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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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A NEW DIRECTION FOR THE HIGHWAY PROGRAM

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In 1972 the California highway program faced a number of problems including rising construction costs, declining revenue growth, and the resulting unmanageable $17 billion project backlog. McKinsey and Company joined the California Department of Transportation (Caltrans) in a 2-year study to pinpoint the causes of existing problems, establish pilot studies in selected districts to test new approaches and tools, and implement the effort throughout the state. The results of the study have been far-reaching and have affected all aspects of the highway decision-making process. Caltrans has shifted from a project-by-project design approach that in effect assumed unlimited funding to a new approach that focuses on achieving maximum systemwide benefits with the funds that are likely to be available. A new planning methodology, new analytical tools, and new controls have been implemented. Caltrans has used this new approach to develop a 20-year slate of highway projects. This slate will cost only a third of the cost of the 1972 project backlog and will result in greater safety and mobility benefits and lower operating costs than would have resulted from the same level of expenditure under previous plans. Moreover, it can be financed with projected funds and completed within 20 years.

•DURING the last several months, the planning approach described in this paper has been applied in every district throughout the state of California. The accomplishments have been twofold. First, a realistic highway program has been developed that recognizes the limitations of future highway revenues and that, when completed, should result in a substantial improvement in the highway system. Second, fundamental changes have been made in the way the state of California plans and builds highways that should lead to lasting improvements in the effectiveness of the highway program. Together, these accomplishments are likely to reduce frustration both within the California Department of Transportation (Caltrans) and among the general public. More important, they are likely to result in a functioning, balanced, and complete highway system.

In the past, Caltrans planned highways to meet exacting criteria. Whenever a segment of a highway was identified as deficient, a solution was planned that would meet not only current needs but also projected needs 20 years in the future. Solutions were planned with little regard to cost because it was assumed that needed funding would be available. By the late 1960s, however, rising construction costs and the leveling off of funding slowed construction. Nevertheless, costly highway projects continued to be proposed. The result was a growing backlog of construction projects and a fragmented highway system of completed and uncompleted highway segments.

Limited funding and rising costs have forced on Caltrans a less ambitious but more realistic objective: to establish, within a foreseeable time horizon, a balanced system that can be funded and controlled. When funds for highway construction are limited and a large backlog of deficiencies is uncorrected, constructing ultimate and costly facilities on a project-by-project basis in accordance with fixed design policies and guidelines is not the most effective way to improve highway system performance. Instead, California

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has adopted a more modest approach that attempts to do the best possible job with the money that is likely to be available. California is not building toward an ideal highway system to be completed in the distant future but is seeking to develop a practical system that will be reasonably complete at any given time. This objective makes it necessary to focus on maximizing system benefits rather than individual project benefits.

Designing for maximum system benefits required a shift in focus from the traditional project view to a broader highway system view. The latter view recognizes that, when funding is limited, greater value is obtained by allocating funds in a balanced manner than by concentrating them in a few problem areas (Figure 1).

An example will illustrate what may be achieved when a deficiency is approached from the highway system view. The segment of Calif-84 from the Dumbarton Bridge, which spans the southern part of San Francisco Bay, to Calif-238 was congested. Because this route is part of a planned freeway system, freeway construction costing about $42 million was proposed to replace the existing two-lane facility.

Analysis of the function of the route and the volume of traffic it would serve suggested that a new freeway might not be required. The type of traffic using this route was relatively short distance; less than 10 percent of the traffic travels the complete length of the route segment. Furthermore, the volume of daily traffic was relatively low (about 15,000 vehicles), although it was projected to grow to between 40,000 and 70,000 by 1995. Further analysis indicated that at least three alternatives (Figure 2) for improving this route were possible:

1. Ultimate—Building a new freeway as currently planned would cost $42 million and would accommodate traffic for more than 20 years;
2. Modest—Improving the existing route and developing a parallel county road (Jarvis Avenue/Decoto Road) into a six-lane expressway would cost about $10 million and would adequately serve projected 1995 traffic; and
3. Spartan—Improving both the existing route and the parallel county road to four-lane conventional standards would cost only about $5 million and would accommodate traffic for several years, although it might not provide adequate capacity to serve 1995 traffic, depending on traffic growth.

From the project view, the $42 million freeway would be the best solution because it would serve a larger volume of traffic and have a lower accident rate than either of the other two alternatives. However, the highway system view led to a different conclusion, because it took into account the fact that deficiencies existing on other routes throughout the state could be improved with these funds. For example, the same $42 million could pay for four $10 million expressway improvements or eight $5 million conventional widening improvements and, in doing so, could triple or even quadruple the total benefits received by the public. And, although the ultimate alternative offered the highest accident cost savings of the three alternatives for this route segment, statewide accident cost savings for the highway program would be considerably higher under the modest or spartan alternative because deficiencies in more locations could be corrected (Table 1).

Achieving maximum system benefits requires more than a new highway system view. It also requires a new methodology for highway planning. A systematic process is needed to achieve the following goals.

1. To establish program funding constraints requires a method for determining how many dollars will be available in the future, how much they will buy, and when they can be spent. When funding constraints are established, possible highway projects can be traded off according to how much each project improves the operation of the highway network.
2. A program must be developed for selecting and evaluating projects. To select only projects that will add maximum benefit to the system depends on a technique for defining and analyzing a broad range of alternative projects and evaluating the various highway systems these projects form. After projects are selected, there must be a method for rigorously determining their priorities and scheduling according to their

importance to the overall highway system.

3. To control the program, that is, to ensure that the techniques are followed and that the planned system satisfies realistic constraints, requires that effective policies be established and rigorously applied.

ESTABLISHING PROGRAM FUNDING CONSTRAINTS

To establish funding constraints for the highway program, one must know how many dollars will be available in the future, when they can be spent, and how much highway improvement they will buy. This information is important to any planning process, but the new approach to highway planning increases the necessity of reliable funding information. Only with an understanding of how many dollars will be available and of the purchasing power of those dollars can the proper decisions be made regarding the kind of highway system to plan. To acquire this understanding, Caltrans had to develop realistic funding forecasts and estimate the future buying power of these projected dollars.

Realistic Funding Forecasts

Realistic estimates of funds likely to be available over the chosen planning horizon are important to the highway program because (a) they establish the size of the total highway program and (b) they determine the timing for constructing proposed projects. If these estimates are not realistic, the same types of inefficiencies develop that occur when no funding constraints at all are recognized. For example, if forecasts of revenues are optimistic, the construction schedule lags when funds do not materialize so rapidly as projected. Project delays in turn make it necessary to repeat much of the planning, design, and scheduling work, a process that is costly and frustrating to both Caltrans and the public. And optimistic forecasts frequently lead to active planning, including route adoption and hardship right-of-way acquisition, on many routes that may never be financed. On the other hand, underestimates of future highway funding lead to less-than-optimal decisions regarding allocation and use of available funds.

Past highway funding estimates have not been realistic. Statewide planning program funding targets have exceeded final budget levels by a notable margin since fiscal year 1971 (Figure 3). This kind of overtargeting has resulted in some very real problems. In the San Francisco Bay area, for example, about $1.5 million in design work was begun and approximately the same value of right-of-way was purchased in 1971 in anticipation of an increase in funding from $100 million to more than $200 million in fiscal year 1977. The increase in funding has not yet materialized; consequently, funds have been wasted on projects that cannot be built during the planning period. Analysis of the causes of inaccuracies in funding projections led to the conclusion that three elements were needed to establish more realistic funding targets in the future:

1. A more sophisticated analytical tool,
2. A controllable time horizon, and
3. Critical reviews of funding assumptions by top management.

Sophisticated Analytical Tool

Although realistic forecasts of future highway program funds are important, they are not easy to develop. State highway funds are derived from a number of interrelated sources, many of which are outside of the control of Caltrans. The majority of funds are obtained from state motor vehicle fuel taxes and federal motor vehicle taxes; a smaller amount of funding is derived from state motor vehicle fees. Because these revenue sources support other activities in addition to the state highway program, the task of estimating highway funds is very complex and requires numerous assumptions about the flow of funds to the right-of-way and construction accounts.

Figure 1. Two approaches to highway planning.

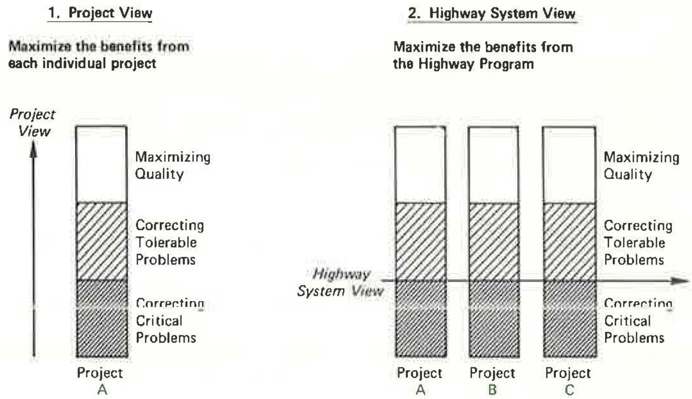


Figure 2. Alternative projects for Calif-84.

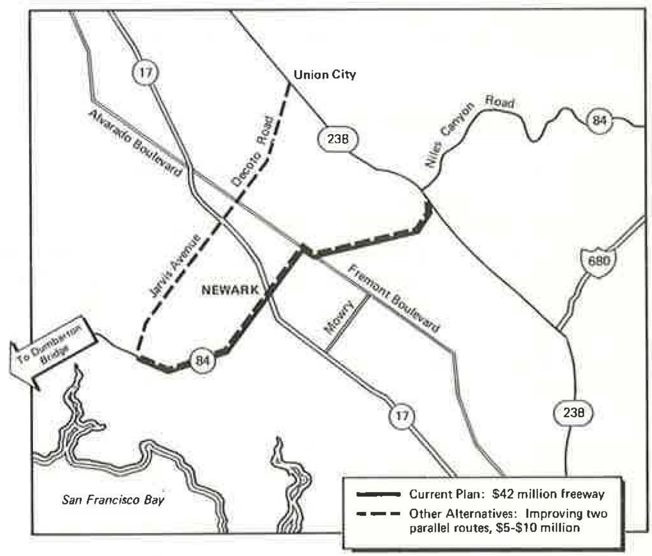
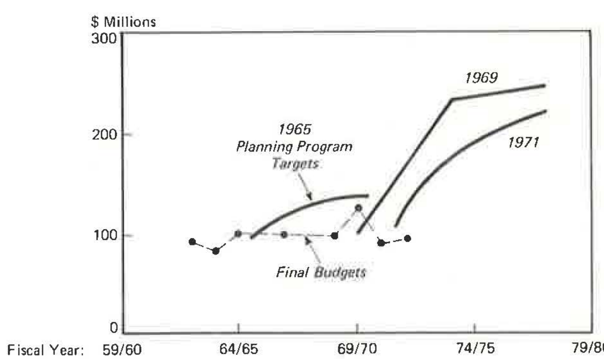


Table 1. Value of accident cost savings over 20 years under Calif-84 alternatives.

	Alternative		
Item	Ultimate	Modest	Spartan
Single-project accident cost savings, millions of dollars	1,680	1,200	1,000
Number of projects financed by $42 million	1	4	8
Total value of accident cost savings from $42 million investment, millions of dollars	1,680	4,800	8,000

Figure 3. Major construction and right-of-way targets compared to recent budget trend.



In view of the difficulties associated with preparing reasonably accurate funds forecasts and the implications of poor forecasts, a quantitative model was developed to assist in preparing these projections. This model, HIGHPLAN, enables the state to conduct sophisticated analyses of the various funding sources.

