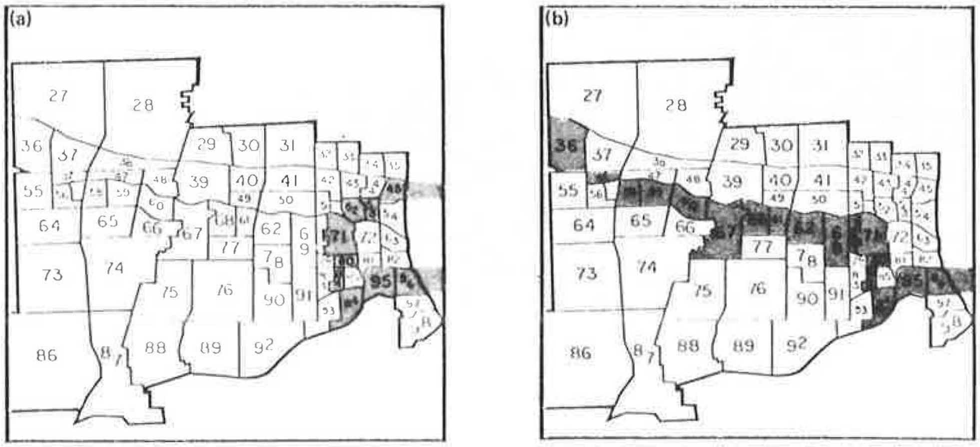
Figure 4. Selected locations (a) without and (b) with zone disincentive multipliers.



consultants. The HLSM offers the transportation planner and engineer a working tool that assists in the highway location planning phase of the urban transportation planning process.

ACKNOWLEDGMENT

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Abridgment

Macroanalysis for Transit Integration

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The purpose of transit integration is to identify the transit services that best fit individual neighborhoods and the best combination of services to meet the needs of an urban area as a whole. The many service options include the following:

1. System options—considering different systems for the same or similar applications;
2. Application options—modifying service areas and system configurations;
3. Integration options—combining feeder-distributor and line-haul services in different ways and different patterns;
4. Level-of-service options—examining different levels of service for particular areas and transit applications;
5. Design options—altering performance characteristics, facility locations, and route alignments within the same general system configuration; and
6. Implementation options—time phasing the services and increments of services in different ways.

To investigate enough integration options to have some hope of finding a good solution, it is necessary to examine 20 or more alternatives. Even so modest a number of investigations is beyond reason if one is compelled to use the traditional network-based algorithms. The macroanalytic regionwide transportation (SMART) model of SYSTAN, Inc., has been specifically designed to explore large numbers of public transit alternatives. This model can provide the first coarse screen by which the number of transit options is reduced to manageable proportions. The model seeks breadth at the expense of detail. It does not take the place of more complex procedures but helps to focus the use of complex models on a small set of highly attractive alternatives.

Figure 1. Modular representation.

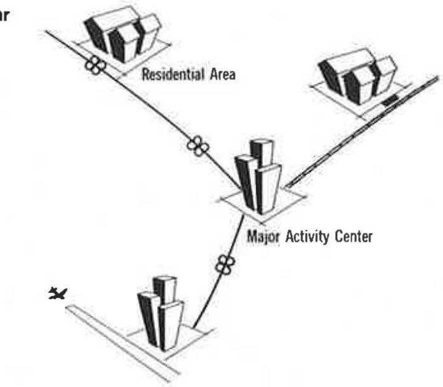
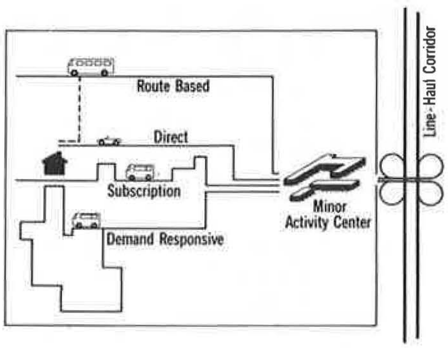


Figure 2. Residential-area service options.



