TRANSPORTATION RESEARCH RECORD

No. 1429

Planning and Administration

Multimodal Priority Setting and Application of Geographic Information Systems

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. 1994

Transportation Research Record 1429
ISSN 0361-1981
ISBN 0-309-05507-5
Price: $25.00

Subscriber Category
IA planning and administration

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Foreword

The 12 papers in this volume were presented at two sessions of TRB's 73rd Annual Meeting in 1994. Five papers focus on techniques for multimodal programming and priority selection. Such strategies include scoring procedures that use a high-precision method for weighting criteria and comparing alternatives; a new approach for evaluating the cost-effectiveness of multimodal transportation alternatives; a common framework for multimodal project selection based on a comparison of the experience of two metropolitan planning agencies; and the use of a regional travel simulation model to estimate system-level impacts of transportation actions allowing for comparison of mobility improvements and infrastructure repair projects.

Seven papers address applications of geographic information systems (GISs). Applications include a data collection process for a sign inventory using global positioning systems with GIS, the use of GIS for planning transit services for people with disabilities, and the building of transportation analysis zones using GIS. Two case studies review implementations of GIS to large transportation planning: the development of a prototype transportation management GIS data base for pavement systems and the application of GIS to urban roadway and infrastructure management.

Developing a Method of Multimodal Priority Setting for Transportation Projects in the San Francisco Bay Area in Response to Opportunities in ISTEA

KRISTINA E. YOUNGER AND DAVID G. MURRAY

After background as to the context provided by the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), the San Francisco Bay Area's leadership role, and the existing institutional structure for transportation decision making in the Bay Area is given, the process led by the Metropolitan Transportation Commission to change this institutional structure is documented. A multimodal method of project selection for the Surface Transportation Program and Congestion Mitigation and Air Quality Improvement Program was established in spring 1992 that brought all of the relevant players to the table, strengthened existing plans and programs, and established a new way of doing business on the basis of partnerships and cooperation. The program of projects that resulted from the application of the developed criteria is balanced and multimodal, and it enjoys widespread support in the region. Future programming cycles will improve on the established process and criteria. Many key aspects of the Bay Area experience are of direct relevance to other metropolitan areas that are struggling to respond to the opportunity of flexibility offered by ISTEA.

The new federal transportation reauthorization, the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), breaks new ground by granting metropolitan regions unprecedented latitude to direct transportation investments toward alternative modes and routes. This combination of funding flexibility and regional decision making will shape transportation investments in the post-Interstate era.

The San Francisco Bay Area's Metropolitan Transportation Commission (MTC) recently adopted its 1993 Transportation Improvement Program (TIP). The 1993 TIP includes the programming of ISTEA's new Surface Transportation Program (STP) and Congestion Mitigation and Air Quality (CMAQ) Improvement Program funds for 225 projects that cut across all modes. Notable examples include alternative fuel buses; signal interconnects; bike lanes and bridges; bus-rail transit centers; paving, restriping, and channelizations; park-and-ride lots; a port intermodal container transfer facility and rail bridge; freeway service patrols; rail transit transbay tube rehabilitation; and even a child-care facility at a rail transit station. Table 1 summarizes the adopted program by project type. A list of the individual projects in the adopted MTC program is available from the authors.

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The process for programming of STP and CMAQ funds was developed by MTC in cooperation with a wide variety of transportation and air quality interests in the Bay Area. So broad was the base of support for the exercise that when MTC acted to release the STP and CMAQ programming for public comment, the audience broke into spontaneous applause. As one participant commented,

> We are very pleased with the results of what I call the "cooperative competition" engendered by ISTEA. While we each compete for our individual projects, the broader we define them, the more everyone benefits. MTC's process enhanced communication both among countywide modal sponsors, who often had not spoken in the past, as well as between counties. New players were at the table and the results of the program indicate that we were all winners. While refinements to the scoring criteria are still needed, the multifaceted criteria made us grapple with what are truly the most productive sets of solutions at the county and regional level. (Brigid Hynes-Cherin, San Francisco County Transportation Authority)

Although some regions have had experience with alternatives analyses or corridor studies, the type of multimodal programming now being undertaken by metropolitan planning organizations (MPOs) is, for the most part, a new field. Many regions have found that the existing literature is of limited practical value in establishing the new transportation programs or the cooperative processes now required in the ISTEA era.

This paper describes the Bay Area's experience in developing a program for STP and CMAQ funds for its 1993 TIP and suggests ways that it may be applied to other regions. It is not a research paper but is intended for practitioners.

CONTEXT OF BAY AREA AND ISTEA

The MTC is the metropolitan transportation planning organization for the nine counties of the San Francisco Bay Area. In spring 1992 MTC was in a unique position to become a proving ground for many of the new opportunities that ISTEA presented to regional planning agencies throughout the country. A number of factors combined to allow MTC to test new methodology for multimodal project selection. They can be summarized as follows:

- MTC, in developing an advocacy position for the formation of ISTEA, forged a partnership with other California and Bay

Area transportation interests, particularly the California Department of Transportation (Caltrans), the nine Bay Area county congestion management agencies (CMAs), the California Transportation Commission, transit operators, and environmental interests. This partnership developed and actively supported a set of principles to be included in ISTEA. These principles included a desire for a level playing field across modes and increased flexibility to make planning and programming decisions at the local level.

- California voters, in passing a gas tax increase in 1990, created county-level CMAs and a category of state funding with some spending flexibility across modes. Highways, local roads, and fixed guideway transit could compete in a flexible congestion relief program category. One programming cycle was completed under these rules before the passage of ISTEA.
- MTC was sued under the Federal Clean Air Act by the Sierra Club and Citizens for a Better Environment. That litigation, over the course of 3 years, significantly modified MTC's practices for conforming its TIP to meet clean air requirements and brought air quality issues to the forefront of MTC's transportation planning and programming.
- In February 1992 a state-level agreement was reached that determined that existing programming commitments embodied in the State TIP would be upheld. Furthermore, it was agreed that the regional increment of additional funds provided by ISTEA would be distributed to the regional agencies around the state according to the formulas contained in the ISTEA for the CMAQ Improvement Program and STP. For this distribution to occur, state legislation exempting these two programs from existing state distribution formulas was required. MTC needed to put together a program of projects in time for incorporation into the 1993 TIP in order to lay claim to these funds and seek the passage of state legislation to reconcile state and federal policies.

Before the passage of ISTEA, MTC had limited experience in programming flexible funds. Transit projects were funded primarily through a separate transit capital priority-setting process for FTA Section 3 and Section 9 programs. Local roads projects were funded primarily through county-level federal-aid urban/secondary processes. State highways were funded through a state-level process. Bicycle and other enhancement projects were funded through small dedicated programs. The 1990 California gas tax increase did provide for some flexibility, as noted earlier, but this flexibility was limited to transit guideways and highways.

ISTEA provided an entirely new opportunity to generate projects to meet the Bay Area's transportation needs through a variety of modes. With the new flexibility, the possibility of meeting multiple objectives became possible.

DEVELOPING THE PROGRAM

Before MTC could take advantage of the opportunities offered by ISTEA, it was necessary to learn about the landmark law and educate others. Toward this end, MTC, in January and February 1992, sponsored a conference and a series of workshops and produced legislative analysis, policy papers, and a reference handbook of the law. MTC was fortunate to receive the participation of FHWA Administrator Thomas Larson and U.S. Representative Norman Mineta of San Jose, one of the principal authors of the legislation, in these early outreach efforts. The extensive educational effort gave the diverse community of transportation interests the knowledge, understanding, and motivation to begin the process. This introduction was particularly important for some of the newer players, including representatives from the ports, airports, and smaller transit operators.

At the same time, MTC sought to lend a structure to the coalition that had been formed originally to advocate key provisions for inclusion in ISTEA. Mutual cooperation, along with program flexibility, became key aspects of the developing program. The Bay Area Partnership was formed with a program called JUMP Start to focus regional implementation efforts on a number of relatively low-cost, operations-oriented transportation projects that could be delivered in a short time frame. This demonstrated that different agencies working together could quickly deliver projects to improve mobility, ease congestion, and clear the air—all major themes in ISTEA.

To help with the multimodal project selection process for the 1993 TIP, some of MTC's existing advisory committees, which

TABLE 1 Summary of Program Areas by Project Type

PROJECT TYPE	STP GUARANTEES		STP DISCRETIONARY		CMAQ	
TRANSIT	20.9%	$11.8M	44.0%	$28.3M	27.0%	$23.4M
SIGNALS	7.3%	$4.1M	1.5%	$984K	29.0%	$25.0M
TOS	0.0%	$0.0	0.2%	$120K	29.0%	$25.2M
HOV	0.0%	$0.0	0.0%	$0.0	9.0%	$8.0M
PARK & RIDE	1.0%	$555K	0.7%	$442K	4.0%	$3.6M
PAVEMENT REHAB	22.2%	$12.5M	2.2%	$1.4M	0.0%	$0.0
ARTERIALS	21.9%	$12.3M	4.2%	$2.7M	0.0%	$0.0
ARTERIALS WITH MULTIMODAL FEATURES	15.8%	$8.9M	19.8%	$12.8M	0.0%	$0.0
BIKE	1.8%	$996K	0.7%	$474K	0.0%	$0.0
PEDESTRIAN	0.3%	$188K	1.5%	$1.0M	0.0%	$0.0
PORT	0.0%	0%	3.7%	$2.4M	0.0%	$0.0
INTERCHANGES	1.4%	$792K	21.0%	$13.5M	0.0%	$0.0
PLANNING PROJECTS	1.9%	$1.1M	0.5%	$300K	0.0%	$0.0
BRIDGES	0.6%	$342K	0.0%	$0.0	0.0%	$0.0
AUXILIARY LANES	4.9%	$2.8M	0.0%	$0.0	0.0%	$0.0
TOTALS	100.0%	$56.4M	100.0%	$64.5M	100.0%	$85.7M

were largely mode-specific, were asked to designate representatives to serve on the Ad Hoc Committee on Multimodal Priority Setting. In the beginning, the committee included five transit operators, five CMAs, five city and county representatives, the Bay Area Air Quality Management District and the state Air Resources Board, two ports, two airports, Caltrans, and the Association of Bay Area Governments. This committee later expanded somewhat to include other interested parties. This large group had two major subcommittees: one on equity concerns and one to develop the ranking and evaluation priorities. The subcommittees developed consensus proposals that the larger group considered and endorsed. The larger Ad Hoc Committee then forwarded its proposal to MTC for consideration and adoption. This institutionalized structure worked because of the following reasons:

- There was a recognition early on that each participant had much to gain from a regional process and much to lose if a regional consensus was not reached.
- The face-to-face meeting of the participants allowed for a wide range of opinions to be expressed. It also forced participants to be less parochial, since other interests were at the table as well. This greatly improved the participants' understanding of the process and criteria and resulted in their overwhelming endorsement of the results.
- MTC was willing to allow the subcommittees largely to formulate the proposals. MTC staff provided support, including setting agendas, facilitating discussion, and recording meetings. MTC provided initial proposals to get discussions going and summarized agreements. MTC staff provided a structure and schedule for the discussions, but the subcommittee meetings were chaired by Ad Hoc Committee members from outside agencies and the final proposals were ultimately those produced by the agreement of the participants.
- An agreement was reached early on that 50 percent of STP projects would be selected at the county level by the CMAs. This later became an element of the state implementing legislation, Senate Bill 1435 by Senator Quentin Kopp of San Francisco. The other 50 percent of the STP and all of the CMAQ programming would be determined by MTC using the adopted process and criteria, which were being jointly developed. The 50 percent STP "guarantee" of a level of funding to the counties with assurances built in for a fair process at that level, also consistent with ISTEA principles, served to increase the participants' willingness to develop the criteria for the regional program while the local proposals were formulated. The guarantee amounts to each CMA were fixed at a given dollar amount on the basis of population shares.

The Equity Subcommittee met frequently in the initial phases of program development. It forged the agreement noted earlier regarding the distribution of programming responsibilities in the process. In doing so, the group resolved fundamental issues regarding geographic, functional, and modal equity. After much discussion, geographic equity was addressed through the 50 percent STP programming amount to CMAs. Within the CMA constituency, the program was not suballocated to a jurisdiction or a mode, and the comprehensive regional screening criteria applied to the half of the guaranteed program as well as the rest of the STP and CMAQ program. Functional equity (replacement versus expansion, for example) and modal equity were recommended to be addressed in specific ways in the scoring criteria. The subcommittee also endorsed the concept of allowing some regional projects to be accepted directly from the project sponsors in the first programming cycle.

The Equity Subcommittee also devised a four-step appeal process for those project sponsors who thought that they had been disenfranchised or treated unfairly in the multimodal priority-setting process. The first two levels of recourse were the CMA staff and its policy board; the next two levels of recourse were the MTC staff and the full commission. One transit operator used the appeals process. The program of projects was not changed, but the issue of the treatment of projects of regional significance was highlighted for future discussion.

The early acceptance of the Equity Subcommittee's findings and recommendations provided a context along with a perception of fairness and opportunity. It allowed the Scoring Subcommittee to work on the criteria simultaneously with the county-level project selection and prioritization process during April, May, and June 1992.

The Scoring Subcommittee approached its task as follows:

1. It agreed that every project would have to meet specific, comprehensive screening requirements. These screening criteria would be a threshold. If any project did not pass one screening criterion, that would be a fatal flaw. Projects passing the screening criteria would then be scored. After projects were scored and ranked, a set of programming criteria and principles would then come into play to address STP versus CMAQ eligibility, basic equity concerns, and any programming policy objectives.
2. It was agreed to start with the 15 factors given in ISTEA:

> (f) Factors to be considered—In developing transportation plans and programs pursuant to this section, each metropolitan planning organization shall, at minimum, consider the following:
> 1) Preservation of existing transportation facilities and, where practical, ways to meet transportation needs by using existing transportation facilities more efficiently.
> 2) The consistency of transportation planning with applicable Federal, State and local energy conservation programs, goals and objectives.
> 3) The need to relieve congestion and prevent congestion from occurring where it does not yet occur.
> 4) The likely effect of transportation policy decisions on land use and development and the consistency of transportation plans and programs with the provisions of all applicable short- and long-term land use and development plans.
> 5) The programming of expenditure on transportation enhancement activities as required in section 133.
> 6) The effects of all transportation projects to be undertaken in the metropolitan area, without regard to whether such projects are publicly funded.
> 7) International border crossings and access to ports, airports, intermodal transportation facilities, major freight distribution routes, national parks, recreation areas, monuments and historic sites, and military installations.
> 8) The need for connectivity of roads within the metropolitan area with roads outside of the metropolitan area.
> 9) The transportation needs identified through use of the management systems required by section 303 of this title.
> 10) Preservation of rights-of-way for construction of future transportation projects, including identification of unused rights-of-way which may be needed for future transportation corridors and identification of those corridors for which action is most needed to prevent destruction or loss.
> 11) Methods to enhance the efficient movement of freight.
> 12) The use of life-cycle costs in the design and engineering of bridges, tunnels, or pavement.
> 13) The overall social, economic, energy, and environmental effects of transportation decisions.

14) Methods to expand and enhance transit services and increase the use of such services.
15) Capital investments that would result in increased security in transit systems. [23 U.S.C. Section 134(f) of ISTEA]

Three other factors were added: implementation of the Federal Clean Air Act, implementation of the Americans With Disabilities Act (ADA), and improved system safety. These 18 factors were then categorized as to whether each would be considered as a screening, scoring, or programming criterion.

3. The screening criteria were established on the basis of state and federal law. There was some experience in using screening criteria in previous cycles of mode-specific programs, so this was a straightforward exercise in most respects. One key aspect of the screening criteria was a requirement that county CMAs certify that all projects proposed in their county were developed according to a cooperative process that, in good faith, brought all transportation interests to the table, included public participation, and used the ISTEA mandates and 15 factors to establish local priorities.

4. The various factors were grouped in large categories. After several attempts, four broad groups were identified: Maintain the Metropolitan Transportation System (MTS), Improve the Efficiency and Effectiveness of the MTS, Expand the MTS, and External Impacts. The External Impacts category was a method of taking into account many of the new mandates of the ISTEA, such as considerations of land use in addition to the Clean Air Act, and the ADA.

5. Weights were established for the four categories after considerable debate. For the 1993 TIP, the weights were 30 points for Maintenance (Category 1), 30 for Improved Efficiency (Category 2), 15 for Expansion (Category 3), and 25 for External Impacts (Category 4). This distribution was also influenced by the MTC program emphasis for the 1993 TIP on cost-effective multimodal projects that could be implemented quickly.

6. The specifics of point assignments within the categories were then established. Elizabeth Deakin of the University of California, who was retained as a consultant to advise MTC on this process, suggested four basic principles to guide the scoring efforts. These principles significantly shaped the criteria that were ultimately adopted.

–The first principle was to tie the solution to the problem wherever possible. This directly manifested itself in multiplying factors for the scale of the existing safety and congestion problems, and the expansion demand in those subcategories that sought to quantify the safety, congestion, and merits of the expansion project, respectively. (Specific information on the quantification of these multipliers is available from the authors).

–The second principle was to use measures that cut across modes, measures that would apply to all modes wherever possible. This was not easy or always possible. However, as a goal, it kept the group focused on the variety of projects to be considered and on measuring the benefits of projects of different modes in a uniform manner. The External Impacts category of point assignments best illustrates this principle in the criteria.

–The third principle was to anticipate the date that will be available in the future from ISTEA-mandated management systems and to incorporate performance-based standards into the criteria. In the Bay Area, this was easiest in the areas of pavement management and congestion management, where the systems already existed. In other areas, this was more difficult.

–The fourth principle was to rely on and strengthen existing plans and programs. This is related to the use of performance-based standards mentioned earlier, but also seeks to better integrate the planning and programming processes. Successful application of this principle can be seen in the air quality points. After much detailed discussion by the Scoring Subcommittee and MTC staff, the final scoring criteria were developed and endorsed by the Ad Hoc Committee. A summary of the final scoring criteria and point assignments is given in Table 2. (A detailed description of the scoring criteria is available from the authors.)

7. The programming principles were developed from STP/CMAQ eligibility and from the prior recommendations by the Equity Subcommittee. The scoring Subcommittee reevaluated the programming principles and supplemented the basic equity concerns with additional guidance, included in the final criteria, as to how increased local contributions, multijurisdictional projects, and cost-effectiveness considerations would influence the final program.

TABLE 2 Summary of MTC Scoring Criteria for STP and CMAQ Program

30 points MAINTAIN/SUSTAIN THE METROPOLITAN TRANSPORTATION SYSTEM (MTS)
Rehabilitations and replacements based on Management Systems are eligible for up to the full 30 points, depending upon the portion of the project that will rehabilitate the system, and the optimization of the proposed improvement with current condition. Rehabilitations not based on a management system, or for support infrastructure like drainage, can only receive a maximum of 20 points.
30 points IMPROVE THE EFFICIENCY AND EFFECTIVENESS OF THE MTS
Safety and security, congestion relief, cost effectiveness, and freight movement are the three subcategories where points can be assigned, up to a combined maximum of 30 points. For both the safety and congestion relief criteria, the magnitude of the (safety or congestion) problem addressed by the project is multiplied by the impact that the project will have in eliminating or alleviating the problem. Guidelines for setting the multipliers are included, and impact scores are based on shared empirical experience (e.g. Class 1 bike paths are safer than Class 3). Cost-effectiveness points measure the ratio of annual benefits in terms of total travel time savings and operating cost savings for the project to annualized total project costs. Cost-effectiveness scores are adjusted to reflect the median of all submitted projects. Freight movement points are assigned based on the facility type and nature of the proposed project.
15 points - SYSTEM EXPANSION
System expansion projects are first evaluated as to whether or not the meet current demand through the use of a multiplier based on average daily traffic and existing level-of-service. Again, the impact that the project will have in meeting demand is set based on shared empirical experience (e.g. the addition of HOV lanes has more impact than ramp metering).
25 points - EXTERNAL IMPACTS
Air quality improvement, land use policy support, energy conservation, and implementation of the Americans with Disabilities Act (ADA) are the four subcategories where points can be assigned, up to a combined maximum of 25 points. Projects with positive air quality impacts are awarded up to the full 25 points if they implement MTC-adopted Transportation Control Measures (TCMs). Projects which are only partially TCMS are awarded proportionately smaller point values, and TCMS are grouped according to their effectiveness in cleaning the air. A project can also be awarded up to 8 points if it supports land use policies that foster a mode shift away from single occupant vehicle trips on regional facilities. Up to 10 points can be awarded for projects with demonstrable energy conservation or modal shift benefits. Up to 20 points can be awarded for implementation of ADA enhancements.
100 TOTAL POINTS POSSIBLE
Planning projects are prorated according to the nearness and necessity of the planning project to direct and immediate transportation improvements.

8. MTC staff reviewed the developing criteria in a variety of forums, including MTC's Minority Citizens and Elderly and Disabled advisory committees and relayed agency and public feedback to the Scoring Subcommittee. The Scoring Subcommittee's recommendations were endorsed, with some modifications, by the larger Ad Hoc Committee and then adopted by MTC.

9. MTC staff was then able to use the criteria to establish a program of projects based on the submittals from the county-level CMAs and regional project sponsors. The process of evaluating more than 350 projects in 4 weeks using this new criteria involved most of the MTC professional staff, organized into teams on the basis of geographic responsibilities.

Through the application of the criteria, MTC discovered the need to develop consistent guidance on the application of the multipliers by MTC staff, as well as specific criteria modification to better accommodate local roads projects with multimodal features (i.e., signal timing, bike lanes, and bus turnouts). Using the established programming principles and taking the highest-ranked projects to the estimated apportionments to develop the draft STP/CMAQ program, MTC staff circulated a draft TIP for public comment consisting of more than 200 STP- and CMAQ-funded projects. Minor modifications to this program were adopted as the 1993 TIP in September 1992, after the TIP was found to conform to air quality requirements.

The actual formation of the program was a direct application of the adopted process and criteria. Although individual project sponsors questioned and debated specific project scores, the prior overwhelming endorsement of the criteria by the people that developed it made the exercise go fairly smoothly. Comments were focused largely on the application of the criteria in specific instances; neither the criteria nor the overall approach were questioned. Opportunities to clarify or provide additional information were limited to a given period after the draft scores were released.

When the draft scores were released, the CMAs were given a limited opportunity to revise their STP guarantee lists. In these lists, however, no new projects could be added that had not already been part of the competitive process. And if a project that did not make the competitive "cut" was moved by a CMA into its guaranteed local priorities on the basis of preestablished priorities, the project that was moved out of the guarantee list was not eligible for consideration in the competitive scoring process.

Table 1 shows the final 1993 STP and CMAQ program by project type.

IMPLEMENTATION OF REGIONAL PROGRAM AND IMPROVEMENTS FOR NEXT CYCLE

As the 1993 TIP neared adoption, MTC recognized that the imperative for timely program implementation requires considerable effort on the part of the many transportation stakeholders in the Bay Area. MTC found it necessary to aggressively ensure that the institutional arrangements for project implementation were communicated clearly to the project sponsors.

The adoption of the 1993 TIP, including the STP and CMAQ programs, precipitated the need for MTC to forge new working relationships with its partner agencies to implement the regional program. MTC, as the first agency in the state to develop a 1993 TIP, began discussions with Caltrans, FHWA, and FTA on program issues. In August 1992 MTC cosponsored a workshop with Caltrans and FTA to review the steps that a project sponsor needs to take to receive the funds and complete a project. With the increased number of new players and new rules, it was essential that consistent information on field reviews, grant procedures, and sponsor reimbursement be circulated. There was an additional series of meetings between MTC, Caltrans, FHWA, and FTA to forge a clear understanding of institutional responsibilities.

As the 1993 TIP was adopted, meetings began on improving the process and criteria for the next cycle of programming. Surveys were widely distributed by MTC staff, asking for comments on the process and suggestions for future improvements. Response to the survey showed the need for improvement in specific areas.

Survey comments were combined with comments received at public meetings. Issues were categorized into screening, scoring, programming, and application form issues. These were then developed into a work plan, and the issues were put on agendas for the Scoring Subcommittee to address at its biweekly meetings. Among the issues to be discussed were the definition of, and process for, regional projects in the process; additional criteria for guarantee projects; further refinement of the scoring criteria, such as cost-effectiveness and the potential for negative scores in some categories; ongoing discussions of the nature of the partnership of the CMAs and the transit operators; the modification and use of the criteria for longer-range planning exercises; the long-term structure and relationship of MTC's advisory committees; and programming schedules. The process and criteria used for the 1993 TIP provide a foundation on which to refine and improve the priority-setting process in the San Francisco Bay Area.

ADVICE TO MPOs EMBARKING ON A MULTIMODAL PRIORITY-SETTING PROCESS

The MTC process may provide certain lessons to other regions that are trying to set transportation programming priorities across modes.

1. *Educate policy board members, and the public, on the new mandates of ISTEA.* Establish public participation and outreach. Bring the players to the table early and frequently, and actively involve them in establishing the criteria. Time spent up front in establishing the ground rules makes for a smooth adoption process later.

2. *Keep it as simple as possible.* The San Francisco Bay Area is a complex region, and MTC criteria reflect that complexity. The basic approach of screen, score, and program can be used anywhere. Starting with the mandated 15 factors, add more factors to reflect any local conditions, or priorities. Sort them into categories and decide on weights. Then figure out how to assign points within categories using the best methods and information available.

3. *Build on what you have already accomplished.* In the Bay Area, MTC's experience in implementing the state flexible program and the formation of CMAs at the county level allowed it to hit the ground running. An organization may have recently completed a long-range plan that can serve as the starting point for the new process mandated by ISTEA. Whatever has been done that has built consensus, moved a project forward, or formed a partnership can and should be built into multimodal priority-setting efforts.

4. *Accept the cyclical and evolving nature of the process.* Be prepared to revise the criteria every cycle to reflect changing conditions, improved information, and new regulations. Build into the criteria from the beginning the capacity to incorporate the results of the newly required management systems.

ISTEA gives regional agencies the opportunity to set programming priorities that meet local needs. The flexibility of the STP, in its wide-ranging project eligibility, allows metropolitan areas to use innovative approaches to solving transportation problems. In the San Francisco Bay Area, MTC seized this opportunity and encourages others to do the same.

ACKNOWLEDGMENTS

The authors thank Larry Dahms, Bill Hein, and Hank Dittmar for their guidance and support in this project, and the members of the Ad Hoc Committee on Multimodal Priority Setting for their ideas and participation throughout the process.

Publication of this paper sponsored by Committee on Transportation Programming, Planning, and Systems Evaluation.

High-Precision Prioritization Using Analytic Hierarchy Process: Determining State HPMS Component Weighting Factors

RONALD F. HAGQUIST

The analytic hierarchy process (AHP) is a scoring procedure that uses a high-precision method both for weighting criteria and comparing alternatives; the scores are scaled, summed, and normalized to give final "goodness" measures to the alternatives. These measures can then be the basis for selection, ranking, or allocation among the alternatives. The Highway Performance Monitoring System (HPMS) is a computer model that determines highway improvement needs by maximizing its "composite index," a performance measurement function that is a weighted sum of nine quantified highway condition factors for the sections of the road system. The weights are the relative priorities given to each of the condition factors. The results are sensitive to the component weights in this performance function, and some states have modified the national average default values in the model to better represent their own specific road condition priorities. Failure to represent these weights correctly would cause the model to optimize with the wrong priorities, producing a highway investment strategy inappropriate for that state. An empirical examination of the extent of uncertainty about what the index weights should be and whether AHP can improve the confidence of this determination relative to the usual single-step approach is presented. The study finds that because the AHP method does not produce the numerical biases seen in the single-step method, the AHP apparently yields these subjective preferences with greater precision. This is a promising approach for assessing competing multimodal projects, where a structured and rigorous method will be useful in scoring the alternatives and weighting the many criteria. These criteria will correspond to the necessarily multiple performance measures of a multimodal system such as time, cost, safety, reliability, and environmental impacts.

The Highway Performance Monitoring System (HPMS) is an analytical computer model developed in the late 1970s by FHWA and the states, originally to assess highway needs and costs nationwide. It is the basis for the FHWA biennial report to Congress *Status of the Nation's Highways and Bridges: Conditions and Performance* and subsequent evaluation of alternative budget proposals and legislative options. The HPMS system was used to define network designation and evaluation criteria for the Highways of National Significance Program. This program was the centerpiece for the post-1991 reauthorization of the federal-aid highway program; it was made available beginning in 1983 to states as a highway planning tool for their level of detail.

Using data from samples of highways, HPMS employs simulation and forecasting equations to analyze highway conditions, investment strategies, and user costs over given time periods.

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HPMS uses a "composite index," a performance measurement function that is a weighted sum of nine quantified highway condition factors. The weights are the relative priorities given to each of the condition factors. The model can be run with no budget limit to determine total needs or with a constrained budget to determine the priority set of highway improvements. However, the model is highly sensitive to the component weights in this performance function, and some states have begun modifying the "national average" default values in the model in an attempt to represent their own specific road condition priorities. Failure to quantify these priorities correctly would cause the model to optimize with the wrong factors, producing a highway investment strategy inappropriate for that state.

Rational determination of priorities (and weightings) is one of the classical problems in the field of operations research. Major advances in decision science have melded the mathematics and psychology of the decision process. These advances centered on the analytic hierarchy process (AHP) developed by Thomas Saaty. This research paper examines the extent of agreement about what the index weights should be and whether AHP can improve the confidence of this determination relative to the usual single-step approach.

The paper is composed of three sections. The first is an analysis of the sensitivity of the HPMS model to changes in the composite index component weights. The second section is a brief exposition of the AHP as used for determining these weights. The third section presents the empirical results of using AHP to determine the weights relative to the usual single-step approach.

HPMS MODEL SENSITIVITY TO COMPONENT INDEX WEIGHTS

The HPMS model allows four procedures for arriving at a priority ranking of highway improvements or capacity increases (*1*,p.III-1). One of these procedures is its composite index, a weighted sum of the values of the following condition factors as given in Table 1.

In algebraic terms, the composite index is the sum of the values of each component times its weighting. There is an established range of measurable values for each component, and the component weights sum to unity:

$$CI = \sum (w_i)(r_i)$$

$$\sum w_i = 1$$

where w_i equals the index component weight and r_i is the rating with respect to that component.

When the composite index procedure is chosen, the model selects those highway improvements that maximize the value of this index, the process shown in Figure 1. It follows that the weights given the components will affect the model output: the total improvement needs relative to capacity needs, and the priority mix of recommended actions.

The expert system module is used in place of a formal multiperiod optimization algorithm. This module recommends investment policies based on heuristic guidelines similar to those that an experienced engineer might use.

The New Jersey Department of Transportation has examined the sensitivity of its state HPMS model to trade-offs among sets of the index components (2). The sets were as follows:

- Condition factors:
  - –Pavement type,
  - –Pavement condition, and
  - –Drainage adequacy.
- Safety factors:
  - –Lane width,
  - –Shoulder width,
  - –Median width, and
  - –Alignment adequacy.
- Service factors:
  - –V/C ratio, and
  - –Access control.

Figure 2 shows the sensitivity of the total highway needs assessed by the HPMS model for the New Jersey highway system. A reversal of emphasis between condition and safety factors from 90/5 to 5/95 (the first and last bars) results in a change of almost $1 billion in assessed highway project needs.

Figure 3 shows the sensitivity of the total vehicle operating costs assessed by the HPMS model for the New Jersey highway

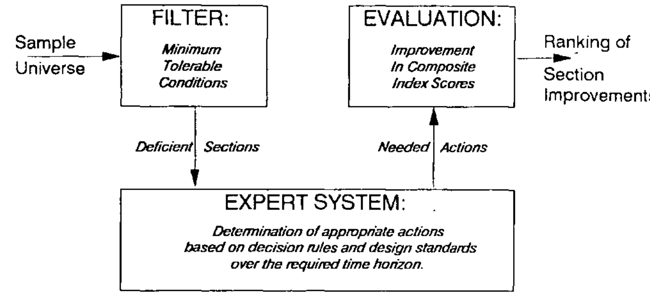

FIGURE 1 HPMS model logic.

system. A reversal of emphasis between condition and safety factors from 90/5 to 5/95 (the first and last bars) results in a change of about $10 billion in assessed vehicle operating costs over the 18-year planning period.

Some states use the default weights, which are the national average numbers that come with the HPMS model. Others change the weights in a one-step process using intuitive judgment about the relative magnitudes of the appropriate numbers (3). An alternative to this one-step determination is the AHP.

TABLE 1 Composition of HPMS Composite Index

CONDITION FACTOR	IMPORTANCE WEIGHT	APPRAISAL RATING	FACTOR SCORE
Pavement Type	W_1	R_1	W_1R_1
Pavement Condition	W_2	R_2	W_2R_2
Drainage Adequacy	W_3	R_3	W_3R_3
Lane Width	W_4	R_4	W_4R_4
Shoulder Width	W_5	R_5	W_5R_5
Median Width	W_6	R_6	W_6R_6
Alignment Adequacy	W_7	R_7	W_7R_7
V/C Ratio	W_8	R_8	W_8R_8
Access Control	W_9	R_9	W_9R_9
Composite Index			$\sum_{n=1}^{9} W_nR_n$

ANALYTIC HIERARCHY PROCESS

Operations research (also called management science) is a discipline dedicated to the development of techniques to help decision makers deal with the increasing complexity of the world. Utility theory, trade-off analysis, and the Delphi process represent contributions to aspects of this problem from the respective disciplines of economics, engineering, and management. During the 1980s there were major advances in combining these approaches, melding the mathematics and psychology of the decision process. These advances centered on the AHP, producing a rigorous yet simple mechanism for better evaluating alternatives using multiple criteria. AHP-based software is now widely used for selection decisions, prioritizing, and budget allocation.

Saaty, the developer of AHP, was a mathematician working on an analytical framework for group decisions for the Departments of Defense and State during the 1970s. He was able to determine the structure and basic logic of the natural decision-making process and then to find the mathematics most appropriate to build a model of this process. Research had already shown that complex decisions are beyond the capacity of the brain to analyze. For example, a classic study by Miller in the 1950s demonstrated that humans can deal with only about seven items at a time. When the AHP is used, a decision problem with too many criteria and alternatives for the human mind to synthesize can be solved with the same natural intuitive logic that the human mind would use had it the capacity to deal with a problem of this size.

The AHP begins with structuring the decision problem much like an organization chart: with the overall goal at the top, the criteria and subcriteria next, and the alternatives at the bottom (Figure 4). Essentially a high-precision scoring procedure, the AHP multiplies each alternative score under each criterion by that criterion's weight and sums these to give a final composite score. These are scaled, summed, and normalized to determine "goodness" scores for the entire set of alternatives. These scores can

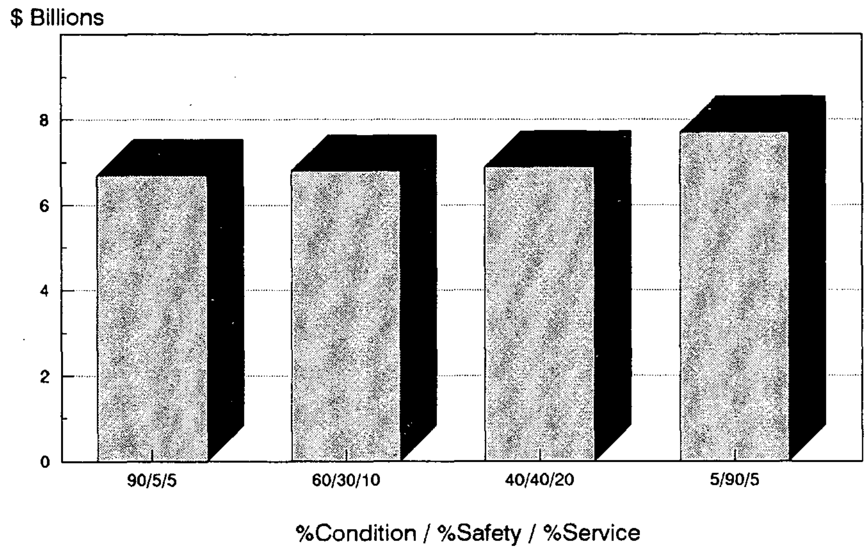

FIGURE 2 Sensitivity of total highway needs to composite index components (source: New Jersey Department of Transportation).

be the basis for selection, ranking, or allocation among the alternatives.

AHP differs from conventional scoring methods in the following ways:

- AHP uses a set of one-on-one comparisons to evaluate alternatives under each criterion. These pairwise comparisons are the smallest "quanta" of decisions.
- AHP uses one-on-one comparisons to assign criteria importance weights.
- AHP does alternative comparisons and criteria weighting in separate steps.
- AHP melds both objective measures and subjective preferences in the form of criteria weights. Typically, only the objective "facts" are quantified.

AHP has the following advantages over conventional scoring:

- The one-on-one comparisons increase the accuracy of the alternative comparisons. Research has found that such pairwise comparisons, properly averaged, can give a 400 percent increase in the precision of estimation.
- The one-on-one comparisons increase the accuracy of criteria weight estimations.
- The internal consistency of the alternative comparison process is quantified.
- The internal consistency of the criteria weighting process is quantified. Pairwise comparisons can contain contradictions among the direct and indirect comparisons.
- Subjective considerations are given a structured framework. Both subjective preferences and objective data are combined ex-

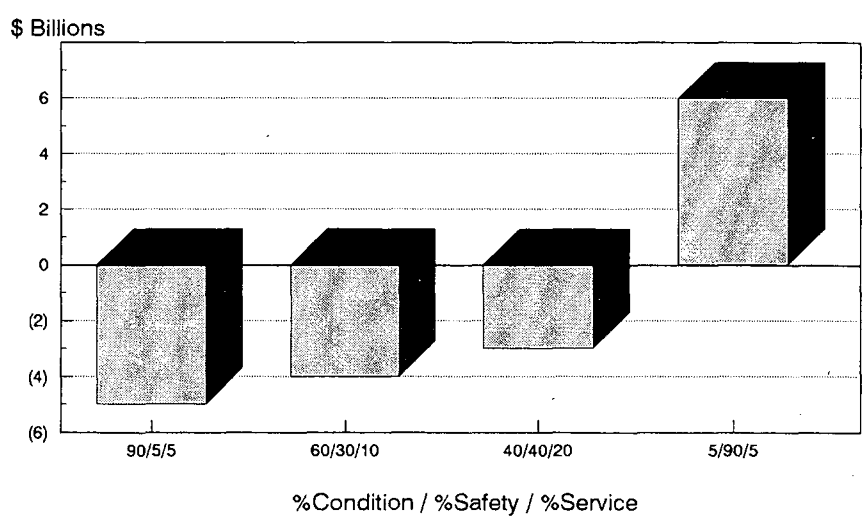

FIGURE 3 Sensitivity of vehicle operating costs to composite index components, over 18-year period (source: New Jersey Department of Transportation).

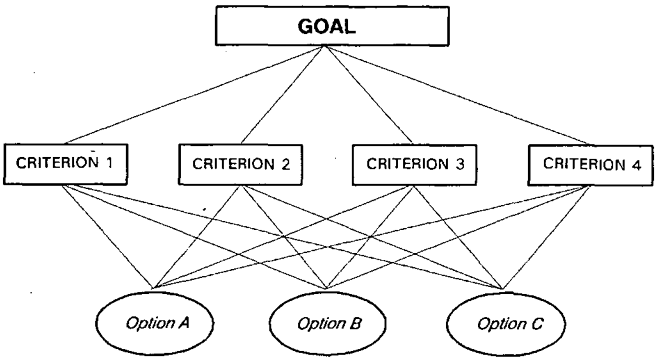

FIGURE 4 AHP structure.

plicitly, making the critical factors in the decision result much clearer.

- Sensitivity of the result is easy to analyze. The extent to which the key parameters can change before the result changes significantly can be seen quickly.

Using the commercial AHP software packages available—DecisionScience Plus, Expert Choice, Best Choice 3, Criterium, HIPRE—the only user input required is one set of pairwise comparisons among the criteria and another set among alternatives specified; the mathematics are internal to the program. These comparisons are facilitated by structured questions or dynamic visual graphics. Most software packages have sensitivity, what-if, and comparison consistency screens. Some allow many levels of criteria and subcriteria.

AHP has been used for private- and public-sector decision applications involving weighting, prioritizing, and selection. A recent literature search found 153 citations in 29 application areas (*4*,pp.39–40). For example, it was determined by Saito to be superior to other prioritizing techniques for highway bridge maintenance decisions (*5*). Empirical work by Foreman has found an improvement of about 400 percent in estimation accuracy by using AHP relative to the one-step process (*6*). In this study it is examined as an alternative to one-step weight assignment for HPMS model composite index components.

EXPERIMENTAL DESIGN

This project consisted of the following steps:

1. The subjects directly assigned weights to the components, which is the usual way that it is done: a one-step process to simultaneously assign weights to all the factors. To avoid possible bias, subjects were selected who had experience with highway issues but who were not familiar with the federal default values being used as weights. The questionnaire is given in Figure 5.

HPMS HIGHWAY CONDITION COMPOSITE INDEX FACTORS		
CONDITION FACTOR	DESCRIPTION	IMPORTANCE WEIGHTING (As a Percentage)
Pavement Type	The nature of road surface, ranging from unpaved to concrete/asphalt.	
Pavement Condition	The extent of roughness, cracking, potholes, and skid resistance.	
Drainage Adequacy	The absence of flooding, ponding, or erosion.	
Lane Width	The space allowed for vehicles in lanes.	
Shoulder Width	Space at the edge of the road available for emergency parking.	
Median Width	Space between opposing lanes of the road.	
Alignment Adequacy	Straightness of road, ranging from straight to hairpin curves.	
V/C Ratio	The traffic density of the road relative to its capacity.	
Access Control	The preference given to through traffic by limiting access.	
	Total	100%

FIGURE 5 Condition factor weighting questionnaire.

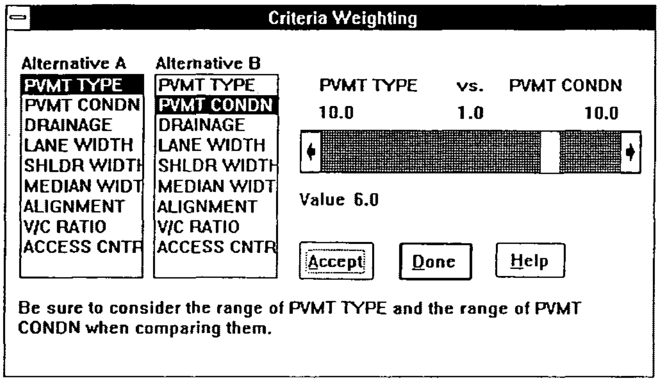

FIGURE 6 Screen for pairwise weighting of condition factors.

2. The subjects complete the AHP matrix of pairwise comparisons, a matrix of pairwise comparisons in which every factor is compared with every other factor once. This is a central feature of the AHP, making a set of one-on-one comparisons to view the factor comparisons in all possible ways and allowing redundancy in the process. Comparisons between each pair of factors was made on a scale of 1 through 10, where 1 meant that the pair was equal in importance and 10 meant that a factor was dominant in importance. Both a visual bar and numerical display were used to facilitate the comparisons shown in Figure 6.

3. Weights were calculated from the comparison matrix by the AHP eigenvector technique, the process of computing the factor weights from the set of pairwise comparisons using the eigenvector method, which effectively averages the matrix entries in all possible ways. An example of the averaged final weights for one of the participants in the following.

RESULTS OF WEIGHT ASSIGNMENT METHODS

Subjects were chosen who had experience and familiarity with the aspects of highway condition represented in the nine components of the HPMS composite index. They assessed appropriate weights using two basic methods: the customary direct assignment method, and then using AHP. These two sets of weights were then analyzed using standard statistical methods to determine their similarities and differences.

Single-Step Estimation

Pavement condition and volume-to-capacity (V/C) ratio had the highest average weightings, considerably above the other factors. As Table 2 indicates, there was substantial disagreement (measured as variance) among the respondents about many of the factor weightings, notably V/C ratio, pavement type, and pavement condition. There was also very close agreement that median width was the least important factor. Lane width, shoulder width, and alignment adequacy were factors with good agreement as well.

Figure 7 demonstrates the differences between the federal default values and the survey values. The largest absolute differences are for V/C ratio, pavement condition, and lane width.

A clearer demonstration of the significance of these differences is seen in the next chart of the differences expressed as percentage of the survey values. The greatest difference is for median width, but the difference is more than 50 percent for drainage adequacy, lane width, and V/C ratio. The average of the absolute values of the percentage differences is 39.7 percent, meaning that for Texas there was a substantial disagreement between the federal default values and the survey using single-step weight determination.

Figure 8 shows a significant bias in the numbers produced by the single-step method. It demonstrates the respondents' tendency to prefer numbers ending in 0's and 5's: 5, 10, 15, 20, and so forth. However, the ending number should be the numbers from 0 to 9 with approximately equal frequency. Instead, the subjects were extremely biased toward both 0's and 5's, with each being used about five times more than would be expected.