Basically, HIGHPLAN forecasts fuel tax revenues by estimating fuel consumption (determined by number of fuel-consuming vehicles and their mileage) and tax rates. To this forecast it adds the likely revenue from minor sources of funding. Incoming revenue from all federal and state sources is then allocated to various uses, including city and county highway programs, state highway maintenance, California Highway Patrol, and right-of-way. The resulting output gives estimates of both short- and long-term funding, which have differed dramatically from those previously prepared (Figure 4).

Controllable Time Horizon

With the HIGHPLAN model, funding can be forecast for as many years into the future as planners desire. However, to establish a realistic funding constraint for the highway program requires that funding forecasts be viewed within a specific, controllable time horizon. Because of the long lead times associated with planning and designing projects, a period shorter than 15 years is probably unreasonable, yet a period longer than 25 years would result in forecasts that are highly uncertain in later years. Thus, 20 years was selected as a practical planning horizon for the highway program because it is long enough to permit planning for a reasonably complete system, yet short enough to permit at least educated guesses about the future.

Top Management Reviews

Even with the use of a sophisticated funding forecasting model, it is unrealistic to expect a single prediction to be accurate for a full 20 years into the future. Major forces over which Caltrans has little direct control can influence the funding situation at any time. For example, pressures have been mounting for several years to divert portions of state highway funds to other forms of transportation; some diversion at both the state and federal levels has already occurred, and more is likely to occur. Similarly, the timing and amount of fuel tax rate increases are difficult, if not impossible, to predict. Therefore, to keep the model up to date, top management will need to review periodically the key assumptions it is using.

Future Buying Power

Although realistic funding forecasts are critical, knowing just the number of dollars that will be available in the future is not sufficient. It is also necessary to know how much these dollars will purchase. Insofar as inflation and other factors cause the costs of planned projects to escalate over time, dollars spent in the future will not be worth so much as they are today. Accurate estimates of the future buying power of the highway dollar are thus essential to establishing highway program funding constraints.

Estimating future buying power basically involves determining how much a dollar of, say, 1985 revenue will buy in today's terms. This determination in turn requires that

1. Likely cost escalation rates be estimated and
2. Projected funds be discounted to reflect these rates.

Cost Escalation Rates

Construction and right-of-way costs have increased dramatically during the last 2 decades. This growth has been particularly steep since 1967, when inflation affected the construction industry greatly. Inflation, however, has not been the only factor to drive up the cost of the highway program. Escalation in design scope, design concept, and design standards and practices has also played an important role. For example, it was found that the construction cost of urban facilities has doubled during the last 20 years on a per-lane-mile basis, and slightly more than half the increase was due to inflation and the remainder due to growth in concept and standards. These statistics do not, of course, take into account the effect of scope escalation.

Project cost estimates in the past tended to be significantly understated. For example, in the San Francisco Bay area, construction costs as shown in the planning program were approximately 30 percent lower than actual costs because the rate of escalation in project costs was not considered. There was, in fact, no systematic basis for considering at the outset either inflation rates or the rate of escalation in design scope, concept, or standards. The combined effect of this underestimated cost escalation and the optimistic funding projections discussed earlier was dramatic. More than 50 percent of the projects scheduled for the Bay area were delayed between 1971 and 1972. The average delay during this 1-year period was nearly 2 years. This lag resulted in significant redesign and internal inefficiencies, as well as increased community frustration.

To avoid such problems in the future requires realistic estimates of the likely rate of future cost escalation. As a result of this study, a provision of 7 percent per year has now been made in most districts for increased costs due to inflation and design escalation. This rate of increase is lower than that encountered in the recent past because inflation is not expected to remain at current levels; the assumed 4 to 5 percent rate appears reasonable over the long term. In addition, although design scope, concept, and standards have escalated at rates well in excess of 2 to 3 percent (7 percent less 4 to 5 percent for inflation), most of this growth is controllable by management, and such a rate appears to be attainable. Furthermore, there is little doubt that, if a higher rate of cost growth is planned, it will certainly be achieved. Only by trying for a low rate of increase and instituting the controls for achieving it is there hope of avoiding further rapid growth in highway costs.

Discount Projected Funds

With the knowledge of probable future funding levels and the rate of decline in the buying power of these dollars, the total number of real dollars available for the highway program over the 20-year time horizon can be determined through a simple computation. The present worth of the future dollars of revenue can be calculated in today's terms by applying the 7 percent per year decline in buying power to the dollars of revenue in each year. The present worth of the future revenue is simply the sum of these equivalent dollars over the planning horizon.

The result of these computations is the number of highway dollars that can be used to construct a highway system within the planning horizon. This number can be compared with today's costs of potential highway projects to determine how many can be built within the period, i.e., the program's size.

DEVELOPING A REALISTIC PROGRAM

After realistic 20-year funding constraints are established, the planning task begins. Its goal is to develop a highway program that will result in the best possible system from the standpoint of completeness and of total benefits to the public.

Because the state highway system is so large, a detailed analysis of the system in its entirety is quite difficult. Consequently, the planning process described here is carried out largely at the district and subsystem levels, and these plans are subsequently compiled to form a statewide highway program. To ensure that funding constraints are considered in the earliest planning stages requires that projected funds be first allocated to the state's 11 districts. This allocation must meet a number of constraints established by the legislature regarding minimum county expenditures and the division of funds between the northern and southern portions of the state. Any discretionary funds, i.e., those not needed to satisfy the statutory minimums, are allocated to parts of the state system judged likely to yield the greatest return. After being allocated to the districts, funds are further divided among the principal subsystems within the district. For example, the Los Angeles area was divided into three subsystems—Ventura, Los Angeles, and Orange Counties.

After this allocation, four major steps are carried out:

1. Generate subsystem alternatives,
2. Evaluate subsystem plans,
3. Develop a statewide highway system plan, and
4. Determine project priorities.

Generating Subsystem Alternatives

Planning begins with the development of a range of alternative 20-year plans for each highway subsystem. Each of these alternatives must meet the established funding constraints, and each must be directed toward achieving a high level of benefits in relation to the costs. The following benefits can be measured.

1. Mobility, which is the relative opportunity for a traveler on the highway system to reach his destination in a minimum of time, is generally expressed in average miles per hour (kilometers per hour), and its economic value to the public is sometimes measured in terms of delay savings.
2. Safety is the reduction in the frequency and cost of accidents on the highway system, in the severity of the expected accidents, and in the number of fatalities likely to occur.
3. Operating savings is a dollar measure of the amount by which a highway project reduces the costs of fuel, maintenance, and depreciation for travel on the highway system.
4. Maintenance savings is the dollar value of reductions in the labor and materials required to keep the system functioning over its life.

In addition, a state highway system provides a number of other benefits that are more difficult to quantify. Three of the most important are given in the following.

1. Interregional transportation—The highway system should form a backbone transportation system for the state. Thus, benefits generated by routes that connect major population centers should be weighed more heavily than those generated by local highways.
2. Special access—A highway system should provide access to important traffic generators (a stadium, recreational area, or shopping center) and to other transportation facilities (bus or railroad station, airport).
3. Social and environmental benefits—The highway program should be consistent with and assist in the application of governmental planning policies on land use and pollution control. Highway construction can have a positive impact (or at least a minimal negative impact) on land development patterns, noise levels, air pollution, and vistas.

Maximizing these benefits is a complicated process that involves considering and trading off numerous possible projects and combinations of projects. By preparing a range of candidate plans that can later be evaluated, planners can help ensure that the one selected will truly provide the greatest benefits. There are no simple decision rules or formulas for carrying out this task, and planners' judgment plays a key role in these early stages. However, in the course of its analyses, the joint study team confirmed that three straightforward guidelines for generating highway improvements can be expected to move a system toward a higher level of total benefits:

1. Design for system balance,
2. Provide for system continuity, and
3. Seek low-cost design alternatives.

Design for System Balance

In selecting candidate subsystem projects, planners should balance the projected quality of service in safety, vehicle operating efficiency, and mobility throughout the network. This does not mean that mobility must be uniform throughout the subsystem or district, for it may be desirable to maintain higher mobility in rural areas than in urban areas, as has been the practice in the past. However, total system benefits are likely to be higher if similar urban or rural routes are designed to provide similar mobility than if one route is designed to perform exceptionally well and, because of funding limitations, the second route is not improved at all. In the same manner, the scope and concept of various projects should be influenced by the goal of maintaining a reasonably uniform standard of safety on the state highway system. A balanced level of safety is likely to result in more total benefits for the dollars invested than will a network in which some routes are very safe and others have extremely high accident rates. In short, designing for system balance is based on the conclusion that spreading the wealth generally results in more benefits for a given level of funding.

System balance also applies to local problems in the highway network, as is illustrated by the following simplified example. In the San Francisco Bay area, improvements were planned for each of two congested facilities. For one facility, a four-lane expressway was to be replaced with an eight-lane freeway, and, for the other, a six-lane freeway was to be expanded to eight lanes. These two facilities joined to form an existing eight-lane freeway for which no improvement was planned. Had they been completed, the planned improvements would have created a highly imbalanced network, with two eight-lane freeways converging into a single eight-lane freeway, which would then have become a bottleneck.

The plan was revised to provide a more balanced system. It involved replacing the existing four-lane expressway with a four-lane freeway, expanding the existing six-lane freeway to eight lanes, and expanding the eight-lane freeway to ten lanes. Under the revised plan, costs are lower, but, more important, the network operates more efficiently overall. As traffic demand grows in the future, the network will provide a high level of service except during peak congestion periods. Moreover, the system is reasonably balanced and it will degrade gracefully as traffic grows.

Provide for System Continuity

In addition to providing a balanced level of service throughout the subsystem, planners should attempt to close all gaps in the existing highway network. One completed route is likely to offer more system benefits than two partially completed routes. This approach is an important one in seeking to maximize system benefits through the relatively large improvement that can be realized for a given level of investment. Although substantial sums of money may already have been spent on many portions of the highway network, the full benefits cannot be realized because critical links are not yet completed. Completing these links may entail relatively small additional investments, yet the incremental benefits are likely to be large because the full benefits of the entire investment will be achieved. For example, a two-lane conventional highway connecting long segments of a four-lane freeway can create such a severe bottleneck that traffic is stop-and-go on significant portions of the four-lane freeway and waits to pass through the two-lane conventional portion of the highway. Construction of the missing link would permit faster and safer travel not only on the segment of highway that is replaced but on the existing freeway as well.

Seek Low-Cost Design Alternatives

Every dollar not spent on one project leaves more money to be spent elsewhere, perhaps at greater return. Conversely, including projects whose costs are unnecessarily high prevents improvements in other locations and makes it impossible to maximize system benefits. For this reason, the broadest possible range of viable alternatives must be considered in the development of candidate plans, and the range must include minimum-cost projects. Only by knowing the benefits that are likely to result from these low-cost alternatives can the incremental value of additional expenditures be evaluated.

The design of low-cost projects is a departure from the traditional approach to highway design. Regardless of whether it meets former conventions of design, no component of a project should be included arbitrarily. Thus, it is not sufficient to propose a four-lane freeway and a six-lane freeway each with a customary design, perhaps including a 70-ft (21-m) median, for a given location. The range of alternatives must also include freeways that have narrower medians and fewer overpasses. And project designs should not provide for expansion after the 20-year planning period. For example, a 70-ft median should not be included to provide for subsequent addition of lanes, unless that expansion will take place during the 20-year planning period. This will avoid expending funds that can otherwise produce benefits during the current period.