DESCRIPTION OF THE MODEL

The SMART model represents urban travel at three different levels: (a) local, (b) door to door, and (c) regionwide. Local transportation is concerned with trips that take place wholly within a local module and with those portions of longer trips that occur within the local module. Local transportation is studied for two types of modules (see Figure 1): (a) residential and (b) major activity center.

Residential and major activity center modules are connected by line-haul corridors that handle all interzonal traffic within an urban region. Line-haul corridors give form to the urban structure by establishing connecting routes between the different modules. Line-haul corridors are given a circular representation: Corridors are either radial or circumferential or they emanate from the CBD. Line-haul corridors do not originate or terminate traffic; they handle traffic that originates and terminates in residential or major activity center modules.

Door-to-door trips cross module boundaries. A trip may originate in a residential module where it includes a local movement from a residential origin to an access point of a line-haul corridor. The trip continues on one or more line-haul corridors to the egress point nearest the destination. A local movement is then made from the egress point to the destination. A traveler can use a single mode between origin and destination, or modes can be changed at access or egress points of line-haul corridors or at transfer points between line-haul corridors. Door-to-door analysis takes the viewpoint of the traveler and traces the route from origin to destination, accounting for mode changes when they occur and the delays associated with them.

The SMART model accumulates regionwide data and prints regionwide summaries.

PROGRAM STRUCTURE

The SMART model calculates deterministic service and performance measures for a large number of transportation alternatives. Variance in travel time is also estimated for each of the activities that make up a trip—walk time, wait time, vehicle travel time, and transfer time.

The SMART model consists of a master computer program and nine subprograms:

1. FEEDER analyzes residential area travel;
2. LINKER analyzes line-haul-corridor travel;
3. DUMPER analyzes distribution ends of trips;
4. BCOST allocates costs between peak and off-peak hours;
5. DOOR aggregates door-to-door costs and travel time;
6. TRIPER computes daily trips between zones;
7. TEMPER distributes trips among the hours of the day;
8. RANDKP computes random numbers; and
9. RGNWDE estimates regionwide transportation performance.

FEEDER models a residential area as a square with one or a group of minor activity centers located at the center of one side of the square adjacent to a line-haul corridor. Measures of transit performance are calculated for trips from the interior of the square to the minor activity center. Service options are divided into four categories: (a) direct, (b) subscription, (c) demand responsive, and (d) route based (see Figure 2). Methods for the analysis of these service types are described elsewhere (1-3).

Direct services, such as automobile, bicycle, and walking, are characterized by direct movement from origin to destination. The distance traveled is the rectilinear distance along the streets.

Subscription services, such as carpool and vanpool, are characterized by a collection phase, a line-haul phase, and a distribution phase. The vehicle may be parked in the destination area to await a return trip, or it may be returned to a residential area to collect another load.

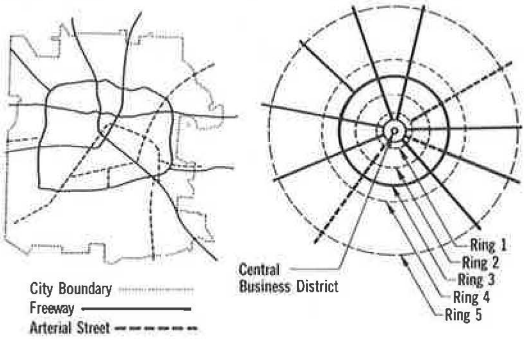
Demand-responsive services, such as dial-a-ride and shared-ride taxi, have three principal modes of operation: (a) many to one, (b) many to few, and (c) many to many. Experience with demand-responsive services indicates that the most common mode of operation is many to few. It is this mode that is represented in the SMART model.

Route-based services, such as conventional bus and light rail, are characterized by regular or semiregular route patterns. Routes can be fixed or flexible with point or route deviation. The fixed-route structure extends from the minor activity center across the residential area. Routes are located symmetrically so as to require the same maximum walking distance everywhere in the residential area.

DUMPER models major activity centers—CBDs, airports, universities, and other employment or commercial centers. If the destination module is the CBD, DUMPER accumulates traffic volumes and estimates congestion delays by using Smeed's equation (4). Vehicles that park in an activity center are charged a parking fee that is divided evenly between entering and leaving trips.