Additional bias can be seen in the distribution of numbers that do not end in 0's and 5's. The numbers closest to the "magic numbers" of 0 and 5 (1, 4, 6, and 9) are further reduced in frequency of selection relative to the numbers farther from 0 and 5. It appears that the desire to use 0's and 5's is so great that it suppresses the use of the numbers closest to them.

In summary, the frequency distribution for single-step weight selection demonstrates a strong bias toward two numbers and a skewed distribution among the other numbers.

AHP Estimation

The volume to capacity ratio had the highest average weight. As Table 3 indicates, there was substantial disagreement among the respondents about many of the factor weightings, notably V/C ratio. There was also high disagreement about alignment adequacy, drainage adequacy, and pavement condition. There was

TABLE 2 Summary of Single-Step Process

	PT	PC	DA	LW	SW	MW	AA	V/C R	AC
AVERAGE	10.7	20.1	7.9	9.1	7.3	6.2	10.5	19.9	8.4
VARIANCE	59.9	56.1	22.6	17.0	17.1	10.9	17.6	79.0	23.1

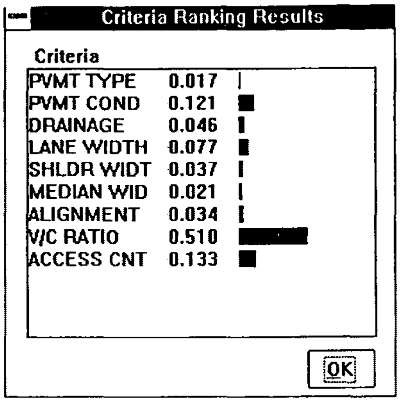

FIGURE 7 Screen showing final averaged condition factor weights.

close agreement that median width was the least important factor, and there was also close agreement about pavement type and lane width.

Comparison of Results

Table 4 presents the differences between the single-step and the AHP values. Since HPMS uses these values as weighting factors (i.e., as cardinal numbers), any differences would show up as changes in the improvements to the roadway system under a given budget. Figure 9 shows that the largest difference (as a percentage of the AHP values) was for pavement type, with other large differences for median width and shoulder width.

Using the non-parametric Kendall test for independence (*9*), the study finds that the ordinal rankings produced by the two approaches are positively correlated. This means that the two methods produce rankings that are similar, although not identical. However, the previous chart shows that there are substantial differences between the actual numerical weightings produced. The average of the absolute values of the percentage differences was 35.3 percent.

In addition, Figure 10 demonstrates that the AHP method does not show the strong numerical biases present in the single-step method. This could explain why the average variance for AHP was greater than for the single-step method, since in effect people are choosing from fewer possibilities when weighting in one step. This further suggests that the AHP method represents these subjective preferences with greater precision.

At the conclusion of the experiments, the participants expressed more confidence in the AHP method, citing its thoroughness in requiring that all pairwise comparisons of the factors be made. It appears that the factor weights are dependent on technique and that of the two approaches examined, AHP appears to be the method of choice.

CONCLUSIONS

Using a standard statistical test, the study finds that the ordinal rankings produced by the two approaches are positively correlated. This means that the two methods produce rankings that are similar. They are not identical, however, and there are substantial differences between the actual numerical weightings produced. The average of the absolute values of the percentage differences was 35.1 percent. In addition, the AHP method does not show the numerical biases present in the single-step method, where numbers ending in 0 and 5 are greatly overrepresented (Figure 11). This suggests that the AHP method represents these subjective preferences with greater precision and therefore is the method of choice to determine them.

HPMS use is not multimodal, but AHP is also a promising approach for assessing competing multimodal projects, where a precise method will be needed to establish the priority weightings for multiple criteria. These criteria will correspond to the necessarily multiple performance measures of a multimodal system such as time, cost, safety, reliability, and environmental impacts.

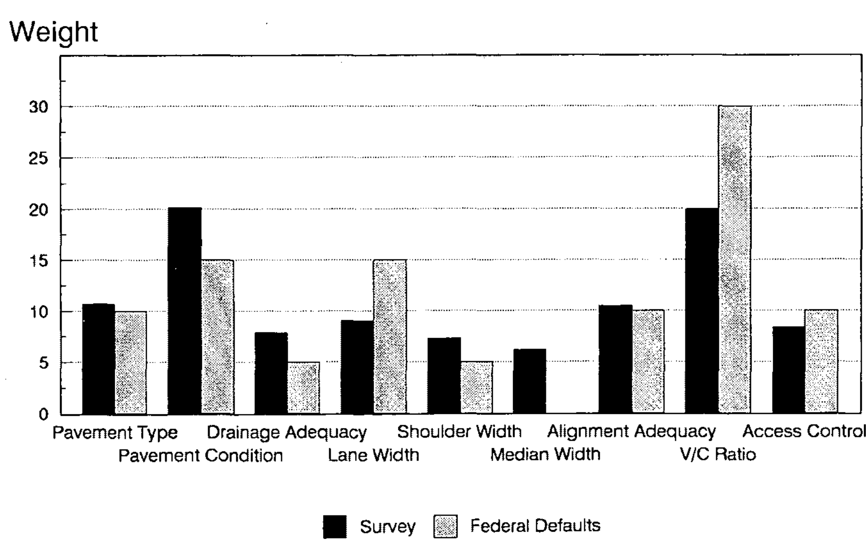

FIGURE 8 HPMS composite factor weights, survey results versus federal defaults.

TABLE 3 Summary for Analytic Hierarchy Process

	PT	PC	DA	LW	SW	MW	AA	V/C R	AC
AVERAGE	5.8	16.4	13.1	8.8	4.8	3.9	13.6	22.7	10.9
VARIANCE	22.4	76.8	85.5	11.9	20.2	12.1	87.8	147.8	67.0

TABLE 4 Combined Survey Results

	PT	PC	DA	LW	SW	MW	AA	V/C R	AC
SINGLE-STEP	10.7	20.1	7.9	9.1	7.3	6.2	10.5	19.9	8.4
AHP-PAIRWISE	5.8	16.4	13.1	8.8	4.8	3.9	13.6	22.7	10.9
DIFF'CE AS % OF AHP WT	85.1	22.4	-39.3	3.8	51.4	56.8	-23.0	-12.4	-23.5

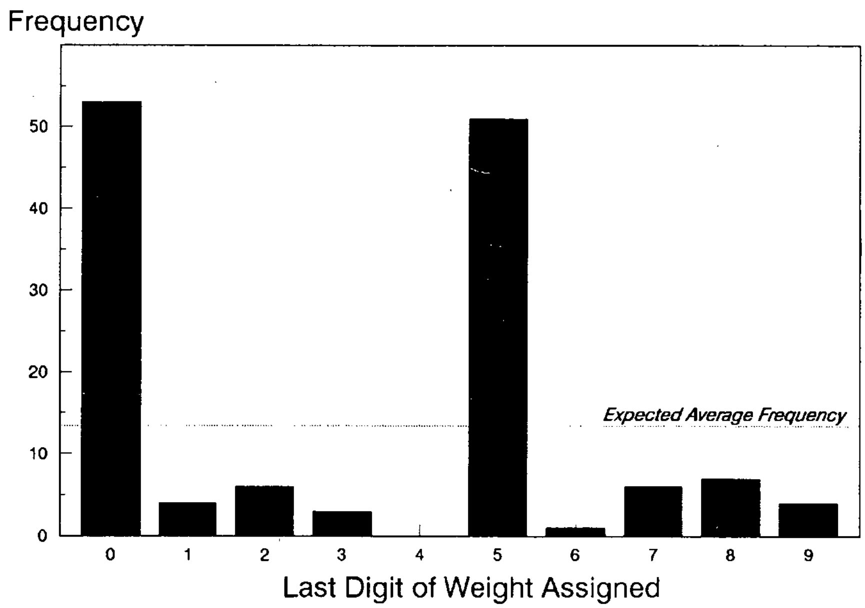

FIGURE 9 Bias of single-step weight assignment.

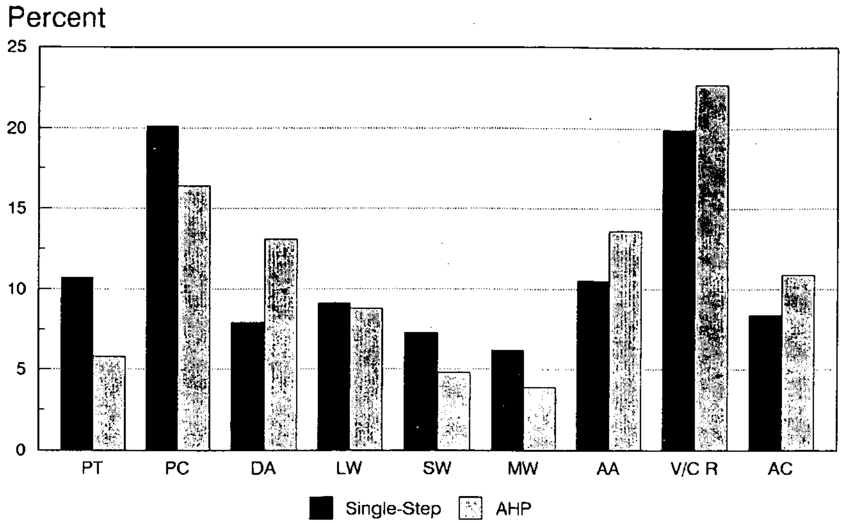

FIGURE 10 HPMS composite index factor weights, single-step method versus AHP.

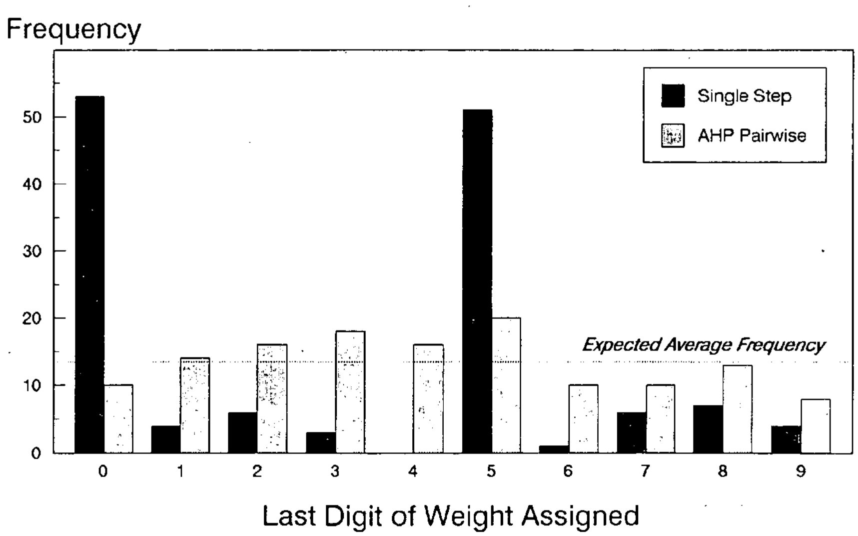

FIGURE 11 Bias of weight assignment methods.

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Publication of this paper sponsored by Committee on Transportation Programming, Planning, and Systems Evaluation.

Comparing Multimodal Alternatives in Major Travel Corridors

PATRICK DECORLA-SOUZA AND RONALD JENSEN-FISHER

In the past, metropolitan planning organizations usually compared transportation projects using measures of effectiveness that are uniquely applicable to a specific mode. But if highway and transit projects are to be compared, as will be necessary under the Intermodal Surface Transportation Efficiency Act of 1991, common measure of effectiveness applicable across modes must be used. Another problem that will arise in such a comparison involves accounting for costs. For valid comparisons across modes, the full costs of each alternative must be taken into account. Public costs incurred by non-transportation public agencies, fixed private costs, and external social and environmental costs cannot be ignored. A new approach for cost-effectiveness evaluation of multimodal transportation alternatives in urban areas is presented. The approach is applicable at the levels of system planning as well as corridor or subarea planning. The advantages of the new approach are that it allows (a) cross-modal comparison, (b) comparison of investment as well as policy alternatives, and (c) comparison of alternative scenarios or policies that could affect rates of future aggregate regional growth, with respect to their cost impacts. The approach is demonstrated through application of a simplified analysis technique using a microcomputer spreadsheet and travel demand model output data from a multimodal transportation corridor study. It is suggested that the approach can be a useful tool for comparing multimodal investment and policy alternatives.

A new approach for evaluating the cost-effectiveness of multimodal transportation alternatives in urban areas is presented. The approach is applicable at levels of system planning as well as corridor or subarea planning. This paper focuses on the corridor/subarea application of the approach.

The advantages of the new approach over other commonly used approaches are that it allows (a) cross-modal comparison, (b) comparison of investment as well as policy alternatives (e.g., land use or pricing strategies that may involve no major public investment as well as a "do-nothing" policy can be evaluated), and (c) comparison of alternative scenarios or policies that could affect rates of future aggregate regional growth, with respect to their cost impacts.

BACKGROUND

Evaluation Issues in the 1990s

Recent changes in federal policy and mandates are making it necessary to give new thought to the technical procedures used by metropolitan planners to evaluate transportation alternatives. Comparisons must be made among modes because of the new intermodal funding flexibility provided by the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). Federal regulations (Section 450.318, 23 C.F.R.) state that "corridor and subarea studies shall evaluate the effectiveness and cost-effectiveness of alternative investments or strategies .... The analysis shall consider the direct and indirect costs of reasonable alternatives." ISTEA also requires consideration of efficiency and socioeconomic and environmental factors in the evaluation process.

Future evaluation procedures will need to (a) give adequate consideration to economic efficiency and social and environmental impacts, (b) allow comparisons across modes as well as across infrastructure investment and management strategies, and (c) provide a means for performing consistent evaluations from the system level down to the project level.

Need for Common Effectiveness Measures

In the past, metropolitan planning organizations usually compared transportation projects using measures of effectiveness that are uniquely applicable to a specific mode. For example, measures of highway project effectiveness commonly used are improvement in highway level of service (LOS), including increases in highway speed, reduction in highway volume-to-capacity ratios, and reduction in congested highway mileage; reduction of highway accidents; and savings in highway user costs. Transit project effectiveness, on the other hand, is usually measured by increases in transit ridership and savings in travel time for existing transit riders. Mobility for the disadvantaged is an important measure of transit effectiveness, but it seldom appears in evaluations of highway projects.

If highway and transit projects are to be compared, as will be necessary under ISTEA, common measures of effectiveness applicable across modes will have to be used. And if cost-efficiency measures are to be emphasized, benefits must be converted to dollar terms to the extent possible.

Need for Comparable Methods of Cost Accounting

Another problem that will arise if highway and transit projects are to be compared involves accounting for costs. In computing the costs for transit alternatives, for example, analysts include vehicle capital and operating costs and costs for garaging the vehicle but seldom consider the costs of roadway use by buses. On the other hand, analysts computing the costs for highway travel may include the variable portion of vehicle operating costs (i.e., costs for gas and oil, maintenance, and tires) but exclude the fixed costs (i.e., vehicle ownership costs and parking or garaging costs at each end

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of the trip). In highway widening projects, opportunity costs for using existing rights of way may also be ignored.

Most evaluations, both highway and transit, exclude any form of economic valuation of environmental costs. In transit analysis, indirect effects are assumed to be proportional to transit or high-occupancy vehicle (HOV) use. However, it is incorrect to assume that the environmental and social impacts of rail, bus, and HOV modes are equivalent. Costs for many types of public services provided for the transportation system (e.g., police, fire, emergency medical services, and court system costs) are often ignored. Economic valuation of other social costs, such as community disruption or loss of cultural and recreational resources, is rarely attempted.

For valid comparisons across modes, the full costs of each alternative will eventually have to be taken into account. Public costs incurred by non-transportation public agencies, fixed private costs, and external social and environmental costs cannot be ignored. From a societal point of view, it is irrelevant whether costs are borne privately, publicly, or socially. Partial accounting of costs may be acceptable for within-mode comparisons, since costs not accounted for are roughly the same for each alternative. But costs not accounted for are vastly different across modes, and therefore correctly defined cross-modal comparisons will require full accounting of all costs for each alternative.

Need for Realistic Base

The base to which alternatives are compared in current practice also poses a problem. In current practice, the base used for comparison is usually a future year "do-nothing," or "no-build plus transportation system management (TSM)" alternative. Benefits of the alternatives are calculated on the basis of savings with respect to the future base condition. However, the savings estimates will not be real if the base itself could never exist in reality, which is often the case. For example, before the large delays forecasted under base conditions could ever occur, it is probable that travelers would change their travel patterns (traveling at different times of the day, by different modes, to different destinations, or by different routes); they may even decide not to make the trip. Patterns of activity and land use growth would also change, or overall regional growth itself might be suppressed. Although these behavior and growth changes would involve economic costs, the costs could be much less than the costs reflected by the unrealistic delays estimated for the base case. It is therefore possible that benefits claimed for alternatives by comparing them to the base are inflated.

NEW APPROACH

An Analogy

The new approach to evaluating alternatives is best explained through an analogy based on the decision-making process used by a family in making an investment decision.

Assume that a certain family of four, consisting of two parents and two children, owns a home with three bedrooms. They are expecting a new child in 9 months and must decide among three alternatives to accommodate the third child in their home:

1. Have two children share a bedroom,
2. Add a bedroom to their existing home, or
3. Move into a four-bedroom home.

The family would total all the costs for each alternative and compare them. The lowest-cost, or TSM, alternative (i.e., Alternative 1) would not necessarily be chosen, although it would achieve their main objective of accommodating the third child. The incremental costs of the higher-cost alternatives (i.e., Alternatives 2 and 3) would be traded off against any benefits (e.g., family comfort or pride in home) achieved by the alternatives over and above the basic need to accommodate the third child, which is "efficiently" accomplished by the first alternative.

This paper demonstrates how such a process may be extended conceptually to an evaluation of transportation alternatives. The objective to be achieved is the accommodation of new travel demand—both person trips and freight trips—to be added during the period between the current year and the future horizon year for which alternatives are being evaluated. The least-cost alternative is first identified; then additional impacts (i.e., net benefits or costs that cannot be easily monetized) are compared with the cost differences and trade-offs are evaluated. Although it is not the subject of this paper, a break-even analysis can be conducted to determine how much any additional net benefits resulting from higher-cost alternatives would have to be worth in dollars to make decision makers indifferent between the lowest-cost alternative and the alternative being considered. Such an analysis allows trade-offs between cost-efficiency and unpriced community benefits.

New Approach Versus Current Practice

The approach attempts to overcome many of the problems and pitfalls of current practice discussed earlier. The major differences from current practice in this new approach are discussed as follows.

Base

Incremental costs of alternatives are calculated relative to a real base—that is, the existing system and existing travel demand and system performance. This base replaces the future do-nothing or no-build plus TSM base used in conventional analysis. Problems related to using a future do-nothing base with unrealistic forecasts of congestion are avoided. (Note that if evaluation of a do-nothing alternative is desired, the new approach allows for computing its total costs along with the other alternatives. This is not feasible under current practice.)

Costs

The approach involves a comprehensive accounting of the full costs of the current base as well as the alternatives, to the maximum extent possible. The full costs of each alternative include both economic and non-economic or unpriced costs. Methods for computing individual cost components are discussed in a later section of the paper. Only impacts of uncertain social welfare (e.g., community pride) are excluded from the cost accounting, for separate consideration in evaluating trade-offs among alternatives.

Effectiveness

The effectiveness of alternatives is measured as "person trips served." This measure of effectiveness measures the ability to accommodate the increment in demand for trips above the base (existing) demand. Each alternative is capable of providing for the new demand, but at differing incremental cost; this reduces the problem to one of finding the least-cost alternative. Differences among alternatives with respect to performance are incorporated into the cost measure—the full costs include costs for travel time and vehicle operation (thus measuring the cost impacts of highway congestion or poor transit service levels), and accident costs.

Management Strategies

The approach can be used to compare incremental costs of alternatives that involve little or no differences in public investment, only policy differences (e.g., land use plan and zoning changes, trip reduction ordinances, and parking surcharges). Note that when policy changes induce commuters to shift modes, the commuters may shift to a slower mode. However, the valuation of travel time does account for the higher time costs that may be incurred by the use of slower modes.

Comparison of Future Growth Alternatives and Across Urban Areas

Incremental costs for the future alternatives are computed against the current base. The incremental cost per added trip above the base may therefore be computed. Incremental cost per added trip is computed by dividing the incremental costs by the increment of trips served. If the alternatives represent different aggregate future regional growth scenarios, the impacts of alternative regional growth rates on incremental costs per added trip can be evaluated. For national studies, the measure allows comparisons among urban areas. The use of the "incremental cost per added trip" measure assumes the following:

- Trips served are equivalent irrespective of the mode of the trip (although the cost of the trip may differ by mode). In other words, the quality of the trip in terms of comfort, convenience, and reliability is ignored, although travel time is included as a cost component. Note that this could be an important issue if unequal inducements or disincentives for alternative modes exist (e.g., larger subsidies for one mode versus another), or if trip makers cannot freely choose their modes because of regulation (e.g., "no drive" days).
- If new trips are induced by an alternative over and above the basic future demand served by other alternatives, the value of each induced trip is assumed to be the same as all other trips to be accommodated in the future year. This simply means that if one alternative serves more trips than another, each additional trip served by it is assumed to be of equal value relative to all other "uninduced" trips. (Since most travel demand models do not forecast trips induced on the basis of supply characteristics of alternatives, all alternatives will generally serve the same number of person trips. However, some new transit service may be designed to specifically "induce" new trips, e.g., new work trips from the economically disadvantaged groups in inner cities to employment locations in the suburbs, and society may actually place a higher-than-average value on these trips.)
- Where policies to shift person travel demand to telecommuting, walk, or bicycle modes are to be evaluated, it is assumed that walk and bicycle trips as well as "eliminated" trips from telecommuting are included in the total of trips accommodated and that their costs are also included. (Generally, travel models do not estimate telecommute and non-motorized trips).

CALCULATION OF COSTS

Travel Markets

Unit costs of travel differ depending primarily on two primary variables: time of day (e.g., peak or off-peak) and type of trip (e.g., personal or freight travel). The value of a trip (or value of benefits from a trip) tends to vary by trip purpose (e.g., work versus non-work). These variables can be used to categorize travel demand into various travel markets. Other variables, such as location within the urban area (i.e. downtown, central city, suburb, or fringe) conceivably can be used to classify markets on the basis of trip origin, destination, or origin-destination pair. For their purposes, the authors have identified six markets, as indicated in the following table. The application example demonstrated in this paper focuses on the peak-period work (person) travel market.

	Peak	*Off-Peak*
Work (person)	x	x
Non-work (person)	x	x
Freight	x	x

Disaggregation by these market segments allows the comparison of the value of trips to their costs. Costs for accommodating higher-value trips (e.g., freight trips and work person trips) may be higher than costs for non-work trips, but they may still be acceptable as long as costs do not exceed the value of the trip produced.

Cost Components

All costs for providing mobility are included in the evaluation of costs for accommodating future trips, whether or not the trip maker bears them directly. Costs may be categorized by whether or not they have market prices. Market-priced costs include dollar costs borne privately by system users and publicly by transportation or other agencies. Costs that have no market prices include travel time costs, environmental costs, pain and suffering components of accident costs, and other social costs such as community disruption. They may be borne by system users (e.g., travel time costs) or externally (e.g., environmental costs).

Typical values of the magnitude of market and non-market cost components are given in Table 1.

Market-Priced Costs

It is important to ensure that only true costs, in terms of economic resource costs, are included. For example, transit fares are not costs but transfer payments, as are gasoline taxes and highway tolls. Similarly, it is not the price paid by highway users for existing parking, in terms of parking charges, that should be considered (since these costs are usually subsidized by employers), but the actual cost of providing new parking spaces.

Vehicle Costs

Only avoidable costs for the specific travel market under consideration should be included. An example of an avoidable cost is the variable component of automobile operation costs—the cost of gas and oil, maintenance, and tires—which are related to amount of use. These were estimated at 8.4 cents per mile in 1990 by the *Characteristics of Urban Transportation Systems* (CUTS) (*1*). Fixed costs for automobile operation such as depreciation, registration, and finance charges may be avoidable costs under certain circumstances. For example, provision of new transit service may allow a three-car family to get rid of one car or enable it to avoid having to buy a fourth car. Fixed costs were estimated by CUTS to average 32.6 cents per mile, which amounts to $3.26 for a 10-mi trip.

Similarly, in the long run, parking costs are avoidable, since reduction in projected future demand will allow fewer new spaces to be built or existing spaces to be redeveloped for other use. The CUTS estimates for parking construction costs per space amount to about $1.00/day for a surface lot and $4.00/day for a parking garage with three or more levels. Land and maintenance costs are not included in the estimates.

Highway Facility Costs

Highway facility costs are borne publicly (i.e., by public agencies) for building, operating, and maintaining highway systems. Development of estimates of highway facility costs associated with peak travel requires particular attention. Costs per added vehicle mile traveled (VMT) (above base year VMT) for providing new capacity can be estimated by taking all highway system costs associated with providing adequate capacity for peak travel and dividing the total by the increment in peak-period VMT. Note that total capital costs must be annualized and then converted to daily costs before dividing by peak-period VMT.

TABLE 1 Example Unit Costs

Cost Component	Unit Cost	Source
Market-Priced Costs:		
Vehicle		
Operation	7.4 cents/VMT	Ref.1 (less 1 cent fuel tax)
Ownership	$ 3.12/trip	Ref.1 (less acc. insurance)
Parking -- Downtown	$ 3.00/trip	Ref.1 (plus land cost)/2 trips
-- Other	$ 1.00/trip	Ref.1 (plus land cost)/2 trips
Highway		
Oper. & Maint. -- auto	1.8 cents/VMT	Ref.2
-- bus	2.9 cents/VMT	Ref.2, bus/car equivalency=1.6
Added capacity -- auto	62 cents/added VMT*	Ref.2, Los Angeles Plan data
-- bus	99 cents/added VMT* (* = not used for I-15 study)	Ref.2, bus/car equivalency= 1.6
Public Transportation		
Bus system -- line-haul	$ 3.00/trip	Ref.3, in current dollars
-- feeder	$ 1.50/trip	Ref.3, divided by 2
Subway system	$ 4.25/trip	Ref.3, in current dollars
Safety & Security		
Public services -- auto	1.1 cent/VMT	Ref.4, in current dollars
-- bus	1.1 cent/VMT	Ref.4, in current dollars
-- rail	0.22 cent/VMT	Ref.4, adj. for acc.rate in Ref.1
Accident (market) -- auto	4.2 cents/VMT	Ref.5
-- bus	8.4 cents/VMT	Ref.5
-- rail	1.68 cents/VMT	Ref.5 adj. for acc.rate Ref.1
Costs With No Market Prices		
Travel time	$ 4.50/hour	Estimated
Environmental		
Air pollution	2.4 cents/VMT	Ref.4, in current dollars
Water pollution	0.2 cent/VMT	Ref.13
Noise	0.16 cent/VMT	Ref.4, in current dollars
Solid/chemical waste	0.2 cent/VMT	Ref.6
Oil extraction	1.5 cent/VMT	Ref.6
(Subtotal)	4.46 cents/VMT	
Accidents (non-market) -- auto	7.8 cents/VMT	Ref.5
-- bus	15.6 cents/VMT	Ref.5
-- rail	3.12 cents/VMT	Ref.5

DeCorla-Souza and Kane have estimated highway maintenance costs at 1.8 cents per VMT on the basis of national data (*2*). Their estimates of the general scale of additional highway capacity costs per peak-period VMT for added lanes on existing rights of way range from 10.1 cents for freeways in outlying areas to 30.8 cents for collector facilities in built-up areas. On the basis of cost and peak-period VMT information from the transportation plans for three urban areas in the United States (*2*), costs for new capacity to serve peak-period users on some combination of existing and new rights of way range from 24 to 62 cents per VMT added above base year VMT.

Public Transportation System Costs

A study by Charles River Associates estimated peak-period costs net of revenues (capital and operating) per passenger trip for transit service to average about $1.98 for rail and $1.33 for bus systems (1983 dollars) (*3*). Corresponding estimates for off-peak service were $1.56 and $1.05, respectively.

Safety and Security Costs

Public costs are also incurred for providing certain types of public services for system users, such as costs for police, fire, emergency medical services, and court costs related to safety and security on the transportation system. FHWA's 1982 *Federal Highway Cost Allocation Study* estimated costs for public services at 0.7 cent per VMT (1980 dollars) (*4*). Another FHWA report estimated accident costs at 12 cents per VMT for automobiles and 24 cents per VMT for buses (*5*). Of these costs, about 35 percent were out-of-pocket costs and losses in wages and household production.

Costs with No Market Prices

Costs that have no market prices may be categorized as travel time costs, environmental costs, pain and suffering components of accident costs, and other social costs.

Travel Time Costs

Travel time unit costs vary by income group, with higher-income groups valuing time at a higher rate. This suggests that travel time unit costs may be lower for HOV and transit modes. Travel time costs are generally converted to dollar terms by valuing time between 33 and 50 percent of the average wage rate of work commuters.

Environmental Costs

Environmental costs may be occasioned during system expansion, system operation, or both. FRA has identified a taxonomy of costs that includes under the environmental category costs for air pollution, water pollution, noise, hazardous materials (hazmat) spills, land use, and electromagnetic radiation. To these may be added the costs of motor vehicle solid and chemical waste disposal.

Various studies have been done to estimate unit environmental costs. FHWA's 1982 *Federal Highway Cost Allocation Study* estimated unit costs per automobile VMT for air pollution and noise pollution at 1.5 and 0.1 cents, respectively (1980 dollars) (*4*). A 1992 study (T. Litman, unpublished data, *Transportation Cost Survey*, Feb. 1992, Victoria, B.C., Canada) did a survey of 15 studies and found that estimates of costs per automobile VMT range as follows:

	Cost (¢)
Air pollution	1.0–7.2
Noise pollution	0.1–0.3
Water pollution	0.16–0.2
Oil extraction, distribution, and use	1.5–4.0

Litman found estimates of land use costs (termed "urban sprawl") to range from 3.5 to 6.3 cents per automobile VMT. He also arbitrarily assumes a cost of 0.2 cents per automobile VMT for solid and chemical waste disposal. The literature does not provide comparable estimates for vans or buses, but most of these cost elements can be expected to be higher for van or bus VMT.

A Natural Resources Defense Council study estimated societal costs per person mile of travel (PMT) for various environmental cost components as indicated in Table 2 (*6*). A World Resources Institute study has also developed national-level estimates of the economic costs of various external impacts of highway use, including costs of air pollution, national security, accidents, noise, and risks of climate change (*7*). No estimates of costs for hazmat spills and electromagnetic radiation are available at this time, but they could probably be developed through research.

Accident Costs

Non-market costs of accidents include pain and suffering and losses in quality of life. They account for 65 percent of accident costs, as estimated in an FHWA study (*5*).

Values of Other Social Impacts

It is unlikely that dollar values can be developed to value social impacts other than travel time, accident, and environmental costs.

TABLE 2 Societal Costs by Mode (¢/VMT)

	Auto (urban)	Bus	Rail
Energy	1.5 to 5.0	0.85 to 2.8	0.39 to 1.3
Noise	0.14 to 0.23	0.05 to 0.1	0.16
Air pollution	4.0 to 7.0	1.6 to 4.5	1.5 to 5.0
Water pollution	0.13	Not estimated	Not estimated

They will simply have to be listed for consideration and traded off against monetized incremental costs in the decision-making process. Examples of these impacts are national defense implications for protection of oil sources; community cohesion or disruption; community pride; aesthetics; accessibility of disadvantaged segments of the population; loss of cultural, historic, recreational, and natural resources; loss of open space and depletion of nonrenewable energy resources.

A recent study by Greene and Duleep has attempted to estimate costs for carbon dioxide emissions (which contribute to global warming) (*8*). A range of $10 to $100/ton of carbon was estimated. (A gallon of gasoline contains 5.38 lb of carbon.) The study also estimated costs for energy security at $10/barrel, including costs associated with the effects of sudden oil price changes and costs associated with maintaining stability in the Persian Gulf region.

Simplified Cost Estimation Procedure

A simplified microcomputer spreadsheet was developed to compute costs. The application of the spreadsheet for system analysis was demonstrated in a recent paper (*9*). This paper demonstrates its application for a corridor example in following section. More detailed methods for calculating costs could certainly provide more accurate estimates of costs, but simplified techniques were used in the example application since the purpose of the example is simply to demonstrate how the approach may be used in real-world situations. A basic assumption of the simplified technique is that conditions in the single future horizon year represent consistently proportional conditions for all previous and subsequent years.

The basic process for computation of costs is indicated in Figure 1. The process relies heavily on output from the four-step travel demand modeling process (*10*), for the base year condition as well as for future year alternatives. Although base cost information could be estimated without travel model output data (for example, by using monitored data for the current year), it is important to use travel model output for the base in order to maintain consistency for comparison with travel measures and costs estimated for future year alternatives.

Basic Inputs for Travel Models

Future socioeconomic and demographic projections used as input to the models should normally vary in their geographic distribution within the urban area for each of the alternatives, although regionwide aggregates of population, employment, and dwelling units should not generally vary by alternative. If aggregate regionwide population estimates differ by alternative, comparing incremental costs of the alternatives will not be appropriate. Valid comparisons of average costs per added trip, per added person, or per added dwelling unit could still be made.

The other travel model inputs are the data relating to investments or policies specific to each alternative.

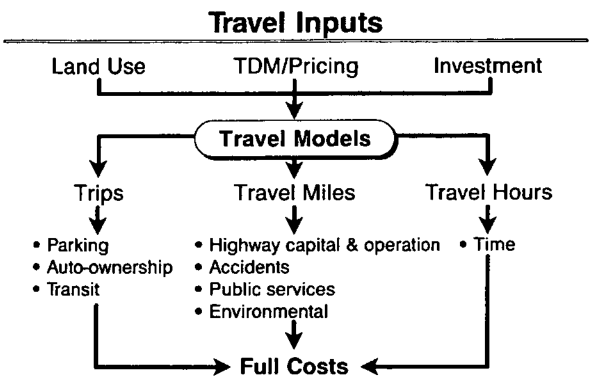

FIGURE 1 Full cost accounting.

Travel Model Outputs

As Figure 1 indicates, the outputs from the travel models needed for input into the costing procedures are the following, for each person travel market:

1. Person trips (from trip generation) as well as person trips by mode (from mode choice).
2. Travel miles (from trip assignment) by mode. This includes PMT on bicycle, walk, automobile, and transit modes as well as VMT.
3. Travel minutes (also from trip assignment). Again, travel time is needed by mode for the base and the alternatives. Alternatively, future travel times can be computed by calculating a "delay" or "time saved" component based on differences between future year and base year average speeds; this component can then be combined with base year travel time to get total travel time. Estimates of travel time on access modes can be based on PMT on these modes and average speeds by mode.

To ensure that travel distance and travel time measures output by the models are realistic, the travel models must be capable of providing accurate estimates of travel speed. In other words, travel models should have been calibrated for speed as well as volume. Also, if significant changes from accessibility levels assumed in model inputs are reflected in the assignment output, these changes should be fed back into earlier steps of the modeling process (i.e., trip distribution and mode choice). The accessibility changes should also be checked against assumptions about the distribution of land use activity.

Cost Models

As Figure 1 indicates, the travel measures output from the travel models are input into cost models that provide unit cost parameters for the various cost components. Unit costs may be costs per trip, per PMT, per VMT, or per minute of travel time. Table 1 presents unit cost parameters that were developed on the basis of estimates from the literature. Costs excluded in Table 1 are environmental costs for land use, hazmat spills and electromagnetic radiation (for which reliable estimates are unavailable at this time), and the "other social impacts" category discussed earlier. These impacts can be considered in trade-off analysis.

CORRIDOR APPLICATION

Data Sources

The application of the spreadsheet model is demonstrated in this section for the peak-period work travel market, for a case study example using data obtained from a multimodal transportation corridor study (*11*).

Travel Measures

The model output data were obtained from a report prepared by the local transportation planning agency. Therefore, it was not possible to get all of the relevant data that would usually be obtained from a travel model run, since all of the information from the model runs was not included in the report. In cases where needed information was not available from the report, national averages from the Nationwide Personal Transportation Study were used (*12*).

Cost Parameters

Where the study report did not provide local cost estimates, national average cost parameters from various sources (*1–4*), as indicated in Table 1, were used. Owing to the liberal use of national average cost parameters, the results from the spreadsheet computations presented in this paper should not be construed as being definitive estimates of the total costs and cost-effectiveness indexes of the alternatives. They are presented here purely for demonstration purposes.

In using the spreadsheet procedure for corridor analysis, the travel demand and cost changes are estimated for the entire urban area, although only alternatives within the corridor are compared. This is because it is difficult, if not impossible, to separate corridor impacts from impacts on the rest of the system, and any corridor improvements are bound to affect the rest of the system in varying degrees.

Alternatives

For this demonstration of the application of the spreadsheet, 3 alternatives were selected from a series of 12 alternatives designed to serve future (year 2010) travel demand in a major travel corridor (Interstate 15) in the Salt Lake City, Utah, metropolitan area.

The alternatives selected for evaluation using the spreadsheet were as follows:

1. Addition of two mixed-flow lanes in each direction on I-15.
2. Addition of one mixed-flow lane in each direction and one reversible HOV lane on I-15.
3. A light rail line on existing rail right-of-way parallel to I-15, along with miscellaneous TSM-type improvements.

The results of the application are given in Table 3, and travel data inputs for the cost estimation procedure are presented in Table 4. In this example application of the spreadsheet, capital costs included in the analysis are only those costs associated with corridor alternatives. Capital costs per peak-period VMT used in the spreadsheet were estimated by dividing total capital costs for each alternative by total peak-period VMT systemwide. Conceivably, capital costs for all other improvements proposed in Salt Lake City's transportation plan could be added across the board for all alternatives. However, since those costs would not vary by alternative, differences between total costs of alternatives would not change relative to the results given in Table 3. (However, costs per added trip are underestimated for all alternatives, since they exclude infrastructure costs for the portion of trips outside the corridor.)

Table 3 indicates that the light rail alternative would save about $30,000 daily relative to Alternative 1 (which added two new mixed-flow lanes), whereas the HOV alternative would save about $13,000 daily. Both estimates are based on travel time's being included in aggregate costs. A large part of the savings would be enjoyed by transportation agencies: $23,000 and $9,000 a day, respectively, or about $6.0 million and $2.3 million a year.

Incremental costs per added peak-period work trip regionwide were also significantly lower for the light rail alternative: $6.18, versus $6.25 for Alternative 1. As stated earlier, these incremental costs would have been higher had capital costs for other regional transportation projects been included in the analysis.

CONCLUSIONS

This paper has explained the need, principles and theory in support of a new approach that can be used in urban areas to evaluate (a) transportation investment alternatives across modes, (b) significant changes in land use and travel demand management policies, and (c) alternative aggregate regional growth scenarios. The approach is based on assessing the relative economic efficiency of alternatives by determining which alternative involves the least total cost for providing mobility for various travel markets.

The approach has been demonstrated through application of a simplified analysis technique using a microcomputer spreadsheet and travel demand model output data from a multimodal transportation corridor study. Results from the analysis have been presented for demonstration purposes only. The application of the approach to the case study suggests that the approach can be a useful tool for comparison of multimodal investment and policy alternatives.

The spreadsheet, with further development, can be a useful tool for transportation planners. However, in its current form, as used for the analysis presented in this paper, it has many limitations about which interested analysts should be cautioned:

- It attempts to monetize many social and environmental costs that are, at best, difficult to monetize. National averages of unit costs, which may not be applicable to any specific urban area, are used.
- The spreadsheet as developed cannot be directly used for analysis of costs for accommodating trips in other travel markets: peak non-work and freight trips, and off-peak trips for work, non-work, and freight.
- It is useful only as a screening tool in its current form. More detailed techniques for estimating impacts and costs will be needed for major investment analysis.
- It is clear from Table 1 that highway and other capital costs comprise a large portion of the total costs of mobility. The sensitivity of the results to differing discount rates should therefore be incorporated in the evaluation procedure.
- The evaluation can be only as good as the demand forecasts and unit cost estimates that underlie the analysis procedure. An analysis of the sensitivity of the results to uncertain forecasts and unit cost parameters should be included in any application of the procedure.

TABLE 3 Costs for Peak-Period Work Travel, Salt Lake City, Utah (million $/day)

		BASE (1986)	2 LANES (2010)	1L + HOV (2010)	LRT (2010)
Market costs:	Vehicle(incl.P/R)	0.592	1.718	1.714	1.713
	Hwy Facility(auto)	0.036	0.173	0.164	0.134
	Hwy Facility (bus)	0.000	0.001	0.001	0.001
	Subtotal hwy fac	0.036	0.174	0.164	0.134
	Public transport	0.044	0.123	0.124	0.146
	Safety/sec.(auto)	0.106	0.307	0.307	0.306
	Safety/sec.(bus)	0.001	0.002	0.002	0.002
	Subtotal safety	0.107	0.309	0.309	0.308
Summary by mode: (market costs)	Subtotal for auto	0.733	2.198	2.184	2.153
	Subtot for transit	0.045	0.126	0.127	0.149
	Total market costs	0.778	2.324	2.311	2.302
	Cost/auto trip ($)	3.343	3.452	3.432	3.390
	Cost/trans trip($)	3.320	3.327	3.326	3.768
	Cost/added auto trip ($)		3.509	3.479	3.415
	Cost/added transit trip ($)		3.330	3.221	4.002
Non-market costs:	Travel time (auto)	0.344	1.000	1.000	0.997
	Trav time(transit)	0.050	0.141	0.142	0.137
	Subtot trav time	0.395	1.140	1.141	1.135
	Environmental	0.089	0.260	0.259	0.259
	Accident pain, etc	0.157	0.456	0.455	0.454
Total costs, including time cost		1.419	4.179	4.166	4.149
Total costs, excluding time cost		1.025	3.039	3.025	3.014
Average cost/trip, $ (incl.time)		6.094	6.195	6.177	6.150
Average cost/trip, $ (excl.time)		4.399	4.505	4.485	4.468
Average cost/added trip, $ (incl.time)			6.249	6.220	6.180
Average cost/added trip, $ (excl.time)			4.561	4.530	4.504
Transportation agency costs -- total		0.067	0.260	0.251	0.237
Transportation agency costs -- incre			0.193	0.184	0.170
Transp. agency costs/trip, $		0.287	0.385	0.372	0.351
Transp. agency costs/added trip, $			0.436	0.417	0.384

TABLE 4 Travel Data Inputs

Travel Data (millions daily)	BASE (1986)	2 LANES (2010)	1L + HOV (2010)	LRT (2010)
Trips:				
Auto trips	0.191	0.555	0.554	0.554
Auto person trips	0.219	0.637	0.636	0.635
Transit trips	0.014	0.038	0.038	0.039
VMT:				
Auto VMT	1.988	5.774	5.764	5.757
Auto P/R access VMT	0.008	0.024	0.024	0.025
Bus VMT	0.008	0.021	0.022	0.017
Total VMT	2.004	5.820	5.809	5.799
Travel time (minutes)	0.395	1.140	1.141	1.135

• The spreadsheet evaluates a single target year. The effects of the timing of costs and of benefits need to be considered.

• Valuation of time is also difficult. Disutility values of time have been shown to differ by travel mode, in-vehicle versus out-of-vehicle time (walk and wait time), and trip purpose, but a single value of time is used in the spreadsheet. An analysis of the sensitivity of the results to different assumed values of time will be needed.

ACKNOWLEDGMENTS

The authors wish to acknowledge the valuable comments provided on an earlier draft by Anthony R. Kane, Associate Administrator for Program Development, FHWA, and by various anonymous reviewers of TRB's Committee on Transportation Programming.

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The views expressed in this paper are those of the authors alone and do not necessarily represent the policies of the U.S. Department of Transportation. Also, please note that unit costs derived from FHWA publications may differ from those presented in Table 1 of this paper.

Publication of this paper sponsored by Committee on Transportation Programming, Planning, and Systems Evaluation.

Multimodal Project Evaluation: A Common Framework, Different Methods

KRISTINA E. YOUNGER

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) provides unprecedented flexibility to metropolitan planning organizations (MPOs) in programming federal transportation funds for multimodal projects. With this flexibility comes the responsibility to analyze and select projects fairly within a practical process. The way in which the Capital District Transportation Committee (CDTC) in Albany, New York, approaches the programming process is examined and compared with the methodology used by the Metropolitan Transportation Commission (MTC) in the San Francisco Bay Area. The two approaches outline both screened projects for minimum requirements and then evaluate project merits. CDTC's methodology puts heavy emphasis on benefit/cost analysis but weighs qualitative factors before programming. MTC's approach negotiates merit criteria and relative weights of those criteria before evaluating individual projects. The strengths, weaknesses, similarities, and differences in project selection methodology are discussed. A common framework for multimodal project selection is offered as a starting point for other MPOs struggling to respond to the opportunities presented by ISTEA.

