/D pairs proved to be very effective. During off-peak periods, all O/D pairs can be served nonstop within a mean wait time of about 3 min if a demand-responsive strategy is used.

Demand-responsive strategies adapt easily to fluctuations in demand. An overall increase of up to 140 percent in the demand levels throughout the network can be handled without creating a serious problem in vehicle flow rates. The system appears to degrade gracefully under increasing demand levels.

The results of the failure experiments (wherein a vehicle, a link, and a station were failed separately for 15 min each), as measured by the extra wait times and the number of passengers that had to be diverted, appeared to be within tolerable limits and were as expected.

A maximum fleet of about 265 vehicles is needed to provide satisfactory service during morning and evening peak periods within a systemwide mean wait time of slightly more than 3 min. Under normal operating conditions, 80-90 percent of the passengers can be served within a 5-min mean wait time during morning and evening peak periods; 97 percent can be served within a 7-min mean wait time. Almost nobody has to wait more than 10 min.

Average systemwide speed is 45-48 km/h (28-30 mph). This takes into account the civil speed limits of 32 and 40 km/h (20 and 25 mph) imposed by right-of-

Table 4. Summary of hourly system performance during different periods of the day.

| | Time Period | | | | |
|---|---|---|---|---|---|
| Performance Measure | 1:00-2:00 a. m. | 8:00-9:00 a.m. | 1:00-2:00 p.m. | 5:00-6:00 p.m. | 9:00-10:00 p.m |
| Number of passengers | | | | | |
| Boarded | 300 | 10 291 | 4918 | 10 323 | 1699 |
| Disembarked | 305 | 10 271 | 4909 | 10 425 | 2032 |
| Station wait time | | | | | |
| Mean wait time (min) | 4.10 | 3.07 | 3.12 | 3.55 | 3.24 |
| Maximum wait time (min) | 7.01 | 8.64 | 9.78 | 11.33 | 7.60 |
| Trips, 5-min wait (%) | ~64 | ~88 | ~85 | ~80 | ~85 |
| Trips, 10-min wait (%) | 100.00 | 100.00 | 100.00 | 99.79 | 100.00 |
| Stops (%) | | | | | |
| Trips, nonstop | 100 | ~90 | 100 | ~91 | ~97 |
| Trips, one stop | 0 | ~11 | 0 | ~8 | ~3 |
| Trips, two or three stops | 0 | 0 | 0 | ~1 | 0 |
| Average system travel speed (km/h) | 49.30 | 45.90 | 52.77 | 44.75 | 48.00 |
| Fleet size | | | | | |
| Time weighted | 34 | 226 | 181 | 252 | 129 |
| Maximum | 40 | 234 | 190 | 265 | 137 |
| Vehicle arrival/departure (vehicle/h) | | | | | |
| Systemwide | 272 | 2 008 | 1415 | 2 105 | 1000 |
| Maximum | 39 | 213 | 178 | 240 | 100 |
| Station number | 2 | 8 | 3 | 8 | 8 |
| Passenger queue | | | | | |
| System average | 2 | 44 | 21 | 51 | 7 |
| Highest average | 3 | 92 | 24 | 128 | 16 |
| Station number | 2 | 8 | 3 | 2 | 2 |
| Maximum link flow (vehicle/h) | 92 | 575 | 543 | 619 | 371 |
| Link number | 34 | 20 | 46 | 20 | 36 |
| Rejections | | | | | |
| Total | 0 | 0 | 0 | 0 | 0 |
| Percent | 0 | 0 | 0 | 0 | 0 |
| Systemwide vehicle load factor | 8.78 | 51.34 | 27.83 | 48.01 | 15.57 |

Note: 1 km/h = 0.6 mph.

way constraints in certain portions of downtown areas and in turnaround links.

Systemwide load factors during morning and evening peak periods are about 51 and 49 percent, respectively. These values are in close agreement with those calculated theoretically. The load factor at night is about 9 percent. The demand at night is very low and passengers should not have to wait too long. The load factor during midday is about 28 percent if a nonstop strategy is used. This seems quite acceptable when the nonstop service and short wait times are considered. However, the load factor can be improved if stops and longer wait times are allowed. It is possible to trade off mean wait time with fleet size, particularly during off-peak periods.

Figure 7. Mean wait time and system average speed during various periods of the day.

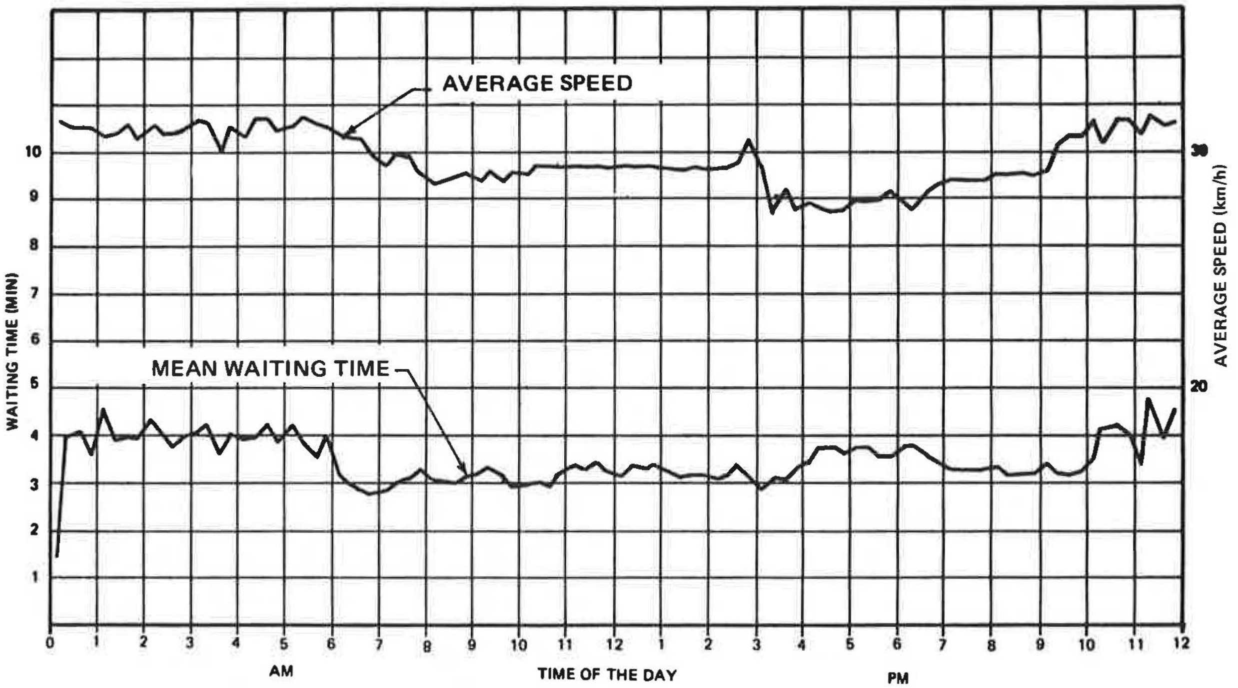
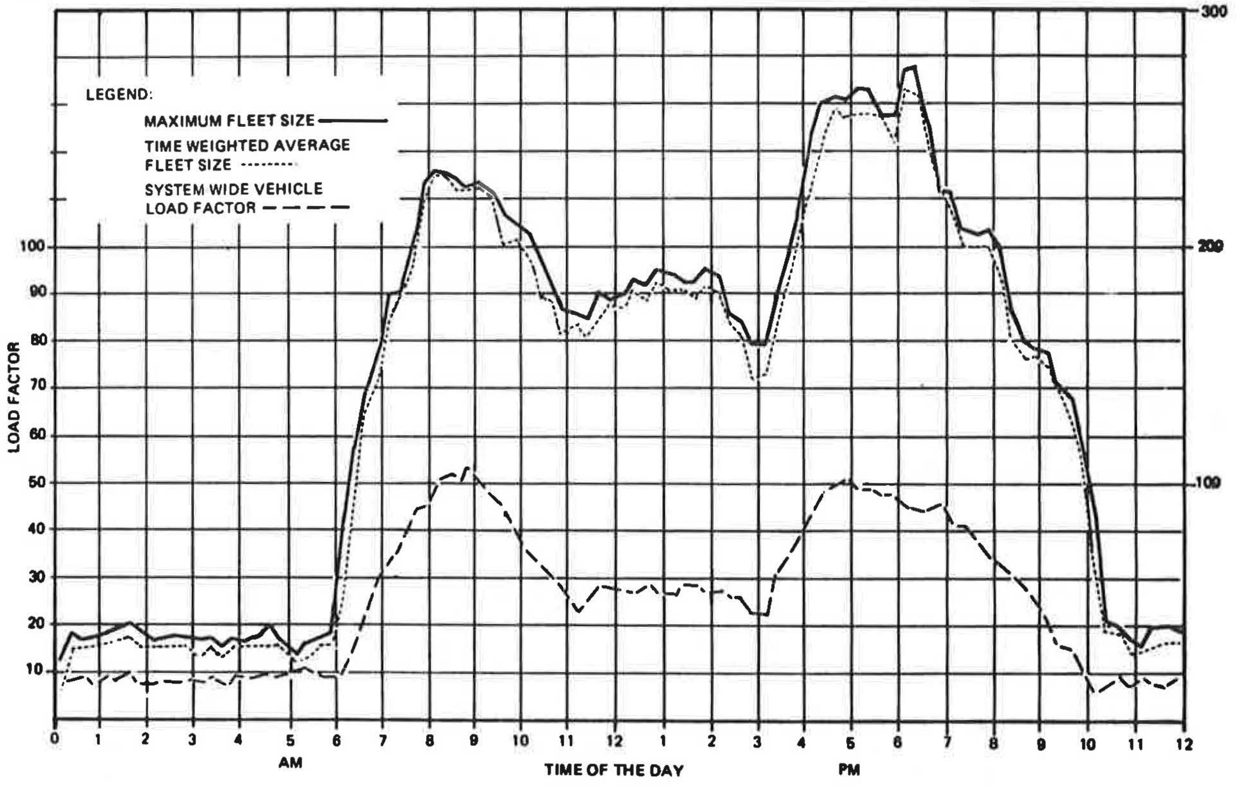