Three categories of travel in the major activity center are examined: (a) street vehicles, (b) fixed-guideway vehicles, and (c) walking. Street vehicles include automobiles, vans, buses, and commercial

Figure 3. Development of circular structure of CBD and major regional travel corridors.



vehicles. Most of these vehicles provide collection and distribution for interarea trips. In addition, there is an intra-area bus service. Fixed-guideway vehicles included light rail and automated-guideway transit. In major activity centers, these vehicles always operate on exclusive guideways. Light-rail characteristics are dictated by station spacing within the major activity center. Automated-guideway services in major activity centers can use any of six route configurations. Walking plays an important role in travel in the major activity center. Many travelers prefer to walk from line-haul interchanges to their activity center destinations. The SMART model assumes that all travelers whose destinations are within 0.4 km (0.25 mile) of an interchange will walk.

LINKER models line-haul movements on high-speed corridors or major arterial streets. Performance measures are computed for the line-haul portion of the trip. Speeds in highway line-haul corridors vary with the volume of traffic carried. Line-haul corridor analysis requires, therefore, that traffic volume data be provided from the regionwide trip distribution or from another source. Traffic volumes can change from hour to hour. The SMART model deals with expected, traffic-influenced speeds. It does not treat phenomena of traffic flow that accompany instantaneous excessive demands, nor does it deal with the queuing problems associated with congested access and egress.

Line-haul-corridor services include (a) mixed-traffic highway services; (b) preferential highway services; and (c) fixed-guideway services. Mixed-traffic highway services introduce transit vehicles into the general traffic that moves along highway corridors of all types. The traffic mix includes automobiles, carpools, vanpools, subscription buses, and conventional buses. Passengers either enter line-haul corridors on vehicles that originate in other modules or transfer to line-haul vehicles at access points. No waiting time is assigned to passengers who do not change vehicles. Waiting times for passengers who board at access points are calculated in one of two ways: (a) half of the line-haul vehicle headway for uncoordinated services or (b) 5 min where feeder and line-haul services have coordinated schedules. Transfers are assumed to take place in well-designed stations or terminals so that the transferring passenger merely needs to walk across a platform to make the change.

Preferential highway services introduce transit vehicles onto exclusive lanes that are set aside for one or more line-haul-corridor services. The exclusive lane is available for both transit and paratransit services, including conventional buses, vanpools, carpools, and others. Fixed-guideway vehicle performance is influenced by station spacing, mean speed between stations, station dwell time, vehicle capacity and headway, and by the technical characteristics of the individual system.

Regionwide analysis accumulates results from all of the modular analyses and aggregates these data for the region as a whole. Unlike modular analysis, which considers many different public transit modes for the same service, regionwide analysis combines the results from an explicit set of modular services to yield regionwide performance. The regionwide analysis requires a complete trip table for the region. Trip tables from comprehensive planning studies can be used, or a trip table can be generated by the SMART model from a general table such as one might find in the Urban Data Book (5) of the U.S. Department of Transportation.

USER OPTIONS

In addition to selecting the characteristics of modules and line-haul corridors, the user of the SMART model can introduce a variety of other options into the model. Some of the more important options are (a) minimum level of transit service, (b) extent of transit service coordination, (c) labor assignment constraints, (d) time-related traffic distribution, and (e) transit mode share.

Because no good methods exist for estimating system ridership, particularly for novel systems and system combinations, the SMART model does not make any attempt to estimate ridership. Rather, the user can introduce eight transit mode shares for consideration. The SMART model will make modular, door-to-door, and regionwide travel calculations for each mode share. The output will also help the user to answer such questions as the following:

1. What are the implications of mode share for the level of operating subsidy?
2. What mode share is needed to justify the desired set of services?
3. What are the impacts of mode share on opportunities for transit integration?
4. What is the impact of different mode shares on traffic congestion?

Transit mode share can also be varied between peak and off-peak periods.