In the course of its work, the study team found that several types of projects were likely to yield low-cost solutions. Among these were nonexpandable expressways, new combinations of freeways and expressway segments, modified freeway-to-freeway interchanges, and ramp metering and special passing lanes that increase highway capacity.

A review of freeway-to-freeway interchange design policies illustrates the potential cost savings of these less conventional solutions. In the design of such interchanges, decisions to include local service interchanges and all direct freeway movements have a major impact on total project costs. Previously, interchange projects in the Los Angeles area included provision for full local service and for all movements. However, elimination of local service within the immediate vicinity of an interchange could reduce costs by approximately one-third. For example, at the interchange of Calif-39 and I-405 planned for Orange County, this savings potential would be approximately $14 million, a third of the project's $42 million cost. Similarly, analysis showed that eliminating reverse moves (four movements that allow a vehicle to reverse its direction of travel) would reduce interchange costs by about 20 percent or an additional $7 million (Figure 5). In total, a savings of $21 million or 50 percent of the project's entire cost could be realized by eliminating these complex design features that provide for full local service and reverse movements. Because freeway-to-freeway interchange costs accounted for 20 percent of the cost of all planned projects in the Los Angeles area, the potential total cost savings of eliminating these customary design features was substantial.

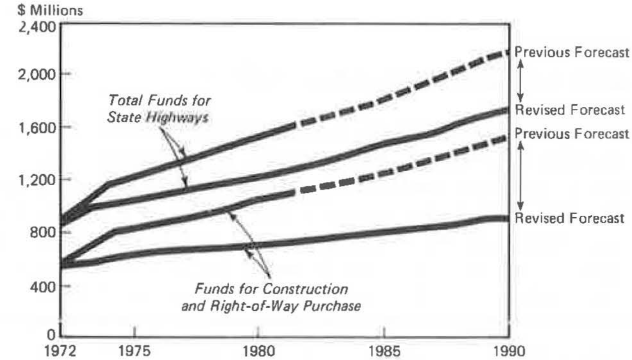
The process of generating alternatives that provide for system balance and continuity at relatively low cost requires that highway funds be allocated in the most productive manner throughout the system. The process should result in a group of candidate plans that offer a high level of benefits. It is unclear at this point which plans, or parts of plans, contribute most to the goal of maximizing system benefits. This is determined only by explicitly weighing the benefits received by the public from various highway system features against their costs. This task is accomplished in the evaluation of candidate plans.

Evaluating Subsystem Plans

To select the plan that maximizes system benefits requires that the benefits and costs of each plan be defined as precisely as possible so that plans can be evaluated in relation to one another. Quantitative measures are useful for comparing the likely impact of proposed plans. However, subsystem plans also will result in certain nonquantifiable benefits, and these also must be weighed at this stage.

To improve Caltrans's ability to measure the economic impact of proposed highway

Figure 4. Comparison of previous funding forecasts and revised forecasts using HIGHPLAN.



Note: Previous projections were for 10 years only; dotted lines extend these forecasts for purposes of comparison

Figure 5. Analysis of freeway-to-freeway interchange costs.

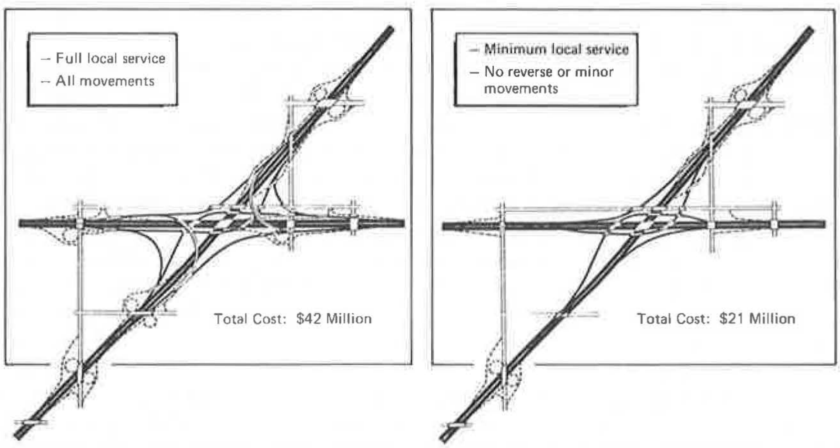
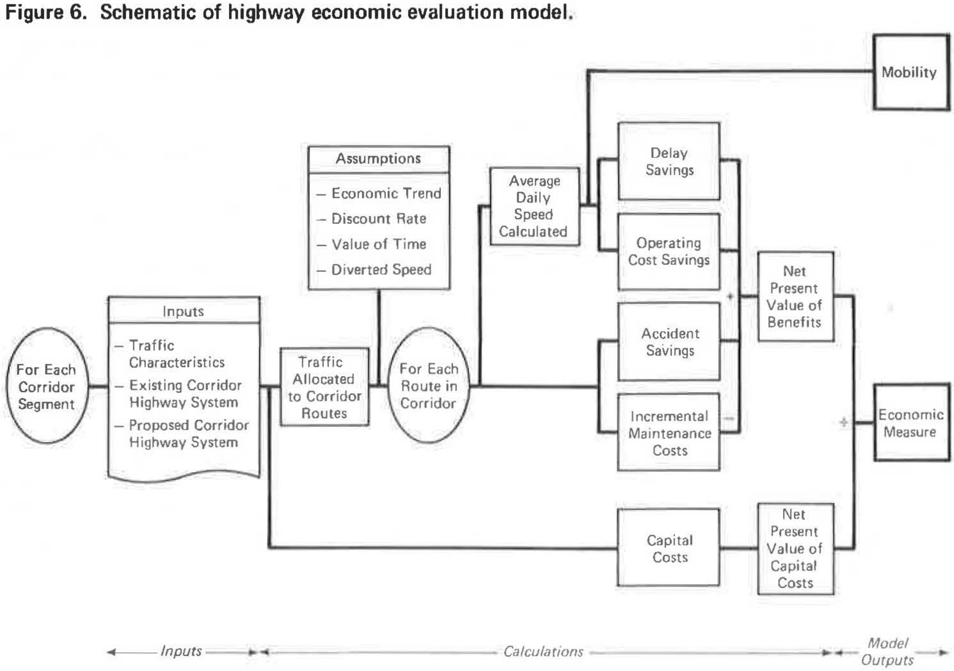


Figure 6. Schematic of highway economic evaluation model.



projects, a computer-based highway economic evaluation model (HEEM) has been developed (Figure 6). The model calculates four types of incremental benefits of proposed projects (savings in delay, accidents, operations, and maintenance) and relates them to the costs of constructing the projects. Through this process, HEEM develops a ratio of benefits to capital costs that provides a basic measure of the relative contribution of each project or group of projects to the highway system. The model also projects the mobility, or average travel speed, likely to result after construction of the proposed projects.

One advantage of HEEM is that it evaluates alternative highway solutions on a corridor basis, taking into account the effects of a highway change on adjacent routes. Another advantage is that HEEM recognizes that benefits received immediately should be assigned greater value than benefits received in the future.

The economic analysis performed by HEEM is helpful to designers and planners in two ways. First, it enables them to identify the plans that provide the highest level of total benefits and the greatest mobility. It thus provides a quantitative basis for selecting the best plan from among several candidate plans for a subsystem. Second, the model can be used to identify the most cost-effective responses for a given location in the network. Thus, high-value portions of the various plans can be isolated and recombined in a new plan offering even greater benefits than those previously developed.

However, noneconomic factors that cannot readily be included in an economic analysis, such as the importance of special access to points in the network and the contribution of interregional routes, must also be taken into account. Consequently, the staffs of local and regional planning bodies must rank the alternative programs according to both economic and noneconomic factors. Their assessment will be combined with the HEEM analysis, and a final decision is made by judging which alternatives appear to be best.

Developing a Statewide System

Selection of subsystem plans is the first stage in the new approach to highway planning. The candidate plans for each subsystem provide the basic components of the statewide highway plan. The next task is to integrate these plans to ensure that a continuous, balanced network is constructed for the entire state. As a first step, district managers consolidate subsystem plans into a single candidate plan for their districts. The next step, integrating these plans to form a single statewide plan, is carried out at Caltrans headquarters because planners at this level can maintain the broad perspective needed to balance statewide needs with those of individual counties and subsystems. The statewide highway plan is analyzed in much the same manner as the subsystems. The various subsystems are pieced together, and the resulting statewide plan is analyzed from the standpoint of the benefits it provides.

Integrating district plans undoubtedly will involve modifying some of these plans to produce a higher level of statewide benefits. Specific projects or groups of projects may need to be traded off, and, in this process, judgments will have to be made on the relative importance of projects at the margin. Economic analysis is useful in these evaluations of specific projects, as is information gathered during discussions with local agency staffs for use in preparing subsystem plans. The approach will likely reveal opportunities to adjust the funding constraints of several subsystems so that the system can be more uniformly balanced and so that gaps that are especially important from a statewide point of view can be completed. This in turn will necessitate some replanning at the subsystem level.

Through this iterative process, a slate of projects will be developed that can be funded and constructed within the 20-year planning period. This slate, called the program guide, will be the basic tool for guiding and controlling highway development. However, once selected, this slate of projects must be ordered so that projects can be built in a sequence that will maximize highway system benefits over time. Furthermore, because this slate represents the highway program over a long period, it must be responsive to the shorter term desires of the public. The process of determining project priorities addresses these needs.

Determining Project Priorities

In the past, highway construction program priorities were based primarily on judgment. Although judgment may have produced adequate priority listings in most cases, a more systematic process for determining project priorities is needed so that regional planning groups, local governing bodies, and the general public can contribute to the highway planning process.

The suggested process for determining project priorities is outlined below. Before the process starts, districts develop a list of all candidate projects that have been included in the program guide and reconfirm that proposed projects are generally acceptable from community preference, social, and environmental standpoints and that these projects are viable, i.e., that they can be built. Three broad steps are then carried out.

1. Develop a technical priority list. As a first step, projects are evaluated and ranked on the basis of technical factors alone, e.g., severity of the deficiency, route function, and operational improvement. This task is performed by management in each district. Although each district uses approximately the same technical criteria in this evaluation, the weightings given these criteria vary according to the characteristics and needs of the individual district. This ensures that the priority listings accurately reflect the relative importance of projects in each district. In the determination of project priorities, consideration is given to projects that complete large parts of the system at an early date. The results of this step, district priority listings, are then reviewed with headquarters management.
2. Modify priorities to include specific environmental factors. The technical priority list is next reviewed and approved by regional planning and local governing bodies. Agreement is reached on specific environmental factors affecting the candidate projects and on modifications to the list required to take account of these factors. This step is performed by district management and the regional planning and local governing bodies working together. Special care must be taken to maintain the funding constraints if modifications are made that might influence project costs.
3. Incorporate community preference inputs. The priority list is then modified to reflect community factors that have a bearing on the proposed projects. To provide this community preference input, local officials may solicit information and reactions from their constituents or other political representatives.

Through this process, project priority is determined on the basis of technical, environmental, and political factors with the involvement of regional planning and local governing bodies. The goal of these joint efforts is to develop a stable list of important projects that return the maximum possible benefits for the available highway dollars and that are acceptable in their design from environmental and political standpoints.

The specific highway construction program, called the 8- to 12-year planning program, is developed from this list by scheduling projects in their order of priority. However, some adjustments may be necessary to satisfy short-term financial constraints such as district and county minimums and federal assistance programs.

THE RESULTS: IMMEDIATE AND LASTING BENEFITS

The joint Caltrans-McKinsey study has eased immediate problems and brought about a decision-making process that should prevent such problems in the future.