"How do you compare apples and oranges? By their nutritional value." (Lawrence D. Dahms, Executive Director, Metropolitan Transportation Commission.)

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) grants metropolitan regions unprecedented latitude to direct transportation investments toward mobility solutions that suit local needs and desires. This combination of funding flexibility and regional decision making will shape transportation investments for many years to come.

Many metropolitan planning organizations (MPOs) are uncertain how to approach this opportunity. The literature in the area provides little insight, as it has not kept pace with the rapid changes wrought by ISTEA. The flexibility provided by the ISTEA comes with a responsibility to evaluate projects fairly, regardless of mode. This poses technical difficulties when analytic tools are unavailable, unfamiliar, or cumbersome to implement. The increased eligibility of a wide variety of projects for federal funding also raises expectations and brings a number of new players to the MPO table. This can greatly complicate matters when traditional transportation needs for rehabilitation far exceed available revenues, even at increased ISTEA authorizations.

This paper, which is not a research paper but is intended for practitioners, compares the project selection methodologies of two very different MPOs and suggests a common framework for project selection under ISTEA. It highlights the strengths and weaknesses of each methodology in order to allow other MPOs to choose methods that will work in their area.

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CAPITAL DISTRICT CONTEXT

The Capital District Transportation Committee (CDTC) is the MPO for the four counties around Albany, New York. With a population of just over 775,000 people, the Capital District has three major cities (Albany, Schenectady, and Troy) and several smaller cities (Saratoga Springs, Mechanicville, Cohoes, Watervliet, and Rensselaer). Population density is lower than in many other areas of similar size, and the lack of a single dominant city center has greatly influenced transportation and development patterns. As the state capital and locus of many state government functions, the area is flavored by a focus on state governance.

The Capital District is currently a marginal nonattainment area for federal ozone standards, but it is expected to be redesignated to a maintenance area later in 1994. Air quality concerns for the state as a whole are generally focused on the New York City metropolitan area, where pollution levels are high. In the Capital District, air quality concerns mirror larger national trends of increasing vehicle miles traveled, increasing vehicle ownership, and general demographic shifts. The transportation system as a whole can be accurately characterized as automobile-oriented, and, with increased suburbanization, ridership on the bus system has shown a long-term declining market share, dropping 20 percent between 1982 and 1992. Transit use represents just over 4 percent of commute trips, only 2 percent of all trips. The vast majority of trips are by way of the single-occupant vehicle.

As part of the greater Northeast United States, Capital District infrastructure is weather-worn and aging. For the past 15 years, 75 to 85 percent of all federal-aid funds have been spent on basic pavement rehabilitation and bridge replacement and rehabilitation. New York State has a history of funding non-federal-aid transportation improvements by a combination of general fund appropriations and short-term bond programs. Until 1993 there was no ongoing dedicated state fund for transportation in place. It is anticipated that the creation of the state dedicated fund will allow the state to absorb many major state highway and bridge rehabilitation needs that were previously federally funded. This was a major factor in the increased federal-aid programming capacity available to the CDTC during 1993 Transportation Improvement Program (TIP) discussions.

State-generated transportation funds, such as bonds, have historically been programmed by the New York State Department of Transportation (NYSDOT) without the direct involvement of MPOs in project selection. This is also true with the state dedicated fund, which is limited by law to the state highway system. In addition, the bonding programs have been categorical in nature.

The New York State legislature has preferred to fund specific projects rather than to establish discretionary, or flexible, programs.

MPOs in New York State are an outgrowth of the 3C (comprehensive, continuing, and cooperative) planning processes established by the state in the mid-1960s. In many metropolitan areas of the state, including New York City, the MPO staff are NYSDOT employees. In other areas, the transit authority or county serves as legal employers of the MPO staff. MPOs in New York State operate by a "consensus of the affected parties"; that is, on a regionwide program such as the TIP, by unanimous consensus of the voting members. The primary source of funding for MPO operations is federal planning funds. Some MPOs, like the CDTC, also have cultivated local funding sources. Other than in-kind services (which are significant), New York State provides no direct funding for regional transportation planning performed by the MPOs.

In the Capital District, the CDTC includes the Capital District Transportation Authority—the regional public transit operator—as a voting member. NYSDOT is also a voting member of the CDTC. With the advent of the ISTEA, the New York State Thruway Authority was added to the traditional membership of 21 county, city, town, village, and other state agency officials that make up the policy board. Federal agencies are ex officio members. The Thruway Authority's mission was broadened by recent state legislation to include the barge canal system and economic development activities, and provisions of ISTEA for the use of toll credits have made the Thruway Authority a large player in transportation decisions statewide.

Over the past 10 years or so, MPOs in New York State have searched for their niche in transportation planning. CDTC has a strong history of state-of-the-practice traffic modeling, corridor and subarea studies, the development of pavement management systems for local roads, and traffic count data gathering. CDTC's reputation for sound technical analysis and fair negotiation has led local government to request a number of traffic impact assessment and other subregional planning studies. There is a strong link between CDTC's long-range planning efforts, particularly as regards strategic mobility concerns, and the development of the TIP. This provides a solid basis for CDTC and its participants to act on the opportunities presented by ISTEA.

CDTC Project Selection Methodology

In March 1993 the CDTC adopted the 1993–98 TIP (*1*). This 5-year program of federally funded capital and transit operating projects represents a major achievement in advancing the project selection techniques used in the Capital District. Major program changes, the creation of the state dedicated fund for many large state highway and bridge projects, and increased monetary authorizations included in the ISTEA resulted in significant programming capacity for new projects ($150 million over 5 years) and a corresponding increase in the number and variety of project proposals. This compares with programming capacities of $20 million to $40 million in federal-aid urban funds in previous TIP cycles.

Together with the Federal Clean Air Act Amendments of 1990 and Americans with Disabilities Act (ADA) requirements, the ISTEA requirements to address intermodal issues, base project selection on performance-based standards, and fairly consider a wider array of eligible projects caused CDTC to modify its project selection approach significantly. However, a history of the use of evaluation techniques based on benefit/cost (B/C) analyses and substantial modeling efforts put CDTC in a strong position to develop a set of criteria to meet the challenges and take advantage of the opportunities presented by this programming exercise.

Basic Approach

CDTC established a working group of transportation and environmental protection interests to develop the project evaluation criteria, review staff project merit evaluations, and develop the program. This working group, with a mailing list of over 200, was regularly attended by 25 to 30 people. CDTC has a staff of 10 people, 4 of whom focused on TIP development activities. The following approach was used in developing the 1993–98 TIP in the Capital District:

1. Minimum requirements were established for each project. These were basic "screening" criteria that ensured that every project considered for programming was consistent with the long-range transportation plan and local land use plans, had reasonable cost estimates and a funding plan, and was justified on the basis of need.
2. The merits of every project that met the minimum requirements were fairly evaluated. Following ISTEA mandates, life-cycle costs and the use of performance-based standards were an integral part of the merit evaluation. The merit evaluation procedure used the best available information from CDTC's models, corridor studies, and the project sponsor (*1*). A traffic simulation model run for every highway and bridge project (114 projects) compared the system benefits of the project with baseline system performance in the reference year 2000. For rehabilitation projects, infrastructure benefits were quantified by using the model to determine the mobility benefits of keeping the facility open and evaluating the current pavement or bridge condition and suitability of the proposed project scope (see the paper by Poorman and Posca in this Record). Wherever possible, measures that cut across modes, such as relative cost effectiveness, were used. A B/C ratio was then calculated for virtually every project. The exceptions were some of the more nontraditional projects, such as an intermodal transfer facility proposed for the Port of Albany. The qualitative benefits of projects—such as environmental impacts, systemwide significance, and intermodal links—were directly incorporated into this merit evaluation procedure. Every project's quantitative and qualitative benefits were summarized on a standardized one-page form, which is shown in Figure 1. This merit evaluation emphasized the intended project benefits [e.g., emissions reductions for Congestion Mitigation and Air Quality (CMAQ) Improvement projects], although the same criteria were used for different project types.
3. A "balanced" TIP that will contribute to a staged regional plan for maintenance of essential facilities and services, demand management, and capacity improvements was then produced. A set of principles to guide the programming was developed that addressed modal, geographic, and functional equity; the ability of the project to be funded through other sources; and project readiness (ability to obligate funds in year of programming). Because project merit was evaluated with different emphasis by project type, the balance of project types was achieved at the programming stage. This approach made the modal, geographic, and functional trade-offs after the merit evaluation was completed and clearly maintained the link with the goals set in the long-range plan.

The TIP as a whole must, according to federal law, conform with the Federal Clean Air Act, be financially "reasonable," be consistent with the long-range plan, and address 15 factors spelled out in ISTEA Section 134(f). Conformity with the Federal Clean Air Act was found, in cooperation with NYSDOT, using a methodology developed cooperatively by NYSDOT and the Environmental Protection Agency. Financial reasonability was determined both at the project level in the screening criteria and for the program as a whole. Consistency with the long-range plan was determined on a project level at the time projects were screened for inclusion in the TIP, and the implementation of Regional Transportation Plan goals and objectives was one of the primary programming considerations. Analyses of how the programming methodology addressed the 15 ISTEA factors and how the TIP and the long-range plan are related were included in the TIP document.

Capital District project submissions for the 1993–98 TIP were primarily pavement and bridge rehabilitations and strategic mobility improvements, although innovative projects such as a travel demand management program, a corridor management initiative, and a comprehensive advanced traffic management system were proposed and ultimately programmed. Several enhancement-type proposals were deferred, pending the surface transportation set-aside program administered by NYSDOT.

BAY AREA CONTEXT

The Metropolitan Transportation Commission (MTC) is the MPO for the nine-county San Francisco Bay Area. With 100 cities, including San Francisco, Oakland, and San Jose, more than 6.2 million people live within MTC's jurisdictional boundaries.

Unique geography and the demands of a burgeoning population have helped to create a diverse transportation network that includes 1,400 mi of state highways, 17,700 mi of local streets and roads, electric trolley buses, a huge fleet of diesel buses, two light rail systems, two commuter rail services, a regional rail system (BART), ferries, and the famous cable cars. The multitude of transportation agencies—ranging from county-level congestion management agencies to more than 40 transit operators—creates an environment of pronounced institutional and political complexity.

PROJECT TITLE ______
LOCATION ______
DESCRIPTION ______
PURPOSE ______

1993-98 PROJECT COST (Federal Share) ($M) ______
POST 1997-98 COST ______
ANNUALIZED COST ($1000/yr) ______

TRANSPORTATION SYSTEM AND USER SAVINGS
Total System and User Savings ($1000/yr) ______
Safety Benefits ($1000/yr) ______
Travel Time Savings ($1000/yr) ______
Energy and User Cost Savings ($1000/yr) ______
Life Cycle Cost Savings ($1000/yr) ______
Benefit/Cost Ratio ______

CONGESTION RELIEF
Daily Excess Vehicle Hours of Delay Saved ______
Daily Excess Vehicle Hours Saved / $ M annual (/ $M initial) ______ ( )

AIR QUALITY
Hydrocarbon Emission Reductions ______
Hydrocarbon Emission Reductions / $ M annual (/ $M initial) ______ ( )

NOISE REDUCTION:

RESIDENTIAL TRAFFIC:

COMMUNITY AND ECOLOGICAL DISRUPTION:

ACCESS TO THE PUBLIC TRANSPORTATION SYSTEM:

MODAL INTEGRATION:

PROVISION OF ALTERNATIVE MODES:

SYSTEM LINKAGE:

ECONOMIC DEVELOPMENT:

OTHER:

FIGURE 1 CDTC project merit evaluation criteria.

MTC was uniquely positioned to take early advantage of the opportunities presented by ISTEA (see the paper by Younger and Murray in this Record). California, in passing a gas tax increase in 1990, created county-level congestion management agencies and a category of state funding with some spending flexibility across modes. Regional transportation planning agencies, like MTC, have historically had a strong role in the state transportation programming process. California's dedicated state highway account was created in the early 1970s.

Traffic congestion and stringent federal *and state* clean air standards have put intense pressure on MTC to fund alternatives to the single-occupant vehicle. As a nonattainment area for both ozone and carbon monoxide, MTC was sued under the Federal Clean Air Act by the Sierra Club and Citizens for a Better Environment in 1989. Over 3 years, that litigation significantly modified MTC's conformity procedures for the TIP and brought air quality issues to the forefront.

In addition, the Bay Area has massive maintenance needs. The BART system is getting older, many bridges and other structures require major strengthening to better withstand earthquakes, and, in tight fiscal times, pavements have generally not been rehabilitated at an optimal rate.

MTC is the state-designated regional transportation planning agency, in addition to being the MPO. The state of California supports regional transportation planning with sales tax revenues. MTC has a broad funding base for its activities, including a portion of regional bridge tolls, specific grants, and other local sources. MTC's unique enabling legislation gives it specific project review powers and establishes the governing board membership. The governing board is composed of locally elected officials from the nine counties and five urbanized areas and representatives from the Association of Bay Area Governments and the San Francisco Bay Conservation and Development Commission. The California Department of Transportation (Caltrans) and federal agencies are ex officio members—they do not vote. Transit agencies do not sit on the policy board, although a legislatively mandated Transit Operators Coordinating Council advises the MTC directly. MTC operates by majority vote.

MTC has carved its niche in the Bay Area transportation community as a broker and a consensus builder. This history of coalition-building and advocacy was advanced by aggressive lobbying efforts during the formation of ISTEA. It has been formalized into the Bay Area Partnership, consisting of the major modal, state, and federal agencies involved in transportation planning, programming, and project implementation. A Blue Ribbon Advisory Committee brings in the perspectives of advocacy groups, the private sector, and other constituencies. MTC's ability to mobilize quickly in response to the ISTEA was largely a result of this history and a commitment to a philosophy of mutually beneficial cooperation.

SUMMARY OF MTC PROJECT SELECTION METHODOLOGY

MTC was among the first to develop a methodology of comparing projects across modes, approving its first ISTEA-era TIP in September 1992 (*2*). This methodology has been widely circulated as the "state of the practice" in 1993 (see the paper by Younger and Murray in this Record).

MTC's basic approach to project selection was established with strong participation by transportation and environmental protection interests. An ad hoc committee of 35 people representing these interests was formed to create the process and criteria by which projects are selected; it has since been institutionalized under the Bay Area Partnership. Face-to-face meetings of participants forced participants to be less parochial and to focus on reaching regional consensus. MTC staff provided the structure and schedule for the discussions and initial proposals, but the final proposals were ultimately the result of the agreement of the assembled group.

Heavy emphasis is placed on process. As a result, the actual formation of the program is a functional application of the previously agreed-on criteria. Although establishing the program is not purely a mechanical exercise (politics does intervene), debate tends to center on the application of the criteria, not the criteria themselves.

The criteria for project selection fall into three basic types: screening, scoring, and programming principles. As in the Capital District, every project is required to meet certain minimum requirements for consistency, fiscal reasonableness, and project readiness before being allowed to progress further. The scoring criteria make up an elaborate matrix that assigns points on a 0-to-100 scale, which is summarized in Table 1. The criteria are multimodal and performance-based wherever possible. Imbedded in the scoring matrix are weights agreed on by the participants for maintaining the existing system, improving its efficiency and effectiveness, expanding the system, and considering the external impacts of project implementation. The scoring procedure gives extra emphasis to a network of transportation facilities identified in the long-range plan as the Metropolitan Transportation System: those streets and roads, highways, mass transit routes, bikeways, transfer points, airports, and seaports considered essential to regional travel.

Programming principles were established to ensure that the overall program of projects would increase mobility, clean the air, leverage the most state and federal resources, and be equitable. Much of the initial discussion in establishing the principles, and annually in formulating the actual program, centers on issues of equity: across modes, geography, and functional classifications. As in the Capital District, the first programming principle enumerated is that project merit is the most important criterion for project selection.

MTC staff screens and scores the projects. MTC has a total staff of 85, about 25 of whom were actively involved in project evaluation during the peak period. Adjustments in project scores are made as project sponsors provide additional information and the proposed program undergoes public review. For the first cycle, more than 500 projects were evaluated for $210 million in available federal funds. Project sponsors in the Bay Area submitted a wide variety of projects for consideration, ranging from a day care center at a transit station to bicycle facilities and repaving jobs. The limits of ISTEA flexibility were put to the test.

COMPARISONS

The two project selection methodologies just outlined have similarities, differences, strengths, and weaknesses.

Similarities

- Both CDTC and MTC used a framework that (a) screens projects for minimum requirements, (b) evaluates project merits fairly across modes, and then (c) establishes an equitable, balanced, cost-effective program that is based on predetermined principles.

- A participation process using working groups of major interested parties was used effectively in both cases.
- A program with broad-based support was formulated in both cases.
- Project merit was the principal project selection criterion in both cases.
- The period for development of the criteria and the program was approximately 6 months in both cases.
- "Regional" projects were forwarded by both MPOs.

Differences

- CDTC set the balance of priorities at the programming stage. MTC built (or hid, depending on your perspective) much of this aspect into the weights using in the scoring matrix as well as into the programming principles. Therefore, significant public influence of the overall program balance occurs much earlier (when the criteria weights are set) following the MTC method.
- CDTC's traffic model was run for every project considered, and quantification of project benefits to the system were able to be produced consistently. Allowance was built into the criteria for those benefits that are not readily quantifiable by using the standard format for evaluation shown in Figure 1. MTC's traffic model was not an available tool for project merit evaluation, because of the number of project proposals, other priorities for the modeling staff's time, including air quality conformity of the overall TIP, and the inclusion of many projects that are not easily modeled. Qualitative project benefits were incorporated into the scoring matrix (summarized in Table 1) in the "External Impacts" category.

Strengths

- Focusing on process and criteria led to a technically and politically defensible program.

TABLE 1 Summary of MTC Scoring Criteria for Surface Transportation and CMAQ Programs

30 points MAINTAIN/SUSTAIN THE METROPOLITAN TRANSPORTATION SYSTEM (MTS)
Rehabilitations and replacements based on Management Systems are eligible for up to the full 30 points, depending upon the portion of the project that will rehabilitate the system, and the optimization of the proposed improvement with current condition.
Rehabilitations not based on a management system, or for support infrastructure like drainage, can only receive a maximum of 20 points.
30 points IMPROVE THE EFFICIENCY AND EFFECTIVENESS OF THE MTS
Safety and security, congestion relief, cost effectiveness, and freight movement are the three subcategories where points can be assigned, up to a combined maximum of 30 points.
For both the safety and congestion relief criteria, the magnitude of the (safety or congestion) problem addressed by the project is multiplied by the impact that the project will have in eliminating or alleviating the problem. Guidelines for setting the multipliers are included, and impact scores are based on shared empirical experience (e.g. Class 1 bike paths are safer than Class 3).
Cost-effectiveness points measure the ratio of annual benefits in terms of total travel time savings and operating cost savings for the project to annualized total project costs. Cost-effectiveness scores are adjusted to reflect the median of all submitted projects.
Freight movement points are assigned based on the facility type and nature of the proposed project.
15 points - SYSTEM EXPANSION
System expansion projects are first evaluated as to whether or not the meet current demand through the use of a multiplier based on average daily traffic and existing level-of-service. Again, the impact that the project will have in meeting demand is set based on shared empirical experience (e.g. the addition of HOV lanes has more impact than ramp metering).
25 points - EXTERNAL IMPACTS
Air quality improvement, land use policy support, energy conservation, and implementation of the Americans with Disabilities Act (ADA) are the four subcategories where points can be assigned, up to a combined maximum of 25 points.
Projects with positive air quality impacts are awarded up to the full 25 points if they implement MTC-adopted Transportation Control Measures (TCMs). Projects which are only partially TCMS are awarded proportionately smaller point values, and TCMS are grouped according to their effectiveness in cleaning the air.
A project can also be awarded up to 8 points if it supports land use policies that foster a mode shift away from single occupant vehicle trips on regional facilities. Up to 10 points can be awarded for projects with demonstrable energy conservation or modal shift benefits. Up to 20 points can be awarded for implementation of ADA enhancements.
100 TOTAL POINTS POSSIBLE
Planning projects are prorated according to the nearness and necessity of the planning project to direct and immediate transportation improvements.

• Flexibility was used to develop a program that met regional needs in both cases.

• Adding new players—such as freight providers—to the mix of people developing the program led to more diversified projects and programs.

• Both methodologies are very good at distinguishing the clearly beneficial projects from the "dogs."

• Preserving the existing transportation system is an important policy concern of the ISTEA, and one of the 15 factors that MPOs are required to consider in developing plans and programs. CDTC's methodology captures the mobility benefits of maintaining the existing transportation infrastructure as part of the B/C calculation. MTC's methodology, by emphasizing projects that accomplish multiple objectives, similarly has forced project sponsors to articulate a project's overall system benefits. For example, a pavement rehabilitation project may benefit the buses and bicycles that travel over it, and savvy project sponsors have learned to emphasize these multimodal aspects to enhance project scores.

Weaknesses

• A merit-based project selection process is highly data dependent—on data that are not always readily available. In the Capital District, the CDTC was blessed with a cooperative regional office of the NYSDOT and a history of data collection on pavement conditions and traffic volumes on local facilities. MTC had a similarly rich history of data collection and cooperation from Caltrans and transit operators. Without such resources, implementation of fair merit evaluations is problematic.

• Both systems of project evaluation tend to be deterministic. They give an illusion of precision of measurement when in fact the difference between a project with a B/C ratio of 2.9 and one of 3.3 (or in the MTC system, a score of 78 versus 85) is not significant. Yet the place where the funding line is drawn often depends on marginal differences in "score."

• The MTC scoring approach prescribes relative weights and maximum scores in different categories, which leads to a program in which projects with multiple objectives rise to the top. Partly this is a policy choice to foster multimodal projects, but it can leave single objective projects, such as bicycle paths, unprogrammed.

• CDTC's approach relies on the ability of the planning committee members to balance program needs—something that works only with a cooperative group of people with an ability to act "regionally" in light of parochial interest in project advancement. In reality, the focus during programming is drawn to the B/C ratio, which was not intended to be the overwhelming criterion, but functionally was. This minimized the effectiveness of having multiple criteria. CDTC addressed this weakness by deciding yes or no on projects where "the numbers don't tell the whole story" before priority ranking other projects according to B/C ratio.

• A key piece of data that is required is reliable cost estimates. These are often difficult to obtain at the programming stage. Improvements in cost estimation techniques, as well as increased communication and "partnering" between project designers and MPO planners, is essential. Otherwise, further refinements in multimodal project selection techniques are less meaningful.

LESSONS FOR OTHER MPOs

Some lessons from the two MPO experiences can be offered.

1. *It can be done.* It is possible to establish a process and criteria that will lead to a multimodal program of capital improvements with broad-based support.

2. *The process and criteria must be based on local experience, expertise, and, above all, participation.* Regional context and historical development patterns cannot be ignored. On the other hand, a host of new players need to be included in the programming process. The two systems of evaluating project merit across modes presented here are useful examples but are probably not appropriate for wholesale adoption in other areas. The processes by which the criteria were developed are by far their most important aspect.

3. *A common framework for multimodal project evaluation and selection worked in two very different regions.* Screening projects for minimum requirements, evaluating their merits using the best available tools, and then formulating a program based on predetermined principles does work. Details appropriately vary from region to region and even from programming cycle to programming cycle: the framework has wide applicability.

ISTEA gives MPOs the opportunity to set programming priorities that meet regional needs and reflect regional consensus. Clearly, a new day has dawned in transportation decision making in America. MPOs representing very distinct metropolitan areas, including the two referenced in this paper, are using the flexibility of ISTEA and its wide-ranging project eligibility to fund innovative approaches to solving transportation problems.

Seize the day!

ACKNOWLEDGMENTS

Both CDTC and MTC are funded in part with federal planning funds made available under ISTEA. The author thanks John P. Poorman for his invaluable guidance and thoughtful leadership. An early draft of this paper was reviewed by Ellen Griffin, Hank Dittmar, Dave Murray, Louis Rossi, Clarence Fosdick, Dick Carlson, Jeff Marko, Glenn Posca, Betty Deakin, Lisa Wormser, and Robert E. Martinez. Their comments and suggestions were extremely valuable. Any inaccuracies or omissions are the responsibility of the author.

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Publication of this paper sponsored by Committee on Transportation Programming, Planning, and Systems Evaluation.

Comparing Infrastructure Renewal Projects to Mobility Improvement Projects

JOHN P. POORMAN AND GLENN POSCA

Procedures that provide for a quantitative calculation of system benefits derived from both infrastructure and mobility projects are described. The procedures were used by the Capital District Transportation Committee (CDTC) in Albany, New York, as part of a comprehensive project evaluation process in the development of its 1993–98 Transportation Improvement Program. The technique involves the use of CDTC's regional travel simulation model to estimate system-level impacts of transportation actions; these impacts include changes in travel time, delay, excess delay, operating costs, accident costs, and vehicular emissions. Metropolitan transportation organizations typically use such calculations to examine the value of mobility projects (highway widenings, signal system improvements, new highway or transit facilities, and other projects that add capacity), but CDTC uses similar calculations to capture the system benefit of repair or replacement of bridges, highways, and transit equipment. This method allows for head-to-head comparison of mobility improvement and infrastructure repair projects. In the CDTC process, the system value of a bridge, highway, or transit service renewal proposal is estimated by simulating system conditions both with and without the facility or service proposed for repair or replacement. The difference between system conditions with the facility (or equipment) in place and with the facility removed is then prorated to reflect the percentage of the natural life of the facility that is extended by the project. For example, if a facility's physical life is 50 years and the repair extends its life 20 years, the system benefit of the repair project is calculated at 40 percent of the calculated system value of the facility.

The Capital District Transportation Committee (CDTC) is the designated metropolitan planning organization (MPO) for the area containing the Albany-Schenectady-Troy, New York, urbanized area. During 1992 CDTC and New York State defined CDTC's metropolitan area boundary as Albany, Rensselaer, Saratoga, and Schenectady counties (with the exception of a small part of Saratoga County, which is within the Glens Falls urbanized area). The total population of CDTC's defined metropolitan area is in excess of 750,000, and the entire area is designated as a marginal nonattainment area for ozone.

CDTC's board is composed of the New York State Department of Transportation (NYSDOT), New York State Thruway Authority, Capital District Transportation Authority, and Capital District Regional Planning Commission; chief elected officials from the four counties; mayors of four central cities (Albany, Schenectady, Troy, and Saratoga Springs) and four smaller cities (Rensselaer, Cohoes, Watervliet, and Mechanicville); and rotating representatives of towns and villages. CDTC operates by consensus, defined as unanimous consent of all affected parties.

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The Capital District is characterized as a collection of small cities with growing suburban areas both within a tri-city area and surrounding that area, particularly along the Interstate 87 corridor in Saratoga County. The fragmentation of municipal structures has historically allowed CDTC to avoid "big city versus suburban county" conflicts in planning and program development. MPO participants have relied on objective information and structured discussions rather than raw political clout for many years. These discussions have their origins in the 3C (comprehensive, continuing, and cooperative) process of the mid-1960s, which produced a long-range transportation plan by 1971.

Further, a strong precedent for objective comparison of competing transportation projects was established in 1977 to facilitate the selection of substitution projects for the withdrawn I-687 project in Albany County. At that time, policy and technical participants from all member agencies and units of government worked cooperatively on a multimodal project evaluation and programming structure. The structure was successful in gaining consensus on a list of state and local highway projects and public and private transit improvements totaling approximately $60 million.

CDTC continued its structured project evaluation process in the 1980s through a formal Project Information Procedure (PIP), which built on the Interstate substitution process and included both quantitative and qualitative evaluations of project merit. The procedure proved useful, but it was generally limited in application to situations in which projects from different sponsors were competing for the same categorical funds. These situations tended to be limited to urban system projects, which constituted only a small fraction of the total federally funded transportation program approved each year by CDTC. It was not applied to federal-aid primary funds, which were exclusively on projects on state highways, for example.

With the passage of the Intermodal Surface Transportation Efficiency Act of 1991, greater flexibility in programming set up much greater potential for competition among projects from different sponsors. During the annual update of its 5-year Transportation Improvement Program (TIP) carried out between October 1992 and March 1993, CDTC engaged in an open process to program approximately $130 million in National Highway System, Surface Transportation Program, and Congestion Mitigation and Air Quality (CMAQ) Program funds available to new projects. This situation was made possible largely by the expectation of a new state dedicated funding program that would lessen the state's demands on federal funds.

The presence of a large pot of flexible funds reinforced CDTC's long-standing commitment to objective comparisons and prompted an examination of ways in which to improve the technical evaluations.

DEVELOPMENT OF 1993–98 TRANSPORTATION IMPROVEMENT PROGRAM

CDTC launched its annual TIP update in October 1992. In contrast to TIP updates of prior years, this effort was characterized by several new features.

1. A major municipal outreach effort was established. Each of the more than 70 municipalities in the metropolitan area was contacted to elicit project proposals. After 1 month, a second letter was sent, citing local roads with poor pavement conditions and daily traffic volumes over 5,000 and containing a request to consider proposing such facilities for repair.
2. A major public outreach effort was conducted. More than 100 community, environmental, and business groups were included in ongoing mailings of TIP material and invitations to open TIP working group meetings.
3. NYSDOT provided full disclosure of its project proposals for both federal and state fund sources early in the process and pledged to work with CDTC staff and local participants in accurately scoping project proposals and in firming up cost estimates of both state and local projects.
4. Participants reaffirmed commitment to an objective evaluation process. Through discussions, this process was defined as a screening, scoring, and programming sequence. Project proposals were screened for consistency with regional and local plans, minimum physical condition for infrastructure work, minimum level of service (LOS) for congestion relief, and other conditions. Projects passing the screen were then scored on a consistent set of criteria. Balance among project types, geographic areas, and project sponsors was struck at the programming stage.

The process continued from October 1992 through March 1993 with ample opportunities for public comment before formal CDTC action. During that period, 114 projects were considered. Of these, most were derived from either CDTC's ongoing regional system planning process or from outreach to municipalities. A minority were the traditional infrastructure repair and replacement projects on the state system, project types that had dominated CDTC's TIP for many years.

The screen, score, and program sequence differed from CDTC's traditional PIP used to evaluate candidate projects by segregating screening criteria from scoring criteria. The PIP traditionally included a weighting factor to allow travel time savings derived from addressing a LOS E intersection to be treated as more important than similar travel time savings derived from addressing a LOS D intersection. In contrast, the screening process eliminated all consideration of LOS D intersections. Similarly, infrastructure projects were screened to eliminate consideration of lower-function roads unless they were in poor condition and major arterials unless they were in fair condition.

This shift in process, along with the broad outreach and large amount of funds on the table, led to a thorough revision of the PIP.

REVISED PROJECT INFORMATION PROCEDURE

CDTC staff and TIP working group participants reviewed the existing PIP and made some significant changes to it. The changes were made to fill holes in previous techniques and to fairly articulate the merits of a wide range of project types. A conscious choice was made not to use a 100-point scale, in order to avoid limiting the effect of a single criterion on the estimation of total project merit.

As in the previous PIP, an attempt was made to provide a single "fact sheet" for each project that summarizes both quantitative and nonquantitative criteria.

Differences from the historic PIP include the following:

1. Safety benefits, travel time savings, and energy and user cost savings were generally estimated using CDTC's regional travel simulation model, using a common reference year of 2000.
2. Hydrocarbon emissions reductions and cost-effectiveness of emissions reductions were added as quantitative criteria. These were also calculated using year-specific, link-level emission rates applied to regional travel simulation model results.
3. Congestion relief benefits were added as quantitative criteria but not counted in the quantitative benefits. These were measured in terms of daily excess vehicle hours of delay (XVHD) saved and the cost-effectiveness of such savings. (Excess delay is defined as the amount of time spent at an intersection or highway link above and beyond the maximum allowable time at LOS D.)
4. "Life-cycle cost savings" (a more correct term may have been "extended facility value") served as a primary measure of the benefit of infrastructure projects. The new life-cycle cost savings measurement was also calculated using results from CDTC's regional travel simulation model.
5. Previous qualitative criteria measured on a scale of -2 to +2 were replaced with a comparable list of narrative criteria. The expressed intent of this switch was to recognize that any one of the nonquantifiable criteria might have sufficient importance to warrant inclusion or exclusion of a given project. For example, if elimination of traffic from a residential area were the sole purpose of a project, the narrative treatment would allow full articulation of the argument for the project. Fact sheets were given a flexible format so that the space devoted to different criteria could be adjusted to fit their importance to each project.
6. Narrative criteria included noise reduction, impact on residential traffic, community and ecological disruption, access to the public transportation system, modal integration, provision of alternative modes, system linkage, and economic development. An "other" category was provided to note characteristics of the project not cited elsewhere.

A sample project evaluation fact sheet is shown in Figure 1. Although many of the criteria are derived from the previous PIP, the differences proved significant. Use of narrative criteria in place of qualitative scores successfully allowed nontraditional projects equal consideration as traditional projects. Participants focused on narrative merit for several projects in adding them to the TIP; this would have been less likely under the previous -2 to +2 scale.

TREATMENT OF INFRASTRUCTURE RENEWAL PROJECTS

The most significant technical advancement of the revised evaluation process is the reworking of the treatment of infrastructure projects. The revised approach proved very effective in articulating the inherent value of infrastructure work.

Improvement in the approach came from asking, "Why are infrastructure projects valuable? What are we trying to achieve by reconstructing a bridge, rebuilding a road, or replacing a bus?" If this implicit value could be quantified, it could be fairly compared with the value derived from other projects, such as new transit services or intersection improvements. Literature in this area was hard to find and provided little insight. Intuitively, repairing or replacing a facility or service integral to the regional system is important because of the value of that facility or service to the transportation system. Bridges are not replaced because they are in poor condition; they are replaced because it is important to keep those links open. Buses are not replaced because they are 12 years old; they are replaced because it is important to continue operating a vital transit service.

As a result, the life-cycle cost savings (or the extended facility value) of an infrastructure project was defined as

$$\text{Extended facility value} = (\text{total facility value}) \times (\%\ \text{extended life})$$

where

total facility value = safety benefits + travel time savings + energy and user cost savings (from the presence of the facility), and

% extended life = (years of facility life added by project)/(normal facility life)

PROJECT TITLE ______
LOCATION ______
DESCRIPTION ______
PURPOSE ______

1993-98 PROJECT COST (Federal Share) ($M) ___
POST 1997-98 COST ___
ANNUALIZED COST ($1000/yr) ___

TRANSPORTATION SYSTEM AND USER SAVINGS
Total System and User Savings ($1000/yr) ___
Safety Benefits ($1000/yr) ___
Travel Time Savings ($1000/yr) ___
Energy and User Cost Savings ($1000/yr) ___
Life Cycle Cost Savings ($1000/yr) ___
Benefit/Cost Ratio ___

CONGESTION RELIEF
Daily Excess Vehicle Hours of Delay Saved ___
Daily Excess Vehicle Hours Saved / $ M annual (/ $M initial) ___ ( )

AIR QUALITY
Hydrocarbon Emission Reductions ___
Hydrocarbon Emission Reductions / $ M annual (/ $M initial) ___ ( )

NOISE REDUCTION:

RESIDENTIAL TRAFFIC:

COMMUNITY AND ECOLOGICAL DISRUPTION:

ACCESS TO THE PUBLIC TRANSPORTATION SYSTEM:

MODAL INTEGRATION:

PROVISION OF ALTERNATIVE MODES:

SYSTEM LINKAGE:

ECONOMIC DEVELOPMENT:

OTHER:

FIGURE 1 Sample project evaluation fact sheet.

Safety benefits, travel time savings, and energy and user cost savings attributable to the facility or service are calculated using CDTC's regional travel simulation model. Specific safety improvements are treated separately using accepted NYSDOT accident reduction factors, applied against accident experience at the site. If specific safety calculations are performed, the safety benefits derived from the calculations are used in place of the regional model's estimates of safety benefits.

The model is run once with the facility or service in place, then a second time with the facility or service removed. The difference in regional system measures between the two model runs is assumed to represent the total value of the facility or service.

For bridges, the facility is removed for purposes of running the simulation model by eliminating the bridge link entirely from the highway network. For highways, the facility is considered removed by reducing the travel speed to 8 km/hr (5 mph). This speed effectively eliminates the facility's through function while allowing the simulation model to maintain access to any traffic analysis zone loading links that might be located along the facility.

For transit service, the service is eliminated by restoring passenger travel as vehicular travel to the highways that the transit service is effectively serving. One key transit replacement project evaluated by CDTC for use of federal "highway" funds was the replacement of a private carrier's express buses along I-87. These buses remove approximately 500 vehicles from the peak direction in the peak hour of a facility that is operating at LOS E in the peak hour. The system value of this transit service is significant.

From this perspective, the value of a bridge repair project can be viewed as gaining 10 or 20 more years of safety, travel time, and energy and user cost savings—compared with allowing the bridge to close at the end of its normal life. Normal facility life was defined as the total span of years from construction to the point of closure (for a bridge), closure to all but local access traffic (for highways) or retirement (for transit vehicles), when only ordinary but not extraordinary maintenance is provided.

Normal facility life was estimated for highways using historic pavement deterioration rates derived from the pavement scoring efforts of the NYSDOT and CDTC. The NYSDOT condition ratings are on a pictorial scale of 1 to 10. The break points on the scale are based on engineering judgment (*1*). These annual deterioration rates vary with the type of facility and the starting condition. Thus, it is possible to estimate the number of years required to take a new facility to the point of being considered passable only to local traffic. This span was estimated at approximately 39 to 47 years for non-state, federal-aid highways and 29 to 42 years for state highways, depending on pavement type. State highways have a shorter projected life because of higher deterioration rates attributable to greater traffic volumes, particularly greater volumes of heavy truck traffic. Because the deterioration rates are developed from a data base of highways that excludes only those roads that have received improvements sufficient to increase the pavement score by two points or more, the rates represent natural background deterioration that assumes routine maintenance. (Routine maintenance includes all improvements that do not improve the pavement condition by more than one point, such as pothole filling and crack sealing.)

In practice, the percentage extended life was determined from tables that relate current pavement condition with percentage extended life. All repairs are assumed to restore highways to a condition of 10 and bridges to a 7. A sample table is presented in Table 1.

Similarly, the normal facility life for bridges was related to NYSDOT bridge condition ratings. The condition rating is a single number that is the weighted average of a broad cross section of elements taken from current inspection reports. The 13 element ratings, composing the broad cross section, range from a structurally insignificant curb element to a primary member element, which is perhaps the most structurally significant rating of the entire inspection report. This number is intended to represent an idea of the overall condition of a bridge (*2*). A bridge score of 2.5 on a scale of 1 to 7 was used as the approximate point at which the bridge would be closed to traffic. Bridge data have not been examined as rigorously as have pavement data to determine condition-specific deterioration rates. Table 2 relates percentage extended life to current bridge condition scores.

For transit vehicles, 12 years is the typical minimum age for replacement. Vehicles are certainly functional at higher ages than 12 years, although greater-than-average maintenance and repair can be anticipated. For transit vehicles, a span of 20 years is assumed to represent the normal life, assuming ordinary but not extraordinary maintenance over the 20-year period. Another table (not shown here) was prepared with percentage extended life related to vehicle age.

The total facility value is prorated because extending the life of a facility involves some overlap between the remaining life of the facility without repair and the service life of the improvement. Unless a repair is made at the exact time that the facility is to become nonfunctional (see Figure 2), the overlap means that a portion of the service life of the improvement is redundant with life that remained before the improvement.

At an absurd extreme, assume a bridge is built with a life expectancy of 60 years. Assume that it is rebuilt 1 year later, again with a life expectancy of 60 years. In this case, the rebuilt bridge has added only 1 year's worth of mobility function to the system, not 60 year's worth. In this case, it would be appropriate to reduce the total facility value by a factor of 59/60 in order to fairly estimate the true incremental value of the rebuilding project (see Figure 3).

Real-world projects are not as absurd, but they each involve some degree of inefficiency. Reconstructing a road in "fair" condition may provide a new life span of 40 years for a road that previously had 15 years of function left. In this case, the procedure would credit the project with only 25/40 of the total annual facility value.

APPLICATION

In the 1993–98 TIP development process, CDTC entertained 114 candidate projects for National Highway System, Surface Transportation Program and (CMAQ) funds. All were subjected to the identical screen, score, and program sequence.

TABLE 1 Percentage Extended Life By Pavement Type for Non-State Federal-Aid Roads

Condition Rating	Rigid	Overlay	Flexible
1	100	100	100
2	100	100	100
3	93	91	92
4	75	74	75
5	56	58	60
6	37	43	43
7	20	27	27
8	11	15	16
9	6	6	7
10	2	2	2

TABLE 2 Relationship Between Extended Life of a Bridge and Its Rating

Bridge Rating	% Extended Life
7	0
6	22.2
5	44.4
4	66.6
3	88.9
2.5	100.0
2.0	100.0
1.0	100.0

Project proposals that were primarily intended to address mobility issues (intersection channelization, signal coordination, new commuter transit services, demand management, highway widenings, arterial management, and expressway management) and those intended to rehabilitate or replace existing infrastructure (bridge rehabilitation or replacement and pavement reconstruction) were evaluated primarily on the basis of cost-effectiveness. Programming decisions "off the top" regarding projects whose benefits are not easily quantified were made first. Projects competing for CMAQ funds, including several transit mobility projects, were evaluated using the method presented here. Funds were sufficient to fund all CMAQ projects. Transit infrastructure projects did not compete against highway infrastructure projects, since the federal money for transit infrastructure projects was sufficient. The remaining projects (including all mobility and infrastructure renewal projects) were considered equally, on the basis of cost-effectiveness. The travel time savings, user cost savings, and accident reduction benefits anticipated from a highway widening, for example, were considered to be equivalent to the travel time, user cost, and safety benefits contained in the life-cycle cost value of infrastructure renewal projects.

Some projects contained a mix of infrastructure repair and mobility improvement. Several highway widenings were linked with replacement of deteriorated bridges, others with reconstruction of poor pavement. Benefits for these projects were defined as the sum of the life-cycle cost value of the renewal of existing facilities and the mobility value of the expanded capacity or other improvements.

The process reserved programming discretion to ensure balance: there was an expressed commitment to producing a balanced program by project type and geographic area and no intention to use the benefit/cost ratios in a deterministic fashion. However, the technical products required very little supplemental effort to produce a balanced program. Mobility and infrastructure projects from various geographic areas were intermingled in the list of projects ordered by descending benefit/cost ratio. After review, the rank order was treated by the TIP participants as intuitively reasonable and understandable and no bias for or against a certain project type was detected.

Important facilities generally produced high benefit/cost values for both mobility and renewal projects except for cases in which the needs were marginal and the improvement costs high. Projects on lower-volume facilities ranked high if costs were proportionately low; high-cost repairs or improvements on low-volume roads ranked low on the list, as expected.

As a result, the technical process for comparing infrastructure renewal with mobility improvement projects proved to be very successful. A total of 53 projects (including 3 transit projects) from the 114 candidates were added to the area's 5-year TIP by unanimous consensus of the CDTC board in March 1993. The total project cost for these projects is approximately $230 million: $130 million for project phases over the next 5 years and the rest related to phases to be completed in the following 5 years. Of the 53 projects, 15 were mobility projects (including 3 transit projects), 17 were pavement renewal projects, 6 were bridge renewal projects, 6 were combined mobility and pavement projects, 2 were combined mobility and bridge projects, and 1 was a safety project. The remaining projects included an enhancement project, a planning study, and a truck bypass intended to separate truck traffic from an historic hamlet. (These were projects programmed without primary concern for quantitative benefits.)

INDICATIONS FOR FURTHER DEVELOPMENT

Speed at Which a Road Is Effectively Closed

As presented earlier in this paper, the value of repairing a road is gauged by testing one traffic simulation scenario with the road functioning normally and a second with the road at a functional speed of 8 km/hr (5 mph). The difference between the two scenarios is the effect of keeping the road open. The speed 8 km/hr was chosen to simulate two conditions on the road: effective closure to through traffic and use by local traffic at a speed likely to occur with a badly deteriorated road.

Although using a speed of 8 km/hr in the model will keep through traffic off the road, it may not be the optimum speed for the analysis. For certain facilities, such as an Interstate highway (as well as some other 55-mph roads), even a 25-km/hr (15-mph) free-flow speed might effectively eliminate through traffic. Therefore, it may be possible that using a higher speed in the analysis could effectively represent closure of the road to through traffic without requiring the assumption of unrealistically low local travel speeds. Use of a refined speed estimate would lead to a refined estimate of the mobility function of a facility proposed for repair.

Pavement and Bridge Condition Thresholds

The process assumes that a highway has reached the end of its service life when the pavement condition reaches a 3 on the scale

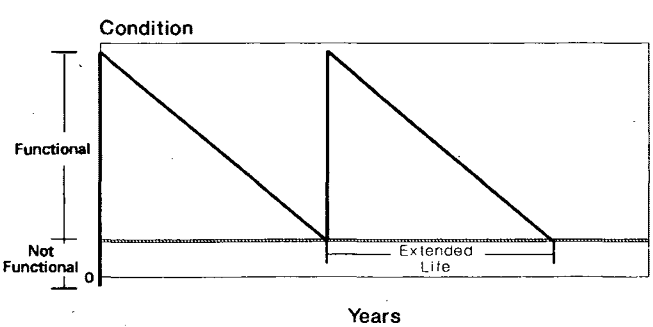

FIGURE 2 Repair at end of service life (assumes linear deterioration).