Figure 8. Vehicle load factor and fleet size during various periods of the day.



## CONCLUDING REMARKS

The computer-aided method and the CMS simulation program discussed in this paper can be used to develop

1. Efficient CMS strategies for urban transportation networks, including vehicle assignment (demand responsive, fixed schedule, and mixed), stopping and routing, empty vehicle management, and failure management for vehicle, station, and guideway link failures;
2. Network geometry details, such as station capacities, location of bypasses and turnarounds, and storage and maintenance areas; and
3. Optimum vehicle fleet size consistent with the desired level and quality of service.

Although the simulation program was developed with reference to an AGRT system that uses 12-passenger automated vehicles, it is highly modular. Those few modules that are unique to a particular system can be easily modified and used to evaluate alternative CMS strategies for other types of transportation systems, such as bus systems or other forms of automated guideway transit systems.

The simulation program was used to develop several CMS strategies for a test network and O/D data provided by UMTA. The test results indicate that CMS strategies are readily adjustable so that 80-90 percent of trips can be accomplished within a mean wait time of 5 min. The generally held notion that fixed-schedule service is superior to demand-responsive service during high-demand periods was found to be incorrect. Some demand-responsive strategies developed and tested for the test network for peak demand periods also gave extremely good results—that is, high vehicle load factors and very short mean wait times. In addition, the demand-responsive strategies were found to be more adaptive to failures and dynamic variations in demand than fixed-schedule strategies.

CMS strategies, particularly for transportation systems that use small vehicles on complex routes, require further research and experimentation so that basic guidelines can be established for the development and refinement of algorithm parameters for planners of future systems. The simulation program developed is a powerful tool with which to test various CMS strategies. It can be improved further, however, to expand its capabilities.

## ACKNOWLEDGMENT

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# Electric Cars for Urban Transportation

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**Within 10 years rapid technological advances will make the production of electric cars by a major manufacturer a likely possibility. Widespread use of electric cars would drastically reduce the amount of petroleum consumed for urban transportation and also cut automotive air pollution and noise significantly. Under current conditions and trends, however, sales of electric cars are likely to be relatively modest, unless a larger role is deliberately planned for them in order to reap their potential benefits for conservation and environmental quality. This paper is a summary of an investigation of the effects of large-scale use of electric cars on energy, the environment, and the economy.**

Electric cars offer major potential advantages for urban transportation: the convenience and mobility of the internal-combustion automobile without its dependence on petroleum or its major environmental problems. Recent electric cars have had very limited appeal, primarily due to the short range between recharges and high overall costs. New batteries that will substantially relieve both range and cost disadvantages are expected soon. With these batteries and more efficient automotive technology, today's electric car ranges (up to 120 km in urban driving) may be doubled or even quadrupled in a few years, and the cost of battery depreciation may be reduced by as much as 70 percent. A federal program plans to demonstrate up to 10 000 improved electric vehicles by the mid-1980s, and General Motors has announced intentions to market urban electric cars in less than a decade (1-3). Thus an important new option may soon become available to transportation planners.

This paper summarizes a study of electric cars made for the Division of Transportation Energy Conservation of the U.S. Department of Energy by General Research Corporation (4). The study investigated the effects of large-scale use of electric cars on energy, the environment, and the economy. It also projected the performance and cost of future batteries and cars, together with their applicability in urban areas. The major beneficial impacts of electric car use are first quantified; then the capabilities and limitations of future electric cars and their potential use in urban areas are summarized.

## BENEFITS

Electric cars do not necessarily require petroleum for fuel, but some of their recharge power may be generated in oil-fired power stations. Figure 1 shows that resultant petroleum use is expected to be a minor factor. Figure 1 indicates that if all automobiles in the United States were electrified in the year 2000, petroleum requirements for automotive travel would be reduced by 83 percent. Possible petroleum savings at intermediate levels of electrification would depend on the location of electrified cars. The band at the bottom of the figure is the projected petroleum use for recharging electric cars. If electric cars were distributed uniformly throughout the United States, the amount of petroleum they use would be at the upper edge of this band. However, if they were first distributed to geographic areas that do not rely on petroleum for generating electricity, almost no petroleum would be necessary for recharge until some 60 percent of all atuomobiles are electrified. Figure 2 shows the fuels that would be used for recharge in each of the nine regions of the National Electric Reliability Council, if all automobiles were electrified in the year 2000. Petroleum use would be