A Realistic Program Under Control

The state of California now has a highway program for the next 20 years that can be financed with the funds likely to be available. The significance of this accomplishment can be measured by the size of the reduction in the program's backlog. When undertaking this effort, Caltrans faced a tremendous gap between available funds and highway deficiencies. Funding forecasts revealed that $6.0 billion in today's dollars were likely to be available for the highway construction program over the next 20 years, but the highway program's backlog of current and 10-year needs consisted of projects totaling $17 billion in today's dollars. To develop a 20-year system plan that was within the $6.0 billion constraint, the dollar value of highway plans had to be reduced by $11 billion or 65 percent (Figure 7). In view of the size of this reduction target, a statewide effort was clearly needed.

The Caltrans-McKinsey team approached this effort with ambitious objectives: Not only would it attempt to develop a 20-year plan that could be implemented with the funds likely to be available, but it would strive to plan the expenditure of these funds so as to provide a 30 percent higher level of service than was likely under the existing highway program. The study has resulted in dramatic improvement not only in the planned highway system itself, but also in the ability of Caltrans to channel its resources and communicate its priorities.

The planned highway system outlined in the program guide provides for substantially greater improvement in the state highway system than would have been likely under the previous planning process. First, the program guide includes more miles (kilometers) of highway construction throughout the system. For example, it outlines a plan for routes of interregional importance that increases effective highway construction by 20 percent, with 1,300 more lane-miles (2100 lane-km) and 292 more centerline miles (470 km) of highway (Figure 8). These additional miles have been made possible by reducing the cost of some planned facilities so that the money could be used elsewhere in the system.

Second, the planned highway system leaves fewer gaps and problem areas because improvements are planned for locations where they will maximize the performance of the highway system as a whole. For example, the plan provides for continuous links in the system that probably would not have been built under the previous approach; these include facilities on Calif-99 from Bakersfield to Sacramento, one of the state's backbone routes, and US-101 from San Francisco north to Calif-20.

Finally, the planned system is likely to meet the team's practical objectives of providing at least 30 percent more service—measured in reduced operating and maintenance costs, greater safety, and less delay—for the available dollars. Although an economic analysis has not been made throughout the state, substantial increases have been confirmed in two subsystems in the Los Angeles area that account for $2.2 billion of the $6 billion in planned expenditures for the period. In Orange County, the total benefits, as measured by HEEM, have increased by 100 percent with the expenditure of the same number of dollars. In Los Angeles County, the increase in benefits is approximately 30 percent. And in the San Francisco Bay area, the increase for Santa Clara County is more than 60 percent. In all of these counties, moreover, the planned system will result in a higher level of mobility (Figure 9).

All of these benefits depend, of course, on the ability of Caltrans to control the program and keep it focused on the task of building a system for the next 20 years. The program guide is the basic control document for the program. Caltrans is taking steps to ensure rigorous adherence to the guide. Only projects included in the guide will be considered, and those projects must be built according to the description and cost estimate in the guide. Design efforts for projects not included in the guide will be discontinued, the routes will be considered for unadoption, and any acquired right-of-way will be disposed of.

By adhering to the program guide, Caltrans has been able to identify 1,200 miles (1900 km) of highway that are candidates for unadoption; only 82 additional miles (132 km) need to be adopted to meet the system plan (Figure 10). This potential for unadoption of routes in turn suggests that the state's right-of-way inventory can be reduced substantially as a direct result of the new program guide. A review of the unconstructed, adopted routes indicates that right-of-way values at more than $100 million can be sold; that substantial sum of money can then be put to work elsewhere in the highway program.

Figure 7. Dollar reduction (in billions of 1972 dollars) in highway backlog.

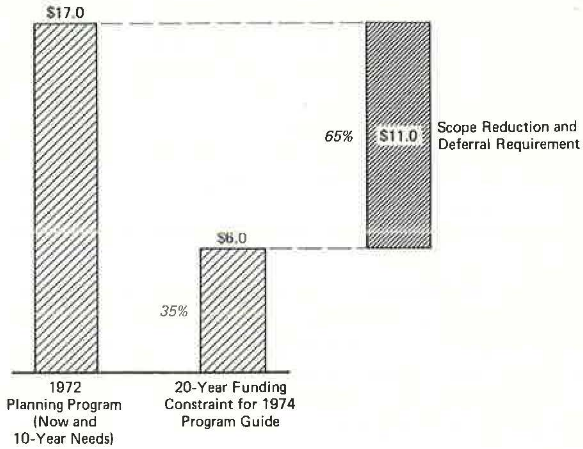


Figure 8. Improvements on routes of interregional importance.

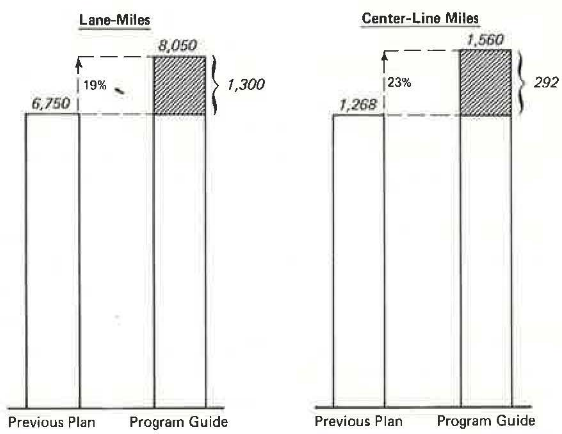


Figure 9. Improvement in highway system performance.

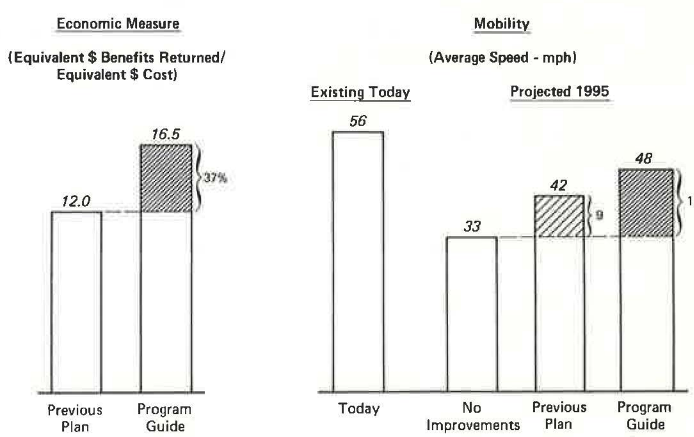


Figure 10. Route adoption summary.

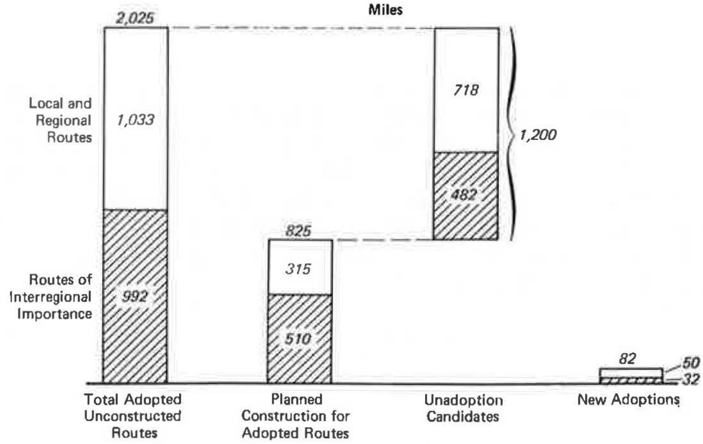


Figure 11. Estimated 1995 state fuel tax requirements.

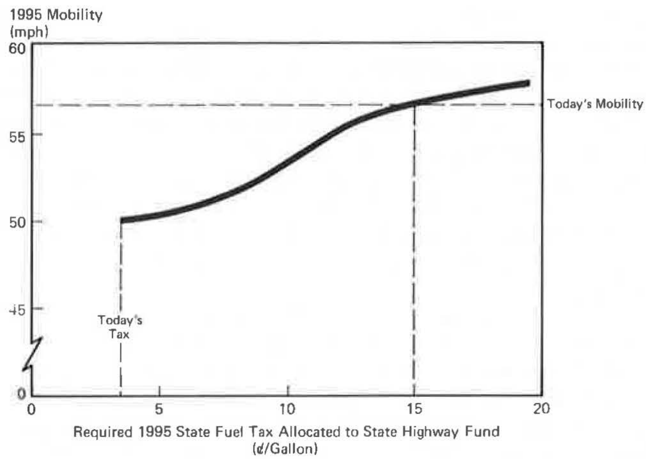


Figure 12. Previous planning process.

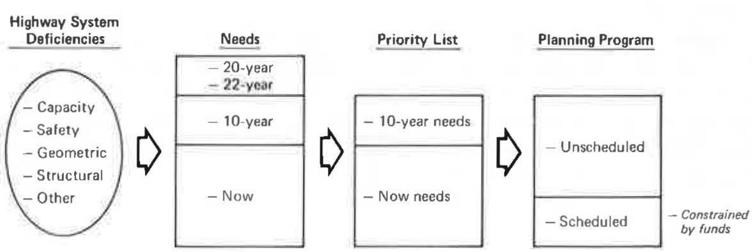
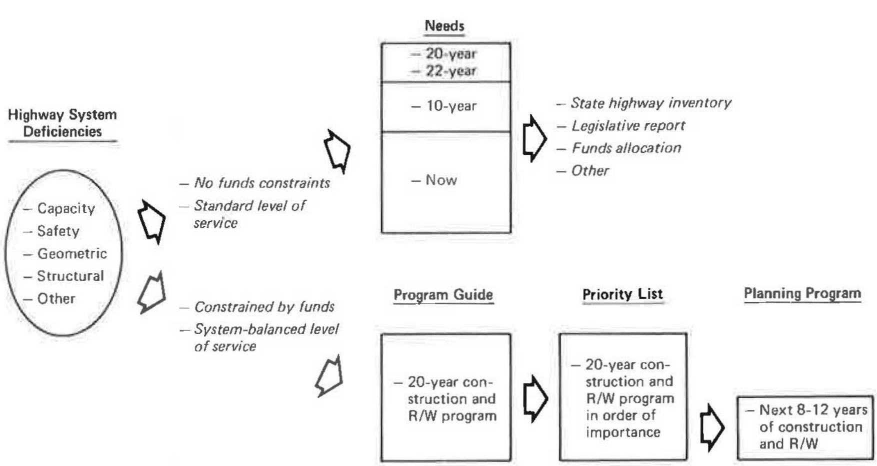


Figure 13. New highway system planning process.



And the program guide has proved to be an effective communication device. During meetings with local and regional authorities, it has enabled projects to be discussed in terms of their relationship to the whole system rather than as isolated, individual project decisions. The new quantitative measures that were used in developing the guide have made it easier to understand the impact of planning decisions and funding levels on the functioning of the highway system and to project what is likely to be constructed during the next 20 years. The program guide is also useful for presenting the system-wide implications of various alternatives of California decision makers, especially members of the California legislature, and has enabled them to more fully understand and evaluate their funding decisions, e.g., assessing mobility and taxing levels (Figure 11).

A More Effective Decision Process

The state of California now has a more effective, better controlled process for critical decisions. From the start, key Caltrans personnel have been intimately involved as team members in developing the new approach to highway planning. They have been actively instituting the required procedural changes. Most important, they have lent their energy and support to the implementation of the new approach. The project-by-project approach has been replaced by a new highway system approach that recognizes that funds are limited and that all possible highway needs cannot be met. It also recognizes that solutions designed within the context of limited funds can and must be significantly different from those designed as if ample funds were available. Now, funding constraints influence planning decisions at the earliest possible stage in the process (Figures 12 and 13).