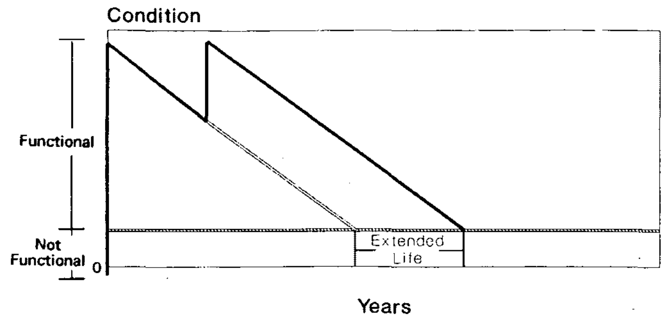

FIGURE 3 Repair early in service life (assumes linear deterioration).

of 1 to 10. A bridge is assumed to reach the end of its service life when the bridge condition reaches 2.5 on a scale of 1 to 7. The percentage extended life is related to these thresholds.

These conditions may reasonably represent thresholds at which further deterioration is not easily predicted. However, they may not truly represent the end of the facility's service life. Many more years may expire between the time a facility reaches the threshold and the time at which the facility is closed or passable only by local traffic.

Further consideration needs to be given to the thresholds selected. Choosing lower thresholds, such as a pavement condition of 1 would greatly increase the theoretical service life of a facility and lower the percent extended life of most improvements, resulting in lower benefit/cost ratios for infrastructure projects. Since deterioration rates are not reliable for roads in such poor condition, it would be difficult to determine the service life of a road below the current threshold.

Difference Between Design Life and Percentage Extended Life

Values for the life of a facility are used both in annualizing the cost of construction and in calculating the benefits of repairing it. In calculating the benefits of repairing a road, the service life is the number of years that it takes to deteriorate from a condition 10 to a condition 3, which could be from 29 to 47 years, depending on the type of road. However, when calculating the annualized cost of the road, the length of the expected life is derived from standard values produced by NYSDOT ranging from 10 to 30 years, depending on the type of repair.

The apparent conflict between design life (for annualizing costs) and service life (for calculating benefits) needs further thought. It would appear desirable to use identical values for the design life of the project and the extended life due to the project. However, the NYSDOT table lists the expected life for more than a dozen different facilities, not just pavement. It would not be desirable to ruin any internal consistency in these numbers; otherwise, the annualized costs of some types of projects might be misrepresented in relation to the others and have an unfair advantage. Possibly the reliability of both sets of numbers warrants examination.

Also, further study is needed to determine if the expected life of a road should be assumed to be the same after a resurfacing as it is after a reconstruction, as they currently are treated in the benefits calculation. Intuitively it would appear that a resurfaced road might deteriorate faster than a reconstructed road, but CDTC has no data to support this.

Calculation of Emissions and XVHD Savings

For projects in which mobility improvements are made, emissions reductions and XVHD savings are calculated relative to conditions in the reference year 2000. They are displayed on the project fact sheet for information purposes but do not contribute to the benefit/cost ratio. In CDTC's 1993–98 TIP process, the contribution of infrastructure renewal projects toward extending the life of facilities' emissions and XVHD benefits was not calculated.

This is a significant item. The absence of emissions and XVHD values of infrastructure renewal projects may not significantly affect programming decisions. However, articulation of these benefits could allow quantitative representation of the importance of infrastructure repair in the region's congestion management program and air quality implementation program. Consideration will be given to articulating these benefits in future applications.

Conflict Between Reference Year and Benefit Year

The analytical process used in CDTC's 1993–98 TIP development used traffic conditions in the reference year 2000 as a base. However, the benefits attributed to an infrastructure repair project are long term, most likely not seen in the reference year. For example, if a road would have lasted another 15 years (in very poor condition) but is repaired now to a life expectancy of 40 years, then the equivalent of 25 years of benefits are attributed to the project, but they represent improved conditions 15 and more years into the future. This indicates that travel time, user cost, accident reduction, emissions benefits, and congestion mitigation (XVHD) benefits attributed to infrastructure renewal projects should be represented relative to traffic volumes and emissions rates that pertain to an appropriate future year rather than the single reference year.

CDTC will investigate the feasibility of such a refinement to the process. The investigation should include consideration of net present value, discount rates, and use of traffic volumes and emissions rates from the first year of benefit. Its incremental contribution to the decision-making process may be negligible and may not justify the additional effort.

Transit Benefits

The question here is this: What are the benefits of replacement of an inner-city bus when the purpose of the bus service is related more to transportation access than it is to congestion relief or travel time savings? CDTC has applied the approach documented in this paper to a transit bus replacement project, yet that particular project related to replacing buses used in express service on a congested expressway. Travel time, user cost, and accident reduction benefits attributable to the service provided a high benefit/cost ratio for that project.

However, much of the urban transit system is not designed with congestion relief as its primary objective. Further investigation is required to articulate that portion of the value of transit service that is related either to provision of transportation to people without access to an automobile or to other purposes. The benefits of transit for these purposes could be economical or social in nature. The value of these benefits must be well articulated before attempting wholesale application of CDTC's approach to comparisons between highway repair and transit bus replacement. Another option would be to include providing transit to the carless as a qualitative benefit.

Treatment of Infrastructure Renewal Projects on Low-Volume Facilities

The procedure used by CDTC effectively ranks projects by importance of the facility and cost of the work. Use of the traffic simulation model provides for greater benefits to be attributed to the reconstruction of a bridge carrying 15,000 vehicles a day than to the reconstruction of a bridge carrying 5,000 vehicles a day. Because the model reflects detour penalties, the procedure also effectively attributes greater benefits to the reconstruction of a bridge carrying 15,000 vehicles a day that has no nearby alternative river crossings than to the reconstruction of a bridge with the same volume that does have nearby alternatives.

However, the procedure will invariably produce a low benefit/cost ratio for expensive reconstruction work on low-volume facilities. In CDTC's 1993–98 TIP process, this did not constitute a major concern for some projects. Lack of priority in the TIP process merely pointed the project sponsor away from federal sources and toward the use of local funds for a more modest project scope.

For other projects, the low priority led to considerable discussion. Particularly for rural highways, the low benefit/cost ratio attributable to major reconstruction and geometric upgrades has led to the consideration of revised design standards for low-volume state and county roads. The benefit/cost calculations have called into question the appropriateness of rural project designs at $1 million/lane-mi for locations with volumes of fewer than 1,500 vehicles a day and limited accident experience. A pilot project on a Rensselaer County highway has been identified by CDTC and NYSDOT to explore new design treatments.

In addition, further thought is required regarding whether infrastructure renewal projects on some low-volume, high-functional-class facilities deserve special consideration. An argument can be made that a rural principal arterial carrying 1,500 vehicles per day should be held to a less-demanding benefit/cost standard than that for an urban minor arterial with 10 times the volume. The argument assumes that there is a qualitative difference between the requirements for facility design and condition of one functional class and another. The current CDTC procedure treats all facilities alike, considering rural and urban travel times as equivalent, rural and urban user costs as equivalent, and rural and urban accident cost reductions as equivalent. Further consideration of this issue is warranted.

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Publication of this paper sponsored by Committee on Transportation Programming, Planning, and Systems Evaluation.

Comparison of Two Sign Inventory Data Collection Techniques for Geographic Information Systems

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Global positioning system (GPS) units are fast becoming powerful tools for collecting data for use with geographic information systems (GIS). The data collection process for a sign inventory conducted by Lee Engineering in Washington, D.C., is described. In the conduct of the sign inventory project, GPS was used where possible. However, the GPS was determined not to be the best method of data collection in all instances. In sections of the study area near the downtown core, taller buildings effectively blocked satellite signals. In these areas GPS collection was set aside for a more manual method of locating sign positions using a measuring wheel. Data collection efforts for the sign inventory using GPS typically required more data collection time; however, the data were quickly and easily exported to a compatible GIS format. Conversely, data collection using manual methods minimized data collection time but required much more effort to enter into the GIS data base. The collection of data using both GPS techniques and manual techniques allows for comparison of both techniques to determine which was more cost-effective.

Global positioning system (GPS) units are fast becoming powerful tools for collecting data for use with geographic information systems (GIS). This type of equipment was recently used in Washington, D.C., to collect sign inventory data for input into a GIS for the National Park Service. However, in areas where taller buildings masked the skyline, creating an "urban canyon" effect, the GPS units were abandoned for more manual methods of inventory data collection. This paper documents the data collection process using the GPS equipment and manual techniques and provides a comparison of the time required to collect, process, and input the sign inventory data collected by each process into the GIS.

STUDY AREA

The sign inventory activities were conducted as part of larger data collection efforts being conducted within two study areas of Washington, D.C. These areas, the White House and Memorial Core study areas, are shown in Figure 1.

The White House study area is bounded by 17th Street to the west, H Street to the north, 15th Street to the east, and Constitution Avenue to the south. This area is basically composed of two land uses. The southern portion, containing the Ellipse, is primarily open park land. The remainder of the study area is more oriented toward the central business district (CBD), with large multistory buildings lining the roadways.

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The Memorial Core study area is bounded by Ohio Drive to the south and west, Constitution Avenue to the north, and 14th Street to the east. This area is primarily open park land and contains the East and West Potomac Parks, the Jefferson and Lincoln Memorials, and the Washington Monument.

The sign inventory activities conducted as part of this project included collecting traffic and pedestrian signage information on all roadways within and one block adjacent to these study areas.

INVENTORY PREPARATION

To conduct the sign inventory, a four-step process was followed. The first step of the process involved project planning or inventory preparation. During this step, several key tasks for the data collection process were conducted. These tasks included

- Develop preliminary list of signs,
- Identify attributes to be collected,
- Develop a data dictionary (data collection program), and
- Conduct mission planning.

Before conducting the sign inventory, an effort was made to identify the types of signs that would be encountered in the field during data collection activities. This was done to obtain a better understanding of the numbers, types, and conditions of signs that would be included in the inventory. To do this, personnel spent several hours in the study areas photographing and identifying the signs that would be encountered. Each unique sign type was then assigned a unique five-digit code for identification. In addition, a computer-aided design (CAD) drawing was made of each sign that included the five-digit code.

The second step of the inventory planning process was the identification of the attributes, or characteristics of the signs, to be collected during the inventory efforts. This task was conducted with much input from the National Park Service. As a result of this task, the following attributes were identified to be collected as part of the inventory efforts:

- Number of signs on the assembly;
- Sign number: from 1 (top sign on assembly) to the total number of signs on the assembly;
- Direction the sign is facing: north, east, south, west, northwest, northeast, southeast, or southwest;
- Mounting height: in feet;
- Sign code: a five-digit code corresponding to a drawing of the sign;

- Sign size: width and height in inches; and
- Sign condition: a subjective rating of good, fair, or poor.

Once the attributes were identified for data collection, a data collection program was developed for use with the GPS equipment. This program allows the user to enter the sign attribute information directly into a hand-held microcomputer that composes part of the GPS unit. This is done through the computer's keypad or a bar code reader (or both). The program was developed using software provided with the GPS unit and was downloaded into the GPS units used to conduct the inventory.

The last task conducted involved identifying satellite conditions (number of satellites and satellite geometry) in the area of the inventory before actual data collection. This process is referred to as "mission planning." To conduct this process, a current almanac file (a file containing the orbital information of all available GPS satellites) was collected using a GPS unit. This almanac file was used to anticipate satellite paths and determine the time periods that good positional data could be obtained in the study areas. This was done using the software provided with the GPS unit.

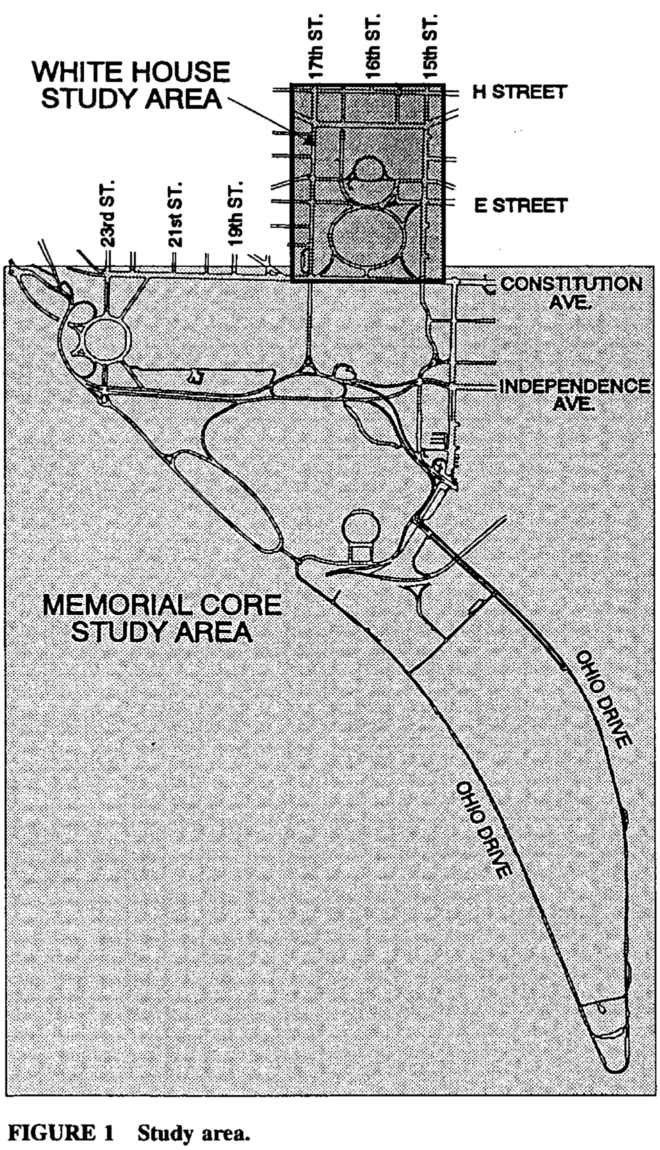

FIGURE 1 Study area.

FIELD DATA COLLECTION

The sign inventory data collection was conducted during four data collection trips to Washington between October 1992 and February 1993. At the onset of the project it was anticipated that the GPS units would be used to conduct the entire inventory. However, on the basis of problems encountered during data collection efforts in October and December 1992, it was decided that the GPS equipment be abandoned for a more traditional method of data collection in parts of the study area. These problems encountered included leaf coverage from trees and tall buildings, which blocked out portions of the skyline and often resulted in insufficient satellite coverage, and poor satellite geometry and possible multipathing as a result of radio equipment in the White House compound.

When the data collection efforts began in October 1992, the trees within the study areas were heavily covered with leaves. During the inventory of signs adjacent to the trees, locks on one or more of the satellites being tracked were frequently "lost" (i.e., the satellite signal was not strong enough to detect or use), often resulting in an insufficient number of satellites being tracked or unacceptable satellite geometry. This problem was fairly easily avoided, however, by using two methods. First, data collection was postponed until December, when the leaves had fallen off most of the trees. Second, a taller range pole (12-ft) was used for the GPS antennae. During the October data collection efforts, an 8-ft antenna was used.

Tall buildings in the area provided a larger problem. Attempts to inventory signs in the downtown CBD portions of the study area were unsuccessful. In these areas where buildings blocked much of the skyline, it was difficult to impossible to obtain signals from enough satellites. In addition, when enough satellites were available, the geometry of the satellites was often unusable. In these areas the GPS equipment was set aside for more manual methods of data collection. The process used for both methods of data collection are discussed in the following.

GPS Data Collection Process

The GPS unit used to collect the inventory data consisted of a receiver, an antennae, a hand-held microcomputer, and an optional bar code reader. The microcomputer controls the receiver and is used to input and store the attribute data. The equipment used provides location accuracies of 2 to 5 m when used with differential correction. Data collection was conducted with the GPS equipment operating in the manual three-dimensional mode. This mode requires a constellation of four satellites with adequate geometry for positioning. This mode also provides the greatest accuracy for data collection and reduces postprocessing time.

To collect the inventory data, the GPS software was started, a file was created to store the field-collected data, and the data dictionary for the sign inventory was selected. The GPS antennae was placed by a sign and the "feature on" key was pressed. This causes the receiver to begin collecting position data, which were collected at a rate of one position per second.

As the position data were being recorded, the data collector was prompted to enter the sign attribute information. When this had all been entered, the data collector pressed the "feature off" key, which causes the receiver to stop collecting position data. The data collector then moved on to the next sign. When a sign was encountered that had not been assigned a sign code, it was assigned a code, sketched, and photographed. A CAD drawing was later made of the sign.

To obtain the best possible accuracy, a minimum of 180 positions were obtained at each signpost location as recommended in the GPS documentation. At locations with more than one sign per post, enough positions were collected for each individual sign so that the sum of all positions collected at the signpost location exceeded the 180 threshold. For example, if the post contained three signs, the data collector might obtain 60 positions for each of the three signs for a total of 180 positions.

At the end of each day's data collection, the data collection file was closed and the data downloaded to a personal computer for postprocessing. Data were collected for 2,772 signs (77 percent) using the GPS equipment.

Manual Data Collection Process

During the manual data collection activities, the sign location was determined using a measuring wheel, and the sign attributes and locational information were noted on hard copy (paper) or audiotape. This information was later postprocessed and entered into electronic form for entry in the GIS package. When a sign was encountered that had not been assigned a code, it was assigned a code, sketched, and photographed, and a CAD drawing was made of it later.

To determine the location of each sign, two measurements were required: the offset from the face of curb and the distance from the face of curb of an intersecting street. Using this information and a digitized map of the roadway network, the coordinates of the sign were determined. Data were collected for 830 signs (23 percent) using the manual method.

Postprocessing GPS Data

After data collection, the data were postprocessed to manipulate them into a form compatible with the GIS packages being used. The first step in postprocessing the GPS data was to differentially correct the rover files (field data collection files). During the data collection process, the National Park Service set up a base station to collect base station data. Using the GPS software, the base station files were referenced and used to differentially correct each day's data. This process eliminates many of the errors inherent in GPS, primarily selective availability, which accounts for the largest portion of all errors.

After differential correction, the attribute information was exported into an ASCII file format compatible with the GIS package used by the National Park Service and the GIS package used by Lee Engineering. This also was done using software provided with the GPS unit.

Processing the position data proved to be a more complicated task than expected, as most of the information collected was for multiple signs on one post. The GPS software, by default, determines the location of a feature by averaging all of the positions collected for the feature, or in this case each sign. However, the location of each signpost was needed. Fortunately, the locations could be found by forcing the software to average the data over time breaks, allowing the position data collected for all signs on a common post to be grouped together and then averaged to obtain the signpost location.

These signpost locations were then exported to an ASCII file format compatible with the GIS packages. Because the number of locations (one for each signpost) was now less than the number of signs, a utility program was developed that assessed the attribute and location data and assigned signpost coordinates to each sign. The new location data were then exported in a format compatible with the GIS packages and the sign inventory was imported into the GIS.

Postprocessing Manually Collected Data

The manually collected data also required postprocessing. The first step in postprocessing the manually collected data was to load a street coverage file that had been previously digitized from aerial maps in the NAD27-CONUS geodetic datum into a CAD program. A street coverage file had been provided by the National Park Service in a .DXF format.

Sign locations were then determined using an offset command and the curb faces digitized from aerial photographs. To enter the attribute information, a ''block'' was created that prompted the user to enter the attribute information collected during the data collection activities. Once all of the signs had been located and the sign attribute information entered into blocks, the data were exported to an ASCII file containing the *x*- and *y*-coordinates of the sign as well as all attribute information. This file was then split into two files, a point file (containing coordinate information) and an attribute file, compatible with the GIS packages. The data were then imported into the GIS.

COMPARISON OF DATA COLLECTION TECHNIQUES

After the data collection activities, an effort was made to assess the time required to collect and process the data for entry into the GIS packages for each of the collection methods. This was accomplished using time sheet information to determine the total number of man minutes required on a per-sign basis to accomplish each task. The results of the comparison are given in Table 1.

As indicated in Table 1, data collected with the GPS equipment were the most cost-effective, requiring approximately 4.6 man-min per sign for collection and postprocessing. The manually collected signs required approximately 5.5 man-min per sign. The signs collected using the GPS equipment require a longer data collection time (4.0 versus 2.6 man-min) but were postprocessed with much less time.

TABLE 1 Comparison of Data Collection Techniques (min/sign)

Task	GPS Collected (2722 Signs)	Manually Collected (830 Signs)
Field Inventory	4.0	2.6
Post-Processing	0.6	2.9
Total	4.6	5.5

The time difference in the data collection (field inventory task) is explained by the fact that 180 positions were collected at each sign location in order to obtain the best accuracy of the GPS equipment. Collecting positions at a rate of one position per second, this required a minimum of 3 min at each sign location. Locations with more than three signs on a post, typically required 3 or more minutes to enter all the attribute data for the signs. However, at locations with one or two signs per post, the attribute data were entered relatively quickly (40 to 60 sec per sign), but the data collector was required to remain at the location for a full 3 min to collect all of the position data. Using the manual method, the data collector moved on to the next sign as soon as the attributes were noted.

Postprocessing, however, was quite different. As the GPS collected data were already in electronic form, data reduction occurred quite rapidly. In part, this was because the data were reduced as a group (one file containing a day's data collection). However, the manually collected data had to be reduced one sign at a time, which resulted in a longer postprocessing time.

The resources and cost associated with each of the two methods were also compared. Many of the data collected with the GPS units were collected by one or two individuals, an engineer and a technician, when two GPS units were available for use. The data collected manually were collected by one or two engineers, although a technician-level person could have been used. In short, both methods used the same personnel resources. However, the equipment requirements were very different. The GPS units used for the data collection cost approximately $15,000 each, whereas the equipment used for the manual collection cost less than a couple of hundred dollars.

DEVELOPMENT OF GIS PROGRAM

The last step in the collection process was the development of a program to display the collected data in the GIS. The program was developed with several goals in mind, including

- Being easy to use (menu-driven),
- Providing the capability to display the locations of all signs or a select type of sign,
- Differentiating sign conditions using colors (i.e., green for good, blue for fair, and red for poor),
- Displaying the attribute information for any selected sign,
- Displaying an image of the sign, and
- Providing panning and zooming capabilities.

The result of the programming effort was the development of a program that met the goals listed. The program allows the user to show the locations of all signs on a roadway coverage of the total study area or any portion of the study area. In addition, the location of a select sign type (stop signs for instance) may be shown and the sign condition may be illustrated in color. To see sign specific information, a second-level menu was developed that allows the user to select a sign or group of signs and view the attribute information of each. The CAD drawing files for each sign were exported into a Raster format so that an image of each sign could be viewed within the GIS program.

CONCLUSION

Several conclusions can be drawn from this study. First, from a time standpoint the GPS data collection activities proved to be more cost-effective than the manual data collection activities, resulting in approximately 1 man-min less effort required per sign to inventory and postprocess the data. This is attributed to the fact that postprocessing the data is a much quicker task when the data are collected with the GPS equipment because the data are treated as a group and not processed separately for each individual sign. Additionally, both methods require similar staffing levels and requirements.

However, equipment costs are extremely different. The GPS units are very expensive pieces of equipment costing thousands of dollars, whereas the wheel and other equipment used for the manual data collection cost only a few hundred dollars.

ACKNOWLEDGMENTS

This paper was prepared based on the results of the sign inventory activities undertaken as part of the Memorial Core Area Transportation Study/White House Area Traffic Data and Analysis project. The inventory was conducted by Lee Engineering, Inc., Phoenix, under subcontract to BRW, Inc., Denver, for the National Park Service, U.S. Department of Interior.

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Publication of this paper sponsored by Committee on Transportation Data and Information Systems.

Application of Geographic Information Systems in Planning Transit Services for People with Disabilities

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The scarcity of data on the travel patterns and needs of people with disabilities makes the planning of public transit system to meet the Americans with Disabilities Act and other requirements a difficult process. This means that approximate methods have to be employed under very broad assumptions to estimate demand, select routes, and schedule services. Even the common approximations such as catchment area method can be cumbersome when route density is high and service area is large. The application of a geographic information system (GIS) to perform the necessary computations is described. It is shown that information such as block group population and percentages of people with disabilities, which is available from census records, and general travel characteristics of people with disabilities can be combined to arrive at reasonable estimates of demand for transit services. The use of the GIS for scheduling demand-responsive services where fixed-route service are unavailable is also demonstrated.

The area within a specific walking distance or travel time of bus stops is usually considered the catchment area or transit service area for purposes of estimating passenger demand. The demand is estimated as a function of the population within these service areas. This estimation process becomes increasingly complex as the length of the route, the number of stops, and catchment area population varies. When the population is composed of special groups such as people with disabilities, there is the added problem of dealing with very diverse needs.

Providers of on-call (demand-responsive) transit services for people with disabilities also face difficulties in scheduling and routing vehicles for pick-up and drop-off. If those functions can be optimized resources, they can be better utilized and the cost of operation can be lowered. Proper scheduling has also shown to enhance user perception of transit and thereby contribute to increased ridership.

The ability to easily estimate the expected number of users with disabilities in a transit service area can save transit planners and providers a great deal of time, particularly when evaluating alternatives route or planning new services. A simplified technique to estimate fleet size needed for providing on-call services and developing optimum schedules for existing and alternative services can also help the planners.

Geographic information systems (GIS) have the potential to become an ultimate time- and cost-saving tool of transit planners. Relevant information and data such as size of population with disabilities, origin and destination of trips, days and hours that trips are made, and so on can be incorporated into or form a GIS data base for corridor and transit service area analysis. Spatial analysis tools available in GIS can then be used to perform service area computations, scheduling, and routing.

This paper is based on a study that was undertaken to examine the pros and cons of using GIS for estimating demand for transit services by people with disabilities and scheduling demand-responsive transit vehicles. TransCAD Version 2.1 GIS package was chosen for this study. It is important to note that the focus and purpose of this study was neither to evaluate the available GIS software packages nor to indicate any preference for one software over the others. The GIS package was used to assess the ease with which computations can be performed and the challenges facing users of GIS when estimating demand for public transit.

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DATA BASE

Information for building the data base came from the Cache County 1990 Final Census Version of Topologically Integrated and Geographic Encoding and Referencing files (TIGER files, tgr49005.f41) and data from a questionnaire survey conducted as part of another study. First, the TIGER files were imported into TransCAD using its TCBuild program. County, state, census tracts, census blocks, block groups, intersections, and roads (including highways and streets) information was included in these files. Then, the 1990 Census data for the block groups were imported into the block group layer of this data base. These data included total population and disabled population by block group.

From this information, the following three data bases were created:

- Line data base (consisting of nodes and links),
- Area data base (consisting of census blocks, block groups, census tracts, county and state layers), and
- Point data base (with only one layer and nodes).

Line Data Base

The line data base consists of a layer of nodes and a layer of links. Links represent road segments with nodes on either side, and nodes represent intersections and sometimes mid-block points at the end of street segments. TIGER files were imported into the software using TIGER translate procedure in the TCBuild program. TIGER files contain information about road segments, and pipeline, rail road, landmark, and other topographical features. Road segment information was selected for the purpose of this study, and an ASCII file was created with that information. From the ASCII file, a line data base was built using the Build Data Base procedure in TCBuild. The data base stores all nodes and link data with respect to specific identification numbers assigned to them according to their longitude and latitude in space. The node layer consists of identification numbers (ID) and longitude and latitude columns. The links layer contains ID, longitude, latitude, name of the street segment, length of that segment, and an additional suffix to identify that segment. Sufficient empty fields were created while building the data base for further data manipulation. The line data base finally showed the road network throughout the county. Any calculations with respect to length can be performed with this data base. Figure 1 illustrates roads in the city of Logan and Cache County, Utah.

Area Data Base

In the area data base, the census blocks in the study area were aggregated into 55 block groups, and these 55 block groups were further aggregated into 18 census tracts. All these layers (census blocks, block groups, and so on) contain the land area of each division. The area data base was also built in the same way as the line data base. Figures 2 and 3 show the total block group population for Cache County and the city of Logan, respectively.

Point Data Base

The point data base contains information about points (e.g., major generators and attractors) such as addresses and coordinates. To build the point data base, an ASCII file with a few known spatial coordinates was created. These coordinates were drawn from the node layer of the line data base. Using the Build Data Base menu in TCBuild, the point data base was built for those points in the ASCII file. The ASCII file needs the ID number and longitude and latitude information in either fixed or comma-delimited format. The format of the input data and the columns in which each identifiable data is located in the input file has to be given using the Edit option before building the data base. More points can be added afterward in the point data base using the Geography Add procedure in the TransCAD program.

Representation of Origins and Destinations

The trip origins and destinations of the people with disabilities surveyed during a previous study were input to a point data base. These points were represented by overlaying the labeled line data base on the point data base. This was done by simply using the same application file for both the data bases and making all the layers active layers. Figure 4 illustrates the primary origins and destinations of people with disabilities in Logan.

Representation of Transit Routes

Separate data bases were built for each direction of the six fixed routes operated by the Logan Transit District (LTD). To do this,

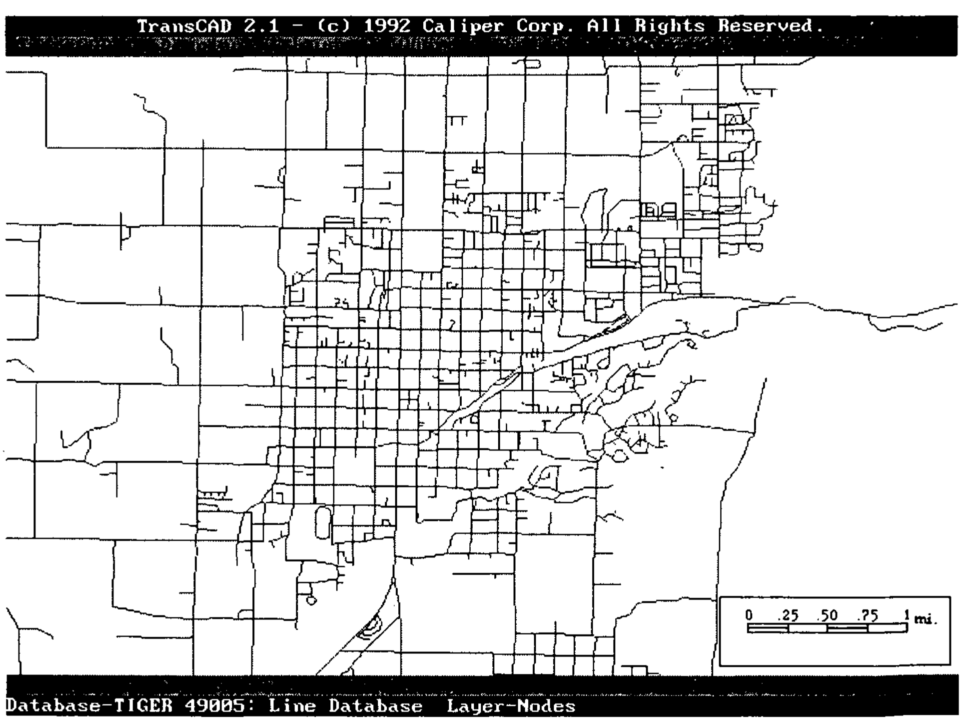

FIGURE 1 Logan city road network.

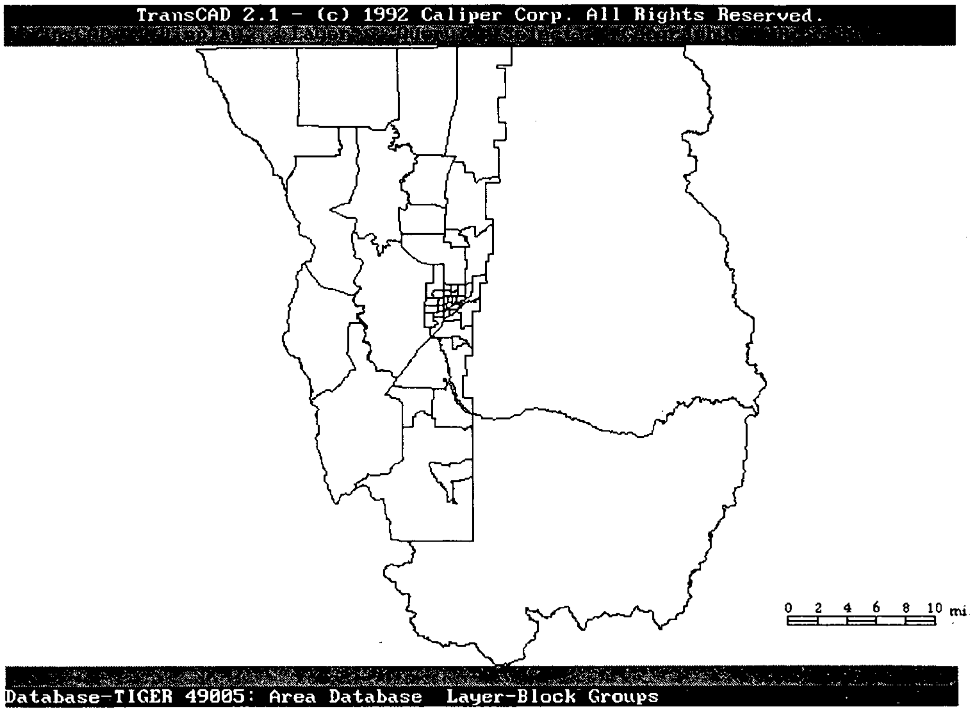

FIGURE 2 Cache County block groups.

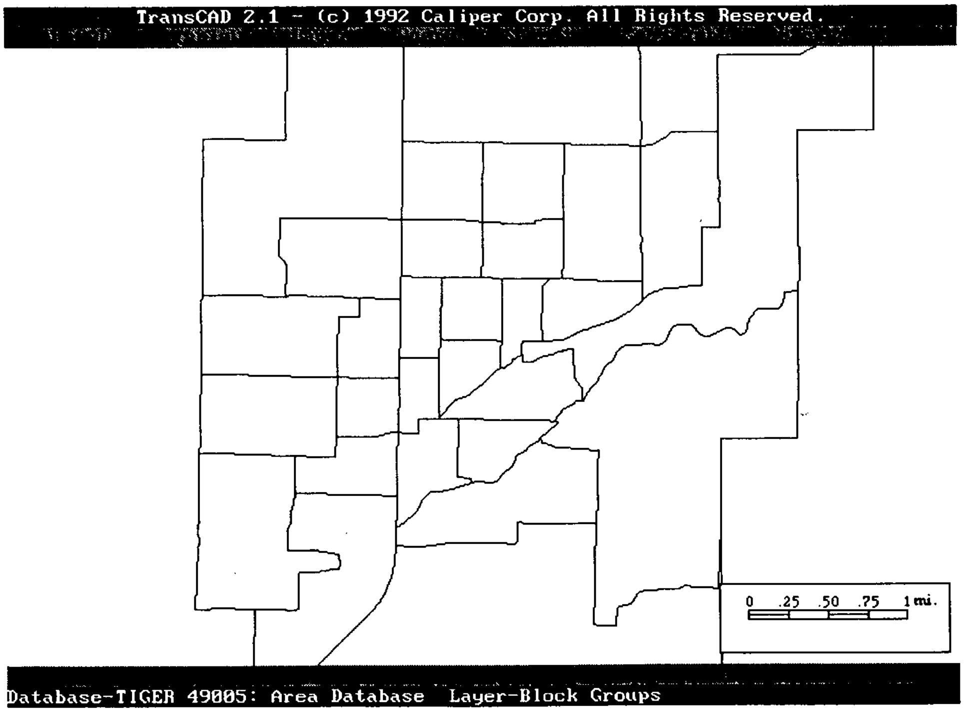

FIGURE 3 Logan city road block groups.

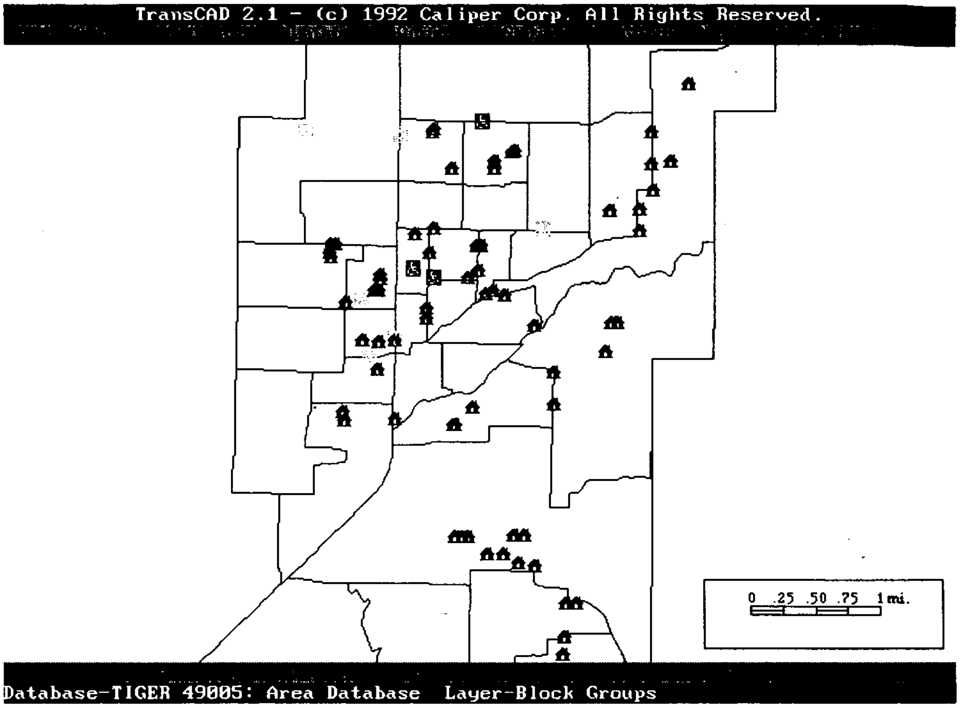

FIGURE 4 Origins and destinations of people with disabilities in Logan city.

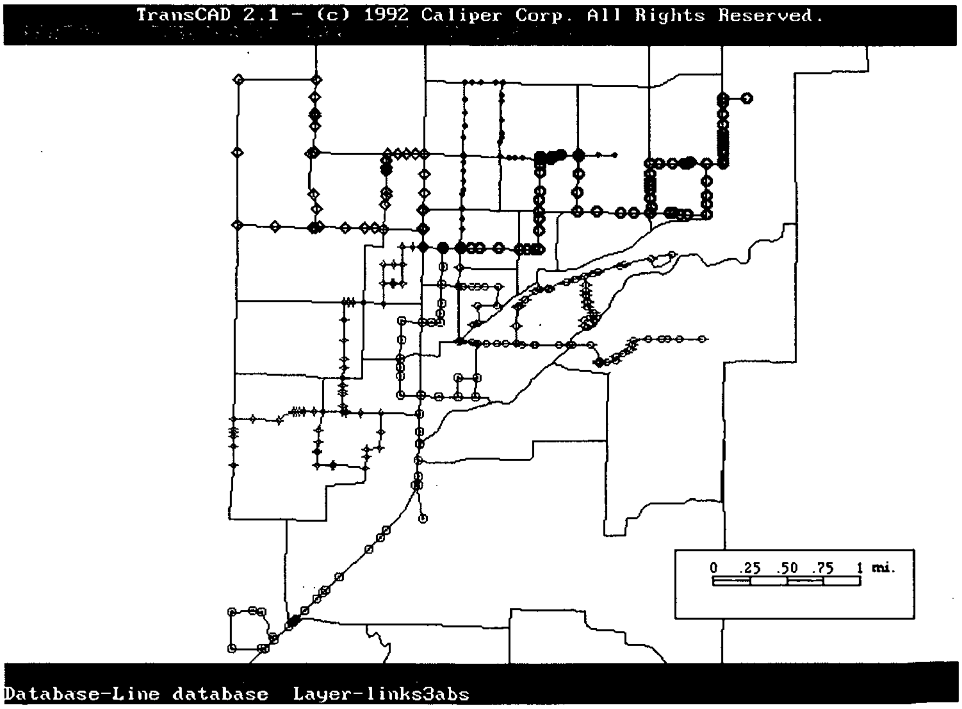

FIGURE 5 LTD transit routes in Logan city.

first the road layer was chosen as the current layer in TransCAD. Then the Select Several by Pointing option was used to select the streets that make up the transit route. The second step was to use the TCBuild program to export the selected links as an ASCII file and then use this file as a source to build a data base using TCBuild. This process was performed for each transit route separately. The LTD routes in Logan are shown in Figure 5.

Definition of Demand

Two methods were used to estimate demand. But both methods are based on the assumption that demand is directly proportional to the number of people with disabilities (population) in the catchment area. Thus, first the service area had to be defined and then the population in the catchment area had to be estimated.

The catchment area for a given transit route has traditionally been defined as the area within a reasonable walking distance from the route or stop/terminals. A quarter mile, or approximately 400 m, has been considered in the past to be a reasonable walking distance (*1,2*).

In densely developed areas, when stop spacings are approximately 0.5 mi (800 m) or less, the catchment area can be considered to be 0.5-mi-wide corridor along the route. If stop spacings are larger, it has been suggested that a circular area with an approximately 400-m radius around each stop on the route (*3*) or various other forms and shapes of catchment areas be used.

In this case, it was decided to use the rectangular catchment area approach to estimate demand and compare it with another approach where demand is assumed to be proportional to the relative length of the transit route. With the latter approach, the population is assumed to be uniformly distributed along each road segment in an area; with the former approach, it is assumed to be distributed uniformly in the entire area.

Estimation of Population

During the course of a study in Cache County (*4*), local service agencies had expressed concerns that the census data understated the number of people with disabilities in their service areas. These agencies have produced estimates considerably higher than the census. This discrepancy prompted a search for a valid estimate of people with disabilities in the study area.

The population of people with disabilities is most easily estimated as a proportion of the total population. In a previous study (*4*), it was estimated that the average percentage of people with disability in the study area is approximately 8 percent. Thus, in the present case, estimates of population in each block group were first obtained a follows:

$$p_i = 0.08P_i$$

where p_i is the population of people with disabilities in block group i and P_i is the total population in block group i.

This approach has a shortcoming in that even if there are no people with disabilities living in a particular block group, 8 percent of the total population is assumed to have disabilities. To circumvent this problem, it was decided to use population figures given in the census data with an adjustment to account for the nonrepresentation of the younger population (under 16 years). The population was estimated in this case as

$$q_i = 2Q_i$$

where q_i is the population of people with disabilities in block group i and Q_i is the census estimate of people with disabilities in block group i.

The multiplier (2) is the ratio of the Cache Valley Study (*4*) estimate to the census estimate of the percentage of people with disabilities.

Estimation of Demand

Area Method

As described earlier, the demand under this method is assumed to be proportional to the ratio of the catchment area to total area in a given block group.

$$D = \sum_{\text{all}\,i} D_i = \sum p_i \text{ (or } q_i) \left(\frac{a_i}{A_i}\right) r_i$$

where

- D_i = total demand for transit in block group i,
- a_i = catchment area in block group i,
- A_i = total area of block group i, and
- r_i = probability that a person with a disability in block group i uses transit.

Road Segment (Linear) Method

The demand is assumed to be proportional to the length of the road segments in the catchment area to the total length of all roads in the block group.

$$D = \sum_{\text{all}\,i} D_i = \sum p_i \text{ (or } q_i) \left(\frac{l_i}{L_i}\right) r_i$$

where l_i is the length of road segments in catchment area and in block group i and L_i is the total length of all roads in block group i.

Estimation of r_i

The probability or likelihood (r_i) of a person's using transit in block group i depends on the composition of the people with disabilities in that block group. For instance, the Cache Valley study showed that people with mobility-related disabilities are more likely to use transit than those with hearing or visual impairments. Thus, r_i is defined as

$$r_i = \sum_{\text{all}\,j} p\left(\frac{t}{d_j}\right) \cdot p_{d_j}$$

where $p(t/d_j)$ is the probability of a person with disability using transit given that the person has type j disability, and p_{d_j} is the proportion of people with type j disability. $p(t/d_j)$ is available in some sources (*4*) where the population of people with disabilities has been identified and their transit use patterns have been examined.

TABLE 1 Demand Estimations

Transit Route	Area Method		Road Segment Method	
population	(p_j)	(q_j)	(p_j)	(q_j)
1AB North	44	37	44	36
1AB South	43	70	39	61
2AB East	70	51	59	37
2AB West	34	41	32	34
3AB East	51	53	52	50
3AB West	40	61	45	70
All Routes	171	179	208	226

Application of Demand Estimation Procedures

To illustrate the application of the procedures described, the demand for six fixed transit routes of the LTD were estimated separately and compared with one another.