**Figure 1. Effect of electric cars on petroleum use by automobiles, 2000.**

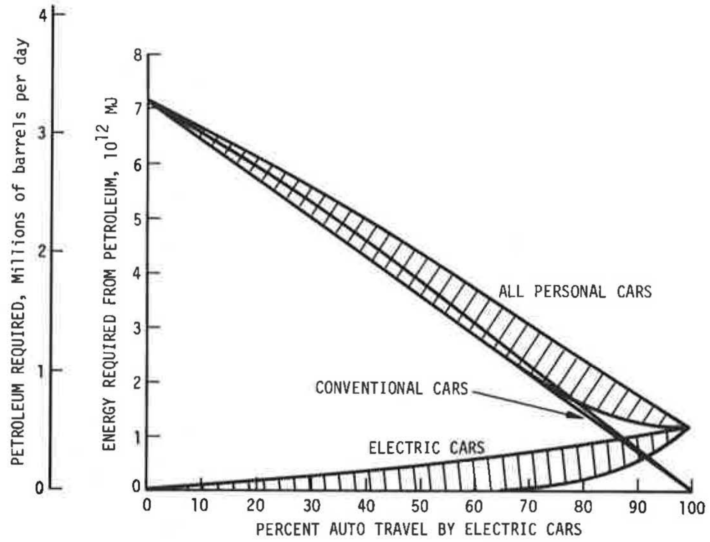


**Figure 2. Fuel mix by region for electrifying all cars, 2000.**

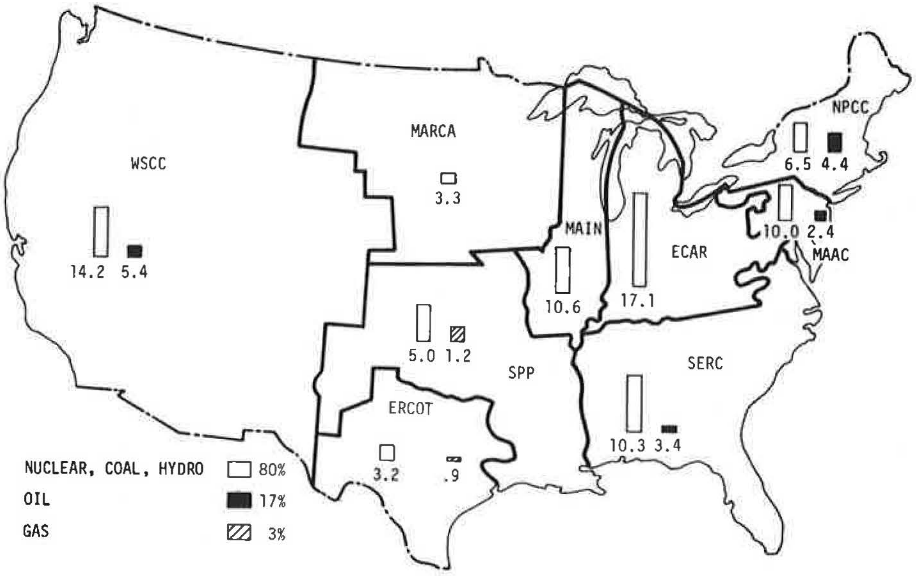


**Figure 3. Energy available on peak days for recharging electric cars, 1980-2000.**

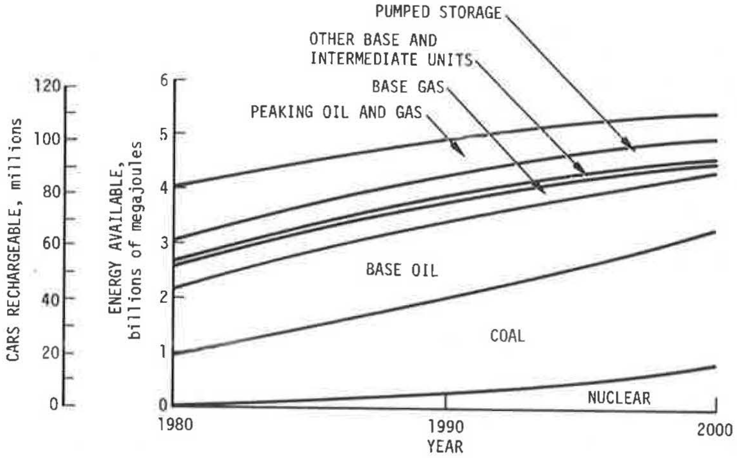


**Figure 4. Effect of 100 percent electrification of cars on regional emissions of air pollutant (population-weighted averages).**

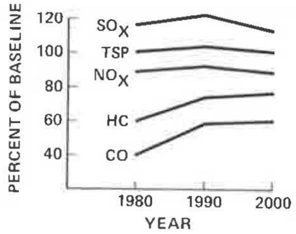
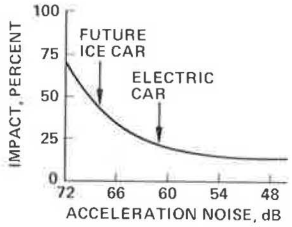


**Figure 5. Impact of future urban traffic acceleration noise versus future level of automobile acceleration noise (percentage of 1974 level of impact).**



significant only in New England, the Middle Atlantic States, and the Far West.

These findings are based on detailed projections for over 220 major utilities in the United States (4). Most new capacity planned by utilities will be coal-fired or nuclear, so the relative importance of oil-fired plants will decline. Typically, utilities expect to have sufficient capacity for the annual peak demands in their service areas. In most parts of the country these peaks occur during hot summer afternoons. During the late night hours, even on a peak day, demand is expected to be far below the peak level, so much capacity that would otherwise be idle could be used to recharge electric cars. Figure 3 shows the projected amount of energy that could thus be provided from various fuels, together with the approximate number of electric cars that this energy could recharge. Electric cars are assumed to require 1 MJ of recharge energy per kilometer of travel and a little less than 50 MJ for the average day's driving. Even on the peak-demand day, enormous numbers of cars could be fully recharged; and on other days of the year, much more recharge energy would be available. Utilities are rapidly moving toward peak and off-peak pricing and to direct load management by remote control. These would concentrate electric car recharging during the late evening hours, when available capacity and petroleum savings would be greatest.

Electric cars emit no air pollutants. The power plants that recharge them may, however, emit pollutants if they burn fossil fuels, and these pollutants may be discharged in the same air quality control region as that in which the cars operate. To some extent, the increased emissions from utilities would offset the decreases due to replacement of conventional automobiles by electric cars. Figure 4 assumes that all automobiles will be electrified (4) and shows projected changes in emissions for the 24 largest urban United States Air Quality Control Regions (AQCRs). This is an upper bound on effects that might be expected from electric cars. Results are shown as a percentage of baseline emissions (i.e., total emissions from all sources projected in the absence of electric cars). Figure 4 indicates that electric cars would substantially reduce the regional emissions of pollutants primarily due to vehicles—hydrocarbons (HC) and carbon monoxide (CO). This benefit would be offset, however, by increases of up to 20 percent in emissions of sulfur oxides (SO$_x$) due to fossil-fueled power plants that generate recharge power. Emissions from conventional automobiles were assumed to decline in line with standards imposed by the Clean Air Act Amendments of 1977. Thus, the benefits of electric cars for HC and CO emissions are less in 1990 and 2000 than in 1980. The overall air quality analysis indicates that sources other than personal automobiles will dominate urban air pollution in future years. This is the reason why the benefits shown in Figure 4 for electric cars are relatively modest.

Traffic noise, the principal noise problem in the United States, was estimated in 1974 to affect adversely almost 100 million people. Noise emissions standards have already been promulgated for trucks, buses, and motorcycles—the noisiest motor vehicles. Standards for automobiles are under development. In urban cruise, where tire noise dominates, electric cars offer little potential advantage. During acceleration, however, engine-related noises predominate for conventional automobiles, and even after considerable improvement, they are expected to be much noisier than electric cars during acceleration. About 15 million people were adversely affected by traffic-acceleration noise in 1974. Required reductions in truck, bus, and motorcycle noise will reduce this to about 70 percent of the 1974 level in future years, even if automobile acceleration noise remains at its present 72 dB level (5). This is shown at the left of Figure 5. Acceleration noise of future internal-combustion engine automobiles is assumed to be reduced to the 68 dB level, which will lower impacts to about 45 percent of the 1974 level (4). The acceleration noise of future electric cars could probably be lower still—about 61 dB (4).

Substitution of electric cars for all internal-combustion automobiles would then reduce noise impacts by almost one-half, to a little over 20 percent of the 1974 level.

## LIMITATIONS

Despite their potential benefits for petroleum conservation and the urban environment, the probable usage of electric cars is likely to be quite modest. Figure 6 shows two recent projections of the percentage of the United States automobile fleet that may be electric in future years (6, 7). Both projections are under 10 percent in the year 2000, due primarily to the higher expected cost for electric cars despite the major improvements in batteries projected for the coming decade. Even with these improvements, electric cars are expected to cost somewhat more and do somewhat less than competing conventional automobiles. This assumes energy prices similar to those of today. If gasoline prices were doubled or tripled (to levels prevalent now in Europe), the cost disadvantage would disappear. The range limitation would remain, however, and even though it might entail travel sacrifices on only a few days of the average year, it would probably be a significant deterrent to the purchase and use of electric cars. Furthermore, the acceleration performance of electric cars will probably remain inferior.