Supporting this change in approach is a large body of new policy and technique. Forecasting funds has been improved through use of a computer model and through the close involvement of top management. A systematic methodology has been developed that permits a wide range of transportation solutions to be evaluated by using new, more accurate measures of effectiveness. Furthermore, this methodology provides for high-level review from a statewide perspective. New methods of updating costs have been introduced and, finally, provision has been made for rigorously considering the priorities of the public.

The state of California can now focus its activity on the attainment of a realistic goal without waste and frustration. The highway program can be better managed and its implications can be better communicated and understood. The public is more likely to receive accurate information regarding which parts of the highway system can be completed and when construction is likely to occur. And it is likely to receive more benefits from the dollars that are available.

MULTIPROJECT SCHEDULING FOR TRANSPORTATION CONSTRUCTION PROGRAMS

Barry M. Mundt, Peat, Marwick, Mitchell and Company

In recent years, the complexities of managing and administering state transportation programs have increased markedly. Federal funding has a significant effect on the structuring of state transportation programs because of the strict and comprehensive controls on the use of such funds. Further, the total amount of federal, state, and local funds available for transportation programs has not kept pace with the needs for new or upgraded transportation facilities. Thus, pressure is being placed on transportation program managers to maximize the use of available resources. The key to efficient use of resources—work force, money, and time—is control of production. Such control can be exercised by applying multiproject scheduling principles during the preconstruction and construction phases of a transportation project. This paper discusses the elements and operation of a multiproject scheduling system that has been implemented successfully by three state departments of transportation. It points out how multiproject scheduling can be used to anticipate resource problems likely to occur in the future and to provide the basis for determining appropriate courses of corrective action.

•IN 1968, Florida Department of Transportation management recognized the need to more closely control its overall highway construction program and the resources necessary to carry it out. Accordingly, a project was initiated to develop a management system that would direct the efforts of all personnel toward the objectives of the department.

The resulting program development, management, and scheduling (PDMS) system has been in operation for more than 4 years. Essentially, PDMS integrates the management functions of multiproject programming, financial management, and multiproject scheduling as they relate to the department's transportation construction programs. The system is designed to

1. Ensure near-term financial balance of all construction funds (programs);
2. Provide the basis for forecasting work force and cash requirements;
3. Provide a direct link among the construction work program, the legislative budget, and the project activity schedules; and
4. Provide a mechanism for identifying areas that are not proceeding in accordance with plans and for determining the most appropriate course of corrective action.

During the last 3 years, the basic elements of the Florida DOT PDMS system have been adopted by the Tennessee and Georgia Departments of Transportation. Where appropriate, these were modified to account for the management environments within each department, but the basic system concepts have been retained. All three states recognize that the key to successful implementation of the system is to gain control of production. The PDMS element that is directed toward gaining production control is the multiproject scheduling system.

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Effective control of any large organization requires that the efforts of all personnel be directed toward desired ends and that deviations from the desired courses of action be detected at an early stage. The multiproject scheduling system provides the necessary information to control production effectively within a transportation department; more important, however, it can act as the nerve center for a comprehensive management system that touches all aspects of a department's construction operations.

Multiproject scheduling is a formal means of planning and monitoring the status of transportation facility preconstruction and construction activities. One of the primary purposes of multiproject scheduling, as opposed to project-by-project scheduling, is to optimize use of all available financial and work force resources. The principles underlying the technique are not new; in fact, they are derived from several accepted scheduling methods. Multiproject scheduling combines the project scheduling methodology of the critical path method, the manpower leveling capability of line of balance charting, and the simplicity of presentation of Gantt charts. In addition, it addresses the troublesome occurrence of multiproject interference—the situation that arises when a number of projects need a particular resource (work force or money) at the same time, i.e., when need exceeds capacity.

Conceptually, multiproject scheduling is rather simple, but in practice it is a complex operation. The routine monitoring and rescheduling would not be practical without the aid of electronic data processing equipment.

FUNDAMENTALS OF MULTIPROJECT SCHEDULING SYSTEM

Several fundamental elements are necessary before a multiproject scheduling system can be implemented; likewise, several basic principles guide the system during implementation and routine operation.

Requirements

Multiproject scheduling cannot operate effectively in the absence of a stable construction work program. By stable, we mean that the work program should include all the projects that are to be constructed in, say, the next 5 to 7 years, based on current priorities. Further, the work program must be financially balanced; i.e., the estimated costs of each project phase must be reasonably matched with expected revenues. When priorities change because of unanticipated developments or updates in transportation needs, the work program can be altered accordingly. Such systematic changes will not impair overall stability of the work program, but indiscriminate changes to priorities and program emphases will cause the multiproject scheduling operation to become unmanageable.

As is true with any new program, support by management is a requisite for success. This is particularly important during implementation of multiproject scheduling, which is a tedious, one-time task. When the system is in operation, however, the tangible benefits are more immediately apparent, and support follows naturally.

Ultimately, the success of the system is contingent both on the personnel who are responsible for operating it and on the capabilities of the support staffs, especially those involved with data processing. An adequate staff whose responsibilities are carefully defined can provide for a smooth transition.

Concepts

The concepts underlying multiproject scheduling and resource balancing are given in the following.

1. Preconstruction and construction activities and events are identified and defined, and their interrelationships are established.

2. Standards are developed specifying the time and work force required to perform the activities on various types of projects.

3. Construction projects that will be active during the next 2 years are identified from the construction work program.

4. Activities and events on these projects are scheduled, and the work force is assigned according to the standards.

5. Resources (work force, money, and time) are balanced to minimize multiproject interference by adjusting the timing of project phases and activities within phases consistent with funding and contract letting objectives specified in the construction work program.

6. Project activities are monitored routinely to alert management of conditions calling for schedule revisions and further resource balancing.

These concepts, their interrelationships, and their relation to other elements of construction program management are explained below.

DEVELOPMENT OF STANDARDS

Basic to the multiproject scheduling system is a set of time and work force standards used to guide the initial project scheduling. Because of differences in production methods, staffing patterns, and environmental conditions, each set of standards is unique to a given transportation department.

Alternative Approaches

A number of approaches are available for developing standards for engineering activities. One common approach uses work measurement techniques; another relies on the experienced judgment of personnel within the department. The selection of one over the other depends on the time constraints imposed and the degree of accuracy desired.

Knowledgeable transportation department engineers, working together in a conference environment, can produce standards of sufficient accuracy for multiproject scheduling purposes. Further, the conference approach can be completed in 2 to 3 months. After the scheduling system is in operation, the initial standards can be refined, if desired, through application of selected work measures or through comparisons with accumulated data. On the other hand, a formal work measurement program requires time to gather the necessary data, which may cause a significant delay in implementing the system.

Conference Approach

Using the conference approach, department personnel in open discussion arrive at acceptable time-work force relationships, based on their familiarity with the work requirements. A series of conferences can be held, one for each logical grouping of activities (e.g., corridor analysis, survey, design and drafting, and the like). Usually, the personnel involved have operating responsibility for the activities under consideration, and they are assisted, as necessary, by personnel with demonstrated expertise in the subject areas. During the conferences, activities critical to the scheduling process are identified and defined, and time and work force requirements are established from any historical data that may be available. At the conclusion of the conference series, the standards are documented and a reference manual is produced.

The conferences also serve as a forum for the exchange of ideas on operating methods and procedures and on areas of concern to individuals. Frequently, matters are introduced that require top management attention. In addition, members of the department who will be working with the multiproject scheduling system are given an opportunity to participate in its development.

Preconstruction Activity Standards

Preconstruction activity standards are used to establish detailed project schedules and to project department work force needs. Each standard includes (a) a description of the activity or event (an activity requires time and work force; an event is a point in time); (b) the skill classes of the work force required, if appropriate; (c) the expected time required of the activity for various types of projects; and (d) the relationship of the activity or event to other activities and events in the same project (i.e., its relative position on the critical path network). This provides the base of information necessary to schedule all the activities of a typical preconstruction project over time. Additional project parameters (such as project length, number of bridges, and estimates of land tracts to be taken) are necessary for the calculation of activity time and work force requirements applicable to a specific project.

Construction Engineering Supervision Standards

Standards for construction engineering supervision activities are used primarily to forecast work force requirements for construction sites. These are not standards in the same sense as preconstruction activity standards because of the differences in responsibility for work activities. In preconstruction, a department often performs most work in-house; therefore, it has the latitude to effectively control production. In construction, a contractor normally schedules and performs the work. The department observes, inspects, and otherwise supervises construction to ensure that it meets the requirements of the contract, but it does not exercise exacting control over the contractor in the scheduling of work. In view of this, the standards for engineering supervision activities represent standard work force requirements for those activities the department performs in its role as construction supervisor.

PROJECT SCHEDULE DEVELOPMENT

Detailed schedules are prepared for all projects, for which some preconstruction or construction phase has been programmed for the forthcoming 2 fiscal years. Projects programmed to begin after that period are not scheduled initially. Detailed schedule and activity control beyond 2 years becomes rather impractical, for even a relatively stable construction program will experience modifications in that time frame.

However, the project schedules that are prepared may include activities beyond the 2-year time frame. In such a case, the complete schedule for the project should be included in the schedule data base. It is simpler to develop the entire schedule for a project at one time than to return at a later date and complete the schedule. Projects that are programmed to begin after the 2-year period are brought onto the file in 6-month increments.

Schedule Data Base

The construction work program provides the essential data for schedule development (e.g., project description, project limits, fiscal-year cost of major phases, and project priority). The activity-event standards provide the guidelines for subdividing the project phases into schedulable elements—the specific activities that are to be performed and critical events that must occur. The schedule data base includes for each activity estimated start date, elapsed time (or activity duration), work force requirement by skill class, and name of person responsible. The status of projects that are under way at the time the system is implemented is obtained from appropriate engineering unit managers.

Project Plan Report

The initial product of the schedule development process is the project plan. The project plan report produced by the system is in the form of a bar chart that displays, for each project, all necessary activities and events in their proper sequence and the time frame during which they are scheduled to occur. Activity and event names for a given project are on the vertical axis, and week-by-week dates are on horizontal axis. The bar is comprised of one or more numbers, each of which represents the amount (in person-weeks) of a particular skill class of work force required during the week for a specific activity. The smallest unit of time considered in the multiproject scheduling system is 1 week, although work force assignments can be made in increments of $\frac{1}{10}$ person-week. Across the top of the project plan report is listed the key descriptive project information (number, name, limits, description, and programmed or allotted funds, by phase). Also shown for each activity are the name of the person responsible and his location.

After the initial project schedules have been developed, the project plans are reviewed by engineering unit managers to ensure that the activity duration and work force assignment are reasonable and to confirm the status of ongoing projects. The schedule data base then is revised to reflect any changes resulting from the review. Later, when work is reported on any activity, the work force actually used and the amount predicted for completion appear in a separate bar beneath the originally scheduled bar. In this manner, both scheduled and actual work force needs are shown on the project plan report.

RESOURCE BALANCING

A balanced construction work program and funding structure are achieved initially through the multiproject programming process. Full resource balancing is accomplished during the work scheduling operation, wherein work force requirements over the 2-year schedule period are leveled within the established funding and time constraints. During the schedule period, there must be continuous interchange between multiproject programming and multiproject scheduling because of resource interrelationships. If projects are programmed without regard to activity time and work force requirements, then the program is unrealistic. Conversely, if project activities are scheduled without regard to program funding availability, then the schedule is unrealistic.