The expected demand is given in Table 1 and based on two population estimates (p_i and q_i) for the block groups discussed earlier. In both cases, a fixed r_i of 8.4 percent, which is the estimated average percentage of person with disabilities using transit in Logan, was used to arrive at the demand estimates.

It can be seen that the method of estimating population does not produce significantly different results. However, the road segment method estimate of demand is approximately 24 percent higher than the area method.

TransCAD Procedure Summary

Area Method

To estimate the demand using the area method, a 0.5-mi buffer was created around each LTD transit route. To do this, the Query Buffer option in TransCAD was used. This option enables the user to select one or more segments, or the entire link layer. If several segments are to be buffered, the links must be selected before buffering using the Select option. The Buffer option will ask for the desired buffer width and the area layer to be buffered (in this case the block group layer). As soon as these two parameters are input, the results appear in a pop-up window, which can be printed. TransCAD Version 2.1 does not have the capability to save the results and the buffered area into a data base.

If there is the need to inspect, for example, an alternative transit route or an extension of a route for the increased coverage of people with disabilities, the link layer can be used to modify or create another layer or select desired segments for buffering. However, the buffer zones can overlap and result in double counting when the transit routes are spaced at less than the desired buffer width. In such cases, overlapping areas can be treated independently by creating a layer containing only the routes or the links that have overlapping service. If a portion of the block group area is inaccessible to the transit route because of a natural or manmade barrier or any other reasons, the buffering operation has no way of finding it or disregarding that portion in the analysis. This is a shortcoming of the area method, and the only way to overcome it is to calculate these areas manually.

Street Segment Method

As mentioned previously, the street segment ratio method uses the ratio of the street segments of a block group in the analysis area to the total block group street length to estimate the population in the service area. To calculate the total street and road lengths in a block group, Data Editor Column Aggregation was used. Then the density of the people with disabilities along streets was

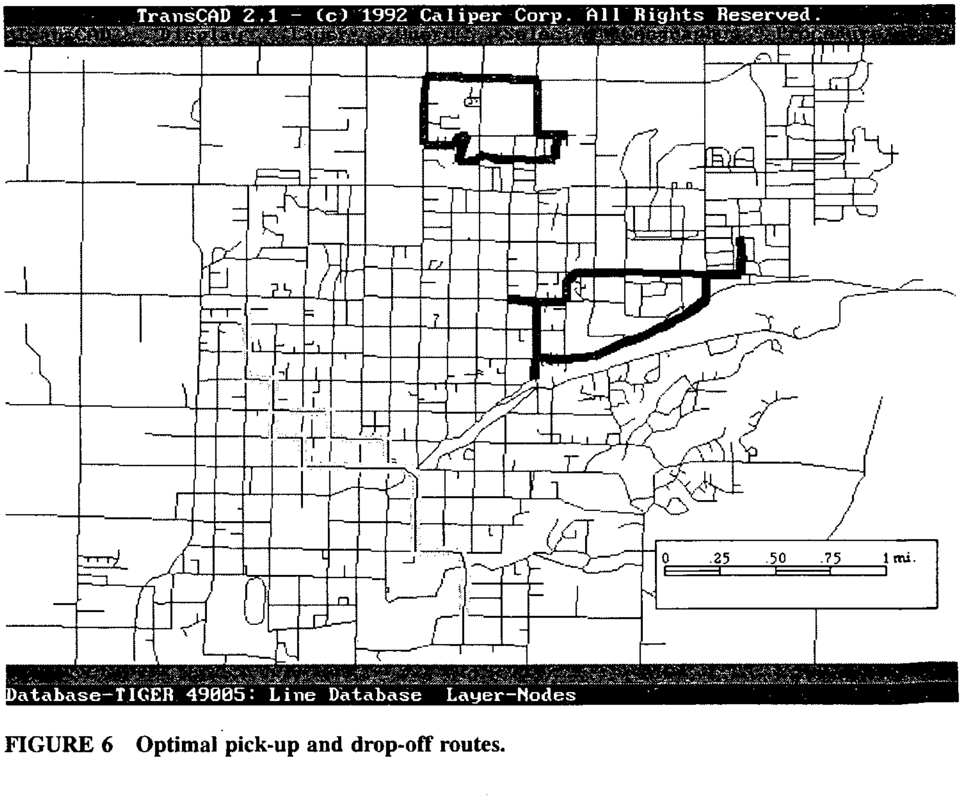

FIGURE 6 Optimal pick-up and drop-off routes.

```
              MVRF02 Report
              =============
Network File: C:\TRANSCAD\FINAL4.NET
Demand Table: C:\TRANSCAD\FINAL6.TAB
Shape Parameter: 1.0
Number of Trials: 20
Vehicle Capacity: 4.0

3 Depot(s):
       1850         3342         3611
10 Selected Points:
       2230         6909         2249         1894         3399
       3526         3776         3469         3276         3384
---------------------------------------------------------------------

[Depot]: 1850
trial         cost
    1         8.90
    2         8.90
    3         8.90
    4         8.90
    5         8.90
    6         8.90
    7         8.90
    8         8.90
    9         8.90
   10         8.90
   11         8.90
   12         8.90
   13         8.90
   14         8.90
   15         8.90
   16         8.90
   17         8.90
   18         8.90
   19         8.90
   20         8.90

[ROUTE PARTITION]:
Route 1: 4 customers:
 Customer  Node_id  Demand    Cost
     2       6909     1.0      2.5
     1       2230     1.0      2.2
     4       1894     1.0      1.6
     3       2249     1.0      1.0
 depot       1850              1.6
 Sum                  4.0      8.9

Total Cost:     8.9

[ROUTE SCHEDULE]: (*: customer, #: depot)

* Route 1 *
Customer Stop sequence: 0-2-1-4-3
Number of links on the route: 29.
   Node   Arrive      Node   Arrive      Node   Arrive
    1848 (  0:00)      2223 (  0:00)      2224 (  0:01)
    2398 (  0:01)      1846 (  0:01)      6909*(  0:01)
    2226 (  0:20)      2225 (  0:20)      2227 (  0:20)
    2236 (  0:20)      2239 (  0:20)      2234 (  0:21)
    2233 (  0:21)      2230*(  0:21)      1906 (  0:39)
    2229 (  0:39)      2245 (  0:40)      2244 (  0:40)
    1918 (  0:40)      1894*(  0:40)      1878 (  0:58)
    1880 (  0:58)      1881 (  0:59)      2252 (  0:59)
    2249*(  0:59)      2252 (  1:17)      2243 (  1:17)
    1879 (  1:17)      1850#(  1:18)
----------------------------------------------------------------------

[Depot]: 3342
trial         cost
    1        12.95
    2        12.95
    3        12.95
    4        12.95
    5        12.95
    6        12.95
    7        12.95
    8        12.95
    9        12.95
   10        12.95
   11        12.95
   12        12.95
   13        12.95
   14        12.95
   15        12.95
   16        12.95
   17        12.95
   18        12.95
   19        12.95
   20        12.95
```

FIGURE 7 Optimal routes and schedules (*continued on next page*).

```
[ROUTE PARTITION]:

Route 1: 3 customers:
 Customer  Node_id  Demand     Cost
     2        3276     1.0      2.8
     1        3469     1.0      5.6
     3        3384     1.0      2.0
 depot        3342              2.6
 Sum                   3.0     12.9

Total Cost:     12.9

[ROUTE SCHEDULE]: (*: customer, #: depot)

* Route 1 *
Customer Stop sequence: 0-2-1-3
Number of links on the route: 42.
   Node   Arrive         Node   Arrive         Node   Arrive
    3344 (  0:00)         3345 (  0:00)         3347 (  0:01)
    3348 (  0:01)         3349 (  0:01)         3311 (  0:01)
    3276*(  0:02)         3311 (  0:20)         3349 (  0:20)
    3348 (  0:20)         3347 (  0:21)         3392 (  0:21)
    3401 (  0:21)         3426 (  0:22)         3453 (  0:22)
    3452 (  0:23)         3458 (  0:23)         3459 (  0:23)
    6947 (  0:23)         6973 (  0:23)         6949 (  0:23)
    6950 (  0:23)         3456 (  0:23)         3470 (  0:24)
    3469*(  0:24)         3470 (  0:42)         3456 (  0:42)
    3419 (  0:42)         3388 (  0:43)         3389 (  0:43)
    3384*(  0:43)         3389 (  1:02)         3388 (  1:02)
    6967 (  1:02)         6966 (  1:02)         3395 (  1:02)
    3394 (  1:02)         3353 (  1:02)         3339 (  1:03)
    3340 (  1:03)         3341 (  1:03)         3342#(  1:03)
------------------------------------------------------------------------

[Depot]: 3611
trial        cost
    1       19.01
    2       19.01
    3       19.01
    4       19.01
    5       19.01
    6       19.01
    7       19.01
    8       19.01
    9       19.01
   10       19.01
   11       19.01
   12       19.01
   13       19.01
   14       19.01
   15       19.01
   16       19.01
   17       19.01
   18       19.01
   19       19.01
   20       19.01

[ROUTE PARTITION]:
Route 1: 3 customers:
 Customer  Node_id  Demand     Cost
     3        3776     1.0      4.5
     2        3526     1.0      7.3
     1        3399     1.0      2.2
 depot        3611              5.0
 Sum                   3.0     19.0

Total Cost:     19.0

[ROUTE SCHEDULE]: (*: customer, #: depot)
* Route 1 *
Customer Stop sequence: 0-1-2-3
Number of links on the route: 59.
   Node   Arrive         Node   Arrive         Node   Arrive
    3609 (  0:00)         3610 (  0:00)         3605 (  0:00)
    3571 (  0:01)         3569 (  0:01)         3524 (  0:01)
    3526 (  0:02)         3471 (  0:02)         3468 (  0:02)
    3432 (  0:03)         3433 (  0:03)         3405 (  0:03)
    3399*(  0:03)         3405 (  0:21)         3433 (  0:22)
    3432 (  0:22)         3468 (  0:22)         3471 (  0:23)
    3526*(  0:23)         3524 (  0:41)         3527 (  0:41)
    3534 (  0:42)         3533 (  0:42)         3572 (  0:42)
    3574 (  0:43)         3575 (  0:43)         3576 (  0:43)
    7018 (  0:43)         3613 (  0:43)         3612 (  0:43)
    3614 (  0:44)         4310 (  0:44)         3648 (  0:44)
    3647 (  0:44)         3658 (  0:44)         3689 (  0:44)
    3710 (  0:45)         3714 (  0:45)         3720 (  0:46)
    3728 (  0:46)         3673 (  0:46)         3757 (  0:46)
    3765 (  0:46)         3776*(  0:46)         3765 (  1:05)
    3757 (  1:05)         3673 (  1:05)         3728 (  1:05)
    3720 (  1:05)         3714 (  1:06)         3710 (  1:06)
    3689 (  1:06)         3658 (  1:07)         3647 (  1:07)
    3648 (  1:07)         4310 (  1:07)         3614 (  1:07)
    3612 (  1:07)         3611#(  1:08)
------------------------------------------------------------------------
```

FIGURE 7 *(continued)*

determined for each block group. The next step was to transfer data from the block group layer to road layer, in which the Data Editor Tag function was used. This was done for the estimates of people with disabilities using the first and second methods.

Conventional buffering of the street segments along the transit route would result in inclusion of the street segments that are within the buffered area but their walking distance is more than the desired value or they are not connected to the streets with transit service due to the existence of a barrier. To remedy this, the Arc/Node partitioning capacity of TransCAD was used. Nodes of each transit layer were used to partition the road segments that were connected to the transit route and were within the 0.5-mi buffer area. This operation selected all the segments within the service area including the segments that were partially in the service area. To find the portion of length of street segments in the analysis area, a simple conditional algorithm was used in Data Editor, and the resulting length was multiplied by the disabled population density of the road segment. The selected links can be exported into a spreadsheet program (e.g., Lotus 1-2-3) to sum the columns for the disabled population. This operation was performed for each transit route in the present case.

VEHICLE ROUTING AND SCHEDULING

The origin and destination information obtained from a previous survey (*4*) was used to create a hypothetical routing assignment. To do this, 10 origins were selected as the pick-up addresses and three destinations were chosen as drop-off locations. Then a road network covering all the pick-up and drop-off locations was created using Build Network. Next, multiple depot vehicle routing assignment was performed using Procedure Routing and Scheduling Models-MVRP02. This procedure identifies a pick-up/drop-off strategy for vehicles by minimizing costs. Cost can include a variety of components such as travel time and operating cost. In this case the travel time (based on an average 20-mph operating speed) was chosen to be minimized, and one drop-off point was allocated to each pick-up point. For this example the following parameters were used:

Parameter	*Value*
Pick-up point	10
Drop-off point	3
Demand at each pick-up point	1 passenger
Vehicle capacity	4 passengers
Fixed service time at each pick-up/drop-off point	0.1 hr
Variable service time at each pick-up/drop-off point	0.5 hr

After 20 iterations, it was found that three vehicles were needed to minimize travel time between the chosen origins and destinations. The output included the routing and arrival times at each pick-up and drop-off point on the route. Figure 6 shows the three optimum routes, and Figure 7 illustrates the fleet size requirement and the pick-up strategy for each route.

It should be noted that the solution does not include the travel path to/from depot. Nevertheless, this analysis can be used to identify the cluster of origins with common destination and their optimum route. It can also be used to find an optimum location for vehicle depot(s) with respect to optimum routes of these clusters.

CONCLUSIONS

The demand for each of the six LTD fixed routes and the entire network was estimated using two methods under two different estimates of people with disabilities. Each method of estimation has its own merits and demerits. One method could be more suitable for a particular set of block groups whereas the other might be more suited for another set. In the present case, because of the existence of many parcels of agricultural land use in the study area, the road segment method derived better estimates. The software was also better suited for treating inaccessible road segments than inaccessible area portions, which must be excluded when using the area method.

Even though a GIS can perform the computations and display results within a matter of seconds, acquisition of suitable information and the development of data bases are major challenges. Most basic information is available from TIGER files and census records, but examining travel patterns, estimating the propensity to use transit (r_i), and refining the data bases will continue to be time-consuming and expensive tasks. For instance, the road layer for Cache County extracted from TIGER files did not have address information, which reduced the precision of vehicle routing and scheduling. The remedy to this problem, which would involve manually gathering starting and ending address numbers of each street segment either by physical inspection or by obtaining the information from the city planning office, would be prohibitively expensive. Entering this information into the proper data base for each road segment would also consume several days.

In summary, a GIS can be a valuable tool for estimating demand and developing strategies to satisfy the demand by proper routing to gain maximum demand coverage. However, the results or planning information generated by GIS depends heavily on the precision of input data, and the benefits will only be derived in the long run.

ACKNOWLEDGMENTS

Funding for the study on which this paper is based was provided by Project ACTION and the Mountain Plains Consortium.

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Publication of this paper sponsored by Committee on Transportation Data and Information Systems.

Building Transportation Analysis Zones Using Geographic Information Systems

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A model is developed to aggregate transportation analysis zones (TAZs) using fuzzy set theory and spatial analysis tools found in geographic information systems (GIS). The purpose of the model is to provide analysts with standardized mathematical and computerized approaches for network design. Approaches for modeling zonal homogeneity are compared, and a model for evaluating zone shape is presented. Implementation of these models is discussed for Arc/Info and Atlas GIS. The focus of the work described is on aggregating TAZs, but the model applies equally well to creating TAZs from smaller units like census blocks.

In order to model travel demand by the Urban Transportation Planning Process (UTPP), transportation analysis zones (TAZs) must be developed. This zone structure is used in transportation planning and forecasting models at regional and subregional scales. However, when conducting site impact analysis, if the region being modeled is large, planners often use subarea focusing to perform detailed analyses of a smaller area. By aggregating zones outside the specific area of interest, organizations can save considerable time and expense. Aggregating zones is also helpful when working with sketch networks, which have a lower level of detail than typical representations of actual road layouts. Although accurate disaggregate data are preferred in transportation modeling and forecasting, privacy rights along with excessive cost of data collection and processing often restrict agencies from using disaggregate data. Research indicates that gravity model accuracy need not be significantly affected by aggregation (*1–3*). However, a planner must exercise caution in aggregating zones to form new zones because zonal characteristics, such as homogeneity, affect model output (*4–7*).

To help minimize the introduction of error into transportation planning models, various criteria for delineating and aggregating zones have been suggested (*8,9*). These criteria are summarized here.

1. Make zones as homogeneous as possible;
2. Maximize interaction between zones;
3. Avoid irregular or elongated shapes;
4. Avoid creating zones within zones;
5. Use census boundaries as much as possible;
6. Employ other political, historical, and physical boundaries as needed;
7. Aggregate only adjacent zones;
8. Construct zones so that roughly equal numbers of trips are generated and attracted between each pair of zones; and
9. Establish a maximum number of trip ends per zone.

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Different analytical approaches have been developed to create and aggregate zones according to these criteria. Techniques reported in the literature emphasize maximizing interaction between zones (*10*), minimizing information loss (*11*), and measuring proximity (*12*). Some planners do not use these criteria but base the zonal structure on the road network (*13*). All methods vary in their degree of automation.

For the most part, these techniques have been applied at the experimental level. In practice, planners often create new zones by exercising professional judgment. Experience and understanding of an area are invaluable to planners. However, nonquantifiable and sometimes subjective decisions result. Therefore, there is a need to develop a standard procedure that minimizes the adverse effects of aggregation on model output. In addition, standardization would permit better comparison of results among agencies and over time.

Developing a process for aggregating TAZs within a GIS framework promotes standardization. Since transportation data bases are increasingly being built in GIS, the GIS seems a logical place in which to design and aggregate TAZs. Furthermore, GIS graphical capabilities greatly facilitate visual analysis of different aggregations. Since many regional transportation planning agencies are adopting GIS technology, a method that uses this technology may be more readily accepted into practice. Several researchers are linking transportation modeling with GIS (*14–17*). The purpose of this paper is to (a) demonstrate the use of spatial analysis tools in a GIS by modeling some of the criteria stated earlier and (b) present a fuzzy C-varieties (FCV) algorithm as an alternative to a thematic mapping approach to model the homogeneity criterion. The conceptual model for aggregating TAZs using GIS is shown in the flowchart in Figure 1.

Several researchers have applied fuzzy set theory in transportation studies (*18–21*) but not in travel demand modeling. The FCV algorithm presented here, developed in the early 1980s by Gunderson and Jacobsen, is applicable to developing and aggregating TAZs because it provides the planner with greater ability to obtain homogeneous zones based on simultaneous analysis of several planning variables without presuming information about the data base.

The use of thematic mapping procedures to create homogeneous TAZs has not been widely explored either. GIS software packages typically offer users a variety of automated and manual algorithms for defining class ranges for each variable. A separate thematic layer may be developed for each individual variable. The combination of these layers identifies boundaries of homogeneous zones.

Three GIS packages have been used in the development of this paper, namely, Arc/Info, TransCAD, and Atlas GIS. Work reported using fuzzy set analysis used Arc/Info and TransCAD, primarily. Discussions on thematic map classification routines relate directly to Atlas GIS. All of the algorithms or procedures identified here are relevant to all packages.

HOMOGENEITY EVALUATION

Thematic Mapping Procedure

A thematic mapping approach to identifying homogeneous areas differs from the fuzzy clustering approach, or any multidimensional modeling approach, in that each variable is considered independently. With multidimensional algorithms, the question "How similar are Area A and Area B?" is answered by considering all variables at one time. With the thematic mapping approach this question is asked as many times as there are variables describing Areas A and B. The thematic mapping approach is similar to the fuzzy clustering approach in that users must define the number of classes (clusters, ranges) used to aggregate (or group) data.

A danger with using the thematic mapping approach is that no areas with similar characteristics may be identified. For example, suppose a data base consists of three ($m = 3$) variables, such as population density, employment density, and average income. Further, suppose that each of these three variables is classified into three groups ($n_i = 3$, for $i = 1, 2, 3$), such as high, medium, and low. (This example is simplified by assuming that all variables are classified into the same number of groups. Actually, each variable may be classified into any number of groups, n_i, where $n_i < > n_j$.) There are n^m, or $3^3 = 27$, possible combinations of values (combined groups) resulting from the overlay of individual layers. The number of possible combinations when $n_i\ n_j$, $\forall(i,j)$ is $G = n_1 * n_2 * \ldots * n_m$. Area 1 may have high population density, high employment density, and high income, or high population density, high employment density, and medium income, and so forth. An example of this is shown in Figure 2. Each of the three variables was classified into four groups such that 25 percent of the observations fell in each group (quantiles). Adjacent cells in the same class are joined into single homogeneous areas. However, when these areas are overlaid on each other, the original 16-cell grid appears.

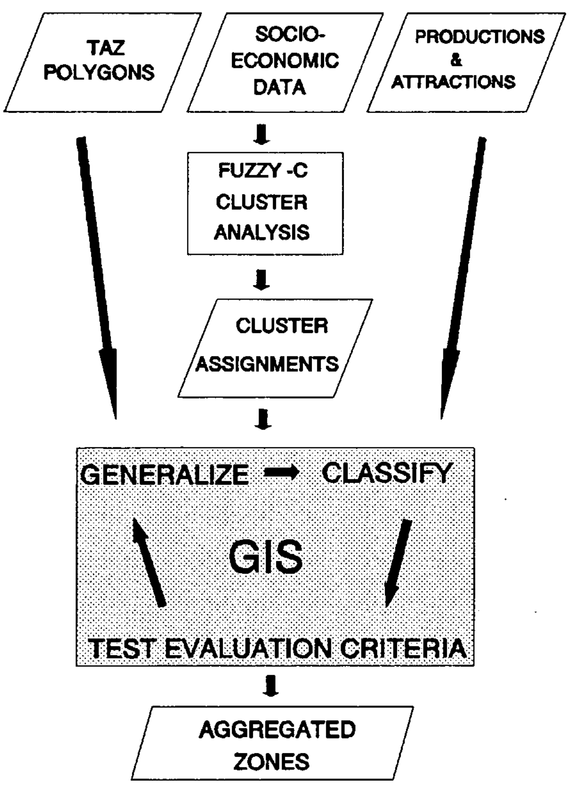

FIGURE 1 Flowchart of TAZ aggregation model.

Another challenge with using the thematic mapping approach to identify homogeneous zones is the selection of the appropriate model for classifying variables. For instance, four automatic and five manual methods are available in Atlas GIS. The four automatic data classification algorithms are as follows:

- Quantiles: ranges for data are determined such that each range contains the same number of observations.
- Equal size: ranges are determined that are equal in size. Range size = (max − min)/number of classes
- Standard deviation: ranges are one standard deviation in size around the mean.
- Optimal: ranges maximize the goodness-of-variance fit that minimizes variance within ranges and maximizes variance between ranges.

The effect of these different algorithms is shown in Figure 3, for the employment density layer. Table 1 presents descriptive statistics generated for each of these ranging approaches. (Data for these demonstrations come from the Salt Lake City regional planning data base. The spatial structure has been simplified by putting it into a 16-grid cell structure.)

Fuzzy Clustering Approach

Fuzzy sets are groupings or classes of objects whose boundaries are not fixed. The concept of fuzziness differs from probability. Fuzzy set theory deals with definition (albeit, fuzzy) of data, not with accuracy. Thus, the ability to describe non-binary aspects of the world is enhanced. Instead of an object being a member of one class and not of others, it receives partial membership in many or all classes. This allows greater flexibility in assigning meaning to fuzzy classes, such as low, medium, and high income.

Fuzzy clustering was selected over other clustering methods because it handles data outliers better. The most common clustering procedure is hierarchical clustering. This method separates n objects into n clusters, then $n - 1$ clusters, then $n - 2$ clusters, and so forth. Once a sample point is assigned to a cluster, it cannot be reassigned to another cluster. This is similar to many taxonomies in which each group is a subset of another group, except for the highest-order cluster. Hierarchial clustering works well with compact and well-separated classes, but it does not do well with sample points that are outliers or fall between two compact centers. If this is the case, outliers need to be eliminated from the data set, which is not permissible with TAZs.

A cluster represents a group of zones with similar demographic characteristics. Each cluster has a center, which represents the average values of each of the socioeconomic variables used to describe the cluster. The FCV algorithm locates a zone in

n-dimensional space where n is the number of socioeconomic attributes used to characterize a zone. Through an initial guess and a series of iterations, the program identifies the n-dimensional coordinate centers of the clusters. The function of the initial guess is to identify the zones that are most dissimilar. Users determine the number of iterations to be performed by specifying a maximum number of iterations, such as 50, and a tolerance on minimum change in membership to be achieved between iterations, such as 0.005.

Instead of the rigid, classical clustering approach of assigning a given zone to whichever cluster it is most similar to, the FCV gives each zone a degree of membership to each cluster on the basis of socioeconomic distance from the cluster center. A membership of 0 means that the particular zone is very dissimilar to the cluster center (average) in terms of its demographic characteristics. A value of 1, on the other hand, indicates that a zone is very much like the center values. However, as with all other clustering techniques, the user must predefine the number of clusters to search for in the data. In the approach described here, the planner specifies different numbers of clusters until each zone has a membership of 80 or 90 percent, for example, in one of the clusters.

The algorithm does not force a class structure on the data. By calculating eigenvalues and the class centers, the algorithm also permits the user to determine the within- and between-class variation. This provides a way to describe how homogeneous the zones really are. Another benefit of knowing the class centers and eigenvalues is the ability to differentiate the importance of certain variables in describing homogeneity. Extraneous variables that do not contribute to the formation of unique clusters may then be excluded from this part of the analysis.

Figure 4 shows three- and four-cluster assignments of zones from the FCV algorithm using population density, employment density, and park and recreational land use density from the Salt Lake City data base. Table 2 contains descriptive statistics for these clusters.

GIS Tools

Regardless of the approach used to define homogeneous areas, the use of certain tools or procedures in GIS packages is required. These spatial analysis tools include classification, evaluation of spatially based criteria, and generalization. A flowchart of a model developed using Arc/Info is shown in Figure 5. TAZ polygon coordinates and FCV or thematic cluster assignments create the data base needed to perform the analysis described here.

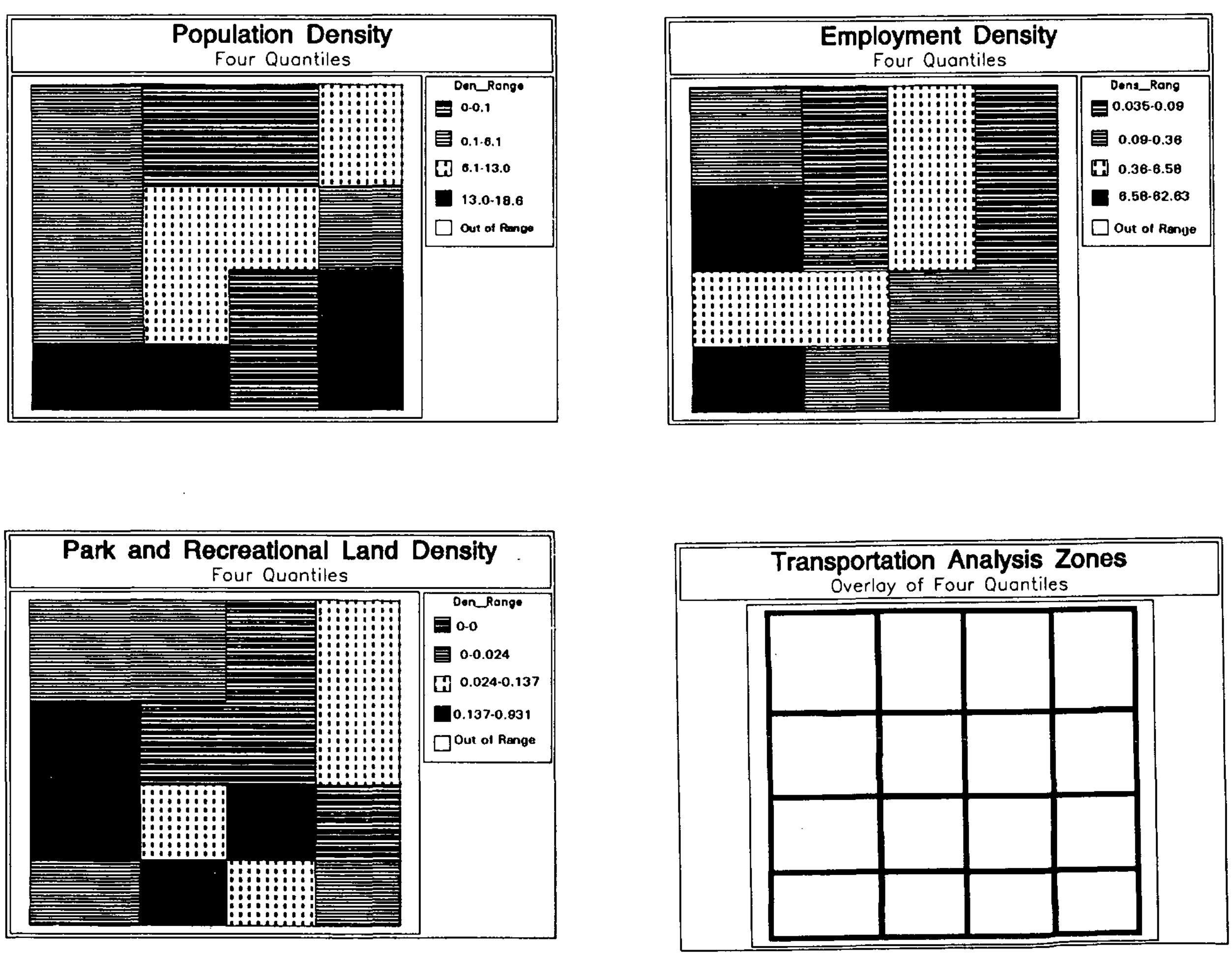

FIGURE 2 Thematic overlay of three variables.

Currently, a routine programmed using Arc Macro Language (AML) which calls executable C programs, has been developed for the fuzzy clustering approach. After invoking this routine, the user specifies the coverage (i.e., TAZ polygons), the item (i.e., cluster assignments) to evaluate, and the value (i.e., zones in Cluster 1, 2, . . .) of the item. Users may aggregate on the basis of a single cluster number or several cluster numbers.

A method for applying the thematic approach is described for Atlas GIS. A separate layer of the base geographic file is created for each variable used in the analysis. This can be accomplished by either opening a geographic file several times under different names (File, Geographic, UseAs) or selecting all features in a geographic layer and writing the selected features to a new file (Select, Layer, File, Geographic, Tools, Write). For each layer, the attribute file structure is changed to contain a blank integer field in which to store the class range value for a zone. (File, Attribute, Tools, Structure). A thematic ranged fill map is generated using the /Replace option. Users must specify the number of ranges and the ranging method (as described earlier). Adjacent areas in the same class can be merged into a single area using the Operate, Union command. Users must specify how each attribute value is to be aggregated to the new zone (i.e., copy first value, leave blank, average, or sum). These new geographic layers are saved and, once all variables have been treated, merged into one geographic file. Separate layers are overlaid, two at a time, to form the final map using the Operate, Union command.

ZONE SHAPE EVALUATION

As mentioned previously, several criteria exist for aggregating zones. The FCV model and thematic mapping address the homogeneity criterion. Analysis of fractal dimensions is used to address shape and compactness criteria. A fractal is defined as

> Objects (or sets of points, or curves, or patterns) which exhibit increasing detail ("bumpiness") with increasing magnification. Many interesting fractals are self-similar. B. Mandlebrot informally defines fractals as "shapes that are equally complex in their details as in their overall form. That is, if a piece of a fractal is suitably magnified to become of the same size as the whole, it should look like the whole, either exactly, or perhaps only after slight limited deformation." (*22*,p.380)

Fractal dimensions are used here to quantify the relationship between the area and perimeter of a polygon. The fractal dimension of a polygon is calculated as

$$f_d = \frac{2 * \ln(T_1)}{\ln(A)} \qquad (1)$$

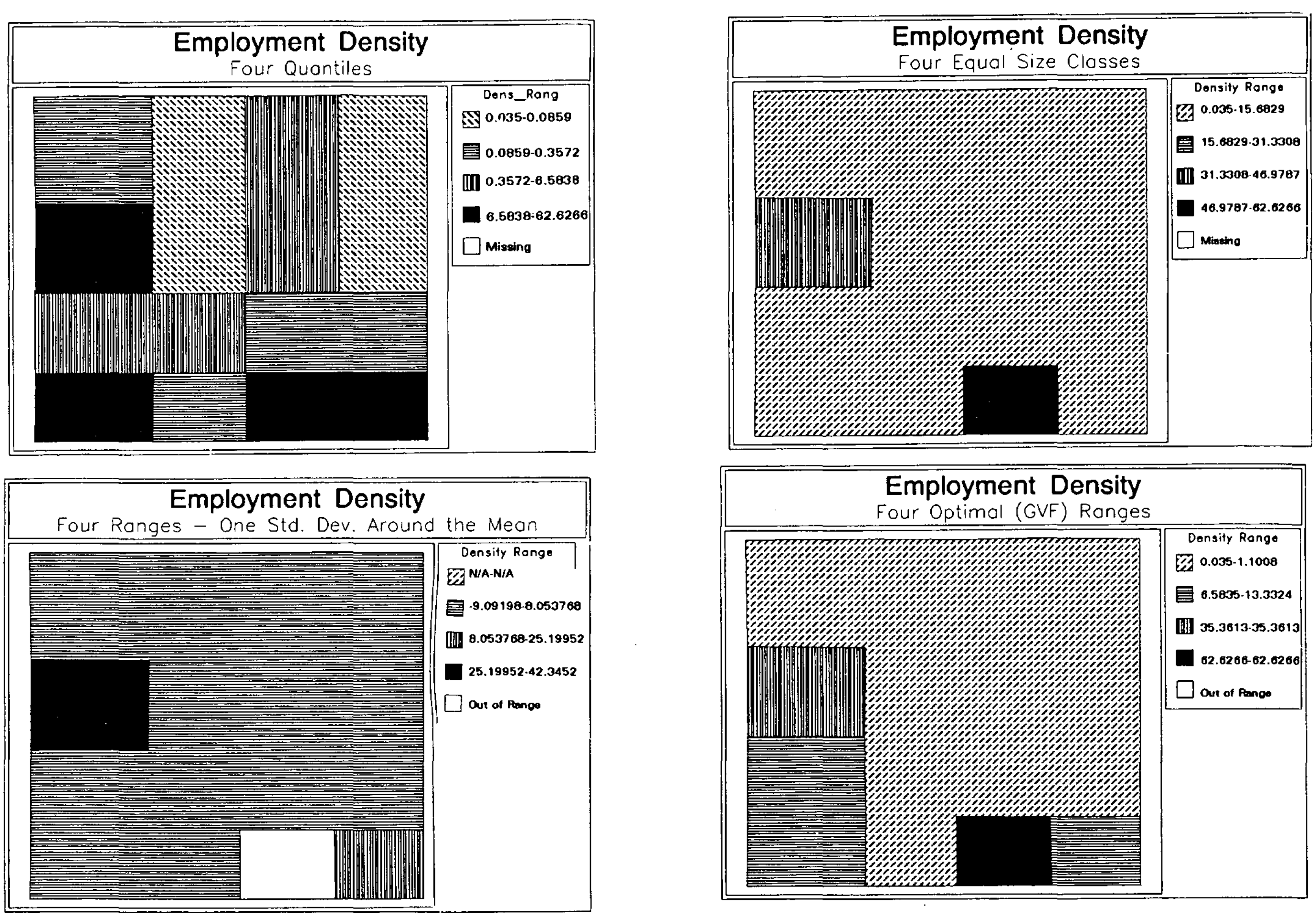

FIGURE 3 Results from automatic thematic ranging techniques.

TABLE 1 Range Statistics for Employment Density Layer

Employment Density Thematic Ranges					
Quantiles					
Class	Minimum	Maximum	Percent Observations in Class	Class Mean	Class Standard Deviation
1	0.035	0.0859	25.0	0.0697	0.0234
2	0.0859	0.3572	25.0	0.203	0.1111
3	0.3572	6.5838	25.0	2.232	2.843
4	6.5838	62.6266	25.0	29.617	25.117
Equal Size					
1	0.035	15.6829	87.5	2.2052	3.989
2	15.6829	31.3308	0	N/A	N/A
3	31.3308	46.9787	6.25	35.361	0
4	46.9787	62.6266	6.25	62.627	0
Standard Deviation					
1	N/A	N/A	0	N/A	N/A
2	-9.092	8.0538	81.25	1.349	2.475
3	8.0538	25.1995	6.25	13.332	0
4	25.1995	42.3452	6.25	35.3614	0
Optimal					
1	0.035	1.1008	68.75	0.3461	0.377
2	6.5838	13.3324	18.75	9.0218	3.744
3	35.3613	35.3613	6.25	35.36	0
4	62.6266	62.6266	6.25	62.627	0

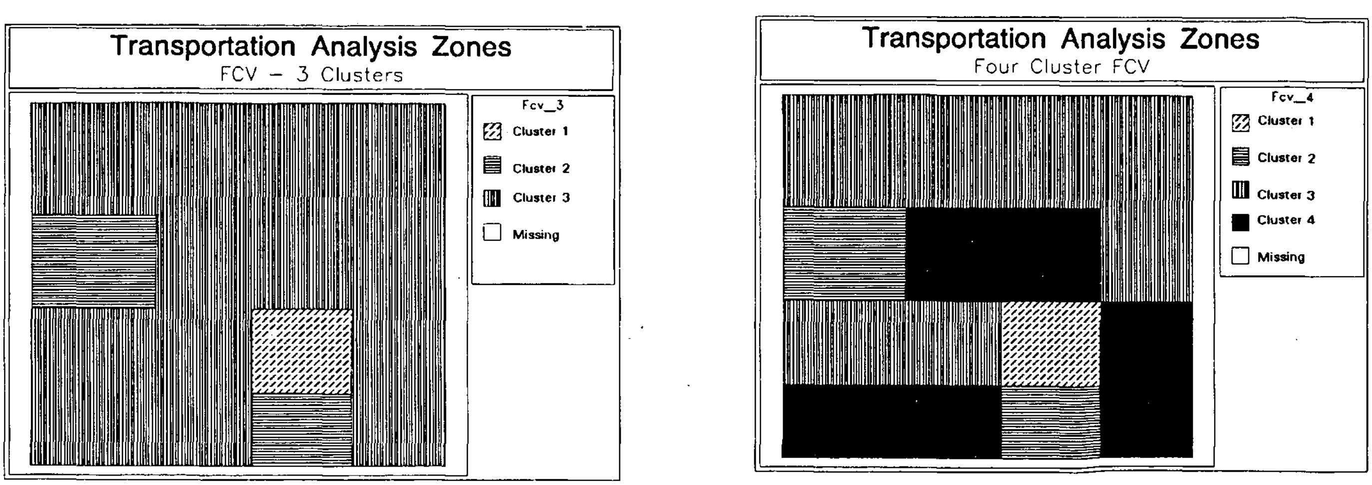

FIGURE 4 TAZs from fuzzy clusters.

where A equals the area of the polygon, and T_1 equals the perimeter divided by $2\sqrt{\pi}$. Note that this equation is scaled, so the fractal dimension of a circle, the most compact geometric shape, is 1 instead of 0.

The approach programmed in an Arc/Info model first identifies all patches in the coverage, where a patch is defined as a group of adjacent zones having the same value of the item being analyzed. The user provides a threshold value, between 0 and 2, that is used to test the shape criterion. A threshold value of 0 forces the shape of the generalized polygons to be more compact than the shape of the original, ungeneralized polygon. A threshold value of 2 allows all polygons to merge regardless of their combined shape.

Within a patch, the model calculates the fractal dimension of each polygon. The polygon with the highest fractal dimension is selected, and an improvement function is calculated for each of its neighbors. The improvement function evaluates the change in fractal dimension if the polygon pair is generalized (i.e., the shared boundary line dissolved). This function is specified as

$$\delta f = 2 * f_{A_1A_2} - f_{A_1} - f_{A_2} \qquad (2)$$

where

$f_{A_1A_2}$ = fractal dimension of $A_1 \cap A_2$,
f_{A_1} = fractal dimension of A_1, and
f_{A_2} = fractal dimension of A_2.

If δf − threshold value ≤ 0, then an improvement occurs and the boundary between the polygon pair may be dissolved. The program selects the pair with the greatest improvement in fractal dimension to aggregate.

A simple example of the generalization process is demonstrated using the four polygons shown in Figure 6. Table 3 gives calculation results for the first iteration of this example. Polygon A_4 has the highest fractal dimension in this patch so it is considered first. The fractal dimension of the intersection of A_4 with each of its neighbors (A_2 and A_3) is determined. The change in fractal dimension is determined using Equation 2 and reveals that dissolving the shared boundary between A_4 and A_2 is appropriate.

If the starting rule is changed, so that one begins by looking at the most compact polygon, then one would consider merging A_3

TABLE 2 Fuzzy Clusters Descriptive Statistics

FCV With 4 Clusters					
Cluster	Minimum	Maximum	Percent	Mean	Std. Dev.
1 Emp. Den.	0.18	0.18	6.25	0.18	0
Pop. Den.	0.04	0.04		0.04	0
%Pk & Rec	0.93	0.93		0.93	0
2	35.36	62	12.5	48.99	13.63
	0.00	6.05		3.03	3.03
	0.14	0.21		0.17	0.04
3	0.03	6.58	43.75	1.25	2.21
	0.00	8.48		2.66	3.31
	0.00	0.14		0.05	0.04
4	0.08	13.3	37.5	3.65	4.99
	10.56	18.0		15.72	2.97
	0.00	0.18		0.03	0.07
FCV With 3 Clusters					
Cluster	Minimum	Maximum	Percent	Mean	Std. Dev.
1	0.18	0.18	6.25	0.18	0
	0.04	0.04		0.04	0
	0.93	0.93		0.93	0
2	35.36	62	12.5	48.99	13.63
	0.00	6.05		3.03	3.03
	0.14	0.21		0.17	0.04
3	0.03	13.3	81.25	2.36	3.95
	0.00	18.6		8.69	7.24
	0.00	0.18		0.04	0.06

with A_1 or with A_4. The improvement function shows that A_3A_1 is the best overall pair to aggregate. To further verify the use of the improvement function in this procedure, the authors have shown that aggregating A_3A_2 is the worst option at the initial stage.

A second iteration of this example is given in Figure 7 and Table 4. Polygons A_2 and A_3 will be generalized at the end of this iteration if the threshold value is less than 0.050764.

The aggregation process continues until all polygons in a patch have been tested. After each decision to generalize a zone pair, essentially a new map is created and the procedure repeated for the remaining polygons. Although this method increases processing time, it ensures that the order of processing polygons does not influence the results. For example, suppose a polygon (*A*) with the highest fractal dimension fails the test to dissolve its border with any neighbor. However, after generalizing other polygons (*C,D,E,,,*) in the patch adjacent to the original polygon (*A*'s) neighbor (*B*) but not (*A*) itself, it is discovered that (*A*'s) border with (*B*) should be dissolved. The program must be able to consider aggregating (*A*) at each iteration for the model to be valid.

Experimentation on the study area is required to establish a threshold value. An evaluation of the distribution of fractal dimensions of the original polygons will indicate the degree of compactness of the original map. However, it is necessary to examine how the distribution of the length of common borders affects merging polygons.

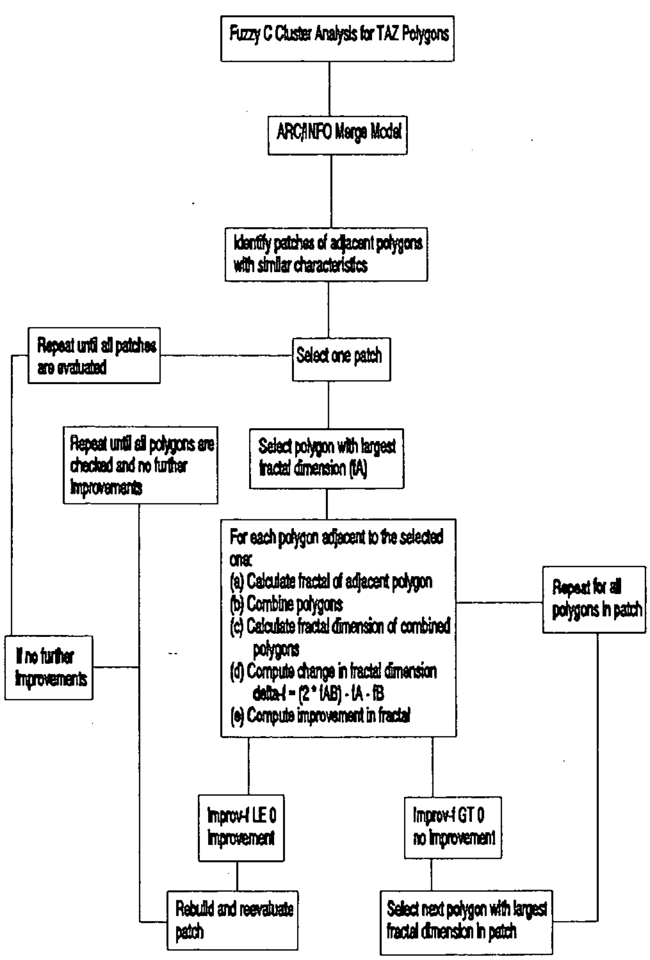

FIGURE 5 Flow chart of Arc/Info based aggregation model.