The basic problem in electric cars has been (and will remain) the battery, which is heavy and expensive in relation to a gasoline tank. Today's lead-acid batteries are roughly 85 times heavier than a tank of gasoline that stores the same effective propulsion energy. Moreover, today's batteries must be replaced, at considerable cost, after 300 or 400 discharges. Major innovations (nickel-zinc and lithium-sulfur battery systems, for example) are expected to double, triple, or even quadruple both energy stored per kilogram and cycle life. Nevertheless, extra weight and extra cost relative to the gasoline tank will surely remain.

Future electric cars will generally be heavier and more expensive than their conventional counterparts. Figure 7 assumes the weight-conscious and efficient automotive technology appropriate to 1980 and after and compares the weights of future electric and internal-combustion-engine four-passenger subcompact automobiles (4). Passenger compartments in the two automobiles are identical in size and weight. The big difference between them is the weight assigned to energy storage: in the electric car, it is almost 15 times greater than in the internal-combustion automobile. The structure and chassis weight of the electric car is substantially greater than that of the conventional automobile in order to support this additional weight. The propulsion weights are about equal and provide roughly equal amounts of power output. The acceleration capability of the electric car is much less, however, because the car is much heavier.

The electric car in Figure 7 is designed for a long range between recharges, which necessitates a relatively large battery. Weight and the associated costs can be reduced if driving range is sacrificed. The trade-off between range and life-cycle cost is shown in Figure 8 for electric cars that have improved technology similar to that illustrated in Figure 7 (4). Figure 8 also shows the trade-off between range and life-cycle cost for electric cars with technology like that widely used one or two years ago and for advanced electric cars with lithium-sulfur high-temperature batteries. In every case, reduction in design range reduces costs substantially. The minimum ranges shown are those at which battery power output is barely sufficient to meet an assumed acceleration requirement. This requirement, 0 to 64 km/h in 10 s, is the minimum considered acceptable for safe entry into

**Figure 6. Projected percentages of electric cars in the U.S. automobile fleet, 2000.**

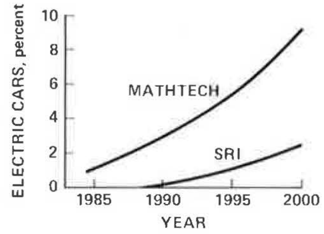
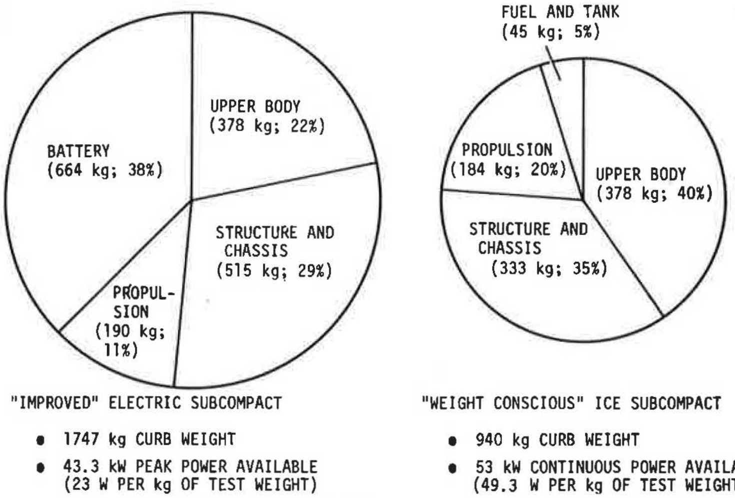


**Figure 7. Comparison of electric cars and conventional subcompact automobiles.**



"IMPROVED" ELECTRIC SUBCOMPACT

- 1747 kg CURB WEIGHT
- 43.3 kW PEAK POWER AVAILABLE (23 W PER kg OF TEST WEIGHT)
- 250 km RANGE (NICKEL-ZINC BATTERY)
- 150 km RANGE (LEAD-ACID BATTERY)

"WEIGHT CONSCIOUS" ICE SUBCOMPACT

- 940 kg CURB WEIGHT
- 53 kW CONTINUOUS POWER AVAILABLE (49.3 W PER kg OF TEST WEIGHT)
- UNLIMITED RANGE (WITH REFUELING)

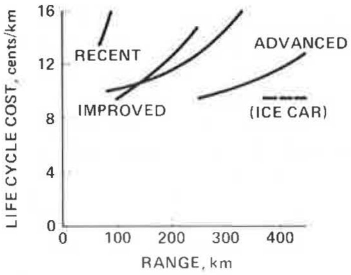


**Figure 8. Life-cycle costs of electric cars versus internal-combustion engine (ICE) automobile design range.**

freeways via typical uphill on-ramps. In all cases, the electric cars can cruise at speeds in excess of the legal limit. The internal-combustion engine automobile costs in Figure 8 are based on those published regularly by the U.S. Department of Transportation (8). The electric car costs are intended to be comparable. They do, however, reflect an assumption of 20 percent longer life (12 years instead of 10) due to the inherent durability and reliability of electric motors and controllers. Battery lifetimes were assumed to be much longer than at present—up to 1000 deep-discharge cycles, or a maximum of 8 years of operation. Average annual driving of 16 000 km/year was also assumed. Further improvements in battery performance and cost would have relatively little effect on these results. Increases in gasoline prices to levels now prevailing in Europe, however, would eliminate most of the disadvantage of the electric cars, even for long-design ranges.

Whether the shorter-range, lower-cost designs of Figure 8 are desirable depends on the intended application. For the most part, urban driving seldom requires long daily ranges. The table below shows driving range requirements sufficient for 95-98 percent of the driving days in Washington, D.C., and Los Angeles (4). These ranges were derived from analyses of trips reported by some 30 000 households in the origin-destination surveys made of the two areas in 1967-1968. The requirements are stated separately for the three principal groups of automobiles identified in the analysis.

| Automobile Group | Range Required for Daily Urban Driving<br>95th Percentile (km) | <br>98th Percentile (km) |
|---|---|---|
| Secondary | 55-75 | 70-105 |
| Only | 85-150 | 115-210 |
| Primary | 110-220 | 140-290 |

About one-third of the automobiles in each region were secondary automobiles at multiautomobile households. By definition, these automobiles were driven less than the primary automobile of each multiautomobile household. Another third of the automobiles were only automobiles of single-automobile households. The remaining automobiles were primary automobiles (those driven farthest) of multiautomobile households. Among two dozen other groupings of automobiles investigated, none showed requirements as low as for secondary automobiles nor as high as for primary automobiles. Comparison of these requirements with the ranges illustrated in Figure 8 shows that current electric cars could handle much of today's urban travel and, with expected future improvements, could handle almost all urban travel. If designed to be secondary cars for short-range use, electric cars would be competitive in cost with conventional automobiles. This may nevertheless be undesirable because (a) few secondary automobiles are purchased new, (b) motorists may prefer extra costs to sacrifices of travel mobility, and (c) nonurban travel capability may also be desired, even of second automobiles.

As improved technology increases the range of electric cars, they will become adequate for the needs of most urban drivers. Facilities for overnight recharge at residences will generally be required. Although battery-exchange stations and battery-recharging outlets on street or in parking lots are technically possible, they appear economically unattractive. Generally, overnight recharging will be easiest at single-family housing units that have off-street parking, where electric outlets with sufficient capacity can be easily accessible. The table below gives the percentage of single-family units in various areas that have garages or carports, estimated from the Annual Housing Survey of the Bureau of the Census (4, 9, 10).

| Place | Available Off-Street Parking<br>Single-Family Housing Units (%) | <br>Multifamily Housing Units (%) | <br>All Housing Units (%) |
|---|---|---|---|
| Los Angeles | 94 | 93 | 94 |
| Washington | 54 | 94 | 71 |
| In all SMSAs | 80 | 92 | 85 |
| Outside SMSAs | 73 | 87 | 77 |
| Entire United States | 78 | 91 | 83 |

The number is surprisingly low in such cities as Washington and Baltimore. The data do not include uncovered parking in driveways or yards, however, which might also be suitable. Off-street parking of some kind is usually available at multifamily housing units. Here, however, provision of secure outlets for recharging may be a serious problem, especially in basement parking garages, where installations might be difficult. Individual metering will probably be a necessary additional expense because an electric car may require as much energy as all other household uses combined.