Multiproject Interference

Schedules are developed on all projects requiring department work force during the forthcoming 2 fiscal years. These schedules first are reviewed by the responsible activity managers and then are revised as necessary so that individually they are reasonable. At this point, whether the schedules, taken as a group, are reasonable has not been determined.

Scheduled activities of many projects are drawing on a common resource, the work force. It is likely that this interaction between schedules has led to multiproject interference—the situation that arises when a number of projects require a common work force at the same time, such that all requests cannot be satisfied. The reverse case is also likely to occur, that is, periods when the available work force is operating below capacity because only a few projects need the resource.

Work Force Pools

As noted earlier, one of the elements of the schedule data base is the size of the work force required for each project activity. The available work force is identified in the data base by work force pool (road design, right-of-way), by skill class (engineer, technician, draftsman, appraiser), and by location (central office, district office, other).

Each pool has an established level of personnel available for project-related work during a given budget year, although this number may vary somewhat from week to week because of vacancies and part-time employment. Related project activities are grouped into separate work force pools. For example, the preliminary plans, right-of-way plans, signal plans, and construction plans activities all might be performed by the design pool. The pools then become the focal point for work force balancing.

Work Force Balance Report

Initially, project schedules are developed without consideration of potential work force conflicts. By comparing a number of project plans, it may be possible to identify areas where scheduled work force exceeds that available for a particular pool. But to locate many such areas, take action to correct them, and assess the impact of such action in this manner would be a tedious process.

To facilitate this task, the work force balance report summarizes the scheduled work force for all related activities in a given pool. Then the scheduled work force and available work force are compared on a week-by-week basis, and net differences are displayed. The result is a week-by-week look at excesses and deficiencies of the work force for the pool. The work force balance report uses basically the same format as the project plan report. However, it lists all projects, by activity, within a work force pool. In addition, it contains appropriate summaries of the number of personnel by skill class within each pool and provides comparisons of required versus available work force. It is distributed routinely to work force pool managers for control of their operations.

Work Force Balancing

The initial work force balance report typically exhibits a random pattern of excesses and deficiencies of the work force and denotes the peaks and valleys of the scheduled work load. The object of work force balancing is to even out these excesses and deficiencies over time and thereby to make more effective and efficient use of the available work force.

The first step in balancing the work force is to adjust the project schedules. On a priority basis, the starting dates of certain activities may be delayed or moved ahead, or an entire project may be shifted forward or backward in time. New work force balance reports are then produced to show the results of the project and activity shifts. This process continues until all pools show reasonable balance. In instances where short-run excesses or deficiencies persist, deliberate assignment of overtime for short periods of time on selected activities may accomplish leveling. Farming out work from pools with deficiencies to those with excesses may also be a short-term solution. But, if long-run deficiencies are apparent for several pools through a major portion of the 2-year period, three basic alternatives should be considered: hire additional personnel; use external personnel (consultants); or revise the construction work program.

This type of analysis is performed before the department's annual legislative budget request is prepared so that the need for additional personnel can be evaluated more realistically. It also provides excellent budget support, as requests for personnel may be expressed in terms of the work to be done. Thus, budget approving authorities, including the state legislature, can readily see the alternatives available.

From a personnel management standpoint, the work force balance report provides transportation program decision makers with a tool for assessing the effect of changes in the established construction work program. The effect of project additions, deletions, and phase shifts on planned work force levels can be readily identified. Thus, appropriate actions can be formulated at an early date to correct potential work force excesses or deficiencies.

Responsibility for Balancing

The responsibility for work force balancing must be assigned to the appropriate level within a department. The adjustment of project activities and phases on a priority basis to even out minor variances can be performed by work force pool managers in cooperation with a centralized scheduling group. Crossing organizational lines (such as farming out work to excess pools) or assigning overtime should be decided at the central or district office management level. Decisions on long-range alternatives (such as adjustments in the work program, use of consultants, and adjustments in major personnel) should be made at the executive management level.

SCHEDULE MONITORING

The multiproject schedules represent, at one point in time, the best estimate by department management of the plan for completing the construction work program. But department management operates in an extremely dynamic environment in which changes that affect the program occur daily. For the schedule to be useful in managing the program, it must present a realistic picture of the work to be done and when it is to be accomplished. To maintain this current status requires that routine progress checks and adjustment of discrepancies be made.

Monitoring the project is the key to successful operation of the multiproject scheduling system. Use of many scheduling systems has discontinued either because routine project progress reporting was not maintained or because the monitoring procedure was so time-consuming and tedious that it was not followed. Thus, a means must be incorporated that will provide ease of schedule monitoring but that will require a minimum of input from the engineering units.

Routine Updating

Periodically, the schedule data base is interrogated and all activities on projects for which work is scheduled in the current period are identified. The resulting update report specifically identifies, by work force pool, each project activity, the person responsible for its completion, and its scheduled status (e.g., due to start, in progress, due to end). The update report is transmitted to the responsible person, who enters the work force actually used during the current period and an estimate of the number of weeks to completion. For events, only the date of occurrence is required. Any work performed ahead of schedule is not printed on the update report; the responsible person must enter this information. The completed update report then is returned to the centralized scheduling group. After the status of all activities and events has been reported for those projects in progress, the schedule data base is updated accordingly.

Updating typically is performed on a biweekly or semimonthly basis. Longer time intervals result in activities and projects getting out of control, as well as a tendency toward improper status reporting. In addition, the biweekly or semimonthly period usually corresponds to the payroll period. Payroll data are used to audit information received through the schedule updates to ensure input data reliability.

Management Reports

The multiproject scheduling system produces management reports when projects are off schedule. If progress is being made as scheduled, no reporting is necessary. However, if projects or activities are ahead of or behind schedule, the work force managers affected need to know. The exception report points out, on an individual activity basis, where progress is deviating from the schedule. Thereby, the manager need not analyze a number of update reports, project plans reports, or work force balance reports to determine the overall status of work in the pool. Based on the exception report, schedules can be adjusted to compensate for early or late completion. After such adjustment, the potential availability of additional workers to handle unforeseen work loads or priority changes can be assessed and the appropriate corrective measures taken.

In addition to furnishing each engineering unit manager with a copy of his own projected work load, progress of the activities that immediately precede his assignments is provided. For example, the design engineer is informed routinely of the progress of the location engineer and can take into account any expected variations in the upcoming work load.

The reports discussed provide detailed information on the project schedules and the progress being made on an activity-by-activity basis. In addition, a consolidated picture of each project and of the overall transportation program in general is required by department executive management. The project progress report is designed to fulfill this need. It groups activities so that only the most significant project elements are shown and displays past performance, present status, and predicted completion. Other pertinent project information is included, such as estimated construction cost, fund structure, and funds allotted to each phase. This report is provided to management on an exception basis. If deviations occur in a project that will alter the work schedule or the proposed contract letting date or if significant technical or funding problems are encountered, the project progress report calls this to the attention of top management.

CONCLUSIONS

Implementation of a multiproject scheduling system that is linked directly to a financially balanced construction work program can significantly change the decision-making processes of management. Specifically, it can transform what is often a mode of reacting to current problems into a forward-seeking process. Executive managers can deal primarily with establishing department policy with regard to future transportation programs. Division-level managers can focus on the near-term planning that is necessary to carry out the established policy. Activity and project managers can concentrate on the development of short-range schedules necessary to accomplish the near-term plans and on supervision of ongoing work. Responsibility for meeting the schedules is assigned to specific individuals, who periodically report their progress and have their productivity measured with respect to a standard. Indeed, successful implementation of multiproject scheduling is characterized by management asking, "What is likely to happen and what alternatives are available?" rather than, "What happened?"

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OPTIMUM STAGING OF PROJECTS IN A HIGHWAY PLAN

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Many transportation studies recommend improvements for some future design year (normally 20 years hence) and stage construction of these improvements by 5-year increments. Numerous methods have been used to stage recommended improvements, but only limited work has been done on developing procedures that optimize a special objective function for priority selection. One previous approach to staging was to examine current capacity-deficient corridors and the target year volumes on the proposed facilities. Priorities were then set so that the facilities needed to relieve existing congestion were first, the facilities most heavily used in the future were next, and the less used future facilities were last. Another approach was to develop intermediate year travel forecasts from land use or traffic assignment models for intermediate years. The staging determination was similar to the full system evaluation process except that the intermediate year alternatives considered were combinations of projects composing the design year plan.

•THE UNDERLYING problem in optimal staging of highway projects can be stated as follows: Given a base year highway network, an ultimate (20th) year highway network, a budget available in 5-year increments, and a trip table for travel demands in 5-year increments, find the optimal assignment of construction projects to 5-year intervals so as to maximize system effectiveness while completing the 20-year highway plan within budget restrictions.

For the conduct of the research, system effectiveness was defined in terms of systemwide travel time saved. Several approaches to approximating systemwide travel time saved were developed and tested. The two prominent methods described in this paper are (a) computing and weighting vehicle hours of travel on a link and across the system and (b) assuming proportionality between time saved and vehicle miles (vehicle kilometers) reduced.

After the contribution of each link to systemwide time saved is approximated by one of the methods, this contribution is compared to the cost of the link by a priority ranking method so that the appropriate order for constructing link improvements can be selected.

In the remainder of the paper, the details of each method along with the results of a test of each method on the highway network for the small community of Hopkinsville, Kentucky, are described.

EFFECTIVE SPEED APPROACH

The research conducted to date based on heuristic methods will provide an operational methodology for staging the construction of improvements on large-scale networks. The improvements are elements of a long-range highway plan. Development of this

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methodology has progressed to a point justifying confidence in its ability to select (within a given budget constraint) transportation system improvements that will minimize the vehicle hours of travel at the budget-year demand level. In addition, the procedures developed summarize other data elements that can be used to evaluate the reliability of the methodology. The steps undertaken to develop this procedure and the results obtained are described below.

Methodological Construct

Assumptions

The assumptions of the procedure are as follows:

1. The improvement elements, their cost, and resulting capacity are known and define recommended system additions for some future year;
2. A travel demand trip table for the future year is used to select the ultimate recommended system; and
3. A network description and travel demand trip table for the current year are available.

Data Generation

With the above-defined data available, intermediate year budgets and travel demand trip tables must be estimated. The steps of the procedure are as follows:

1. The minimum distance paths between all zones are computed by using the recommended network;
2. The minimum time paths between all zones are computed by using the recommended network;
3. The distance from the minimum distance path is divided by the time from the minimum time path for each zone pair to determine the effective speed between zone i and zone j; and
4. The distance and effective speed between zone i and zone j are then used to enter a table of effective speed standards established for the urban area under investigation.

Table 1 gives the standards used to analyze the Hopkinsville, Kentucky, test system. When the table is entered with a distance and effective speed between two zones, travel between those zones can be classified according to the area of the table in which it falls: below minimum standard, standard, and above standard.

The procedure described in item 4 above is used to disaggregate an intermediate year demand trip table into demand trip tables for three intermediate years. Then the budget from the current year to the intermediate year is estimated; each of the demand trip tables for the three intermediate years is assigned to the recommended system network, and the volume on each improvement link produced from each assignment is stored for analysis.

Basic Data Analysis

The analysis procedures used in this research compare the total volume for the three assignments with the capacity for each improvement. If the volume of the assigned improvement exceeds the original capacity, the difference is computed and multiplied by the length of the facility to determine the vehicle miles of excess demand on the facility. This value is divided into the cost of the improvement to determine a measure of cost effectiveness that can be compared to the cost effectiveness of all other improvements. If, however, the assigned improvement volume is less than the original capacity, the cost-effectiveness ratio of the improvement facility is assumed to be infinity.