MODEL VERIFICATION

The subprograms for residential area, major activity center, and line-haul corridor were tested against a large number of transit operations. In each instance, the SMART model results can be judged to come from the universe of operating data. Both Student's t and Kalmogorov-Smirnov tests were used at a 5 percent level of significance. Future verification is planned for entire urban areas to test both the application of the SMART model and the accuracy of the results.

REGIONWIDE REPRESENTATION

A regionwide structural representation, shown in Figure 3, is prepared from maps, aerial photographs, census, and other demographic data. The analyst begins by identifying the CBD and the major transportation corridors in the region. These corridors are then represented in terms of a circular structure that has the same area, population, employment, and kilometers of freeways and arterial streets as the urban area (Figure 3). Radial routes can have any angular relation to one another. Urban representations need not be complete circles. Lakes or harbors can be represented by assigning zero population and employment. Discontinuities can be introduced into corridors to reflect rivers or other geographical barriers. Once the corridor structure is established, residential and major activity center modules are identified and located on the circular structure. The product of the representation work is an urban structure that can be entirely or partially analyzed by using the SMART model.

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Discrete Optimization in Transportation Networks

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In most cases, planning capital investment in transportation networks is an unwieldy job because the number of investment options grows so rapidly. The real situation faced by the transportation planner is, in general, when, where, and by how much to allocate available resources. The transportation investment problem can be characterized as the location and timing decisions to be made by the planner. A branch-and-backtrack algorithm is presented that tackles both location and timing aspects of the capital investment problem in small and medium transportation networks. The results presented are encouraging for future research in which the technique can be applied to larger, actual transportation networks.

The problem addressed in this paper is a common one in transportation planning. Given an existing network of M links, a set of future supplies at each origin in the network, and a set of future demands at each final destination, when, where, and by how much should additional investment be dedicated to each link?

For the purposes of this paper, a link can be either a physical connection between two geographically separated points, such as a rail line or a big highway, or it can be a transshipment facility such as a port. It is assumed that demand at each destination and supply at each origin are inelastic—that is, independent of transportation cost. Under this assumption, minimization of present-value social costs aggregated over the network is consistent with maximum national income, and this is the objective function used throughout. The algorithm presented can be extended to price-sensitive supply and demand without computational difficulty by using Devanney's method (1) and replacing cost minimization with maximization of the present value of the sum of the consumer's and producer's surplus. It is also assumed that, whatever the investment, all links are priced at their marginal social cost. In the transportation planner's vernacular, "system-optimized" rather than "user-optimized" operation is assumed. This is in part a reflection of my interest in freight rather than in passenger transportation and in part a reflection of my philosophy that, wherever the results of user-optimized operation differ greatly from those of system-optimized operation, the costs of administering a marginal-cost toll system on nonurban networks can and should be borne.

Finally, it is assumed that future growth of demand and supply is known with certainty. Before we can tackle uncertainty, we must have an efficient algorithm for handling investment with certainty (2). Indeed, one of the goals here is an algorithm that is efficient enough to be routinely run over a range of hypotheses for growth of demand and supply.

Even given all the assumptions above, the magnitude of the problem can be appreciated by considering a network with M links, T possible investment periods, and N possible levels of investment on each link in each period. Then the number of possible investment strategies is N^{M^T}. Consider a very small network with four links, three levels of investment on each link, and five investment periods. The number of potential investment strategies is 3.5×10^9. To solve such a problem, for each such investment strategy examined one must

1. Compute the set of equilibrium flows in the network for each period and present value and the resulting link flow costs and
2. Combine the present-value flow costs with the present value of the fixed costs associated with this investment strategy.

In short, each investment strategy examined requires the solution of T network flow problems. Even with the very efficient available algorithms for network flow, direct enumeration of all investment strategies is clearly out of the question for even a very small network.

The major reason that our problem is so different is that we have combined allocation in space with allocation in time. Most work on investment across links has assumed only a single possible investment point in time. Either an investment in a link is made at that time, or it is never made. In reality, given the generally continuous growth in transportation demand, investment timing is as important as investment location. Yet most work on investment scheduling has assumed