## CONCLUSIONS

Future use of electric cars on a large scale would cut petroleum consumption drastically for automotive travel and cause significant attendant reductions in air pollution and traffic noise. Despite their probable availability from a major manufacturer within a decade, sales of electric cars are expected to be relatively modest. Future electric cars will be capable and economical, but they will still cost somewhat more and do somewhat less than competing conventional automobiles.

This situation is not without precedent. Low-pollution conventional automobiles are more expensive and more troublesome than uncontrolled internal-combustion automobiles. They would not sell well either if their advantages had not been considered so important that a major role in United States transportation was planned and implemented for them. More recently, fuel-efficient automobiles have received the same treatment. In the future, electric cars may deserve similar treatment. Transportation planners in urban areas where petroleum use and pollution from internal-combustion automobiles remain important problems should give serious attention to electric cars.

Electric cars are, of course, only one of several technological options under development and evaluation at the federal level for the reduction of environmental pollution and petroleum consumption. Electric cars may be unique, however, in that existing federal and industry programs already promise to make them widely available in the marketplace within a relatively few years. Thus, where pollution, conservation, and continued high mobility are important considerations in transportation system planning, electric cars deserve to be considered along with such frequently proposed possibilities as parking restrictions, exclusive bus and carpool lanes, automobile-free zones, automobile taxation, transit subsidy, transit expansion, and land-use controls.

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# Assessment of Market Potentials for Electric Vehicles

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**The widespread use of electric vehicles within the transportation system is essential for improvement of environmental quality and reduction of the consumption of petroleum-based fuels. This paper describes the development and application of a market assessment model that is used to estimate the market potential for alternative electric vehicle technologies by relating service needs to range capabilities. The market assessment model uses stratified household travel data to simulate typical daily travel patterns over a period of a year. Alternative scenarios of vehicle use are introduced to relate the sensitivity of the market potentials to household travel behavior. An approach to analyzing commercial vehicle market potentials is also presented. The analysis results reveal the interrelationships among the market potentials, vehicle-range capabilities, and vehicle-use assumptions and indicate the application of these findings to identification of an effective electric-vehicle technology development program.**

Gasoline- and diesel-powered vehicles are the single largest consumer of petroleum supplies. As a means of relieving the demand for petroleum within the transportation sector, the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, as amended, was passed to foster the accelerated integration into the market of electric and hybrid vehicles. The act provides resources to encourage the early demonstration of the state-of-the-art technology and the long-range development and commercialization of improved vehicle technology. A total of $160 million has been appropriated to support these activities.

The passage of this act reflects the nation's concern over environmental degradation in urban areas caused by conventional petroleum-fueled vehicles and the need for substitute forms of energy to mitigate the adverse consequences of continued reliance on imported petroleum. Many consider that the key to resolution of these concerns, and the principal objective of the act, is in the large-scale commercialization and operation of electric vehicles (EVs) within the transportation sector. Numerous technical problems must be overcome before an EV system that is capable of replacing a significant share of the conventional and commercial vehicle fleet is available to the transportation consumer. In order to facilitate the early commercialization and marketability of EV technologies within resource constraints, a resource allocation strategy must be developed to guide technology development in an orderly and efficient manner (1).

A critical component of the allocation strategy, and the focus of this paper, is a dynamic market assessment model that identifies the market potential for alternative EV technology configurations. The market assessment model identifies the scale, composition, and requirements of potential EV markets and facilitates the application of an iterative procedure whereby alternative technology and market focus strategies can be analyzed and modified to maximize program objectives.

## MARKET ASSESSMENT MODEL

The market assessment model analyzes the potential for the substitution of EVs for conventional vehicles by identification of generic vehicle type and user groups and determination of the compatibility of an EV to the travel and service requirements of the user groups. If a match can be established between the functional service needs of the user and the functional capabilities of the EV, this

**Table 1. Single-vehicle household stratification and intracity travel characteristics.**

| Income Quartile | Number of Daily Vehicle Work Trips | Total Households (%) | Average Work Trip Length (km) | Average Daily Nonwork Trip Frequency | Average Nonwork Trip Length (km) |
|---|---|---|---|---|---|
| Low | 0 | 7.9 | N/A | 1.1 | 9.0 |
| | 2 | 2.0 | 13.7 | 1.1 | 9.0 |
| Low-middle | 0 | 7.2 | N/A | 2.0 | 8.7 |
| | 2 | 8.1 | 13.5 | 2.0 | 8.7 |
| Upper-middle | 0 | 3.5 | N/A | 2.7 | 8.2 |
| | 2 | 10.7 | 15.9 | 2.7 | 8.2 |
| High | 0 | 1.6 | N/A | 3.0 | 8.0 |
| | 2 | 8.0 | 18.0 | 3.0 | 8.0 |

Note: 1 km = 0.62 mile.

**Table 2. Multivehicle household stratification and intracity travel characteristics.**

| Income Quartile | Number of Daily Vehicle Work Trips | Total Households (%) | Average Work Trip Length (km) | Average Daily Nonwork Trip Frequency | Average Nonwork Trip Length (km) |
|---|---|---|---|---|---|
| Low | 0 | 0.7 | N/A | 2.0 | 9.5 |
| | 2 | 0.5 | 15.3 | 2.0 | 9.5 |
| Low-middle | 2 | 4.5 | 15.3 | 3.7 | 9.5 |
| | 4 | 0.7 | 15.3 | 3.7 | 9.5 |
| Upper-middle | 2 | 3.5 | 18.2 | 5.1 | 9.0 |
| | 4 | 5.9 | 18.2 | 5.1 | 9.0 |
| High | 2 | 2.6 | 20.6 | 5.7 | 9.0 |
| | 4 | 12.2 | 20.6 | 5.7 | 9.0 |

Note: 1 km = 0.62 mile.

is an indication that the potential exists for the EV substitution. This analytical approach was used to study both passenger and commercial vehicles.

Perhaps the most salient, distinguishing characteristic of an EV is its limited range, that is, the number of kilometers that a vehicle may be operated between recharge periods. Other researchers have recognized and addressed the importance of the range limitations in their estimates of the market potential for EVs. Perhaps the most comprehensive work on this subject was conducted by Hamilton, who related the assessment of EV applicability to vehicle range characteristics and the availability of off-street parking (2). Range is a direct function of the limitations of the particular energy storage system used in the vehicle. Because of the restraints posed by energy dissipation and the recharge cycle, these range limitations effectively become the maximum distance that a vehicle can travel in the course of one day. The market potential analysis focuses on the daily range requirements of users as the principal functional determinant for estimating EV substitutability.

The distinction between market potential and vehicle sales projections is important and the limitations of this work should be stressed. This analysis is an assessment of the market potential or market segments that appear to have travel requirements that could adequately be served by an EV. Vehicle sales within this potential market sector is a different issue. The actual sales level achieved will be a function of a much broader spectrum of vehicle attributes, such as initial and life-cycle costs, acceleration, gradability, reliability, style, serviceability, and even who the manufacturer is, as well as the nature of the actual marketing program used. The issue of actual vehicle sales is an extremely complex problem, one that many researchers feel cannot be adequately addressed given the current lack of relevant market data. It will not be addressed directly in this analysis. This limitation notwithstanding, the systematic assessment of the EV market potential provides an important link in the selection of an optimum resource allocation plan to achieve the objectives of the act.