The cost effectiveness of each improvement is computed, and the improvements are ordered from the most cost effective to the least. Then, the least cost-effective improvements are eliminated until the cost of the improvement retained in the network is less than the available budget.

This is one cycle of the process. For the second cycle, the first grouping of intermediate year improvements selected is assumed to define a new recommended system, and then the process is repeated with a new intermediate year budget and demand trip table.

The analysis presented below assumes that the recommended system is to be completed in 20 years at a given cost. Staging of facilities is then accomplished for the fifteenth, tenth, and fifth intermediate years.

Analysis Variations

The procedure described was modified for this program in a number of ways. First, provisions were added so that the excess demand on a facility from each of the three assignments could be factored differently for each effective speed category. Then, the service provided to one class of trip could be more significant than that provided to another. In the studies that follow, below minimum standard trips were given a smaller factor than above standard trips.

Second, provisions were made to vary the factors incrementally between limits. This permitted the cost effectiveness of all improvements to be computed with multiple sets of weighting factors. The results are then aggregated to show the percentage of all possible sets of factors that produce a given priority for a given facility.

Third, the procedures can set capacity restraint on the networks so that there is a consistency between network speeds and volume-capacity ratios on system elements. This is done by loading the intermediate year demand trip table to the recommended year network with capacity restraint. The restrained network is then used for the individual assignment and summary of the three classes of trips.

Research Results

The effective speed procedures produce a near-optimal solution in terms of total vehicle hours of travel when the intermediate year demand trip table is stratified by the three classes of trips and when selected factors are applied to each of the three effective speed classes in a logical way. These findings may be verified from the description of the research results that follows.

One method used for determining optimal system staging was to establish the following weighting factors for the three classes of trips:

1. Below minimum, range between 0.1 and 1.0 in increments of 0.1;
2. Standard, range between 1.0 and 2.0 in increments of 0.1; and
3. Above standard, range between 2.0 and 4.0 in increments of 0.2.

These ranges and increments yield 1,210 combinations of factors for investigation. By applying each set of factors to the intermediate year assignment of each class of trip, improvements are ordered according to effective cost. By aggregating the results from the 1,210 applications of this procedure, the number of times that a particular facility is ranked in a specific position is obtained. The results of this consensus analysis are given in Table 2 for the 15-year demand assignment to the 20-year recommended network. The improvements to be made by the fifteenth year with this process are assumed to be those that are most cost effective and that are within the 15-year budget constraint. Based on this evaluation, improvements 3, 5, 11, and 16 (stage 2) were removed from the 20-year network to create the 15-year network.

The process was rerun by using the 10-year intermediate demand trip tables and

Table 1. Effective speed standards for Hopkinsville.

Trip Length (miles)	Below Minimum Standard Trips (mph)	Standard Trips (mph)	Above Standard Trips (mph)
0.5	<14.5	14.5 to 17.0	>17.0
1.0	<14.5	14.5 to 17.0	>17.0
1.5	<18.9	18.9 to 22.0	>22.0
2.0	<19.2	19.2 to 23.7	>23.7
2.5	<21.4	21.4 to 24.8	>24.8
3.0	<22.4	22.4 to 25.5	>25.5
3.5	<24.2	24.2 to 28.1	>28.1
4.0	<25.3	25.3 to 29.6	>29.6
4.5	<25.4	25.4 to 29.8	>29.8
5.0	<26.1	26.1 to 30.0	>30.0
5.5	<28.1	28.1 to 31.5	>31.5
6.0	<29.0	29.0 to 32.3	>32.3
6.5	<31.5	31.5 to 33.5	>33.5
7.0	<31.7	31.7 to 34.0	>34.0
7.5	<36.0	36.0 to 37.5	>37.5
8.0	<36.5	36.5 to 37.5	>37.5

Note: 1 mile = 1.6 km; 1 mph = 1.6 km/h.

Table 2. Composite ranking of improvements to be deleted from 20-year network.

Improvement	Stage	Rank 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.03	0.09	0.19	0.24	0.45	0.0	0.0	0.0	0.0	0.0	0.0
2	1	0.0	0.0	0.0	0.0	0.80	0.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1	0.0	0.0	0.35	0.65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.74	0.26	0.0	0.0	0.0	0.0
4	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.97	0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1	0.02	0.35	0.28	0.35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.27	0.20	0.05	0.48	0.0	0.0	0.0	0.0	0.0	0.0
6	2	0.0	0.0	0.0	0.0	0.16	0.32	0.16	0.07	0.29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
8	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
8	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.97	0.03	0.0
9	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.61	0.36	0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.77	0.23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	1	0.0	0.63	0.37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.03	0.96	0.0
13	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.25	0.68	0.07	0.0	0.0	0.0	0.0	0.0	0.0
14	1	0.0	0.0	0.0	0.0	0.04	0.13	0.24	0.12	0.47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	1	0.0	0.0	0.0	0.0	0.01	0.35	0.59	0.04	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.26	0.74	0.0	0.0	0.0	0.0
16	2	0.98	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3. Composite ranking of improvements to be deleted from 15-year network.

Improvement	Stage	Rank 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	0.0	0.0	0.0	0.0	0.0	0.0	0.20	0.43	0.12	0.25	0.0	0.0	0.0	0.0	0.0	0.0
2	1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
4	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.13	0.59	0.27	0.01	0.0	0.0	0.0	0.0	0.0
6	1	0.0	0.0	0.0	0.0	0.0	0.0	0.24	0.07	0.16	0.30	0.22	0.0	0.0	0.0	0.0	0.0
6	2	0.0	0.48	0.28	0.04	0.14	0.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.99
8	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.81	0.19	0.0
8	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
9	1	0.0	0.0	0.0	0.0	0.28	0.72	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	1	0.0	0.0	0.02	0.89	0.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.19	0.80	0.01
13	1	0.0	0.0	0.0	0.0	0.0	0.0	0.56	0.37	0.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	1	0.0	0.02	0.21	0.07	0.49	0.21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	1	0.0	0.50	0.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.05	0.18	0.77	0.0	0.0	0.0	0.0	0.0

Table 4. Composite ranking of improvements to be deleted from 10-year network.

Improvement	Stage	Rank 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	0.0	0.0	0.0	0.0	0.08	0.20	0.66	0.04	0.02	0.0	0.0	0.0	0.0	0.0
4	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.33	0.67	0.0	0.0	0.0
4	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.31	0.69	0.0	0.0	0.0	0.0	0.0
6	1	0.0	0.0	0.0	0.0	0.0	0.02	0.04	0.65	0.29	0.0	0.0	0.0	0.0	0.0
6	2	0.0	0.0	0.03	0.09	0.62	0.11	0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.12	0.03	0.85
8	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.94	0.06
8	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.67	0.33	0.0	0.0	0.0
9	1	0.0	0.0	0.0	0.0	0.18	0.67	0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	1	0.0	0.92	0.08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.88	0.03	0.09
13	1	0.0	0.0	0.27	0.61	0.12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	1	0.0	0.08	0.62	0.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

the new 15-year recommended network. The results, given in Table 3, provided the basis for selecting improvements to be removed from the 15-year network to develop the 10-year network. Based on this evaluation, improvements 2 and 15 were removed from the 15-year network. Table 4 gives similar results when the 10-year network was analyzed to determine the first and second 5-year improvement programs.

The 15-, 10-, and 5-year networks were also developed by using a weighting factor of 1.0 for all three classes of trips. This procedure resulted in a different ordering of the improvements based on cost-effectiveness values. Table 5 gives the 20-year improvements to be included in the 15-year network, the 15-year improvements included in the 10-year network, and the 10-year improvements to be included in the 5-year network for both procedures.

The order of staging is different for the two methods. Furthermore, there was no assurance that either method gives the best staging solution. (Most probably they did not.) Therefore, the results of the analysis were used to establish a series of 15-year networks (by removing logical candidates from the 20-year network). The 15-year networks with the 15-year demand trip tables were then used to assign trips and summarize results to determine whether the consensus 15-year networks did, in fact, produce the minimum vehicle hours of travel. This analysis was reasonably reliable inasmuch as most of the candidate systems that satisfied the budget constraints could be defined and the number of improvements was small enough to keep track of manually. The assignments and results are given in Table 5. The assignment descriptions indicate the improvements that are assumed to be removed from the 20-year network to create the 15-year network. Assignment 3-5-11-16(2) is the consensus network. The total assignment is the assignment of the 15-year demand trip table to the 20-year recommended system.

From Table 6 it is evident that improvements 3, 11, and 16 produce the minimum vehicle hours of travel of all 15-year networks analyzed. In addition, a rough cost-benefit analysis for each system was developed from the output data. Vehicle miles of travel were multiplied by $0.135. Vehicle hours of travel were multiplied by $2.50, and the system capital costs were multiplied by 0.0667 to develop an estimate of annualized cost. Based on this rough measure of the benefit-cost ratio, wherein the unit costs were assumed, improvements 15 and 11 were better than the consensus system results (improvements 3-5-11-16). However, when the two were compared directly by using the secondary benefit procedure discussed below, improvements 3, 5, 11, and 16 proved to be the superior system.

These results led to further evaluation to determine why improvement 5 was eliminated from the 15-year network in the consensus analysis. The location of the improvement in the fringe of the CBD was causing it to attract trips which, without the improvement, would travel through the CBD. Consequently, adding improvement 5 to the 15-year network produced significantly increased trip speeds and substantial benefits. However, the speeds were not increased enough to put the trips in the standard or above standard categories, which caused them to be insensitive to the factoring techniques. A procedure, possibly a preprocessor, must be developed to handle improvements of this type. If improvement 5 could be handled properly, then improvements 3, 11, and 16 would be the consensus network.

After the consensus procedure was modified, it identified the best 15-year network. This led to an approximation procedure useful in determining the specific weighting factors that should be applied to define the best system.

Test Network

Figure 1 shows the Hopkinsville test network.

Table 5. Summary of intermediate networks by consensus of factors and number of factors methods.