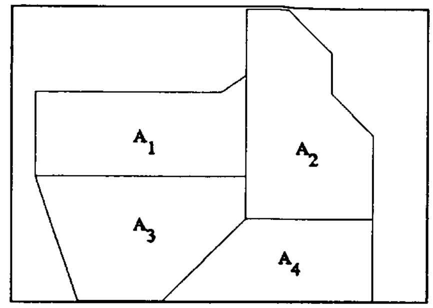

FIGURE 6 Example polygon patch for aggregation.

CONCLUSIONS

GIS is a very useful tool for defining TAZs according to specific criteria established in traffic theory. However, the use of GIS does not preclude the need for experienced, trained transportation planners in the design process. In fact, even the most sophisticated models require sound judgment to produce meaningful results.

This paper explores the use of GIS in addressing homogeneity and shape criteria for developing TAZs. Other TAZ modeling criteria may be incorporated into this model, such as evaluation of intrazonal trips. An AML, script, or C-procedure may be programmed to determine whether the number of intrazonal trips in a merged zone pairs falls below a user-specified tolerance. The tolerance level established here considers the appropriate ratio of intrazonal trips to interzonal trips for the merged pair. If a pair of polygons is chosen to be aggregated from the shape test, a trip distribution routine calculates the intrazonal and interzonal trips associated with the aggregated pair. A pair must pass this test, as well as the shape test, to be generalized.

Another possible routine to be added to the model considers the size (i.e., area) of the candidate pair for generalization and the centroid-to-centroid distance from this pair to the study area site. The farther a pair is from the study area, the larger it may be.

As mentioned earlier, one benefit of integrating FCV and GIS spatial analysis tools is that it standardizes a procedure for developing and aggregating zones. A process that is fairly well automated and quantitatively based decreases the excessive time requirements and subjectivity usually present. This model incor-

TABLE 3 Results of Example, Iteration 1

Polygon	Area	Perimeter	Fractal Dimension	Improvement Function
A_1	253.0	70.61	1.081312	
A_2	300.0	74.14	1.066115	
A_3	287.5	69.95	1.053578	
A_4	200.0	64.14	1.093010	
A_4A_2	500.0	108.28	1.100378	0.041631
A_4A_3	487.5	105.81	1.097409	0.048232
A_1A_3	540.5	90.56	1.029957	-0.074970
A_2A_3	587.5	134.09	1.139608	0.159523

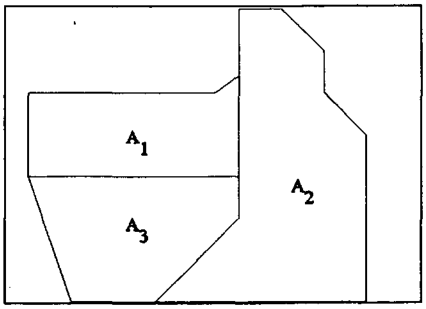

FIGURE 7 Second iteration map.

TABLE 4 Results of Example, Iteration 2

Polygon	Area	Perimeter	Fractal Dimension	Improvement Function
A_1	253.0	70.61	1.081312	
A_2	500.0	108.28	1.100378	
A_3	287.5	69.95	1.053578	
A_2A_1	753.0	154.89	1.140449	0.099208
A_2A_3	787.5	139.95	1.102360	0.050764

porates the experience and judgment of the user using thresholds and tolerance levels. The planner also must decide how many FCV clusters or thematic ranges and the ranging method to use, and therefore the degree of homogeneity.

The evaluation criteria need to be put into algorithmic form and ranked in terms of sequence and perhaps weight. In addition, the street system will be overlaid on zones aggregated by the given criteria and road patterns used to aid in defining zones. Further research plans also include running a gravity model with aggregate and disaggregate data and comparing the results.

ACKNOWLEDGMENTS

The authors would like to thank the Wasatch Front Regional Council for providing socioeconomic and land use data as well as the Vice President for Research at Utah State University for funding this project.

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Publication of this paper sponsored by Committee on Transportation Data and Information Systems.

Geographic Information Systems Applications to Transportation Corridor Planning

DAVID T. HARTGEN AND YUANJUN LI

Geographic information system (GIS) applications to large transportation corridor planning are reviewed in two cases: a large multicity urban region considering a major regional ring road, and a 120-mi, 10-county rural corridor recently upgraded to Interstate status. In both cases, the use of a transportation-oriented GIS, TransCAD, was found to greatly facilitate the display and understanding of information and the decision-making process. A wide variety of GIS procedures—data display, buffering, opinion surveys, traffic statistics, land use patterns, and traditional modeling—was found to be applicable. Examples are shown of how the use of the GIS added value to decision making, at a reasonable investment in time and effort by agency and support staff.

Nothing short of a technological revolution has been taking place in transportation planning in the past decade. The outlines of this revolution are now well-established. The primary elements are as follows:

1. The diffusion of microcomputing capability in transportation planning organizations. By recent count, approximately 80 percent of metropolitan planning organizations now have access to microcomputer capability.
2. The diffusion of support software for microcomputer systems, particularly the widespread availability of spreadsheet and word processing systems, supported extensively by data base management systems and (more recently) PC-based versions of the standard urban transportation planning system (UTPS) modeling system.
3. The development of geographic information systems (GISs), particularly PC versions, that tie transportation planning to more generally used regional demographics and other statistics.
4. Recently, the evolution of so-called GIS-T (GIS for transportation) software blended systems that contain both analytical and modeling procedures common to transportation planning studies and more conventional GISs for storing and displaying spatial data. These systems permit not just faster and smoother operation of activities done previously, but also increased functionality. Not only can things be done faster, but new activities and analysis can be undertaken.

These systems have substantially changed the balance of power between transportation planning organizations, putting considerable analytical capability within the hands of even the smallest agencies and citizens groups. With this shift of power has come an increase in the responsibilities of various groups to conduct cooperative transportation planning and input to the decision-making processes of urban regions and corridors. Less common is the use of these tools to diffuse power and develop regional consensus in rural or non-urban settings. This paper describes two recent applications of GIS-T technology to transportation corridor planning, that is, the study of transportation alternatives or impacts over large areas or long corridors.

Applications of GIS-T have increased rapidly in the past few years. Initially, GISs were used primarily for site and corridor analysis of transportation alternatives—for storing, gathering, and displaying information. Data related to modeling were transported from other systems into GIS for display purposes (*1,2*). Examples of these applications include studies in Dallas and Northern Virginia (*3*), suburban Atlanta (*4*), and Logan, Utah (*5*). Recent applications in the Charlotte, North Carolina, area involve development of noise contours along roads to parcels that may be suitable for industrial development as opposed to residential development. More recently, applying GIS to virtual reality, Parsons Brinckerhoff developed a view of how a new road proposal in Tennessee would fit within the landscape (*6*). Modeling applications in which transportation forecasting models are embedded in GISs has also increased in frequency. Most of these applications use GISs tied to microcomputer models or specialized GIS software packages such as TransCAD (*7,8*). This is because commonly available GISs such as Arc/Info do not have extensive transportation modeling capability (although it is reportedly in development). Traditional UTPS-type models using GISs are also reported in the literature (*9*) for outlying communities of Philadelphia and for other cities (*10*). Recent applications have been developed for transit planning, and selected regional corridor studies. Whether these studies actually improved decision making, however, is another matter. As more experience is gained with GIS-T tools and reports come in from this field, we will soon see.

This paper describes several case studies in which GIS procedures have been applied to transportation corridor planning. These are corridors 50 to 100 mi (1 mi = 1.6 km) long and perhaps 50 mi wide in which traditional transportation routing demand issues and economic impact issues both need attention. The two studies relate to quite different applications. The first focuses on display capabilities of the GIS process to assist in analyzing a rural multicounty corridor recently upgraded to an Interstate system corridor. The second focuses on travel demand modeling, using as an example the study of a ring road around a large metropolitan area. Both studies use the same GIS software engine, TransCAD, and were operated on an IBM PS2/386 with a 70MB hard drive.

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CASE 1: I-40 ECONOMIC IMPACT STUDY

Situation and Goals

The last section of Interstate 40, connecting Wilmington to Raleigh, North Carolina, a distance of about 120 mi, was completed and opened to traffic on June 29, 1990. The construction took place over 10 years at a cost of $241 million. The road serves the 10-county rural region between Wilmington and Raleigh in eastern North Carolina (Figure 1) and provides a significant increase in accessibility of the mid–North Carolina coastline. The completion of I-40 is likely to have enormous implications for eastern North Carolina. Its increased accessibility will in turn accelerate economic and population growth and changes in environment and lifestyle. Recognizing these impacts, the North Carolina Division of Community Assistance, in cooperation with a steering committee consisting of local governments and agencies and the private sector, initiated a study to identify the impacts of I-40 and to determine what actions might be taken to maximize the positive effects of the highway. Specifically, the goals of the study are to

1. Identify the major impacts of I-40 on the 10-county region, and
2. Recommend actions and strategies for governments and others to reduce negative impacts and maximize positive impacts.

The study effort consisted of 14 technical tasks, organized into three groups: data gathering, analysis, and policies.

The study, which was initiated in May 1990 and completed in fall 1991, is reported in its entirety elsewhere (*11,12*).

Use of GIS-T

The GIS-T software system TransCAD was used as essentially a data storage, manipulation, and display tool for technical reports related to the study. TransCAD has many analytical capabilities, some of which are described in Case 2, but the focus of this effort was on its display and storage features.

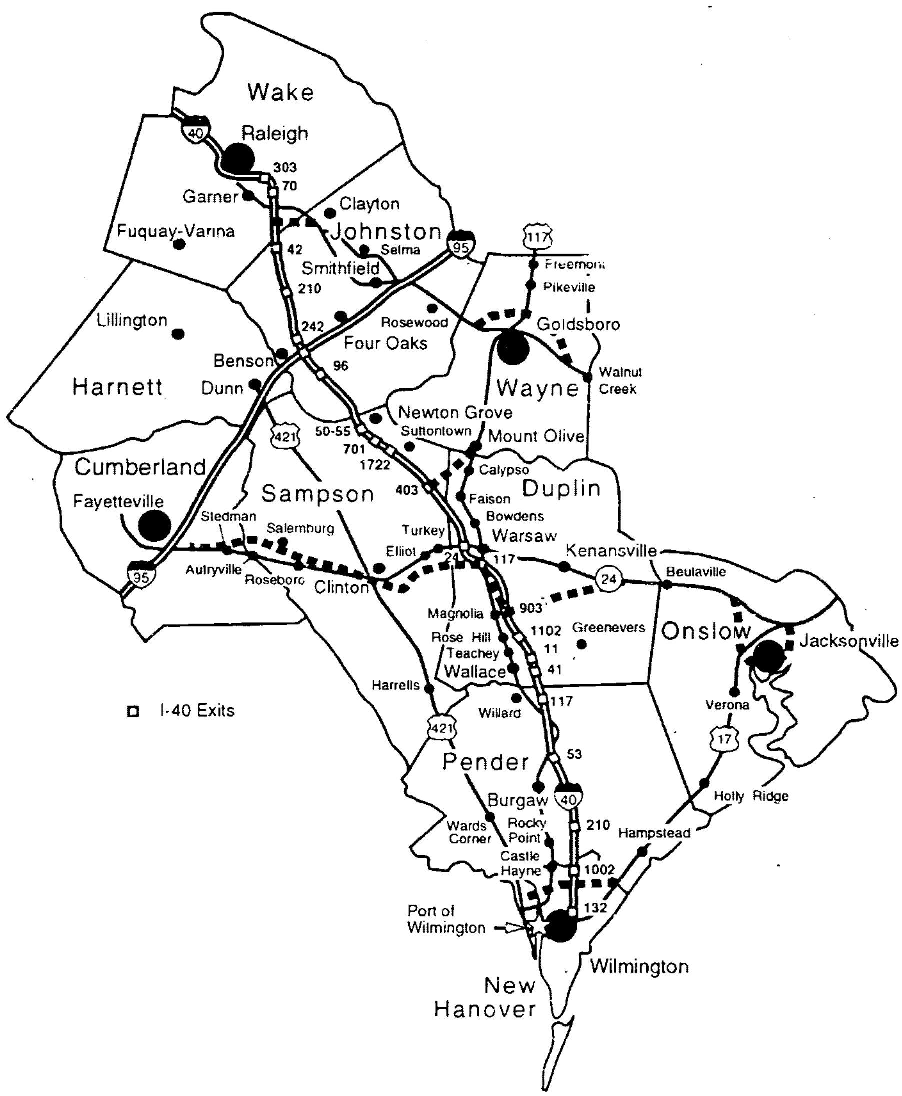

FIGURE 1 Planned major road improvements, I-40 corridor.

A series of layers was constructed to describe extensive data items related to the study. The primary layers developed are as follows:

1. *Polygon layers,* primarily statistics on counties, towns, Zip codes, and census blocks in the corridor. This includes a variety of demographic and socioeconomic information from the 1980s to the 1990s (Figure 2).
2. *Road-related statistics,* including a complete high-level highway network for the corridor, with attributes describing traffic volumes, capacities, speeds, truck usage, and intersections with I-40 (Figure 3).
3. *Point or node statistics,* including data on cities, respondents in business surveys and citizen surveys, and characteristics of street intersections. In addition, point data were also developed for manufacturers throughout North Carolina that might use I-40 for shipping (Figure 4).

Use of Information

Extensive use was made of the information collected in the early data-gathering phases of the study. Statistics were compiled describing each information layer, particularly demographic and socioeconomic data concerning the counties along the route. This information was then supplemented with additional displays showing the traffic circumstances, both present and projected, in the corridor, population and household statistics for counties and towns, and information describing business responses to telephone surveys and citizen responses obtained from public hearings and forums. The TransCAD system was also used to assist in the development of sampling plans for surveys, focusing on Zip codes.

During the course of the 14 study elements, approximately 300 displays of information were prepared and described in either GIS or graphics form. The display-making features of the TransCAD system permitted the data display process to proceed very rapidly. Slides were prepared describing the information in simple terms, for presentation to local citizen and business groups.

Analysis of Information

As the project proceeded, information gathered in the earlier phases was subjected to extensive analysis. Among the many analyses undertaken, the following three make extensive use of the GIS.

Growth at Exits

GIS was used to analyze the extent to which each of the 22 exits on I-40 were accessible from surrounding communities and other traffic corridors (Figure 5). Basic data describing each exit were used to predict the probability that each exit would permit sustainable growth. This information was displayed in the form of business graphics and pie charts (graduated circle) for transmittal to local officials. The results of these studies formed the underpinnings for the key study recommendation that growth in the corridor be clustered at a select number of small locations rather diffused all along the corridor.

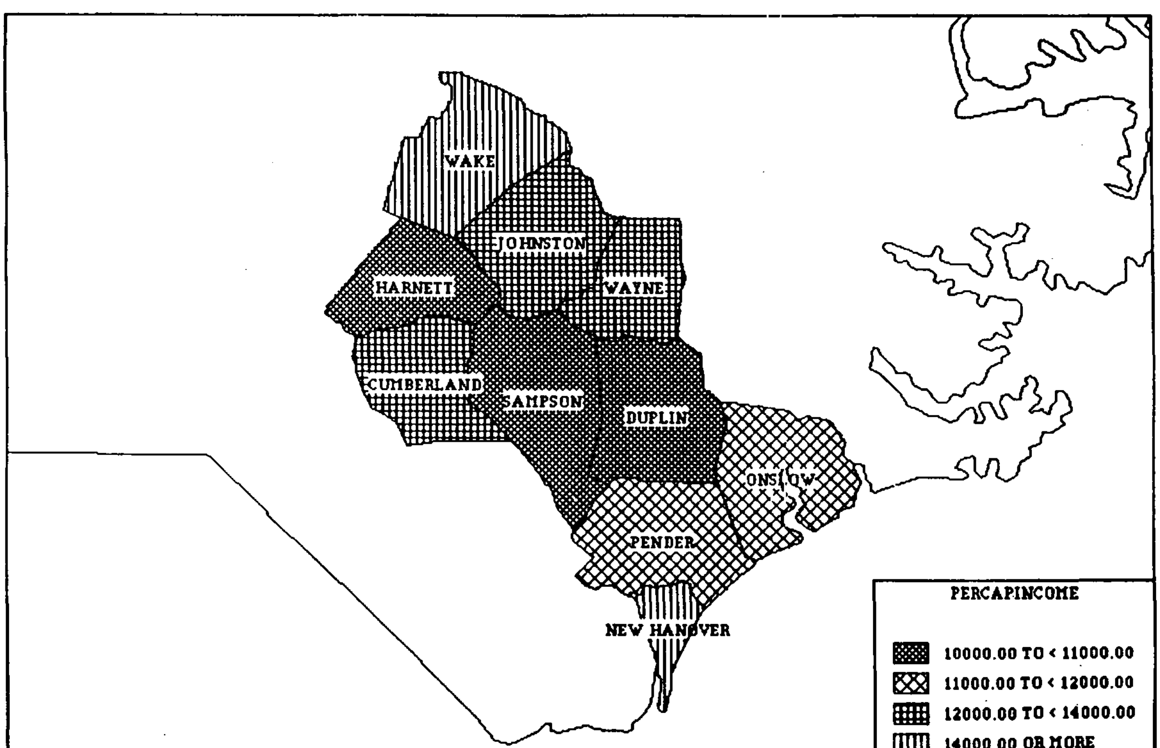

FIGURE 2 Per-capita income.

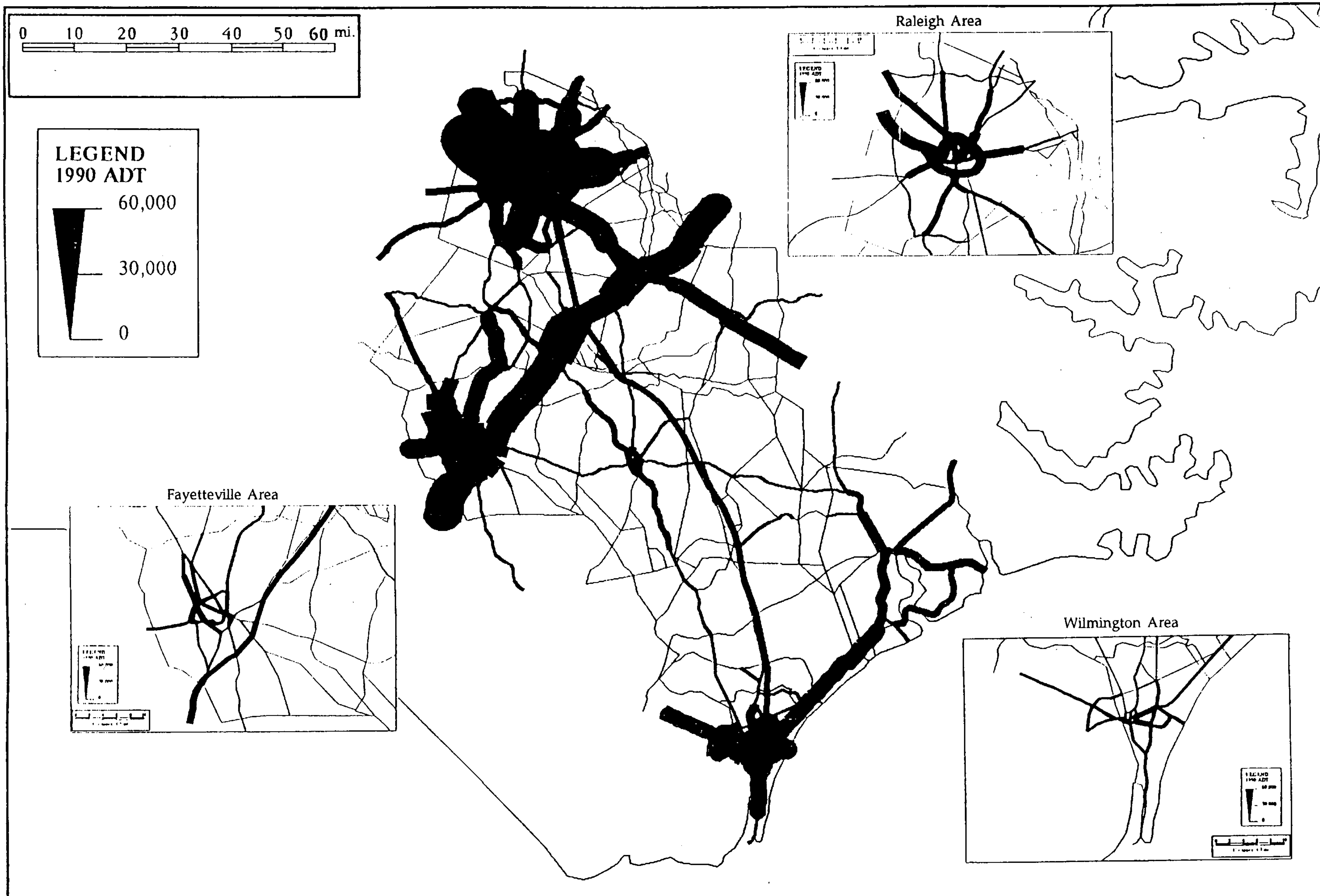

FIGURE 3 1990 average daily traffic for I-40 corridor.

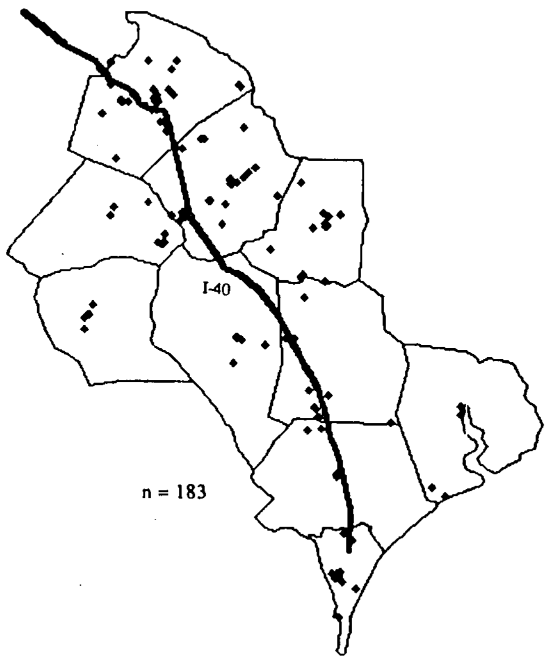

FIGURE 4 Respondents who believe I-40 will help their businesses.

Impacts on Port of Wilmington

The Port of Wilmington, a shipping port located on the mid–North Carolina seacoast, was relatively isolated from the U.S. highway system. I-40 significantly changes accessibility of the port to importers in the mid-Piedmont area of North Carolina, between Raleigh and Greensboro. These manufacturers historically were shipping through Norfolk, Virginia, or Charleston, South Carolina, to the south (Figure 6). The GIS-T data base analyzed the specific locations of each of several hundred manufacturers in North Carolina to determine their shipping patterns. Data from the PIERS system were used to obtain the overall geography of these patterns related to the existing Interstate system connecting these sites to the ports and the new Interstate system as changed by the I-40. Revised proximal areas (that is, areas of North Carolina that are closer in time to Wilmington than to other ports) were developed, and the proximal area feature of TransCAD was used to determine how market share would shift to the Port of Wilmington, based on travel time and increases in accessibility. The analysis found that the coming of I-40 would essentially halve the travel time from the Port of Wilmington to major manufacturers, thus providing the port with a unique opportunity to make its case to North Carolina exporters.

Changes in Commuter Sheds

An important impact of I-40 is that isolated towns in the corridor are now within easier commute distance of larger cities that may

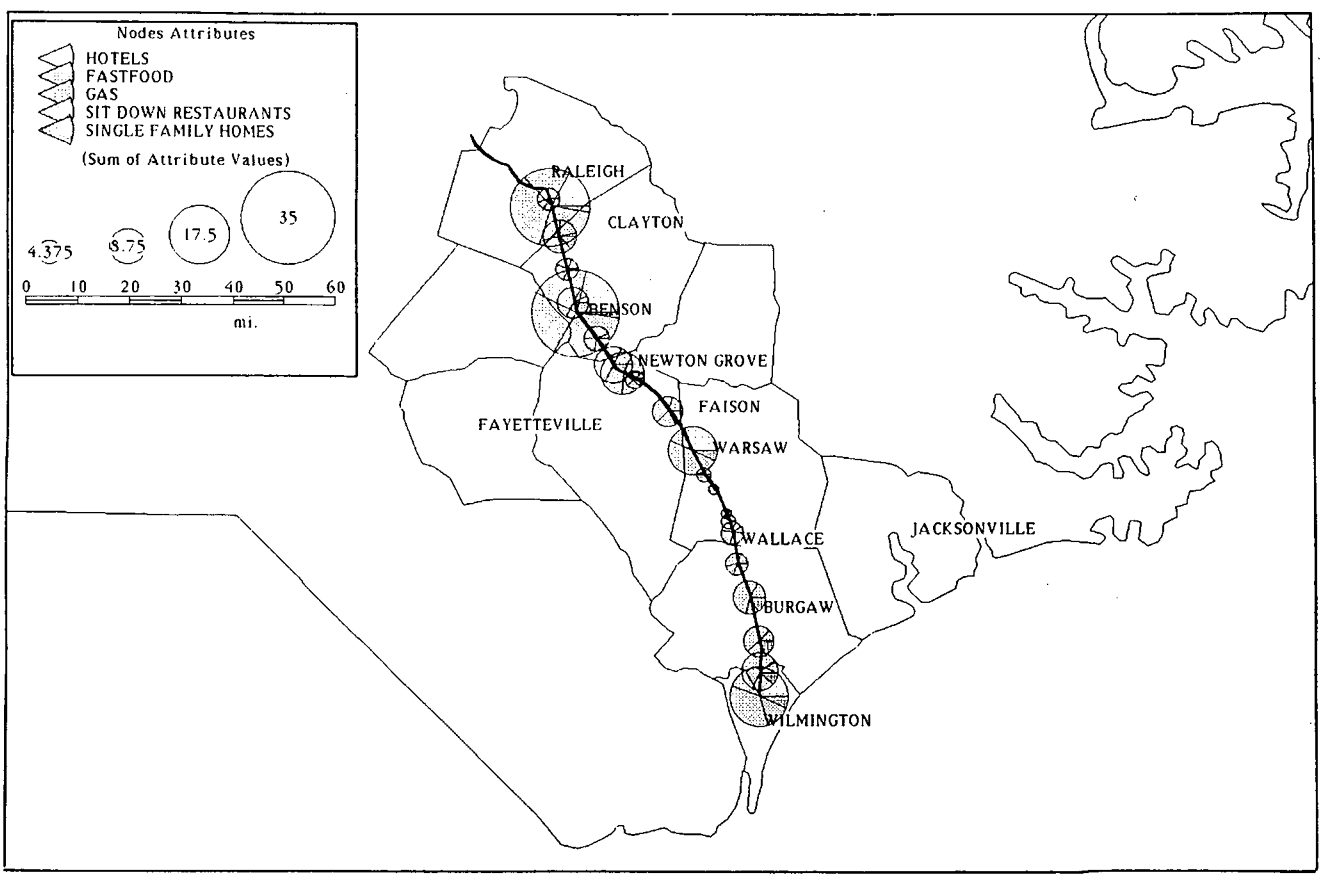

FIGURE 5 Development pressure at I-40 exits.

now compete with them for labor. The result may be significant out-migration of workers to the larger cities, where wages are typically higher. A similar effect occurs with shopping statistics, in that retail "leakage" from rural areas adjacent to metropolitan regions often increases when those areas are connected to the metropolitan region by a high-speed transportation facility. Using the GIS-T and travel time skimming capabilities, the research team was able to identify travel time contours from each major town within the corridor and to determine the number of residents and work force participants whose travel time to large metropolitan areas is likely to have shifted substantially (Figure 7). The team was thus able to analyze the extent to which communities within the corridor would be affected negatively by greater accessibility to big cities.

Summary

In short, the GIS-T permits the analysis to take on a very graphic and map-oriented feel, as opposed to the more common data tables approach typical in studies of an earlier era. The result was that communities and citizens were able to visualize the effect of I-40 on the corridor more clearly and to understand its probable impacts on their communities. The GIS-T served as a basic tool for facilitating communication between planners, data gatherers, citizens, and policy makers.

CASE 2: CAROLINAS PARKWAY

Situation and Goals

The Carolinas Parkway study is an example of an application of GIS-T technology to transportation demand forecasting and network modeling. The specifics of the proposal are described in other papers (*6,9*); suffice it to say here that the Carolinas Parkway is a proposed outer ring road around the greater Charlotte metropolitan region. It is envisioned as a limited-access road, four lanes wide, at a distance of 20 to 40 mi from Charlotte, that is designed to link I-77, I-85, and other radial highways. The concept was developed by the Carolinas Transportation Compact as part of a 50-year transportation visioning effort. The Carolinas Parkway would provide circumferential access in the region, permitting through traffic to avoid the developed part of the region and encouraging economic development in rural isolated counties of the area. It is part of a broader transportation vision study intended to coordinate land use and transportation planning in a way that creates an attractive efficient regional transportation system that supports economic development objectives.

The Carolinas Parkway proposal was cooperatively studied by the state highway agencies of North and South Carolinas. The consultant (Parsons Brinckerhoff Quade and Douglas) contracted with University of North Carolina–Charlotte to develop traffic forecasts for the parkway. Considerable work had been undertaken by the university earlier to develop a regional transportation network for the greater Charlotte metropolitan area (Figure 8). As a result, a calibrated demand model and network was available for modeling future alternatives. The goal of the modeling study was to develop a series of traffic and land use forecasts for the years 2010 and 2030, with and without the parkway (Figure 9).

Use of GIS-T

The primary functional features of the GIS TransCAD were in transportation modeling. Display of information was also deemed an important feature, particularly to show information in different ways.

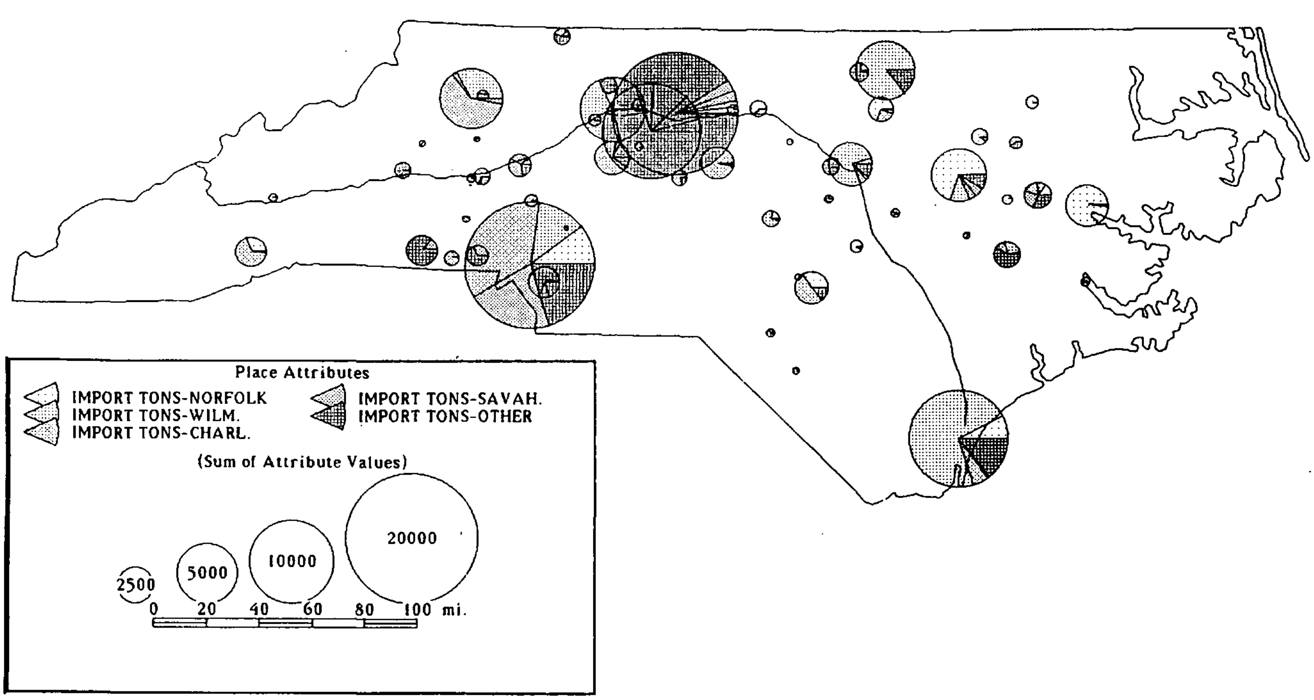

FIGURE 6 Import tons to North Carolina companies, July through September 1990.

The TransCAD modeling system itself consists of a PC-based GIS augmented with many procedures for transportation modeling. The GIS portion contains the usual features and capabilities:

- Layers:
  - –Points (cities and nodes),
  - –Areas (zones, tracks, counties), and
  - –Lines (street links).
- GIS-T capabilities:
  - –Data capture (digitized or scan),
  - –Data storage and retrieval (editor to store, display, and update information),
  - –Query (query certain features on the screen or label features),
  - –Display (with color, four selected features),
  - –Spatial analysis (overlay polygons and generate area buffer zones), and
  - –Cartographic products (thematic maps, etc.).

The TransCAD modeling engine in the system may be thought of as a traditional but simplified UTPS model. It consists of a simplified gravity modeling procedure using one trip purpose (later versions allow more purposes) supported by a number of assignment capabilities. Data can be developed from population and employment statistics, as in spreadsheet environments. In this case, trips were loaded directly onto the TransCAD network through loading nodes, intersections on a sketch regional network about 100 mi across. No formal zone structure was used, as is common in other packages. Additional future road proposals were also coded into the system to represent the transportation improvement programs of the regional organizations in the area. Travel modeling was done using an all-or-nothing assignment methodology, without capacity restraint. This was necessary because the regional network is a sketch network that does not contain all roads.

Modeling and Analysis

Calibration was achieved by comparing estimated and actual traffic volumes on the sketch network, then adjusting the decay coefficient of the simplified gravity model to improve accuracy. After overall network performance measure in vehicle miles traveled (VMT) and vehicle hours traveled (VHT) was achieved, remaining differences between estimated and actual traffic, by link, were pivot-pointed into the future and applied to future projections. Essentially, the researchers traded off the need for greater accuracy

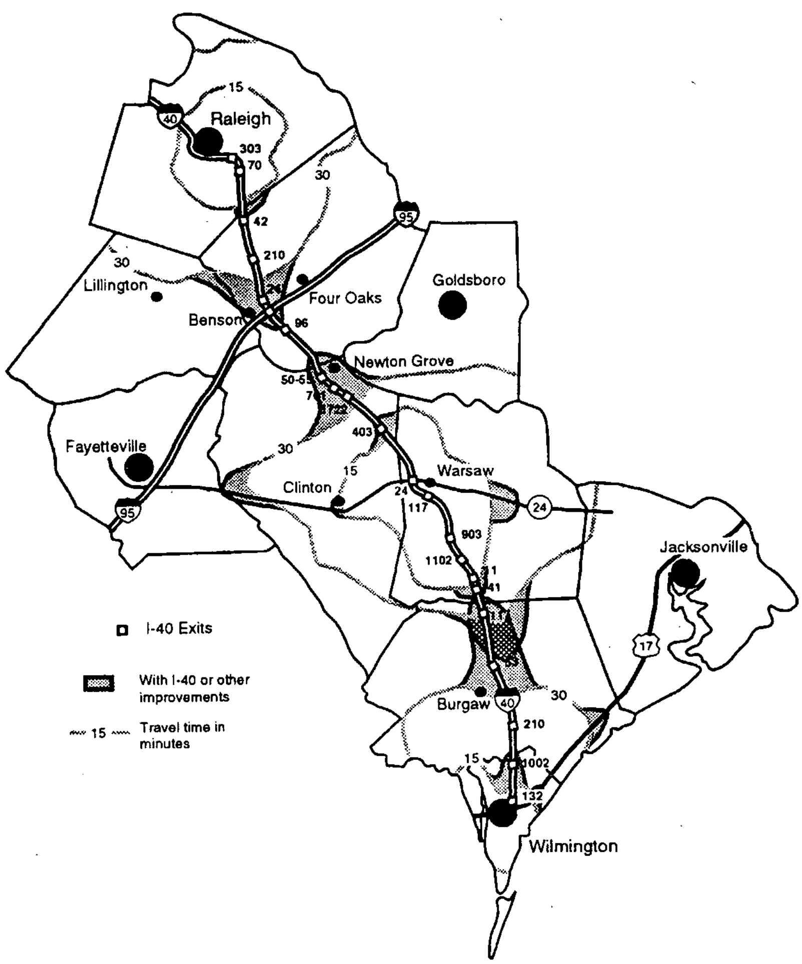

FIGURE 7 Commuter areas for Raleigh, Warsaw, and Wilmington, I-40 corridor.

and greater detail, recognizing that the 40-year forecasting horizon would not be consistent with a detailed network structure or detailed zone structure. This application is therefore a sketch model application, highly idealized and very long range, so the many details that would be needed in other models (e.g., multiple trip purposes, trip length, link-level calibration) are not necessary.

Development of alternatives was undertaken by the consultant working closely with the transportation modeling team (Figure 10). All total, seven separate proposals were prepared and analyzed, in addition to a base year consisting of 1989 traffic. These seven proposals are combinations of years (2010 and 2030), land use patterns, and parkway presence or absence. Traffic was forecasted by growing future trip ends according to projections developed in land use forecasting portion of the study. Raw results from assignment were adjusted by multiplying the forecast volumes by pivot points gained from model calibration. No speed feedback analysis was used for the study, nor was capacity restraint used in estimating traffic.

Analysis and display of assignment results relied heavily on the GIS. Forecasts for each assignment were stored automatically in the GIS by link, where it is a simple matter to show percentage change or ratios with base traffic (Figure 11). Several comparative analyses were prepared, showing traffic on key road segments in the region, and the usual tables for regional VMT, speed, VHT, and emissions were also developed. Thus a visual feel for the parkway's impact was quickly developed, and the GIS-T was very useful in showing how changes in local road volumes would occur with and without the parkway. The entire modeling study was undertaken in about 4 months, including preparation of the technical reports.

OBSERVATIONS

Among the positive benefits of using GIS-T's for studies such as these are the following:

1. Increased visual power,
2. Rapid multiple evaluations,
3. Coordinated view of the entire region,
4. Speed of analysis,
5. Empowerment of citizen and local groups using diffused technology, and
6. Efficient data storage.

On the other hand, the studies also showed that the GIS analysis capabilities also imposed significant limitations and constraints on the planning process. These include

1. Awkward blend of models, which may be missing desirable features;
2. Oversimplicity;
3. Lack of accuracy;
4. Incompatibility of results with other modeling systems;
5. Simplistic analysis capability compared with statistical methodology; and

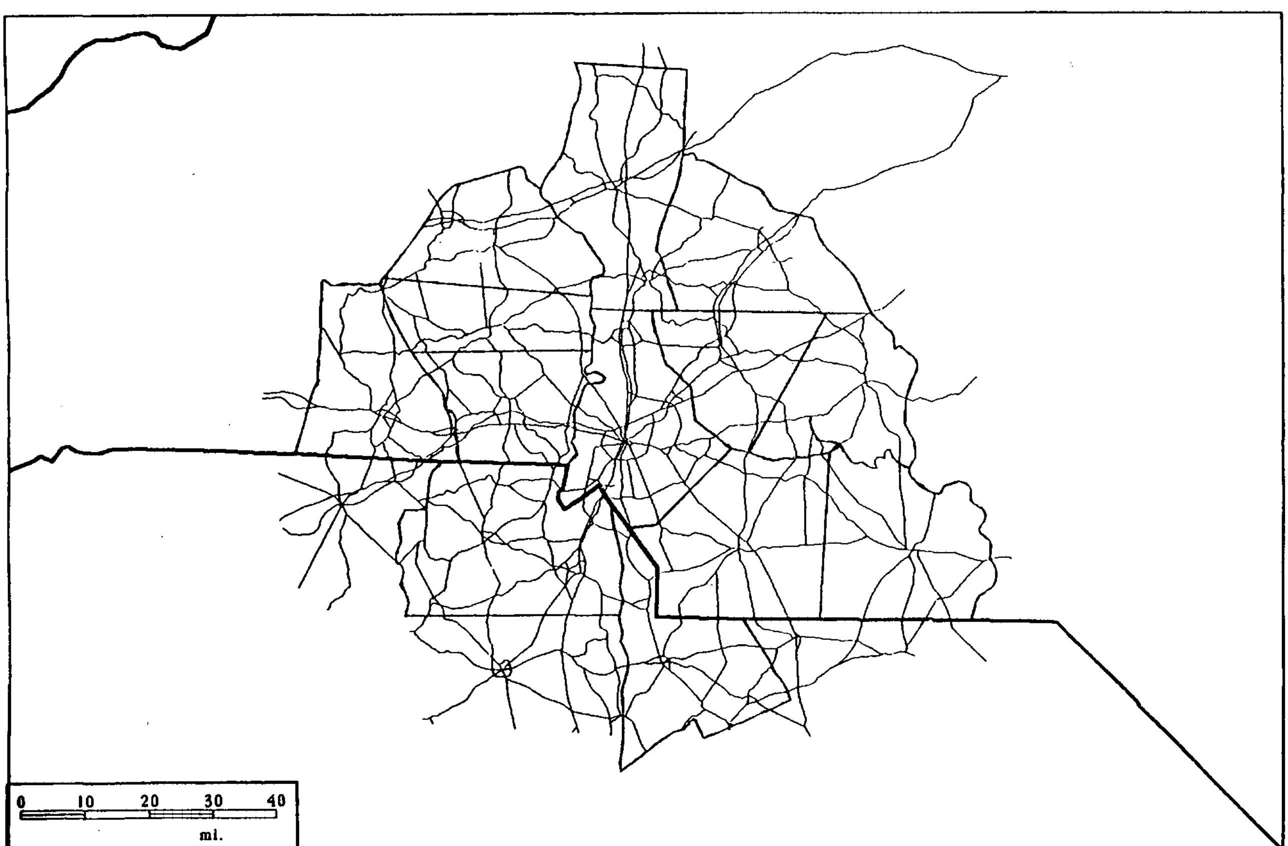

FIGURE 8 Base network for Charlotte metropolitan region.

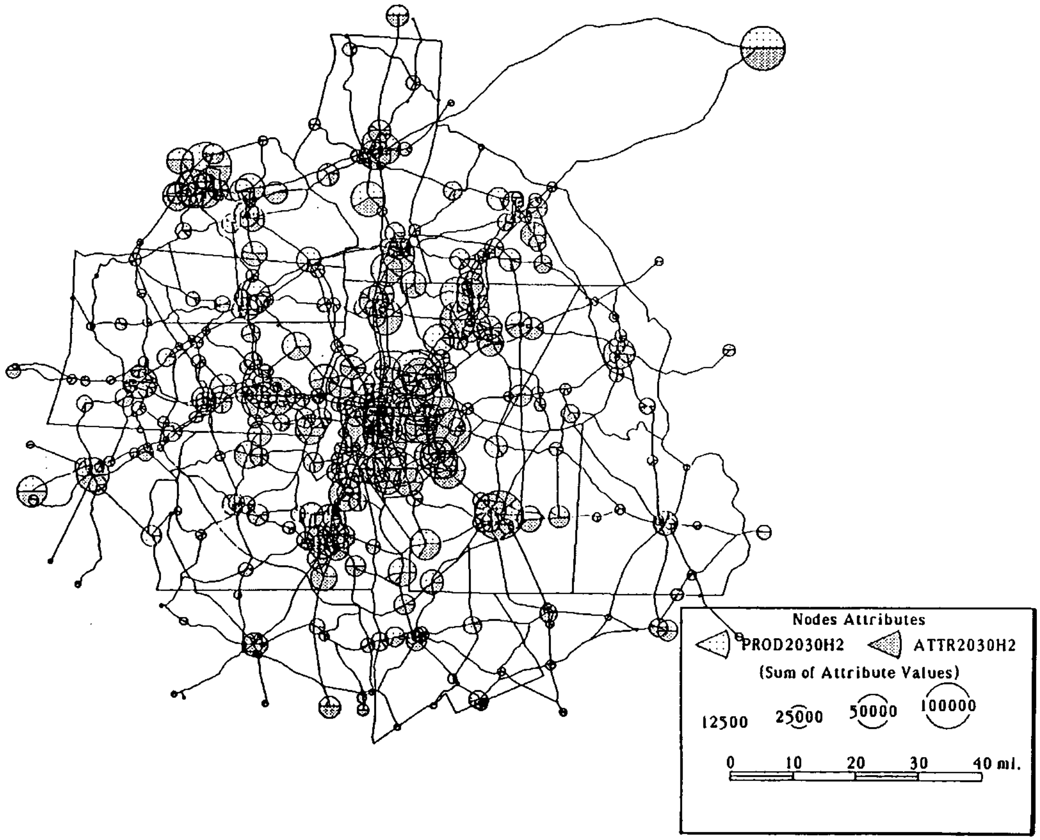

FIGURE 9 Productions and attractions for 2030 high influence.