## Passenger Vehicles

The analysis of the market potential of the use of EVs for passenger vehicle applications is based on a stratification of all households into market segments that display nearly homogeneous patterns of trip making. Households are stratified by

1. The number of passenger vehicles owned (zero, one, two, or more);
2. Income quartile (low, lower-middle, upper-middle, high); and
3. The number of daily vehicle work trips.

For each market segment, average lengths of work and nonwork trips and average frequency of daily nonwork trips were derived from data provided by the Nationwide Personal Transportation Study (3). The trip length and frequency data reflect typical intraregional travel. Because of the limitations on EV range capabilities, EVs were not considered to be a feasible option for long-distance trips, which are defined as trips that have a one-way distance in excess of 80 km (50 miles). In the analysis, it was assumed that an alternative vehicle would be used to make these long trips, either a conventional vehicle or an alternative mode. The analysis was conducted under the assumption that no more than one EV would be bought by a single household.

The resultant market segment data reflect average weekday intraregional travel characteristics. This information is summarized in Tables 1 and 2. Typical weekend travel was indirectly treated by this orientation. When occasional long-distance trips are disregarded, the daily travel requirement for a typical weekend day is found to be less extensive than a typical weekday's travel (3). Therefore, if the weekday's travel requirement is served, weekend travel needs can be satisfied.

The trip data are used to simulate the use of the passenger vehicles during a period of one year (250 weekdays) in order to determine the range requirement distribution for household groups within each market segment (i.e., the distribution of the vehicle ranges necessary to serve various portions of the market segment). The establishment of the range requirement for each household group within a market segment did not assume a specific percentage of days for which vehicle range requirements must be met; rather, we assumed that the needs of all local trips on all days in a typical 250-workday year must be met.

The derivation of daily range requirements in the simulation is highly dependent on the assumptions made as to the manner in which vehicles in a household are and will be used for making a series of trips.

Seven alternative vehicle-usage scenarios were developed and analyzed. Each scenario represents a unique user response-accommodation behavior to EVs. The scenarios are defined as follows:

Scenario 1—EV used only for work travel in multiautomobile households;
Scenario 2—EV used for all trips in single-automobile households and used principally for nonwork trips in multiautomobile households;
Scenario 3—EV used for all trips in single-automobile households and used principally for work trips in multiautomobile households;
Scenario 4—Same as scenario 2 but one nonwork trip eliminated through better trip planning;
Scenario 5—Same as scenario 2 but two nonwork trips eliminated through better trip planning;
Scenario 6—Same as scenario 3 but one nonwork trip eliminated through better trip planning; and
Scenario 7—Same as scenario 3 but two nonwork trips eliminated through better trip planning.

In general, the first three scenarios represent usage options that approximate typical conventional use of vehicles. The last four scenarios represent situations where the household members willingly modify their typical travel routine to facilitate the use of an EV.

The first vehicle-usage scenario limits the vehicles to work trips only. This restriction dictates that only multiautomobile households may be served, since another vehicle must be used for other trip needs. In addition, an EV would only be used in multiautomobile households that make at least two daily vehicle work trips. Within these market segments, the use of the vehicles are limited to two work trips daily.

The second and third vehicle-usage scenarios are less restrictive. In single-automobile households, all local trips are to be made by the vehicle. In multiautomobile households where no work trips by automobiles are encountered, one-half of the household members' nonwork trips are to be made by the vehicle. In multiautomobile households where four daily work trips are made, the EV must serve two work trips plus one-half of the household members' nonwork trips. The second and third vehicle-usage scenarios differ in their treatment of the multiautomobile household where two daily vehicle work trips are made. In the second scenario, the vehicle performs all of the household members' nonwork trips, and in the third scenario, the vehicle performs the two daily work trips.

The remaining four vehicle scenarios are modifications of the second and third scenarios. Nonwork trips are assumed to be eliminated by either linking more trips, sharing them in a different proportion, or postponing them to another day when fewer trips (and fewer total kilometers driven) are necessary.

When a vehicle-usage scenario is selected to be tested, the appropriate simulation technique must be identified. The simulation procedure distinguishes work trips from nonwork trips because work trips tend to be constant in rate and length, as opposed to the more random nature of nonwork trip rates and lengths.

If the vehicle-usage scenario prescribes that a vehicle is to make only work trips, the simulation is quite straightforward. Since the number of work trips to be made is constant within any segment of the households analyzed, the distribution of round-trip work-trip lengths becomes the distribution of range requirements for the market segment. The distribution of the duration of work trips for each market segment was approximated from the values for the average duration of work trips and the variance in the duration of work trips by using a gamma function (4).

To apply the gamma approximation, the work-trip lengths (distances) were covered to work-trip durations (time). This was accomplished by use of a log-log least-squares fit of the relation between trip length and trip duration from the Nationwide Personal Transportation Study (3). The resultant equation is

$$\text{(Trip Duration)} = 8.884\ \text{(Trip Length)}^{0.459} \tag{1}$$

The variance of work-trip duration was calculated from the best-fit line of the relation of work-trip duration variance to average work-trip duration (4). The equation of the best-fit line is

$$\text{(Variance)} = 0.000\,153\,1\ \text{(Average)}^{4.944} \tag{2}$$

A gamma distribution was calibrated by conversion of the average work-trip length of a market segment to an average-trip duration and calculation of the variance. This became the distribution of range requirements for the market segment.

When the vehicle-usage scenario prescribes that only nonwork trips are to be made by the vehicle, a Monte Carlo simulation approach is used. The actual simulation is preceded by several steps. First, the average daily nonwork trip rate for the household groups within a market segment is assumed to be distributed normally. This distribution reflects the fact that each household group within the segment makes nonwork trips at a different average daily rate. An upper limit is placed on the normal distribution to reflect the impossibility of obtaining very large average daily nonwork trip rates. Given a value for the average nonwork trip rate, a Poisson distribution is then used to identify the probability of making any particular number of trips during a one-day period. The Poisson distribution reflects the randomness of trip making and was applied previously by Schwartz (5) to simulate automobile use patterns. The relation between the probability that a specific number of trips are made in a day and the average number of trips made in a day can be estimated by

$$P(x) = N^x e^N / x! \tag{3}$$

where

$P(x)$ = the probability that x trips are made in a given day,
$N$ = the mean number of trips made per day, and
$x$ = the number of trips made on a given day.

Once the probabilities of making different numbers of trips in a day are estimated, these probabilities are con-

**Table 3. Typical Poisson distribution of nonwork trip rates.**

| Number of Trips | Days per Year | Number of Trips | Days per Year |
|---|---|---|---|
| 0 | 0 | 9 | 19 |
| 1 | 3 | 10 | 12 |
| 2 | 10 | 11 | 7 |
| 3 | 20 | 12 | 3 |
| 4 | 31 | 13 | 2 |
| 5 | 39 | 14 | 1 |
| 6 | 40 | 15+ | 0 |
| 7 | 35 | | |
| 8 | 28 | Total | 250 |

verted to the number of days in a 250-weekday year that a particular number of trips will be made. Table 3 provides an example of the resulting distribution.

Nonwork trip lengths are also distributed by gamma distribution. Origin-destination survey data from selected transportation studies were used to verify that the gamma distribution could also be applied to approximate the actual nonwork trip duration distribution.

By use of this procedure to estimate the distribution of average daily trip frequency by household group, the distribution of trip frequency by the number of days in a year, and the distribution of nonwork trip lengths, the Monte Carlo simulation can be performed for any particular daily trip frequency. For each daily trip frequency generated by the Poisson distribution, that many trip lengths are randomly chosen from the gamma distribution and added together. This is repeated for the appropriate number of days so that the simulation randomly generates total kilometers driven on each day of the year. For each household group, the maximum number of kilometers driven in any one day of the year, referred to as the maximum daily travel, was used to establish the range requirement. The simulation was performed five times and the maximum daily travel for each iteration was averaged so that the actual value used for the household group's range requirement would be representative of a typical 250-workday year.