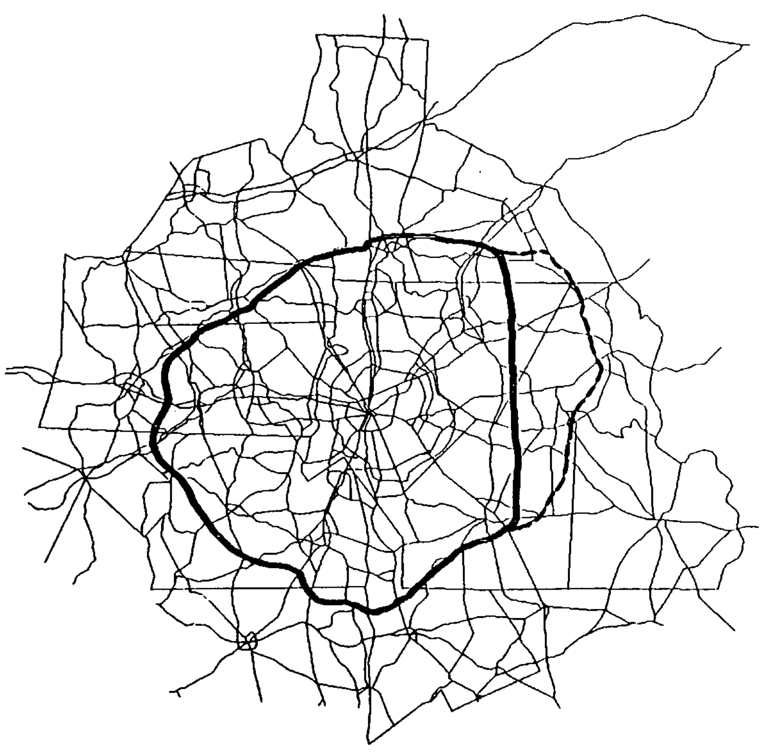

FIGURE 10 Carolinas Parkway alternatives.

FIGURE 11 Traffic forecast for 2030 high Parkway influence

6. A tendency to focus on "gee whiz" displays rather than on substantive findings.

Although these features are inherent in the development of rapid sketch planning technologies, the GIS-T's provide a means by which transportation planners can conduct their business more effectively. The greatest payoff of the use of these tools is not the speed of the analysis (which is a substantial feature) but the capability of the tools to transmit complex relationships that could not be understood except in graphics and map form. If one picture is worth a thousand words, then one map may be worth a thousand pictures. The key is the ability to describe findings spatially and to show how communities and subelements of a region are related, whether the region is a transportation corridor or a group of counties bound together by economic circumstances. The use of GIS-T technology produces a "eureka" effect in participants, often enlightening them to see relationships between communities within a region that were previously not well understood. The tool thus provides a mechanism for generating political support and consensus for interregional transportation proposals that could not be otherwise generated. Time will tell whether these capabilities ultimately have the effect of increasing the strength of regional groups, and whether that strength is ultimately translated into more cost-effective investment.

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Publication of this paper sponsored by Committee on Transportation Data and Information Systems.

Geographic Information System Environment for Transportation Management Systems

BRAD H. JOHNSON AND MICHAEL J. DEMETSKY

The management systems that are required of states by the Intermodal Surface Transportation Efficiency Act of 1991 have a common element in their need for a well-established data base. In this regard, computerized geographic information systems (GISs) are emerging as efficient and effective tools for managing transportation information resources. These systems integrate geographic (or spatial) information displayed on maps, such as roadway alignment, with attribute (or tabular) information characterizing features, such as composition and age. The development of a prototype transportation management GIS data base for pavement management is described to illustrate the use of a GIS framework for transportation management systems. The data base that was developed covered two counties in Virginia, and the representation of the roadway system in these two jurisdictions established the reference for the pavement attribute data. The same geographic data base could be used for other management systems, although it would need to include slight additions for safety and bridge management and additional facilities for congestion, intermodal, and public transportation management.

In December 1991, the President signed into law the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) (P.L. 102-240). Among the provisions of ISTEA is a requirement for state highway agencies to establish formal information management systems related to bridge management, intermodal transportation, pavement management, public transportation, safety, and traffic congestion.

At least one of these systems, pavement management, has existed since March 6, 1989, when FHWA issued a series of guidelines "to set forth a policy to select, design, and manage federal-aid highway pavements in a cost-effective manner and identify pavement work eligible for federal-aid funding" (*1*).

The policies in the *Federal-Aid Highway Program Manual* (FHPM) address five functional areas: pavement management systems, general pavement design considerations, pavement design of new and reconstructed pavements, pavement design of rehabilitated pavements, and safety. In light of the provisions of ISTEA, the portion of FHPM concerned with pavement management systems is of particular significance. According to the FHPM, a pavement management system is "a set of tools or methods that assist decision makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in a serviceable condition" (*2*).

The policy section of the FHPM establishes the federal policy concerning pavement management systems as follows: "each State Highway Agency (SHA) shall have a pavement management system (PMS) that is acceptable to FHWA and is based on concepts described in American Association of State Highway and Transportation Officials publications including its 1985 *Guidelines on Pavement Management*" (*2*).

In establishing this policy, FHWA recognized that because of rising costs, reduced resources, increased system utilization, needs that exceed revenues, and a changing emphasis from system expansion to system preservation and rehabilitation, a systematic approach to managing pavements was needed to protect the investment in today's highway network infrastructure and to maximize the use of every available highway dollar. FHWA judged that a pavement management system could give decision makers key information to address these needs.

A frequent problem with providing this information, however, is that the relevant data have typically been collected and compiled by a number of units within state and local government. Even when the existence of these data is known, often the data are not readily usable in the decision-making process because they are of a form or content different from other data being used. This is the classic condition of being data rich and information poor.

At this time, state departments of transportation have gained experience only in developing pavement and bridge management systems, although some are only in the formative stages of development, especially bridge management. The states are only beginning to consider the scope and structure of management systems for highway safety, traffic congestion, public transportation facilities and equipment, and intermodal transportation facilities and equipment.

One common element of all these management systems is the need for its data base to include information from a variety of sources. The data base is the driver of a process that includes assessment, forecasting, development of alternatives, evaluation of alternatives, decision analysis, and implementation.

Thus for any transportation management system to be effective, a sound data base methodology is required. In this regard, computerized geographic information systems (GISs) are emerging as efficient and effective tools for managing transportation information resources. These systems integrate geographic (or spatial) information displayed on maps, such as roadway alignment, with attributes of the geographic features, such as the composition and age of the roadway's pavement structure.

PURPOSE AND SCOPE

This paper describes the development of a prototype transportation management GIS geographic information base for pavement man-

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agement. It was decided to use Virginia's Albemarle and Greene counties as the geographic study area. This will serve as a demonstration of the capabilities of GIS for providing the framework for any type of management system. For example, the entire data set for a safety management system may differ from that of the pavement management system, but some elements will be common and the geographic base will be the same. Hence, an integrated data base that serves both systems is a more effective design than separate systems.

Infrastructure managers are typically concerned with three fundamental questions: What is the current condition of their area of responsibility? What is the trend of this condition? How long before some major action is necessary? The more informed the manager is, the more effective the manager's decisions are. Managers also need to know average trends in order to identify anomalies and act before small problems become major problems. Managers need to know how much time they have to act, as well. This information is needed not only for deciding which technical course of action to take, but also for forecasting budgets.

Pavement management, for example, is concerned primarily with budgetary issues, such as how much money is needed to maintain the roadway system at a prescribed level of condition, which is usually set by policy. Therefore, to support this decision-making process, the GIS will need to

- Identify current pavement conditions,
- Identify current pavement condition trends, and
- Forecast when and where major maintenance actions will be needed.

Such requirements for pavement management illustrate the types of questions that drive any transportation management system. For example, an intermodal management system might need to

- Identify current conditions of intermodal terminals,
- Identify ground access to intermodal facilities, and
- Forecast intermodal facility needs.

These management systems are viewed as providing information for decision makers for planning and programming. All will possess a common geographic base and require similar data bases among themselves.

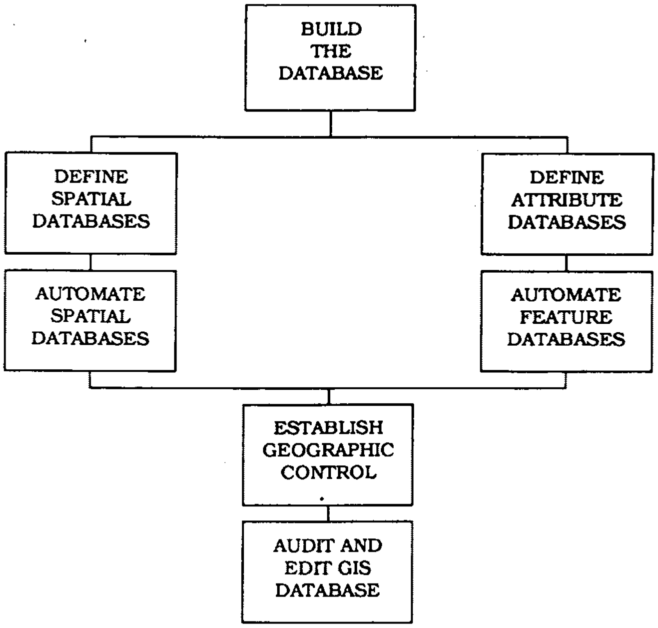

FIGURE 1 Building of GIS data base.

FIGURE 2 Study area (cover: DLG-orig).

METHODOLOGY

The approach to developing a GIS data base for pavement management was organized around three major tasks: defining the problem, developing the GIS, and developing GIS applications.

GIS Development

A review of current microcomputer architecture and software was undertaken, and an appropriate workstation was acquired. With regard to software, compatibility between programs was critical, since the condition/format of relevant spatial and attribute data was unknown. Therefore, software was selected that would access the widest possible spectrum of data formats.

TABLE 1 Unique Graphic Line Elements

Interstate Routes	Virginia Routes	National Routes	Political Boundaries
I-64	VA-6	US-29	Albemarle County
	VA-20	US-29 Business	Charlottesville (M)
	VA-22	US-33	Charlottesville (C)
	VA-53	US-250	Jack Jouett (M)
	VA-151	US-250 Business	Rivanna (M)
	VA-230		Samuel Miller (M)
	VA-231		Scottsville (M)
	VA-240		Scottsville (T)
	VA-302		White Hall (M)
	VA-317		Greene County
	VA-388		Monroe (M)
			Ruckersville (M)
			Shenandoah (NP)
			Standardsville (M)
			Standardsville (T)

NOTES: (C) = city
(M) = magisterial district
(NP) = national park
(T) = town

The microcomputer GIS software PC-Arc/Info was offered for evaluation. Since this is one of the more frequently used GIS platforms and since it offers data interchange capabilities with a wide range of other GIS and non-GIS formats, it was chosen for this research. Other off-the-shelf software packages used in this research included AutoCAD, dBase, Lotus 1-2-3, and WordPerfect. The use of these five software packages eliminated the need for custom programming.

GIS Application Development

GIS application development involved bringing all of the pieces of the management system together: the establishment of the geographic base map (or spatial data base as it is commonly called); the establishment of the thematic, or attribute, data base related to the management system of concern; and, most important, the establishment of the geographic referencing scheme, which will tie the spatial and attribute data bases together.

Before proceeding, it is important to understand how a GIS organizes its data bases into a single data base. Within a GIS data base, data are organized into one of four types (*3*): lines (or arcs), points, areas (or polygons), and attributes (or features). Lines, points, and areas refer to spatial data, and attributes refer to the thematic data associated with the management system. Last, a coverage is the term that Arc/Info assigns to a GIS data base once it has been established within the GIS environment. Since a coverage has both spatial data and attribute data, it is used to distinguish integrated data sets from component spatial and attribute data sets.

Spatial Data Base Development

Spatial data base development, as shown on the left side of Figure 1, began with an extensive search to determine whether any local agency had previously established a GIS within the two-county study area. None was found. The search then concentrated on finding existing automated cartographic data bases for the two counties within the public sector, of which only one was found: U.S. Geological Survey (USGS) digital line graphs (DLGs).

The DLGs for Albemarle and Greene counties had recently been updated in conjunction with the U.S. Census Bureau's 1990 Decennial Census for use in its Topologically Integrated Geographic Encoding and Referencing (TIGER) system. These DLGs were developed from the 1:100,000 scale USGS map series. The quadrangle maps constitute the foundation of the spatial data bases. A copy of the DLGs for these counties was obtained from the State Data Center at Alderman Library (Government Documents Section) at the University of Virginia.

The DLGs had been processed into three Arc/Info coverages, but no other processing had taken place. These three coverages encompassed Albemarle County (excluding the city of Charlottesville), the city of Charlottesville, and Greene County.

The three coverages contained political boundaries; electric, gas, and telephone trunk lines; rivers and lakes; as well as the

TABLE 2 Initial GIS Coverages

Coverage Name	Coverage Type	Contents
BOUNDARY	Polygon	Albemarle & Greene County Boundaries
JURISDIC	Line	Magisterial & Municipal Boundaries
COUNTIES	Polygon	BOUNDARY & JURISDIC contents
PRIMARY	Line	Interstate & Primary Highways
MAJORSEC	Line	Major Secondary Highways

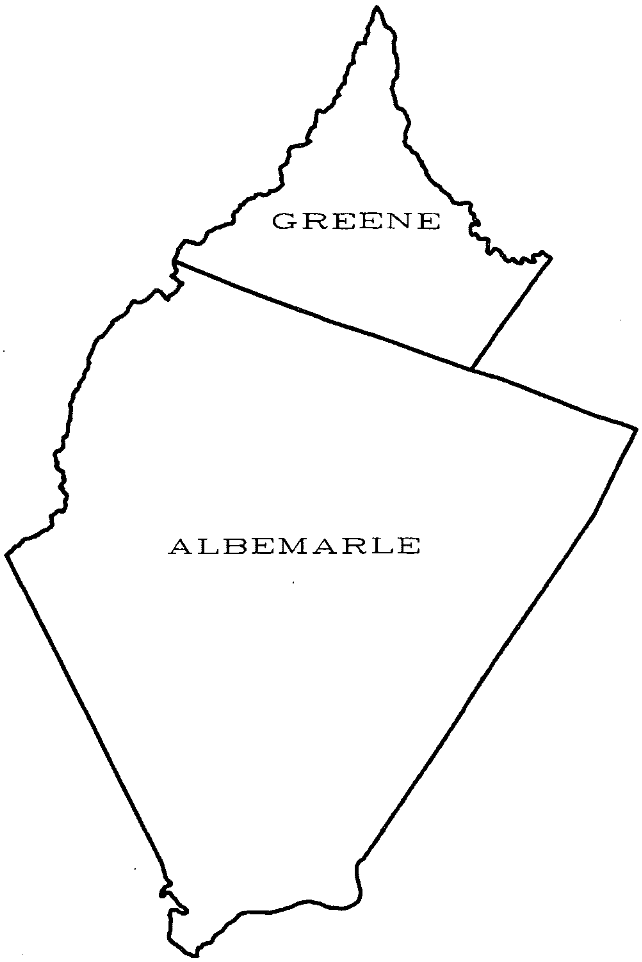

FIGURE 3 Limits of study area (cover: Boundary; source: DLG-Orig).

roadway system. However, these features were intermingled in such a way that a road was indistinguishable from a river or any other line feature. This was an error not in the data, but in the way that the data are routinely distributed.

Automating these spatial data bases required digitizing by the USGS, conversion of the initial DLGs to Arc/Info GIS coverages, and editing the resultant coverages to define individual graphic elements. The first two steps were accomplished external to this research and no verification of the accuracy of the original data was performed. In fact, several errors were found during data editing (e.g., lines representing no apparent physical feature).

Editing the spatial data (defining the individual line elements) was completely within the scope of this research. The first step was to combine the three coverages (Albemarle County, Charlottesville, and Greene County) into one coverage encompassing the entire study area (Figure 2). Although this step was not technically necessary, it aided the editing process.

This combined coverage was next transferred to a computer-aided design and drafting (CADD) environment for graphic editing. This transfer was done because the CADD environment is better suited than the GIS environment to the nature of the graphic editing task. The GIS software contains an established set of routines for accomplishing this task.

Once transferred to CADD, each graphic element contained in the file had to be examined to ascertain whether it was a segment of a road and whether it was a segment of an Interstate highway, primary highway, secondary highway, or another road. If the graphic element was a road and part of an Interstate, primary, or an intersecting secondary road, the element was copied to a new layer within CADD. If it was not a road but a political boundary, it was also copied to a new layer within CADD. If the element was neither, a new element was selected.

When this task was completed, each new layer was examined with individual segments of each roadway or boundary connected to form a continuous line element. For example, after the first step, one might have 30 or even 130 discrete pieces of roadway, which when combined represent the extent of a given roadway. This step combined these individual pieces into one piece. After this step, the line elements shown in Table 1 had been established.

After graphic editing, the next step was to reintroduce the edited graphic file back into the GIS. Arc/Info also contains a routine to accomplish this task. On completion of this step, five unique coverages had been established within the GIS (Table 2).

Arc/Info establishes four standard fields in polygon data bases: "area," "perimeter," "cover_," and "cover_id." Although "area" and "perimeter" are self-explanatory, "cover_" and "cover_id" need further clarification. "Cover_" is a reference number that Arc/Info assigns to each polygon within the coverage. "Cover_id" is a reference number that the user may assign to each polygon within the coverage.

Figure 3 displays the polygon coverage Boundary, the limits of the study area. The data dictionary (or structure of the data base) for this coverage is shown in Table 3. The cover_id, "boundary.i," was assigned the respective Virginia Department of Transportation county reference number: 2 for Albemarle and 39 for Greene. In this fashion, existing search, sort, and reporting routines could be used. The last three fields ("co_name," "co_symbol," and "sq_miles") were added to facilitate processing. The field "co_name" is self-explanatory. "Co_symbol" contains a number used for shading the counties on displays (Figure 4). "Sq_miles"

TABLE 3 Boundary Data Dictionary

Field Name	Field Type	Field Width	No. of Decimals
Area	Numeric	13	6
Perimeter	Numeric	13	6
Boundary_	Numeric	11	0
Boundary_i	Numeric	11	0
Co_Name	Character	9	
Co_Symbol	Numeric	2	0
Sq_Miles	Numeric	6	2

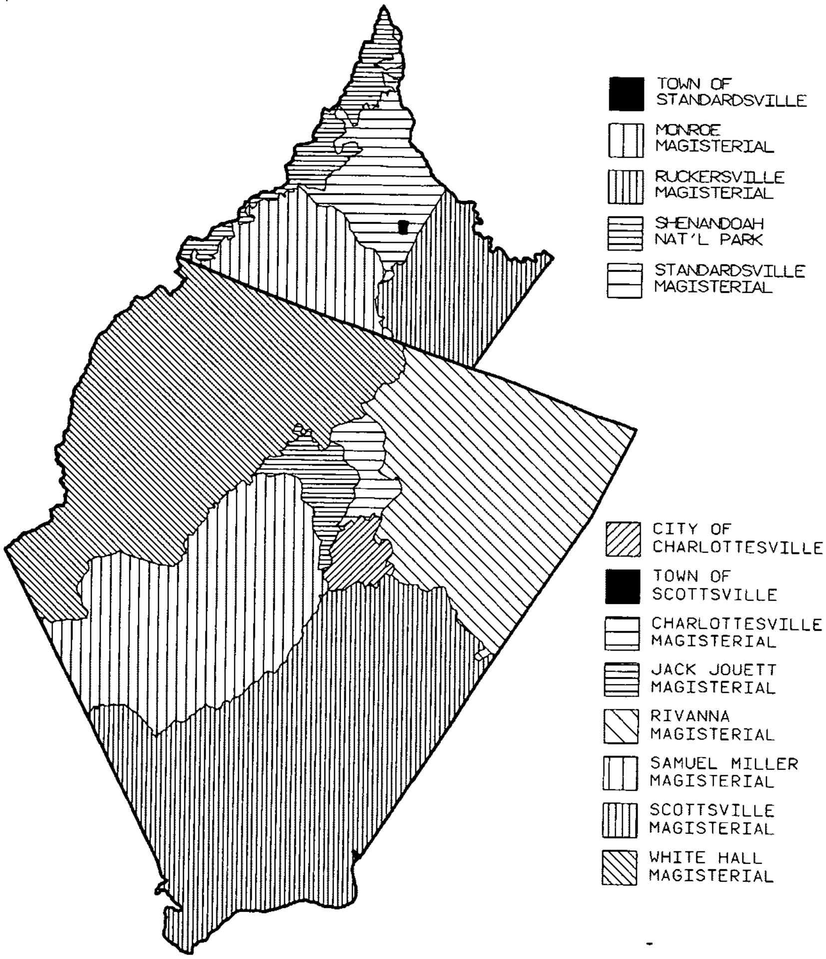

FIGURE 4 Counties in study area.

is also self-explanatory and has been calculated on the basis of the value for "area," which was entered in square meters in the original DLGs.

Arc/Info establishes seven standard fields in line data bases: "fnode_," "tnode_," "lpoly_," "rpoly_," "length," "cover_," and "cover_id." "Fnode_" is the internal Arc/Info node number from which the line originates, and "tnode_" is the internal node number at which the line ends. "Lpoly_" is the "cover_" of the polygon to the left of the line, and "rpoly_" is the "cover_" to the right. "Length" is self-explanatory; "cover_" and "cover_id" are similar to those used in the polygon data base except that here they are related to line elements.

Table 4 gives the data dictionary for the line coverage Jurisdic. When overlaid with the Boundary coverage, internal political jurisdiction boundaries are shown as in Figure 4. This new coverage, Counties, functions as both a polygon and a line coverage. The data dictionary for this coverage is shown in Table 5.

TABLE 4 Jurisdic Data Dictionary

Field Name	Field Type	Field Width	No. of Decimals
Fnode_	Numeric	11	0
Tnode_	Numeric	11	0
Lpoly_	Numeric	11	0
Rpoly_	Numeric	11	0
Length	Numeric	13	6
Jurisdic	Numeric	11	0
Jurisdic_	Numeric	11	0

TABLE 5 Counties Data Dictionaries

Database	Field Name	Field Type	Field Width	No. of Decimals
Poly	Area	Numeric	13	6
Poly	Perimeter	Numeric	13	6
Poly	Counties	Numeric	11	0
Poly	Counties_i	Numeric	11	0
Poly	Boundary_	Numeric	11	0
Poly	Boundary_i	Numeric	11	0
Poly	Co_Name	Character	9	
Poly	Co_Symbol	Numeric	2	0
Poly	Jurisdic	Numeric	11	0
Poly	Jurisdic_i	Numeric	11	0
Poly	Jur_Name	Character	25	
Poly	Jur_Symbol	Numeric	2	0
Poly	Sq_Miles	Numeric	6	2
Line	Fnode_	Numeric	11	0
Line	Tnode_	Numeric	11	0
Line	Lpoly_	Numeric	11	0
Line	Rpoly_	Numeric	11	0
Line	Length	Numeric	13	6
Line	Counties	Numeric	11	0
Line	Counties_i	Numeric	11	0
Line	Line_Code	Numeric	2	0

TABLE 6 Primary Data Dictionary

Field Name	Field Type	Field Width	No. of Decimals
Fnode_	Numeric	11	0
Tnode_	Numeric	11	0
Lpoly_	Numeric	11	0
Rpoly_	Numeric	11	0
Length	Numeric	13	6
Primary_	Numeric	11	0
Primary_id	Numeric	11	0
Rt_Number	Numeric	4	0
Rt_Suffix	Character	3	
Rt_Name	Character	11	
Line_Code	Numeric	2	0
Distance	Numeric	5	2

TABLE 7 Majorsec Data Dictionary

Field Name	Field Type	Field Width	No. of Decimals
Fnode_	Numeric	11	0
Tnode_	Numeric	11	0
Lpoly_	Numeric	11	0
Rpoly_	Numeric	11	0
Length	Numeric	13	6
Majorsec	Numeric	11	0
Majorsec_i	Numeric	11	0
Rt_Number	Numeric	4	0
Rt_Suffix	Character	3	
Rt_Name	Character	11	
Line_Code	Numeric	2	0
Distance	Numeric	5	2

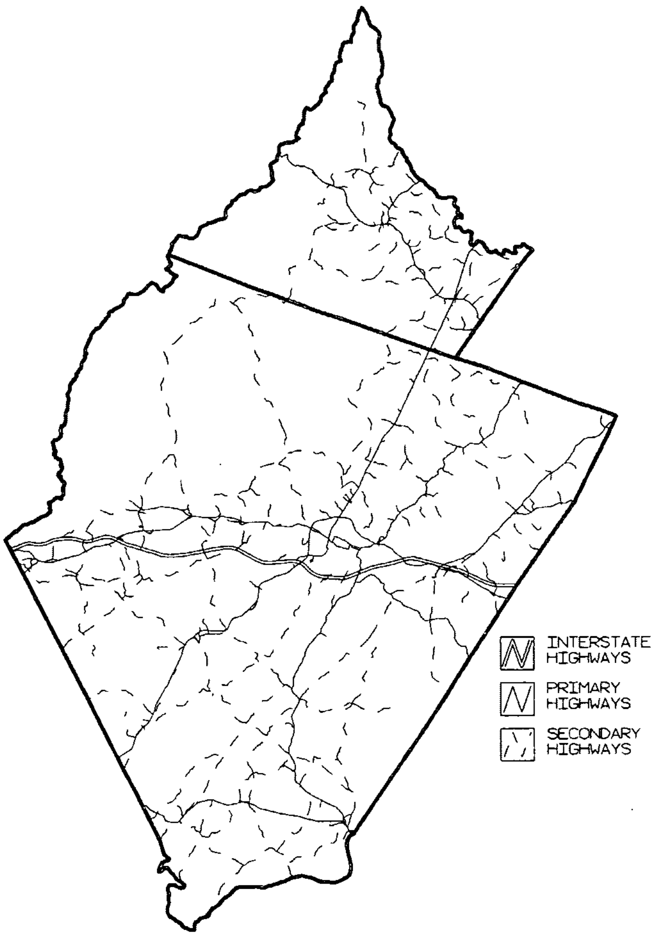

FIGURE 5 Major roadways in study area (covers: Boundary, Primary, and Majorsec).

The data dictionaries for the line coverages, Primary and Majorsec, are given in Tables 6 and 7. Overlaying Counties with Primary and Majorsec produced Figure 5 showing the major roadways within the study area.

Attribute Data Base Development

The spatial data base established a referencing framework for all transportation management systems. The common activities inherent within the management systems that will dictate the requirements for the attribute data of the catalogued facilities include

- Defining and monitoring the magnitude of the problems,
- Identifying transportation improvement needs,
- Analyzing alternative solutions to the problems and assessing their effectiveness in solving them, and
- Measuring the effectiveness of the implemented actions.

To address these issues, data, such as traffic volumes, will be required for all of the management systems; others will be tied only to a specific management system such as pavement design data, bridge structure data, or transit vehicle data.

A GIS must therefore start by evolving from a basic reference system to a highly sophisticated collection of attribute data that can be used to illustrate and analyze the questions and issues of decision making.

CONCLUSIONS

A roadway data base was developed on a GIS for aiding in the pavement management decision process. The data base that was developed encompassed two counties in Virginia. A representation of the roadway system in these two jurisdictions provides the basis for establishing attribute data to be used for pavement management purposes. Other roadway-based management systems, such as safety or bridge management, can use this reference base with only slight additions. Other management systems—such as congestion, public transportation, and intermodal management—can supplement the data with additional facilities data and subsequently add to the attribute data. Ultimately, the facility or infrastructure reference system can be used to support all six management systems and share various attribute files as well.

ACKNOWLEDGMENTS

This study was conducted under the sponsorship of the U.S. Department of Transportation and the Virginia Department of Transportation through grants from the Mid-Atlantic Universities Transportation Center. Special thanks go to David C. Wyant, of the Virginia Transportation Research Council; Sonny Daria, of the Environmental Sciences Department at the University of Virginia; and Jack Dangermond, of the Environmental Systems Research Institute, for their contributions to this research.

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The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.

Publication of this paper sponsored by Committee on Transportation Data and Information Systems.

Geographic Information System Decision Support System for Pavement Management

BRAD H. JOHNSON AND MICHAEL J. DEMETSKY

The development of an attribute data base in a geographic information system (GIS) for pavement management is addressed. Two primary types of roadway data are considered: inventory data describing the physical characteristics of the traveled way, and pavement management data describing the actual surface condition of the roadway. The resolution of problems inherent in tying data bases with different geographical references is addressed. The resulting data base is applied to demonstrate how the information is used to support decisions regarding pavement maintenance and rehabilitation. The applications described include annual pavement condition reporting, annual change in pavement condition, change in condition over extended periods of time, and analysis of remaining pavement service life. It is shown that the spatial data base must include the smallest possible roadway segments based on available attribute data bases. It is also shown that once relational links are established between spatial and attribute data, any application within the attribute data file can become accessible through the GIS.

A key element of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) is the requirement for each state to develop and implement management systems in six areas:

1. Highway pavement of federal-aid highways,
2. Bridges on and off federal-aid highways,
3. Highway safety,
4. Traffic congestion,
5. Public transportation facilities and equipment, and
6. Intermodal transportation facilities and systems.

The states must also establish traffic monitoring systems for highways and public transportation.

It is the goal of these management systems to provide data that will improve decision making regarding the infrastructure of multimodal transportation systems. Transportation infrastructure managers are typically concerned with three fundamental questions: What is the current condition of their area of responsibility? What is the trend in this condition? How long before some major action is necessary? This information is needed not only for deciding which technical course of action to take, but also for forecasting budgets.

These requirements can be accomplished with the aid of geographic information system (GIS) technology. The GIS is designed to handle both topology and attribute data. Topology is concerned with the spatial relationship between connecting or adjacent spatial objects such as points, lines, and polygons. Spatial data are used for the graphical representation of a map's subject (e.g., roads, rivers, jurisdictional boundaries, etc.). Attribute data are facts and figures that describe the subject (e.g., pavement width, surface type, thickness, etc.), and they are layered on a geographical base.

For example, consider the application of GIS to pavement management. Here, the decision-making process is enhanced by

- Identifying current pavement conditions,
- Identifying current pavement condition trends, and
- Forecasting where and when major maintenance and rehabilitation actions will be needed.

PURPOSE AND SCOPE

This paper describes the development of an attribute data base for pavement management purposes. A spatial data reference has been developed and described elsewhere (*1*). Two primary types of roadway data are considered: inventory data describing the physical characteristics of the traveled way, and pavement management data describing the actual surface condition of the roadway. The resolution of problems inherent in tying data bases with different geographical references together is addressed. The resulting data base was applied to demonstrate how the information is used to support decisions regarding pavement maintenance and rehabilitation. The process that is described can be extended to each of the individual management systems required by ISTEA, and it can also be expanded to integrate a master data base for all of the management systems.

INFORMATION SOURCES

The desired attribute data for a pavement management information base were found in various files that were converted to the GIS base. The Roadway Inventory System (RIS) and the Highway Traffic Record Information System (HTRIS), both maintained by the Virginia Department of Transportation (VDOT), were used as primary sources of roadway inventory information. Other sources included the Virginia "tourist" map and individual county roadway maps, also produced by VDOT. Pavement management data were found in two places: HTRIS and its predecessor, the Pavement Management Information System (PMIS).

In reviewing the data, it was found that only 1992 pavement management data were being entered into HTRIS and that pave-

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ment rating data for other years, which are contained in PMIS, would not be converted. The significance here is that the old PMIS and the new HTRIS use different referencing systems. PMIS, like RIS, employs a milepost system, which begins anew at each county line for each route. Although in many cases a regimen is followed for assigning these milepost numbers (i.e., north to south, east to west), this has not always been so. HTRIS, on the other hand, strictly follows such a regimen (south to north or west to east) and does not reset its mileposts (referred to as "nodes") at county lines. Furthermore, even though 1992 ratings have been incorporated into HTRIS, no file or map equating the two referencing systems was found. This makes simultaneous use of the two data bases difficult and is an example of how two data bases that cover identical information can be incompatible because of format.

It was also determined that individual ratings were tied to roadway maintenance sections, which are the portions of the roadway between mileposts or nodes. The problem is that these maintenance sections can vary as each maintenance project is undertaken. In other words, only part of a segment that was resurfaced in earlier years might be resurfaced in a subsequent year, and at that time the maintenance sections are redefined. This points to an incompatibility resulting from data storage and collection techniques, since identical maintenance section numbers from different years may or may not represent the same section of highway.

Thus, automating the existing data bases was not straightforward, because compatibility issues had to be resolved. For the manual data, information was directly entered into the GIS using the keyboard. Information extracted here was limited to route numbers and political jurisdiction names. Information from the RIS was also entered using the keyboard, since the two computer environments (the mainframe for RIS and the microcomputer for the GIS) could not be linked effectively. Data from the PMIS were provided on computer diskette in dBase format. Data from HTRIS were provided on computer diskette in both dBase and text formats as well as in printouts, depending on the subject of the data.

Table 1 presents a summary of the attribute data transferred into the GIS. Also shown is the source of the data item, in what form it was received, and the manner in which it was transferred into the GIS. Since the GIS can directly read dBase-formatted data, the term "data bridge" is used to describe this transfer process.

To minimize the amount of new information that a pavement manager would need to learn, the original coding of the attribute data was retained. Five years of pavement rating data were received: 1988–1991 (from PMIS) and 1992 (from HTRIS). Since this amount of data is impractical to include in detail, a common technique is to generate a data dictionary. Data dictionaries identify the name of the data item, the type of data (alphabetic, numeric, logical, etc.), the number of characters contained in the field, and, for numeric fields, the number of decimal places included in the number. Additionally, when similar data covering multiple years, or periods, are stored in a common data base, a data dictionary will typically include a series of flags to notify the potential user of what data are available for what years or periods. Table 2 presents such a data dictionary for the attribute data included in the GIS.

As is indicated in Table 2, many field names were changed between 1991 and 1992 when HTRIS was implemented. In many cases, the contents of the fields actually remained the same or were altered only slightly. More important, however, information concerning the pavement surface type and its current condition were removed from the main data base in HTRIS and established in separate lookup data bases. These are the data referred to as "Q???" fields at the end of Table 2. These "Q???" fields are links to separate data bases. No particular explanation was found for this major change in data storage. The point is that even where the fields contain the same data between years, if the field name changes, the information cannot be linked electronically—even in normal data processing applications—without considerable additional work. For this reason, data structures should be changed only when absolutely necessary.

DATA INTEGRATION

The next step in building the GIS involved integrating the attribute data base and spatial data base. To accomplish this, geographic control must be established between all related data bases. As in

TABLE 1 Summary of Feature Data

Data	Source	Form	GIS Entry
Route Numbers	Maps/RIS	Paper	Keyboard
Political Jurisdiction Names	Maps	Paper	Keyboard
Highway Type	PMIS/HTRIS	*dBase*	Data Bridge
Surface Mix	PMIS/HTRIS	*dBase*	Data Bridge
Ride Index	PMIS/HTRIS	*dBase*	Data Bridge
Ride Rating	PMIS/HTRIS	*dBase*	Data Bridge
Cracking Frequency	PMIS/HTRIS	*dBase*	Data Bridge
Cracking Severity	PMIS/HTRIS	*dBase*	Data Bridge
Rutting Frequency	PMIS/HTRIS	*dBase*	Data Bridge
Rutting Severity	PMIS/HTRIS	*dBase*	Data Bridge
Pushing Frequency	PMIS/HTRIS	*dBase*	Data Bridge
Pushing Severity	PMIS/HTRIS	*dBase*	Data Bridge
Patching Frequency	PMIS/HTRIS	*dBase*	Data Bridge
Patching Severity	PMIS/HTRIS	*dBase*	Data Bridge
Ravelling Frequency	PMIS/HTRIS	*dBase*	Data Bridge
Ravelling Severity	PMIS/HTRIS	*dBase*	Data Bridge
Flushing Frequency	PMIS/HTRIS	*dBase*	Data Bridge
Flushing Severity	PMIS/HTRIS	*dBase*	Data Bridge
Date of Survey	PMIS/HTRIS	*dBase*	Data Bridge

TABLE 2 Pavement Rating Data Dictionaries

Field Name	Field Type	Field Width	# of Dec	'88	'89	'90	'91	'92
District	Character	20		yes	yes	yes	yes	yes
Residency	Character	20		yes	yes	yes	yes	yes
County	Character	20		yes	yes	yes	yes	yes
RteNum	Character	4		yes	yes	yes	yes	no
BegMile	Numeric	5	2	yes	yes	yes	yes	no
EndMile	Numeric	5	2	yes	yes	yes	yes	no
Length	Numeric	5	2	yes	yes	yes	yes	yes
BegDes	Character	19		yes	yes	yes	yes	no
EndDes	Character	19		yes	yes	yes	yes	no
System	Character	10		yes	yes	yes	yes	yes
CompMonth	Character	2		yes	yes	yes	yes	no
CompYear	Character	2		yes	yes	yes	yes	no
SurfMix	Character	20		yes	yes	yes	yes	no
SurfPrt	Character	8		yes	yes	yes	yes	no
SurfCode	Character	2		yes	yes	yes	yes	no
SurveyDate	Date	8		yes	yes	yes	yes	no
SDate	Character	6		yes	yes	yes	yes	no
RideRating	Numeric	3	1	yes	yes	yes	yes	no
RideRate	Character	2		yes	yes	yes	yes	no
DMR	Numeric	3	0	yes	yes	yes	yes	no
Remarks	Character	80		yes	yes	yes	yes	yes
HwyCode	Character	2		yes	yes	yes	yes	no
HwyType	Character	45		yes	yes	yes	yes	no
DirCode	Character	1		yes	yes	yes	yes	no
LaneCode	Character	1		yes	yes	yes	yes	no
MasterKey	Character	22		yes	yes	yes	yes	no
CrkFreq	Character	1		yes	yes	yes	yes	no
CrkSevr	Character	1		yes	yes	yes	yes	no
RutFreq	Character	1		yes	yes	yes	yes	no
RutSevr	Character	1		yes	yes	yes	yes	no
PushFreq	Character	1		yes	yes	yes	yes	no
PushSevr	Character	1		yes	yes	yes	yes	no
PatcFreq	Character	1		yes	yes	yes	yes	no
PatcSevr	Character	1		yes	yes	yes	yes	no
RavlFreq	Character	1		yes	yes	yes	yes	no
RavlSevr	Character	1		yes	yes	yes	yes	no
FluFreq	Character	1		yes	yes	yes	yes	no
FluSevr	Character	1		yes	yes	yes	yes	no
Factors	Character	6		no	no	no	yes	no
Rte_Id	Character	14		no	no	no	no	yes
BMP	Numeric	5	2	no	no	no	no	yes
EMP	Numeric	5	2	no	no	no	no	yes
Dir	Character	1		no	no	no	no	yes
Lane	Character	2		no	no	no	no	yes
Surf_Date	Character	4		no	no	no	no	yes
Surf_Code	Character	3		no	no	no	no	yes
Surf_Type	Character	2		no	no	no	no	yes
Beg_Desc	Character	30		no	no	no	no	yes
End_Desc	Character	30		no	no	no	no	yes
Rd_Key	Numeric	5	0	no	no	no	no	yes
Rec_Pref	Character	4		no	no	no	no	yes
DRC	Character	6		no	no	no	no	yes
Ref_Node	Character	6		no	no	no	no	yes
Ref_Off	Character	5	0	no	no	no	no	yes
No_Lane	Character	2	0	no	no	no	no	yes
Rated	Logical	1	0	no	no	no	no	yes
Rate_Date	Date	8	0	no	no	no	no	yes
Sched	Character	1	0	no	no	no	no	yes
Q111	Numeric	4	0	no	no	no	no	yes
Q112	Numeric	4	0	no	no	no	no	yes
Q113	Numeric	4	0	no	no	no	no	yes
Q114	Numeric	4		no	no	no	no	yes
Q115	Numeric	4		no	no	no	no	yes
Q117	Numeric	4		no	no	no	no	yes
Q412	Numeric	4		no	no	no	no	yes
Q414	Numeric	4		no	no	no	no	yes

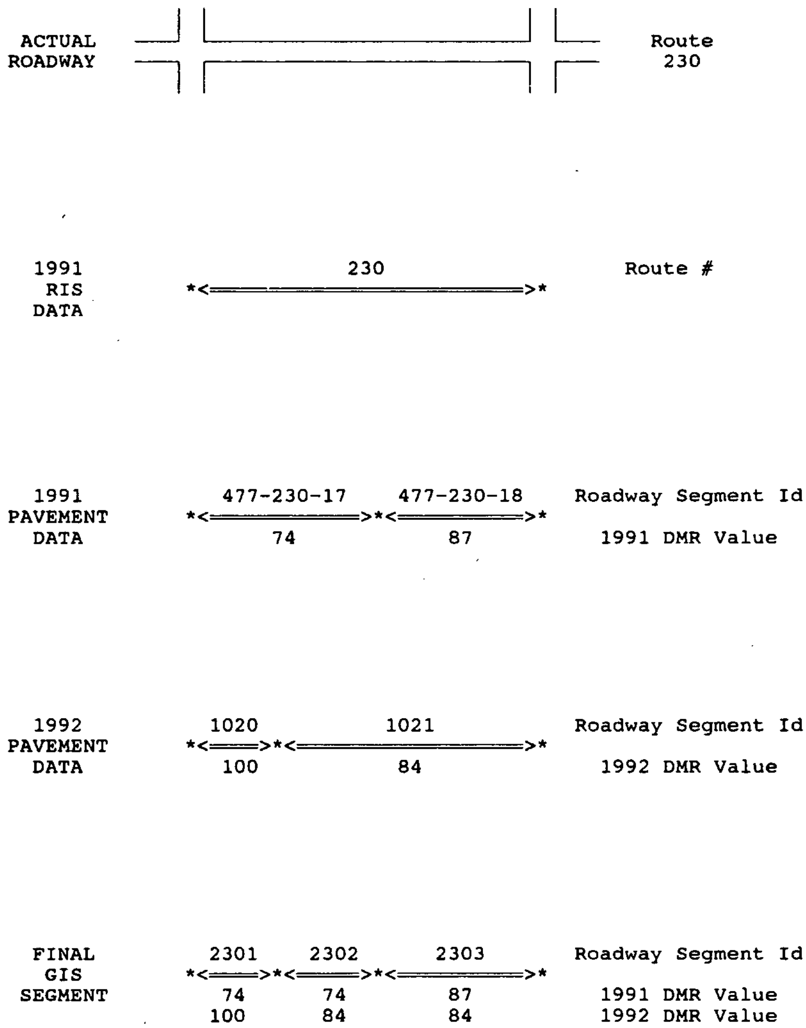

FIGURE 1 Comparison of attribute data structures.

any relational data base, data are linked by fields that contain the same information. For example, the field "address" in one data base can be linked (matched) to the field "address" in another data base, and desired information from the two data bases can then be combined into a single data base.

In a GIS, however, this concept must be extended to encompass the spatial nature of the base-map data. In this research, this was accomplished at the link, or roadway segment, level. Although all of the attribute data bases key data records to a segment of roadway, each data base has its own independent referencing system. Therefore, between the RIS, PMIS, and HTRIS, three numbering schemes exist. Each one, while often describing a similar location, is nevertheless numerically different.

To begin matching these different files, data were sorted and examined by link segment and year. This revealed how often these roadway sections changed. In the case of this study, most sections remained unchanged over the 5 years of pavement data, although the termini of the segments often changed between 1991 and 1992 as the HTRIS coding regime was initiated. An example of this is shown in Figure 1.

Figure 1 displays an actual segment of a hypothetical Route 230. The top of the figure illustrates how this segment exists on the ground. Below this, in order, is the way that this segment is recorded in the RIS, the PMIS (for 1991), and HTRIS (for 1992). In 1991 this segment of roadway was divided into two segments numbered 477-230-17 and 18. These segments had distress management rating (DMR) values of 74 and 87, respectively. In 1992, this same segment was still divided into two segments; however, the termini of the segments had changed as a result of the resurfacing of part of 1991 Segment 477-230-17. The 1992 segment numbers, now in HTRIS, were 1020 and 1021 with DMRs of 100 and 84, respectively. To properly represent this segment in the GIS, it would be necessary to establish three segments for this portion of Route 230 (Figure 1). With this type of geographic referencing, the data from both 1991 and 1992 are now accessible even though they are in differently structured data bases. The GIS establishes an equivalency such that an inquiry as to the 1991 condition of Segment 2301 is retrieved from PMIS Segment 477-230-17 and an inquiry as to the 1992 condition of Segment 2301 is retrieved from HTRIS Segment 1020.

To establish a link between the spatial and attribute data bases, each data base had to include a common reference field. Since none existed, one was established and named "seq" to represent a sequence number for each link along a route. This number was composed of the route number and a sequence number. The route sequence number shown at the bottom of Figure 1 is an example of the "seq" field.

The next step in establishing the link between spatial and attribute data involved combining these spatial roadway segments into groups that matched the pavement condition data records. This was an interactive process using both spatial and attribute data bases. As a spatial group was defined (i.e., Segments 601, 602, and 603 may represent one PMIS roadway maintenance section), the "seq" field that had been added to the PMIS data base was assigned the sequence numbers 601, 602, and 603. In this example, the single PMIS roadway maintenance section data record was duplicated twice, and the resulting three data records were each assigned a unique "seq" number. After the PMIS data base was completely processed in this manner, the HTRIS data base was processed.

Herein lies a drawback to GIS. After this processing, the resulting attribute data bases were significantly larger than they had

TABLE 4 Pavement Condition GIS Data Dictionary (Typical)

Field Name	Field Type	Field Width	# of Decimals
Fnode_	Numeric	11	0
Tnode_	Numeric	11	0
Lpoly_	Numeric	11	0
Rpoly_	Numeric	11	0
Length	Numeric	13	6
Primary_	Numeric	11	0
Primary_id	Numeric	11	0
Rt_Number	Numeric	4	0
Rt_Suffix	Character	3	
Rt_Name	Character	11	
Line_Code	Numeric	2	0
Distance	Numeric	5	2
Seq	Character	5	
DMR_xx	Numeric	3	0
BegMile	Numeric	5	2
BegDes	Character	19	
EndMile	Numeric	5	2
EndDes	Character	19	
Miles	Numeric	5	2
Dir	Character	4	
Surf_Year	Numeric	11	0
Suf_Type	Character	21	
MasterKey	Character	22	
No_Lane	Numeric	1	0
Lane_Miles	Numeric	9	2
Rate_Year	Numeric	11	0
Remarkds	Character	80	
DMR_??	Numeric	3	0
DMR_Chg	Numeric	4	0
DMR_PChg	Numeric	6	1
RideRating	Numeric	3	1
CrkFreq	Character	1	
Crk Sevr	Character	1	
RutFreq	Character	1	
RutSevr	Character	1	
PushFreq	Character	1	
PushSevr	Character	1	
PatcFreq	Character	1	
PatcSevr	Character	1	
RavlFreq	Character	1	
RavlSevr	Character	1	
FluFreq	Character	1	
FluSevr	Character	1	

TABLE 3 Pavement Condition GIS Coverages

Coverage Name	Coverage Type	Description
RATE1988	Line	1988 Pavement Condition Ratings
RATE1989	Line	1989 Pavement Condition Ratings
RATE1990	Line	1990 Pavement Condition Ratings
RATE1991	Line	1991 Pavement Condition Ratings
RATE1992	Line	1992 Pavement Condition Ratings

been previously as a result of the number of data records that had to be duplicated. Whereas in the original PMIS data base, only one data record existed for this particular section of VA-6, inclusion in the GIS broke this single segment into three segments; thus one data record was replaced with three. An alternative concept was envisioned during this processing that might overcome this drawback. A master roadway reference equivalency might be created to function as a bridge between the spatial and attribute data bases. This lookup table could be entered with either the spatial sequence number or the attribute maintenance section number, and the respective equivalent reference number could be found. The advantage of this is that it would eliminate the need to augment the attribute data base. The disadvantage is that a new data base would need to be developed and maintained. Further, in a more powerful computing platform, such as a UNIX-based computer, the GIS software offers a dynamic segmentation option that automatically segments the attribute data records.

At the conclusion of these steps, spatial data and attribute data were tied to a common geographic referencing system through the use of these sequence numbers. The final step in building the data base involved auditing and editing the various data bases to ensure their relative accuracy. Although in this project this effort was straightforward (if not labor-intensive), a more complicated application could require that significant time be spent carrying out this step. This step should not be overlooked, since any subsequent analysis performed on these data will reflect any errors contained in it.

APPLICATION FOR DECISION ANALYSIS

Having now established, linked, and edited both the spatial and attribute data bases, an applied analysis to demonstrate how the GIS can be used to quickly provide information for evaluating pavement conditions was undertaken. The first step was to combine the spatial data base with the individual pavement rating data bases. This process established five "new" GIS data bases, one for each of the rating years. Since these new data bases contain their own spatial and attribute data sets, they are considered coverages as defined earlier. These new coverages are given in Table 3.

Each of these five data bases is structured in a similar fashion. Table 4 presents the typical data dictionary for one of these new coverages. Those fields shown above the dashed line in the table represent the spatial component of this combined data base; those below represent the attribute component.

Figure 2 displays the condition of roadways that were asphalt-surfaced and rated in 1991, as evidenced by the existence of DMR

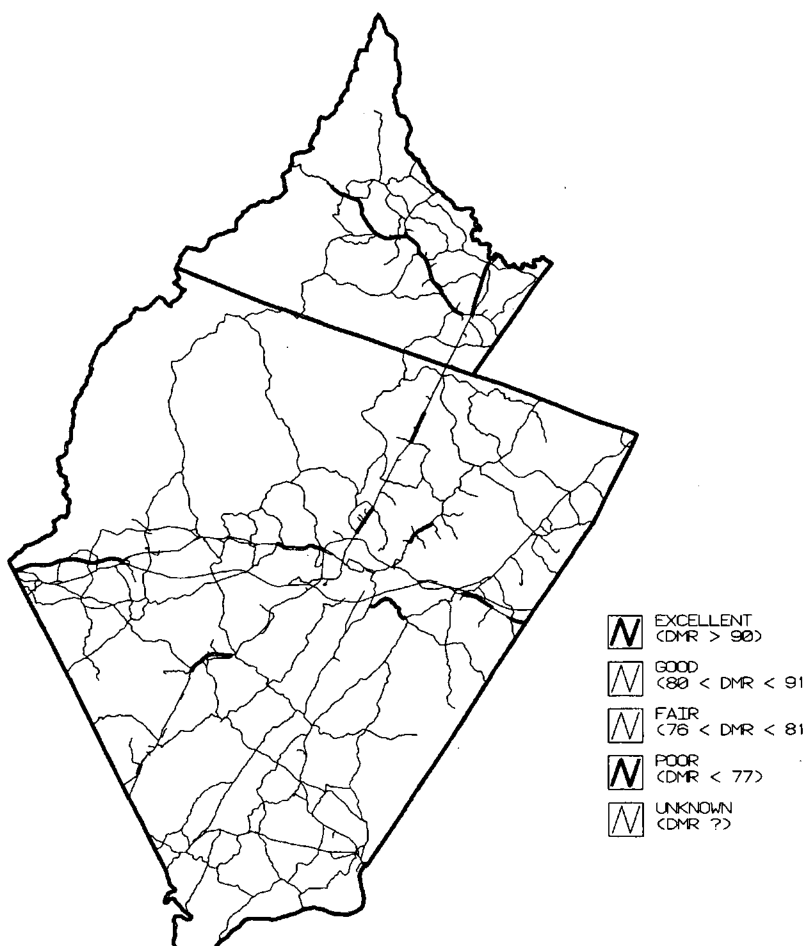

FIGURE 2 Condition of roadways asphalt-surfaced and rated in 1991.

values. This rating, which currently exists only for asphalt-surfaced roadways in Virginia, is derived by formula from the frequency and severity of a number of pavement distresses (Table 1). Within VDOT, a DMR value of 100 represents a roadway in perfect condition, whereas a value of 76 is the threshold at which, ideally, a section is scheduled for maintenance (typically, an overlay for bituminous pavements).

Figure 2 highlights those segments of roadway that in 1991 had DMR values of less than 76. These segments would be considered in poor condition and in need of major maintenance during the next maintenance season. Depending on the needs of the analyst, this map could also represent ranges of DMR values. As shown, 941.66 lane-mi of roadways were rated in 1991. Of these, 143.12 lane-mi (15.2 percent) were in poor condition.

Another goal of this research was to examine the change in a roadway's DMR during consecutive years (Figure 3). It is important to point out that Figure 2 was generated by linking the spatial data base to the PMIS data base, whereas Figure 3 linked the spatial data base to the HTRIS data base. The display categories in Figure 3 are identical to those used in Figure 2; thus, of the 941.66 lane-mi of roadway rated in 1991, 37.5 lane-mi were rated in 1992 as being in poor condition.

To better clarify these changes, Figure 4 was generated by, in effect, subtracting Figure 2 from Figure 3. The display in Figure 4 is based on the change in the DMR values between years and highlights those roadway segments that were acceptable in 1991 but poor in 1992, and it demonstrates the ability of GIS to integrate data between disparate data bases. The 37.5 lane-mi highlighted in Figure 3 as being in poor condition were in either acceptable condition in 1991 or they were already in poor condition. By integrating the two data bases, it was found that 35.1 lane-mi (94 percent) were considered to be in acceptable condition in 1991. Put another way, although between 1991 and 1992 the total quantity of roadway surface rated poor decreased (from 143.12 to 37.5 lane-mi), 35.1 lane-mi (3.7 percent of the Interstate and primary roadway network, which was rated in both years) deteriorated enough to be considered poor in 1992, whereas 96.3 percent either remained the same or improved. These figures support a first-in/first-out policy of performing major maintenance activities, since only 2.4 lane-mi of the 143.12 lane-mi that rated poor in 1991 were still rated poor in 1992. This represents a backlog of only 1.7 percent.

Another application of the GIS was to show the change in pavement condition over an extended period. Present in the PMIS and

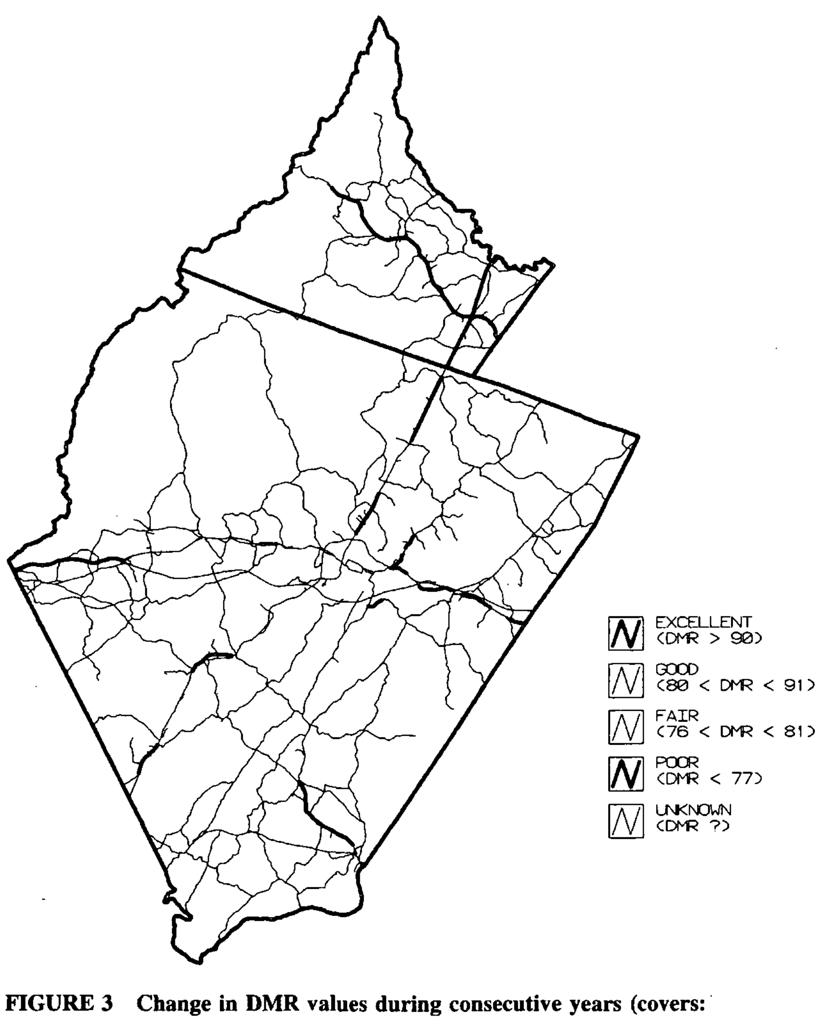

FIGURE 3 Change in DMR values during consecutive years (covers: Boundary, Primary, Majorsec, and Rate1992).

HTRIS data was a field that identified when a roadway section was last surfaced. In some cases, the data went back to 1980. Figure 5 summarizes the average change in DMR value per year since the last resurfacing and highlights those sections in which the DMR had dropped the most (by more than five points per year). This rate of decline would reduce a newly resurfaced roadway to poor condition in fewer than 5 years. As shown, 7.96 lane-mi (0.8 percent) fall into this category. On observing this rate of deterioration, particularly if the proportion was greater than 0.8 percent of the system, the pavement manager might opt to further investigate those roadway sections to ascertain the cause for the accelerated wear.

The remaining goal of this research was to examine the issue of the remaining service life of pavements. Figure 6 illustrates these findings. Building from Figure 5, the individual DMR values from each of the five pavement rating data bases (1988 through 1992) were extracted into a new data base. These values were then examined and, through linear regression, a trend line was established. This trend line was then extended (if necessary) until it reached a DMR value of 76. The number of years until this occurred is displayed in Figure 6. Pavement sections that are currently at or below the DMR threshold of 76 and those with 1 to 5 years of remaining service life are highlighted.

As shown, 623.92 lane-mi (66.3 percent) of the rated pavements will need to be replaced within the next 5 years. This lane mileage includes the 37.5 with no remaining service life, as well as 586.42 that are likely to fall below the DMR threshold of 76 within the next 5 years. This is a substantial percentage of an area's roadways. This type of examination not only aids in projecting maintenance needs, but it is also useful for budgetary planning.

Another type of remaining service life examination looks at the change in the individual distress indexes (e.g., cracking, rutting, etc.) and establishes a trend line. Although this type of analysis was not performed herein, the data necessary for this type of analysis are contained in the five pavement rating data bases. Additionally, although the existing DMR calculations were used in this research, the actual formula used to generate these values could also be incorporated into the GIS, thereby allowing the user to vary the weights assigned to each of the individual distress indexes.

As with most computerized information management systems, once the data have been entered into the automated environment,

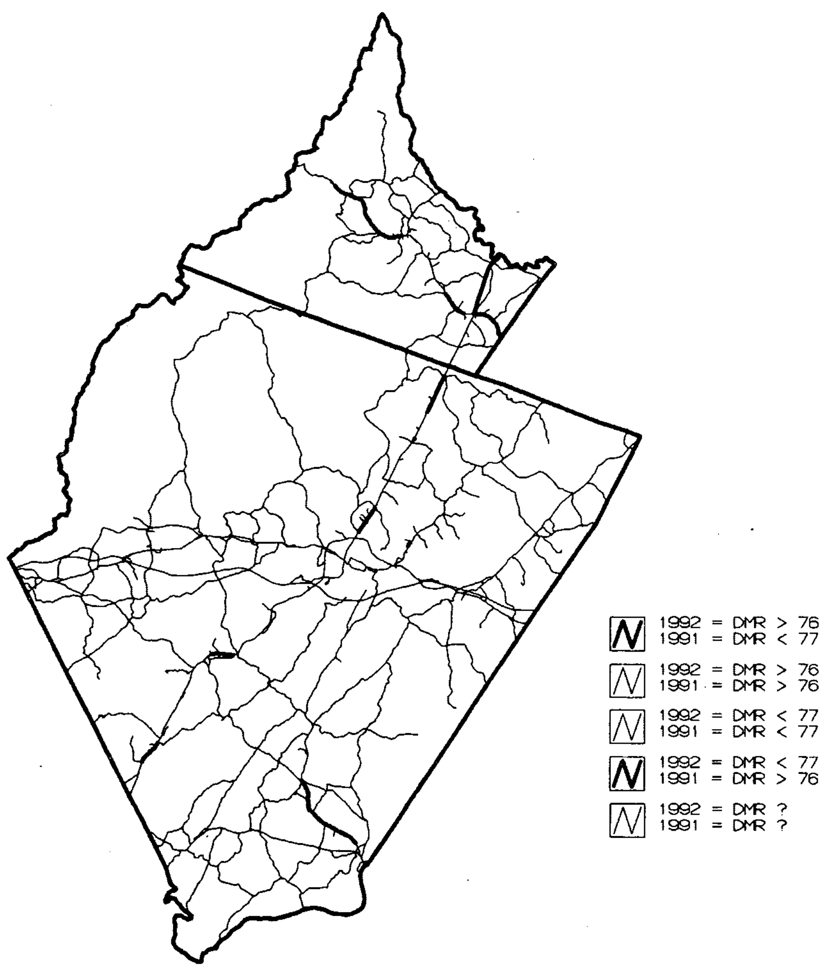

FIGURE 4 Change in DMT values between years.

the types of analysis that are possible are limited only by the user's imagination.

CONCLUSIONS

The development and use of a pavement attribute data base within a GIS environment to support pavement management decision making was demonstrated using several types of applications, including annual pavement condition reporting, changes in pavement condition from one year to the next, changes in pavement condition over an extended period, and an analysis of remaining pavement service life. The data used by the GIS covered two adjacent counties and came from eight independent sources, including three U.S. Geological Survey digital line graphs, four VDOT pre-HTRIS pavement management data bases, and the VDOT HTRIS pavement management data base. These data were transformed into information using standard locational referencing techniques and were displayed in both map and tabular form.

Evaluating whether using GIS in this effort was more efficient than not using GIS is not a simple matter. In this specific effort, the hundreds of hours spent in developing the GIS environment could easily have been equal to or greater than the hundreds of hours required to complete the effort manually. As with any automated decision support system, few if any benefits are realized as a result of one application of the technology. The benefits accrue over time. A second application of this GIS decision support system (i.e., changing the DMR threshold by 10 percent) will require far less time to complete than the same change would take to process manually. Subsequent applications (within pavement management) will take even less time as system operators continue to learn how the system functions. Other applications of the technology within the HTRIS data base will also proceed much faster, since locational referencing has now been established at least in these two counties.

This clearly points to the systematic nature of GIS. Although it is no longer necessary for the format of all data to be identical in order to be processed by computer as with traditional management information systems, still some measure of routine and commonality proves beneficial to the GIS environment. In the end, garbage in equals garbage out. For example, if established common data collection techniques do not exist, it might be extremely difficult (but not necessarily impossible) to establish links between data sets. In this application, for example, roadway segments were

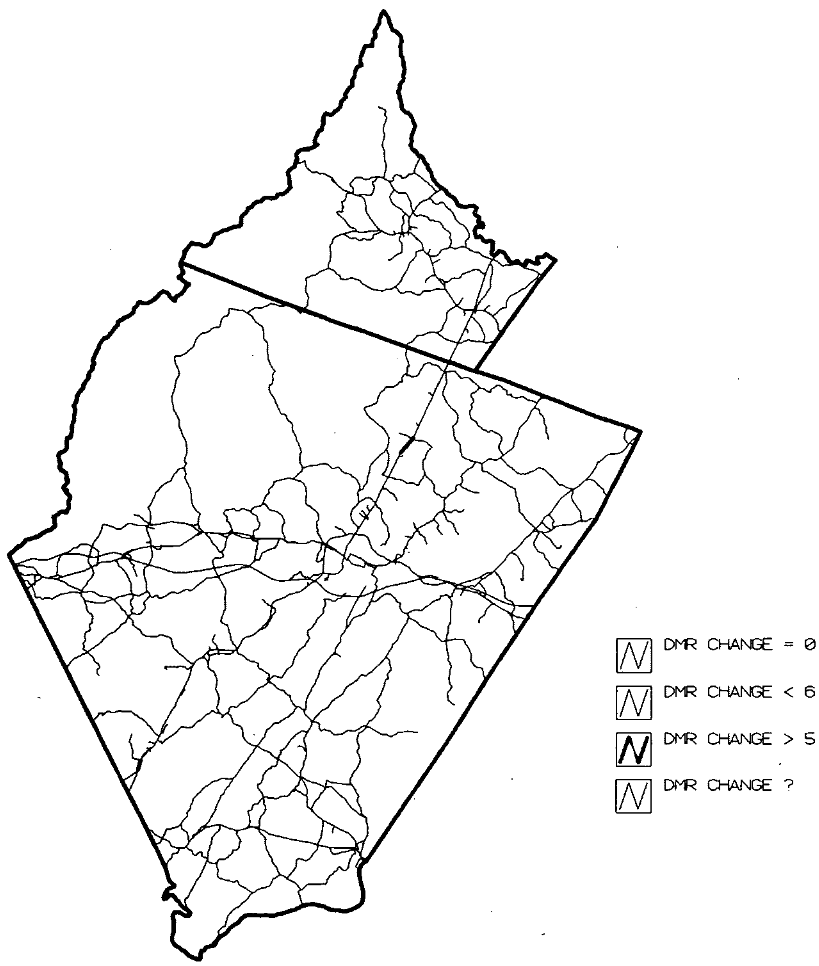

FIGURE 5 Average change in DMR values per year since last resurfacing.

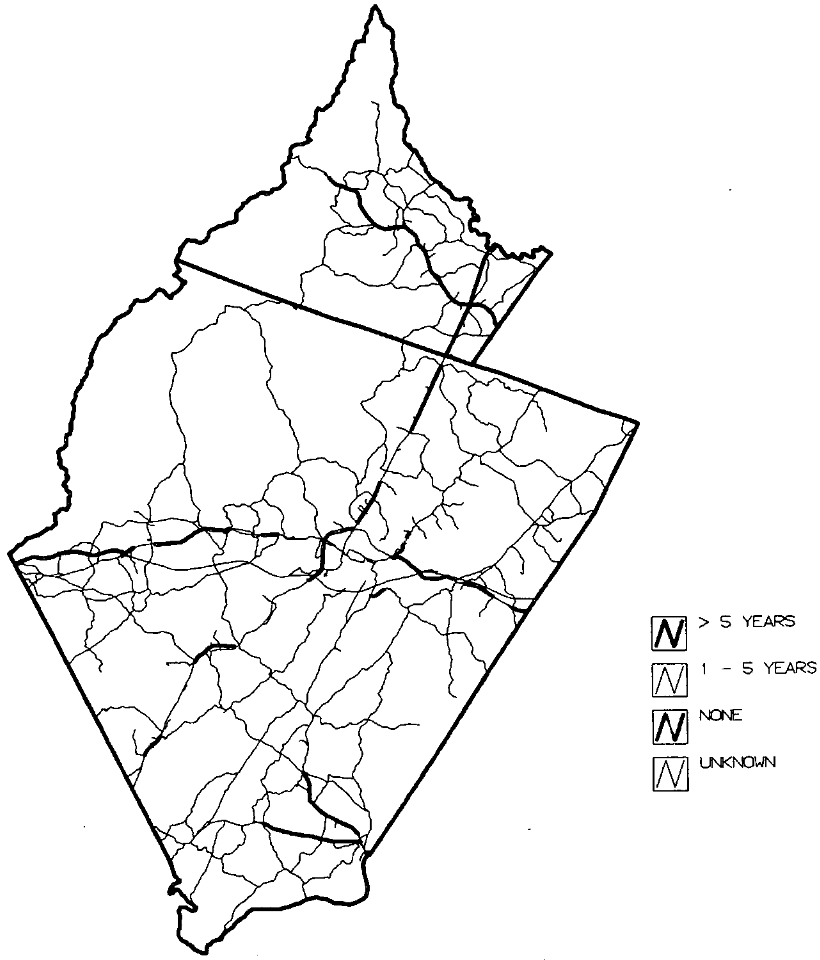

FIGURE 6 Remaining service life of pavements.

fairly stable over time. If this had not been the case, the matching of roadway segments by year would have been far more difficult.

Because of this, a key conclusion from this research was that the spatial data base must include the smallest possible roadway segment based upon the available attribute data bases. This facilitated combining the roadway sequences to relate to PMIS and HTRIS record keeping. In the larger GIS platforms—for example, those based on UNIX—this factor is minimized through dynamic segmentation. This technology allows roadway sections to be segmented on the fly.

Another key conclusion is that once the relational link was established between spatial and attribute data, particularly HTRIS data, any application within HTRIS becomes accessible through the GIS. HTRIS is composed of a number of application modules, of which pavement management is only one. Other applications include (or will include) accident data, traffic volumes, and so forth. These data sets can now be accessed by the GIS through the sequence field, thereby allowing for the integration, for example, of pavement rating and accident data, or pavement ratings and traffic volumes, or even pavement ratings, traffic volumes, and accident data. Therefore, GIS also allows for data integration within existing data bases.

ACKNOWLEDGMENTS

This study was conducted under the sponsorship of the U.S. Department of Transportation and the Virginia Department of Transportation through grants from the Mid-Atlantic Universities Transportation Center. Special thanks go to David C. Wyant, of the Virginia Transportation Research Council; Sonny Daria, of the Environmental Sciences Department at the University of Virginia; and Jack Dangermond, of the Environmental Systems Research Institute, for their contributions to this research.

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The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.

Publication of this paper sponsored by Committee on Transportation Data and Information Systems.

GIS Integrated Pavement and Infrastructure Management in Urban Areas

ZHANMIN ZHANG, TERRY DOSSEY, JOSE WEISSMANN, AND W. RONALD HUDSON

Infrastructure management is the process of properly coordinating, systematically evaluating, and effectively maintaining the infrastructure related to basic services. Infrastructure management system links those activities required for these actions, such as planning, design, construction, maintenance, rehabilitation, and evaluation, through a series of rational, well-ordered analysis procedures. Effective management of pavement and other infrastructure in the urban area can greatly increase the service life of these facilities and reduce user costs. Efforts to apply geographic information system (GIS) to urban roadway and infrastructure management are summarized. A user-friendly application program, GIS-URMS, which was developed under this research, is described. In addition, some important issues with regard to developing implementable GIS applications are discussed.

The urban roadway network is a major component of any municipal infrastructure system. Effective management with systems methodology can greatly increase the service life of these facilities and reduce user operation costs (*1*). To achieve such objectives, many municipal transportation agencies in the United States have operational pavement management systems (PMSs) in one form or another. As a further development and improvement of the management technology for transportation systems, many transportation agencies are currently investigating the adoption of geographic information systems (GISs) for transportation applications (*2,3*).

GISs are computerized data base management systems with unique capabilities of managing and manipulating spatially referenced data and presenting it in an easily understandable graphic format. GIS can perform two major functions to support management decision-making processes in many diverse fields such as natural resources, environmental protection, transportation management, and municipal infrastructure management, to mention a few. One function is to generate computerized visual map displays for accessing, editing, and presenting data from different sources; the other is to provide a platform for data integration so that a common location reference system can be developed (*4*). The applications of GIS in the transportation community are growing rapidly. To evaluate the potential applications of GIS in urban roadway and infrastructure management systems, efforts under research at the University of Texas at Austin include

- Conceptual evaluation of GIS technology,
- Review and comparison of available GIS software,
- Identification of digital geographic data for urban areas,
- Development of a pilot application, and
- Conclusions and recommendations for implementing this technology in urban areas for pavement and infrastructure management.

The research results reported in this paper were developed under an Energy Research in Applications Program project at the University of Texas at Austin.

WHY GIS?

Although GIS applications for pavement and infrastructure management are still at their early stage compared with applications in other areas, infrastructure management in urban areas strongly suggested that there is a need for such technologies. To address urban infrastructure management in an effective and practical way, an advisory panel was set up with panel members from the Public Works Departments from cities in Texas. The advisory panel meet periodically at the University of Texas at Austin to discuss practical issues regarding urban infrastructure management. From the panel discussions, several important aspects with regard to developing GIS applications were noted. These are described as follows.

Infrastructure Management from Perspective of City Planners

Although the traditional infrastructure management systems have been in operation for a long time, city planners in most cities are now either trying to improve the existing systems or seeking a new management system approach for their infrastructure. The general idea that emerged from the discussions with the advisory panel was to develop an overall or comprehensive management system so that all the infrastructures such as pavement, bridge, water supply, waste water, gas, electric, and such could be integrated on a common platform to improve managerial decisions. This concept of integrated overall infrastructure management system is illustrated in Figure 1, where GIS is the common location reference system (*5*).

Feasibility of Integrated Management System

Because of the unique geographical location of municipal infrastructure systems, a common location reference system can be

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used to integrate the subsystems outlined in Figure 1. Whereas electricity supply and pavement are normally along street lines, water supply, waste water, and gas are normally under the street pavement, as illustrated in Figure 2, special considerations need to be made for those elements that do not follow the direct street courses (*5*).

Availability of Technology

The significant decrease in the price of personal computers and the dramatic improvement in their performance have enabled more and more agencies to afford the investment in PC platforms. GIS development has now entered a period of expanding applications, and PC versions of GIS packages are available at an affordable price (*6*). In fact, PCs are now almost a commonplace in most cities' public works departments. Some of them have already had some sort of GIS packages. Austin, and even smaller cities like Round Rock and Georgetown, Texas, own and operate PC Arc/Info GIS packages.

Current Practice

Some cities are now developing integrated infrastructure management systems as illustrated in Figure 1 and some are planning to do so. As an example, efforts are under way in Georgetown, Texas, to develop an integrated management system that coordinates water, waste water, electric, and pavement management systems with PC Arc/Info.

PLATFORM AND GIS PACKAGE

A pilot GIS application for Urban Roadway Management System (GIS-URMS) program was developed for demonstration and to serve as a starting point for cities willing to implement GIS integrated infrastructure management solutions. The computer platform used for developing GIS-URMS was a 486/33MHz PC with 200MB hard disk.

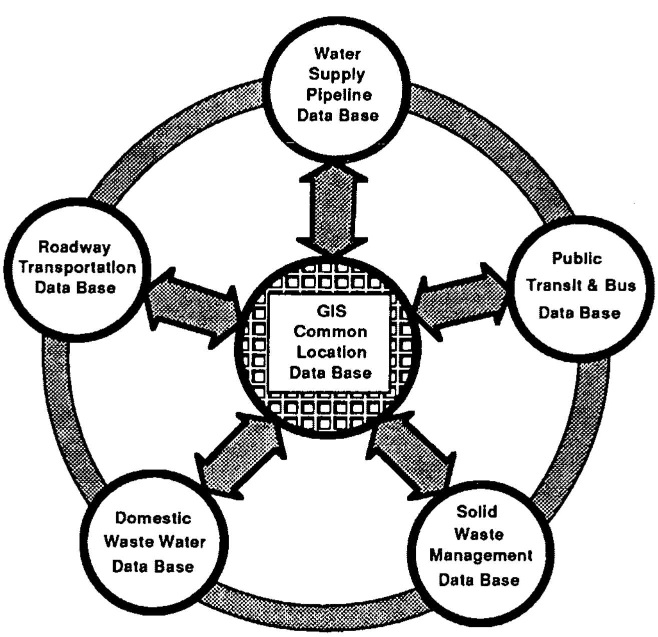


FIGURE 1 Concept of integrated overall infrastructure management system.

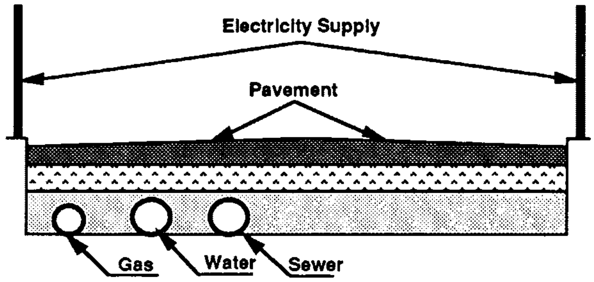


FIGURE 2 Example of common location reference system.

From a literature evaluation of several GIS packages, PC Arc/Info, a GIS package developed by the Environmental Systems Research Institute, was selected to develop the pilot applications. PC Arc/Info is one of the most widely used GIS packages for personal computers. The package consists of six separate modules (*7*):

- PC Arc/Info StartKit,
- PC ArcEdit,
- PC ArcPlot,
- PC Data Conversion,
- PC Network, and
- PC Overlay.

PC Arc/Info can be run on any 286, 386, or 486 PC with DOS 3.1 or higher, 640K or more RAM, a minimum of 40MB hard disk storage, 1.2MB or 1.44MB floppy disk drive, and a math coprocessor. A parallel port is required for the PC Arc/Info hardware key that copy-protects the software. An EGA/VGA or compatible monitor is recommended for the various interactive graphics operations. Two serial ports are usually required if a digitizer and a plotter are desired, and a modem is needed for host communications.

GEOGRAPHICAL DATA BASE

The city of Austin, Texas, was selected to conduct the pilot study. TIGER (Topologically Integrated Geographic Encoding and Referencing)/Line files provided the digital geographical data used to develop the geographical data base for the pilot GIS-URMS. The TIGER files obtained are for the county of Travis, Texas. It is inefficient to use all the blocks in Travis County as the geographical data base for the Austin area. The extra blocks outside the Austin boundary consume disk storage space and increase the processing time required by various operations. To establish a geographical data base that contains only the street segments of the Austin area, several spatial data operations were conducted using PC Arc/Info. The boundary data for the Austin area was first extracted from the City90 file, which contains all the city boundaries in Travis County. The extracted Austin boundary file was then used to intersect with the block file Block90 to get the geographical data base for Austin area.

PAVEMENT ATTRIBUTE DATA BASE

The pavement attribute data is from Austin's pavement data base, PIBASE. PIBASE was supplied in dBase III+ format with 126 data fields. Included in the data base is major pavement information such as riding condition index (RCI), surface distress index (SDI), annual average daily traffic (AADT), and so on. RCI values were rated on a scale from 10 to 0 (best to worst). Thirteen types of distress were considered for flexible pavements: rippling and shoving, raveling and streaking, flushing and bleeding, distortion, excessive crown, progressive edge cracking, alligator cracking, potholes, map cracking, longitudinal and meandering cracking, transverse cracking, wheel track, and patching. These distress manifestations were then combined on the basis of their extent and severity, in order to calculate an SDI. An SDI value of 10 stands for a perfect surface, whereas a value of 0 indicates a totally unacceptable surface. Other data such as pavement geometric dimensions, layer thickness, and maintenance and rehabilitation (M&R) history are also included in the data base.

LINK BETWEEN GEOGRAPHICAL AND ATTRIBUTE DATA BASES

The TIGER file (geographical data base) and pavement data (attribute data base) are maintained separately in the system. The two data bases can be dynamically linked together by the control program when the connection is necessary. The linkage is accomplished through a common item in both data bases, taking advantage of a relational data base management system. The common item used for this purpose is the pavement segment identification. Figure 3 illustrates the data linkage concept.

The most important advantage of this dynamic connection between the geographical data base and the attribute data base is that each of the data bases can be updated or modified separately. Both geographical data and attribute data are associated with a time variable. The data base needs to be updated for any change of geographical features. TIGER files are also subject to periodic updates by the U.S. Bureau of the Census. Pavement condition data changes with time and the attribute data base must be updated to reflect such condition changes.

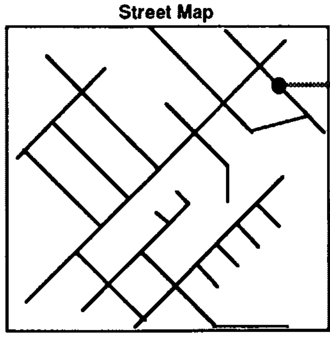
CONCEPTUAL DESIGN OF GIS-URMS

Figure 4 illustrates the conceptual structure of GIS-URMS. The user accesses GIS-URMS through a user-friendly, menu-driven interface. The interface takes any command sent by the user to actuate the control program written in the PC Arc/Info's Simple Macro Language (SML). Connected to the control program are a series of function modules, including draw, label, query, list, applications, utility, clear, and quit. The outputs from GIS-URMS are various pavement condition maps, reports, and statistics with corresponding bar charts. The geographical data base (TIGER block file) and the attribute data base (pavement condition data from Austin) are separately maintained and will be dynamically connected to each other where such a connection is required by the control program. The control program is also open for development of an interface with URMS (*5,8*) or any other management system.

FUNCTION MODULES

Using the SML provided with PC Arc/Info, various functions were programmed as modules under different levels of the control menu. These function modules are depicted in Figure 5 and discussed as follows.

Street Map



Geographical Database (TIGER Block File)

ZBLOCK90-ID	FNODE	• • •	FULLNAME	CFCC
000900	345	• • •	Red River St	1
000910	347	• • •	Red River St	1
000920	349	• • •	Red River St	1
000930	350	• • •	Grande St	1
•	•	•	•	•
•	•	•	•	•
•	•	•	•	•

Pavement Attribute Database

SEC-NO	ABT-STREET	• • •	RCI_MEAN	RCI_DATE	SDI_MEAN	• • •
000870	ML King Blvd W	• • •	6.8	10/15/91	7.4	• • •
000880	ML King Blvd W	• • •	7.2	10/15/91	8.0	• • •
000920	Red River St	• • •	7.0	10/15/91	7.8	• • •
001110	Bandera	• • •	5.5	10/16/91	6.0	• • •
•	•	•	•	•	•	•
•	•	•	•	•	•	•
•	•	•	•	•	•	•

FIGURE 3 Link between geographical and attribute data bases.

Draw Module

Drawing different types of maps is a basic function of any GIS application package. Under the draw module of GIS-URMS, the user can choose the specific map (coverage) to be drawn with the desired color. Sixteen colors are provided with a color selection menu for the user's interactive use. A ''zoom'' function is included in this module so that the user can examine a specific area of interest in detail.

Label Module

In certain instances it is convenient for the user to put street names on the map so that streets can be identified easily; in other cases it is better to draw the map without street names for a clearer overall view of the area of interest. Using the Label function, street names can be attached easily to the corresponding streets or removed from the map simply with a touch of the mouse.

Query Module

One of the most important features of a GIS is its interactive graphic querying capability. The Query function lets the user identify any feature in the map interactively with a mouse. Information concerning any specified feature will be displayed within a designated window.

List Module

Information from both the geographical data base and the attribute data base can be retrieved through the List module. It could be all the information available in the data base for that block or a portion of the data that meet certain specified conditions. The information retrieved can be either displayed on the screen or written to a text file for further processing.

Selection Module

Map features or pavement segments that meet certain user-defined criteria or conditions can be selected and displayed on the base map and color-coded. Once the selection menu is activated, the system prompts the user to provide the name of the base map (coverage) from which the features are to be selected and then for the criteria or conditions for the selection. For example, the user can select or display all the pavement sections with a traffic volume equal to or greater than 1,000 or for all the streets with a specified street name, etc.

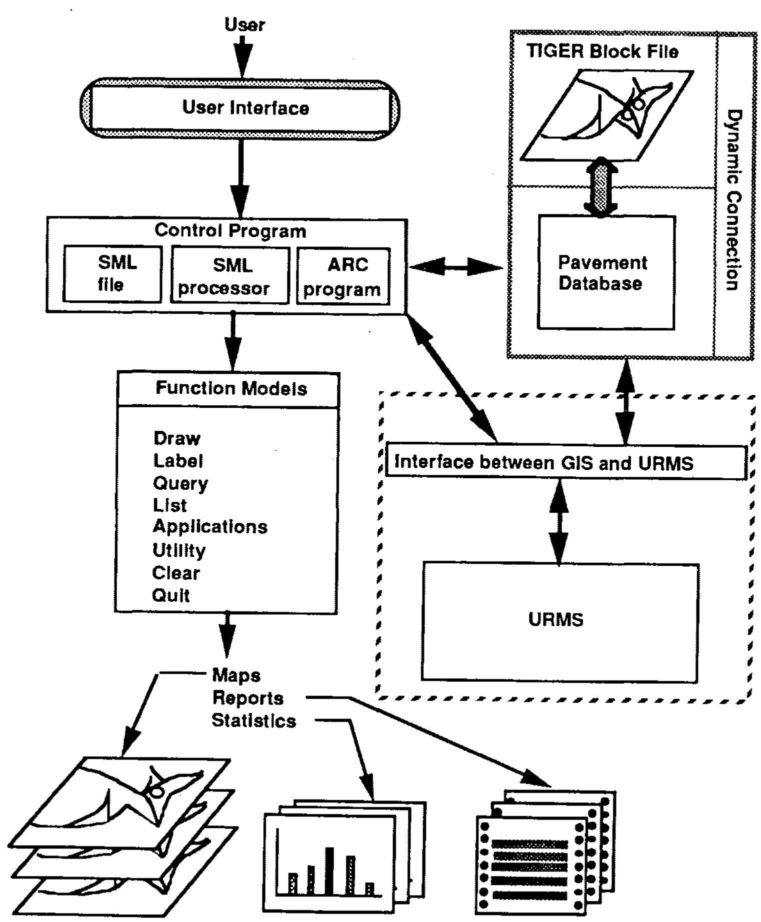


FIGURE 4 Conceptual design of GIS-URMS.

Network PMS

Under Network PMS, pavement conditions such as RCI, SDI, AADT, M&R recommendations, and subgrade soil condition (Soils) can be classified and displayed on the map. Associated with the condition map are the statistical information and corresponding bar chart for each class of information.

The outputs from GIS-URMS are various pavement condition maps, reports, and statistics with corresponding bar charts. The control program is also open for developing an interface with URMS or any other management system, as mentioned previously (*5,8*).

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the research on GIS technology reported in this paper and its potential applications in pavement and infrastructure management, some important issues with regard to developing implementable GIS applications are as follows:

- Because of the significantly improved performance and decreased cost, PCs are capable enough as platforms of developing GIS applications for urban roadway and other infrastructure management in small and medium-sized cities.
- TIGER/Line files are a good source of digital data for developing GIS applications in urban roadway and other infrastructure management; it is recommended that these files should be first evaluated for potential use before digitizing data from existing maps.
- PC Arc/Info is a powerful and flexible GIS package. The SML featured with PC Arc/Info can be used to develop customized user-friendly applications.
- Because of its modular structure feature, the developed GIS-URMS is open and easy to interface with pavement management systems or any other infrastructure management systems.
- Because the link between geographical location data base and attribute data base is the most important step for the realistic implementation of GIS, an algorithm for automatically linking a geographical data base and an attribute data base should be developed in future research.
- The basic segment unit in TIGER/Line files is a street block, but in practice the pavement segment used for maintenance and rehabilitation is usually more than a block long. To make TIGER/Line files more useful for urban roadway management, an algorithm for performing dynamic segmentation should be developed so that practical maintenance and rehabilitation segments can be generated with TIGER/Line files.

In summary, the development process of pilot GIS-URMS demonstrated that GIS is a powerful and flexible tool for integrating geographical location information with attribute data for pavement and infrastructure management and also for graphical display. The

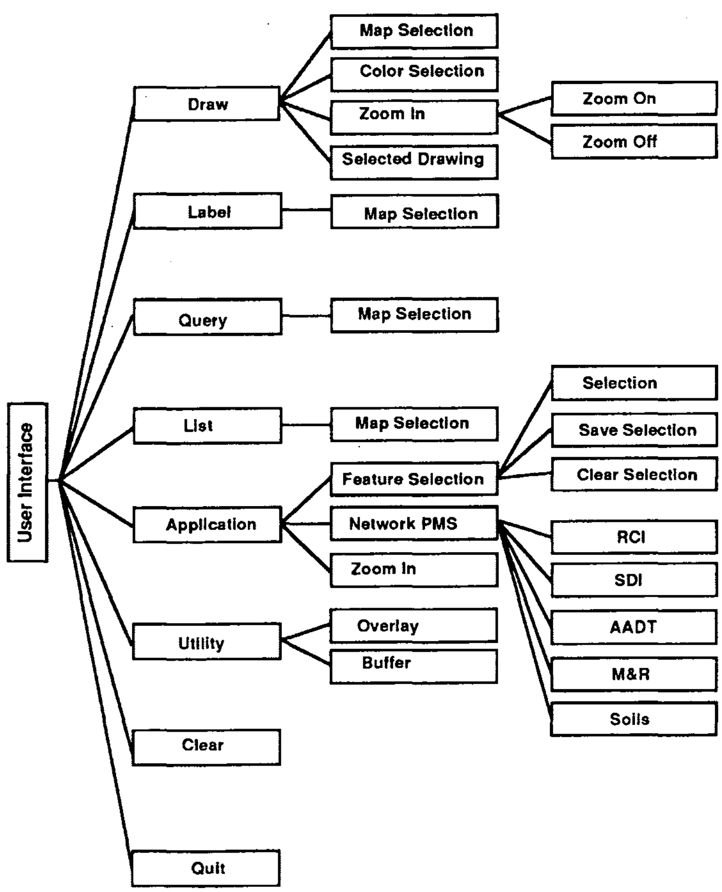


FIGURE 5 Major function modules in GIS-URMS.

user-friendly, menu-driven interface of the GIS-URMS greatly simplifies GIS application procedures. In addition, because of its modular structure feature, the GIS-URMS can be easily modified for other municipal infrastructure management applications.

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Publication of this paper sponsored by Committee on Transportation Data and Information Systems.