This simulation was subsequently performed for each household group within a market segment. Thus, a distribution of required ranges for the market segment was based on the normal distribution of nonwork trip rates. Similarly, the process was repeated for each separate market segment and aggregated to obtain the overall market potential for a specific vehicle-usage scenario.

When the vehicle-usage scenario prescribes that both work and nonwork trips are to be made, the work-trip simulation and the non-work-trip Monte Carlo simulation are performed as described previously. It is assumed that making work trips is independent of making nonwork trips. Two separate range requirement distributions are generated and combined to reflect the requirement that both types of trips be made by the household group.

### Commercial Vehicles

The analysis of the market potential of EVs for commercial applications is severely hampered by two factors: (a) the lack of data regarding vehicle usage (such as average daily trip frequency and lengths), which could be used to perform a simulation such as the one used for passenger vehicles; and (b) the great variability in vehicle characteristics and vehicle use, which demands a much more extensive stratification of the commercial vehicle fleet. As a result of these limitations, the market analysis for commercial vehicles is much more descriptive in nature.

The 1972 Census of Transportation Truck Inventory and Use Survey (5) allows a partial stratification of the nation's commercial vehicle fleet by vehicle type, vehicle use, range of operation, and total annual travel. Range requirements for commercial vehicles can only be inferred from the vehicle's stratification characteristics. To do this, a ratio of range requirement to average daily travel needs to be estimated for each market segment. Applying this ratio to the value for the average daily travel will provide an estimate of the vehicle range requirement, the satisfaction of which represents a condition for the potential substitution by an EV. For example, if the range requirement ratio for a certain commercial vehicle is 3.5 and the average daily travel is 32 km (20 miles), this implies that the EV must have a range in excess of 113 km (70 miles) to be feasible as an alternative to the conventional vehicle. Unlike the distribution of range requirements calculated for the passenger vehicle analysis, only a single typical range requirement can be estimated for each commercial vehicle market segment.

Because of the complexity in estimating the ratios of the range requirement to average daily travel market potential, estimates were not available at the time of this writing.

## RESULTS

The results of the passenger vehicle analysis are summarized in Figures 1 and 2. Each curve shown in these figures represents the aggregation of range requirements across all household market segments for a particular vehicle-usage scenario. Market potential in these figures is expressed in terms of the percentage of the total passenger vehicle fleet that can potentially be replaced by an EV. A maximum potential of approximately 73 percent corresponds to the assumption that no single household will purchase more than one EV.

Figure 1 shows the relation between the market potential and the range required under vehicle-usage scenarios 1, 2, and 3. The figure shows that in order to achieve a specific market potential, different EV range capabilities would be required, depending on which of these three scenarios is pursued. This has an important implication in terms of identification of an effective market orientation. For example, if the range capability of the EV is less than 97 km (60 miles) the best marketing strategy would be to focus on the use of an EV as a commute-to-work vehicle for multi-automobile families. If the range exceeds 97 km, then the marketing strategy should shift somewhat to stress that the EV is a general purpose vehicle.

These results can be used directly to estimate the market potential for alternative vehicle technologies. For example, an EV powered by a lead-acid battery that has an idealized range of approximately 120 km (75 miles) would have the potential to replace approximately 22-29 percent of the vehicle fleet. A 322-km (200-mile) range nickel-iron battery would be able to replace approximately 70 percent of the vehicle fleet. This latter figure is probably conservative, because as the range increases, the constraint that stipulates only one EV to a household can be relaxed.

It is interesting to compare these basic results to those obtained by Hamilton, if we disregard the requirement that off-street parking be available. Hamilton derived estimates of EV market potentials that are 50-75 percent greater [over the vehicle range interval of 75-225 km (47-140 miles)] than the market potentials depicted in Figure 1 (2). These differences reflect the more relaxed range suitability condition used by Hamilton in his analysis: An EV that could serve the household travel needs for 95 percent of the travel days was

Figure 1. Range requirement distributions for alternative EV usage scenarios.

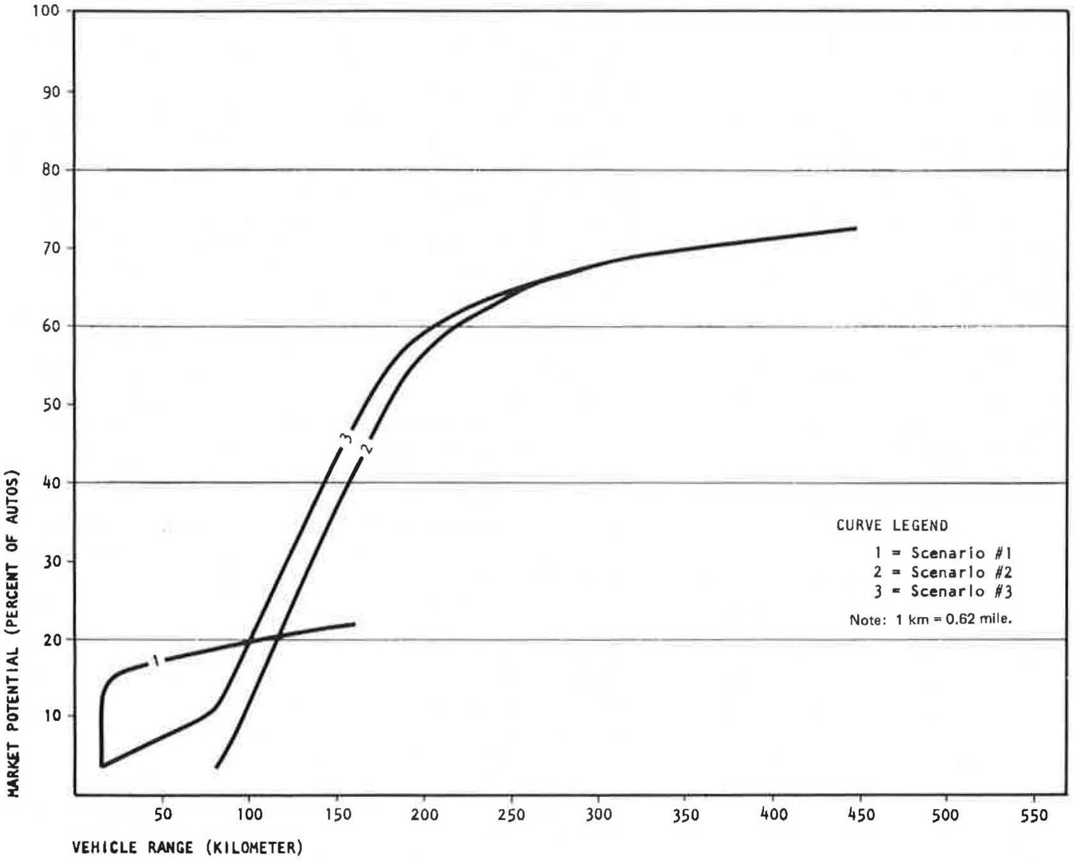
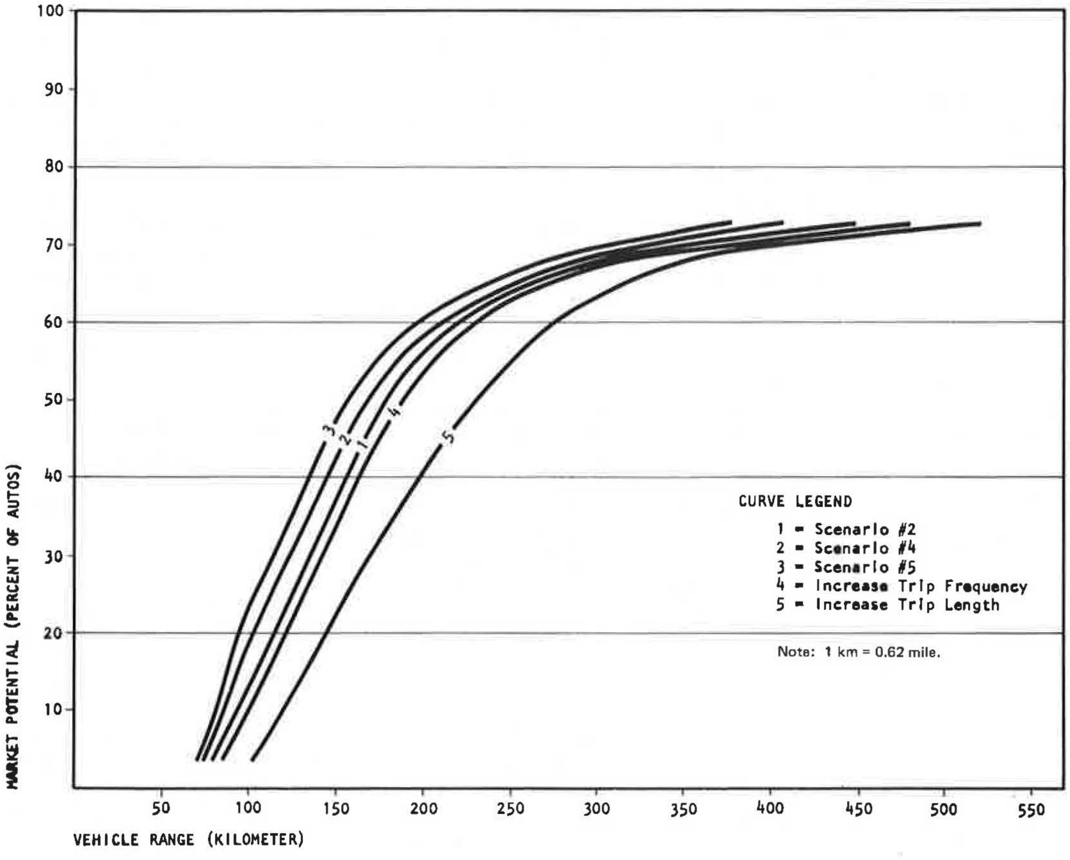


Figure 2. Range requirement sensitivity.



considered to be a reasonable substitute for a conventional automobile. In this paper, the travel requirements for a maximum day of travel established the condition for EV applicability.

Figure 2 demonstrates the sensitivity of the market potential results under conditions of modified travel behavior. This is achieved by showing scenario 2 as the base condition, as well as scenarios 4 and 5, which reflect increasing degrees of travel reductions through trip planning. Also shown are two additional travel variation schemes that reflect the effect of, in one case, a 20 percent increase in the nonwork trip frequency and, in another, a 20 percent increase in trip length.

The curves for scenarios 4 and 5 show that at the 130-km (80-mile) range, if two nonwork trips could be eliminated (through linking, shifting, or postponing), the market potential could be increased by approximately 50 percent, from 26 to 38 percent of the passenger vehicle fleet. As the range increases, the sensitivity of the estimates of market potential decreases. However, for those ranges encompassed by the technology options for the near term, the effect of usage patterns is significant.

Figure 2 also indicates the impacts of increased trip frequency and increased trip length. Of the two, trip length increases have the greatest impact on the market potential. Not shown is the effect of reductions in these travel factors, which tend to reduce the range requirement but to a lesser extent than the effects depicted by the increase in travel.

A separate analysis was conducted to evaluate the range requirement for individual market segments within a given scenario. What was found was that, within an automobile ownership level, as income increases, the range requirement tends to increase as well. For example, for scenario 2, the range required to achieve a market potential of approximately 35 percent (assuming 2 work trips/household) is 120 km (75 miles) for the low-income quartile and 177 km (110 miles) for the high-income quartile. The effect is less pronounced for multiautomobile households but nonetheless present. The effect of increases in automobile ownership level is mixed and depends on the income level. For below-average income levels, increases in automobile ownership have the effect of increasing the range requirement; however, above-average income levels tend to show no change or a small reduction in the range requirement when automobile ownership levels increase.

As lower-income households increase their automobile ownership levels as well as their general household income levels, EV substitution will be made more difficult because of corresponding increases in range requirements. These results are also disturbing in a more indirect manner: Our general contention is that, because of the anticipated higher initial cost of purchasing an EV rather than a conventional vehicle, the higher the household income, the greater the opportunity to replace a conventional vehicle with an EV. However, we find that these same households are more capable of buying an EV but have higher service needs. In a similar vein, multiautomobile households are expected to be more likely to purchase an EV than would a single-automobile household because they still would have a conventional vehicle for long trips. Again, however, we found that these same households have, in general, higher service requirements that frustrate EV substitution.

## IMPLICATIONS

This analysis has focused on what is perhaps the single most critical functional characteristic that distinguishes an EV from a conventional vehicle—range. Although other functional attributes of EVs could be used to sort out the market potential, such as their recharge and storage capabilities, these factors are viewed as less absolute and, therefore, less amenable to generalization. These shortcomings notwithstanding, the results of the market potential assessment provide a systematic treatment of travel behavior and a consistent basis on which to estimate the possible substitution of EVs into the nation's vehicle fleet. Subsequently, the market assessment model can be used to test alternative technology configurations and application situations to identify market impacts and to indicate an orientation for the development of a marketing strategy.

An important conclusion is the recognition of the interrelation among the vehicle range distributions, the patterns of vehicle use, and the household travel characteristics, specifically trip frequency and length. Changes in use patterns or travel behavior can have a pronounced impact, both positive and negative, on EV range requirements. What makes these factors difficult to deal with is their dynamic nature. Changes may also be brought about by technology or market factors as well as by changes in lifestyle, which are quite independent of transportation system factors. Whether these changes will be compatible or in conflict with EV commercialization strategies is uncertain. To facilitate successful implementation, the analyst's task is to recognize these options and to identify and test the integrity of the technology development strategy within the scope of possible futures. The analysis framework described here provides an initial step for doing just that.

Identification of the petroleum conservation implications of these results is less direct and requires further analysis. The amount of petroleum saved by implementing the EV as a local travel mode will be a function of the travel behavior of the households that will operate the EV, the battery recharging facilities and policies, and the electric-power-generating characteristics of the particular regions. However, the market potentials obtained in this analysis can be used to provide a first-order approximation of the maximum potential for petroleum savings through EV implementation.

As an example, the analysis of scenario 2 shows that an EV that has a range of 75 km (47 miles) has a market potential of approximately 5 percent yet diverts less than 1 percent of the total number of vehicle-kilometers traveled by all passenger automobiles. EVs that have ranges of 150 and 225 km (93 and 140 miles) could divert approximately 10 and 40 percent of the total vehicle kilometers of travel, respectively, compared to their market substitution potential of 35 and 60 percent. The point is that the correspondence is not one-to-one between the number of conventional vehicles substituted and vehicle kilometers of travel (which is a surrogate for petroleum consumption) diverted to EVs. This suggests that the introduction of low- to medium-range EVs will have only a marginal effect on reduction of petroleum consumption.

This analysis indicates ultimate market potentials. Given that the vehicle fleet replaces itself at a rate of about 10 percent each year, a number of years under economic conditions favorable to EVs will elapse before these market shares can be achieved. Moreover, the extent to which these potentials are in fact achieved is a separate and complex issue. Much more information is needed before credible sales estimates can be made. How will potential EV owners make purchasing decisions? What is the relation between the actual range requirement and the perceived range requirement? To what extent will potential EV users be willing to rely on other vehicles or modes for making long-distance trips? [As part of this analysis, we estimated that the cost of using a rental automobile to make only long trips, amortized over the life of an EV, would be in the range of 2-3 cents/km (3-5 cents/mile).] What factors are considered when deciding whether to purchase a new or used automobile when an existing vehicle is being replaced? These and other questions will need to be resolved. However, in the interim, systematic market potential estimates can play an important role in EV technology and resource allocation decisions.

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