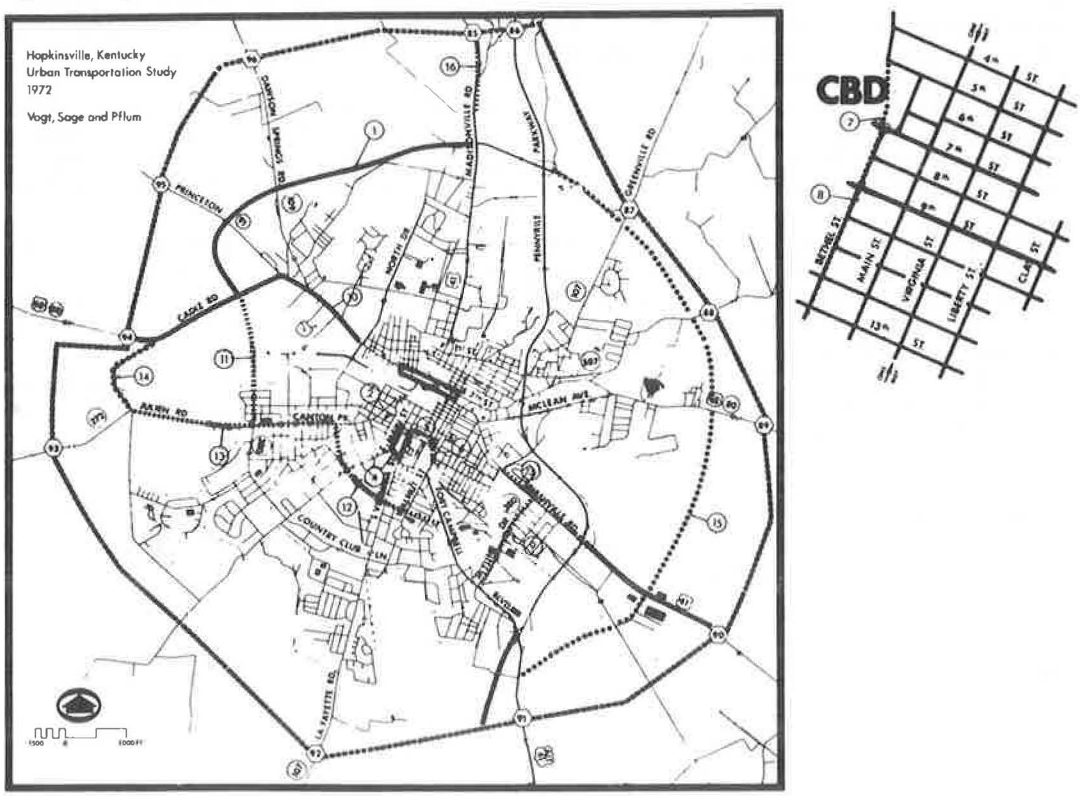
Item	15-Year Network		10-Year Network		5-Year Network	
	Consensus of Factors	Number of Factors	Consensus of Factors	Number of Factors	Consensus of Factors	Number of Factors
Improvements needed	1	1	1	1	1	4(1)
	2	2	4(1)	4(1)	4(1)	4(2)
	4(1)	4(1)	4(2)	4(2)	4(2)	6(1)
	4(2)	4(2)	6(1)	6(1)	6(1)	6(2)
	6(1)	6(1)	6(2)	6(2)	7	7
	6(2)	6(2)				
	7	7	7	7	8(1)	8(1)
	8(1)	8(1)	8(1)	8(1)	8(2)	8(2)
	8(2)	8(2)	8(2)	8(2)	9	9
	9	9	9	9	12	12
	10	10	10	10		13
	12	12	12	12		
	13	13	13	13		16(1)
	14	14	14	16(1)		
	15	15	16(1)			
	16(1)	16(1)				
Improvements not needed	3	3	2	2	2	1
	5	5	3	3	3	2
	11	11	5	5		5
	16(2)	16(2)	11	11	5	10
			15	14	6(2)	11
			16(2)	15	10	14
				16(2)	11	15
					13	16(2)
					14	
					15	
					16	

Table 6. Summary of results based on effective speed methodology.

Improvements	Vehicle Miles	Vehicle Hours	Below Minimum Standard Vehicle Miles	Below Minimum Standard Vehicle Hours	Below Minimum Standard Trips	Annual Operating Cost (dollars)	Total Capital Cost (dollars)	Benefit-Cost Ratio
15, 2	530,262	17,190	178,798	6,729	64,604	41,814,400	9,423,000	5.043
15, 11	531,396	17,122	176,091	6,547	62,796	41,808,195	9,126,000	5.217
15, 14	530,867	17,114	174,718	6,504	62,546	41,774,980	9,806,000	4.906
15, 16	530,932	17,096	174,626	6,501	62,494	41,761,840	9,520,000	5.074
2, 3, 11	527,705	17,147	178,027	6,707	64,918	41,649,420	9,773,000	5.116
3, 11, 16	528,383	17,056	173,417	6,468	62,735	41,599,780	9,870,000	5.141
3, 5, 11, 16	528,972	17,069	173,172	6,461	62,625	41,640,660	9,834,000	5.097
3, 6, 11, 16	528,417	17,061	173,574	6,477	62,797	41,613,285	9,835,000	5.138
3, 11, 14	528,216	17,072	173,837	6,482	62,849	41,605,985	10,156,000	4.987
2, 10, 11, 14, 16	528,170	17,246	182,859	6,900	65,844	41,762,570	9,619,000	5.021
2, 10, 11, 16	528,621	17,217	180,657	6,832	65,512	41,758,555	9,829,000	4.920
3, 10, 14	529,423	17,173	181,852	6,769	64,548	41,757,825	9,789,000	4.941
3, 11, 12	527,543	17,264	184,857	6,971	66,404	41,747,970	9,698,000	5.003
All	528,593	16,934	166,434	6,207	60,943	41,498,675	13,065,000	4.000

Note: 1 vehicle mile = 1.6 vehicle kilometer.

Figure 1. Hopkinsville test network.



TIME-SAVED APPROACH

Objective

The methods described thus far have been oriented to identify the contribution of an individual improvement to this objective. After the contribution of an improvement is obtained, a cost-effectiveness cost-contribution ratio is calculated to rank the improvements.

Vehicle Hours as an Estimate of Contribution

One estimate of the contribution of an improvement to the systemwide objective is that of vehicle hours saved. The process of assigning vehicle loads to individual links is based on the construction (using the Federal Highway Administration's urban transportation planning software package) of minimum time paths in the 20-year network for origin-destination combinations in the 15-year trip table. Thus, vehicles are attracted to improvements if these improvements reduce travel time. Past experience has indicated that, generally, time saved is related to the length of an improvement. The longer vehicles travel at a higher speed, the more time they will save.

If a proportional relationship between time saved and vehicle miles on an improvement is assumed, the method of ranking improvements according to their contribution to system time saved is cost/(k × vehicle miles). When k is the same over all links in the system, it may be dropped from the ratio and the quantity cost/vehicle mile is the ranking criterion.

Relaxing the Assumption That the Proportionality Factor Is Constant Over the Entire System

Because not all vehicles traveling over a given improvement require the same travel time, individual origin-destination information was considered to determine the contribution of the improvement to systemwide time saved. Specifically, individual vehicle miles on an improvement from a given origin to a destination were weighted according to their relative importance to total time saved and were summed to obtain a weighted estimate of vehicle miles on an improvement. It was felt that such a weighting reflected the contribution of an improvement more accurately than assigning equal importance to all trips. The process of assigning weights to trips was based on quality of service considerations. For each trip loaded by the FHWA package, trip length and average speed were computed. As before, based on the speed and trip lengths, the trip was classified into three categories with respect to quality of service: below minimum standard, standard, and above standard. Those with below minimum standard quality of service were given low weight; those with standard quality of service were assigned higher weight; and those with above standard quality of service ratings were given highest weight.

The assumption is that system time saved is accurately defined for all improvements by the quantity cost/weighted vehicle mile where

$$\text{Weighted vehicle miles} = \Sigma_{O_iD_j} (k)_{\text{length, speed}} (\text{vehicle miles})_{O_iD_j}$$

Allocating Total System Time Saved Directly to Individual Links

Experience with the first two methods of computing the contribution of an improvement tended to suggest that some direct allocation of total systemwide time saved to improvements might be even more desirable in the ranking process. Several methods for performing this allocation were hypothesized, and one method was tested. Test results are presented subsequently.

A reasonable measure of total systemwide time saved can be computed in the following manner: Use the FHWA package to build shortest time trees in the base year and 20-year networks. For each origin-destination pair, the difference between the base year travel time and the 20-year travel time is the amount of time saved for each trip between that origin and destination. Multiply these time savings/trip by the 15-year trip table to get an estimate of total travel time saved by all vehicles in the system.

The Allocation Problem

After the systemwide time saved has been estimated, it must be allocated among the individual improvements. Using the network shown in Figure 2 will illustrate the point. The dotted lines indicate possible improvement links that could be added to the existing network, which is indicated by the solid lines. Suppose the origin-destination demands are A to D, 100 trips, and B to D, 300 trips.

Without the improvements, A to D traffic can only be routed A to C to E to D and B to D traffic must go B to E to D. If, however, improvement links BC and CD were available, then B to D traffic would go B to C to D. If the solid lines in the figure represent the base year network and the dotted lines the improvements added to form the 20-year network, total travel time saved may be as given in Table 7. Thus, total travel time saved equals 14,000 min. This total time saved must be allocated to the improvement links BC and CD. Clearly, the 2,000 min saved for AD traffic is independent of whether link BC is added to the network and hence should be allocated completely to link CD. The problem is in allocating the 12,000 min for the BD traffic. One method is to allocate the time saved as a function of the total link lengths. If both BC and CD are the same length, 6,000 min would be allocated to each. Thus, BC would be responsible for saving 6,000 min and CD for saving 8,000. Suppose, however, that the cost-effectiveness ratios turned out such that BC was preferred over CD, and, because of budget restrictions, only BC would be constructed. In such a case, no time would be saved because, without link CD, link BC is of no value in reducing travel time for BD traffic. In effect, links BC and CD are interdependent. If only CD is built, the total time saved would be 2,000 min. If only BC is built, no time would be saved, but, if both are built, the total time saved would be 14,000 min.

In this simple case, we have what might be called a second order interaction. This problem can be modeled as a quadratic 0,1 integer programming problem. Although it is conceptually and theoretically a correct formulation, in no way does it aid in solving optimum staging problems, since quadratic 0,1 integer programming problems are much more difficult to solve than linear 0,1 integer programming problems. It is possible that an interactive type of procedure could be developed wherein the allocation of time saved is changed at each interaction and the process stops when the predicted time saved, according to the allocation, is within reasonable limits of the actual time saved. The problem becomes even more complex when higher order interactions, which occur in most actual problems, are included.

Heuristic Approach: Maximize and Allocate Time Saved

As the research team defined, tested, and either rejected or modified various solution approaches, the need for an approach that could obtain satisfactory answers rapidly was clearly recognized. Therefore, a concept was designed to determine which improvement links should be added to a system so that the total budget is not exceeded and so that the total time saved by all system users is the maximum when compared to all other combinations of improvements that satisfied the budget constraint. Development and application of this concept required that a method be defined for allocating total time saved to individual improvements such that the summation of the time saved by the addition of each individual improvement equalled the total time saved when all improvement links were added to the network. With this capability, the procedure can rank

Figure 2. Sample network for allocating time saved.

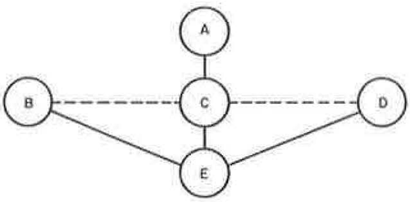


Table 7. Time savings for network shown in Figure 2.

Origin-Destination	Demand Trips	Base Year Time (min)	20-Year Network Times (min)	Time Saved (min)
AD	100	60	40	2,000
BD	300	90	50	12,000

each improvement in order by a time saved-cost ratio.

IMPLEMENTATION OF THE HEURISTIC APPROACH FOR MAXIMIZING TIME SAVED

A series of 360 FHWA battery and FORTRAN programs was developed to implement the theory of maximizing time saved. The programs were written to obtain answers as rapidly as possible. Computer efficiency and operational ease were not prime considerations. The programs determine the impedance saved over any time span for each improvement in any highway plan. Based on the cost for each improvement, a final program ranks each improvement in order of a time saved-cost ratio.

Methodological Construct

The programs initially subtract the future year impedance matrix from the base year impedance matrix. The resulting matrix is then multiplied by a trip table, and a matrix of total impedance saved is created. Various programs are used to segregate portions of the total impedance saved into five categories. All impedance saved within a category is identified by an improvement number. The categories are as follows:

1. All impedance saved that goes through only one improvement—The impedance saved for this category is self-explanatory.
2. All impedance saved that goes through an improved link in the future year and goes through the same link (unimproved) in the base year—The impedance saved is defined by the difference between the base year and future year impedance for the link.
3. All impedance saved that goes through only one improvement in addition to those defined in 2—The impedance saved for the one improvement is the total impedance saved for an interchange minus the impedance saved for those links defined in 2.
4. All impedance saved that goes through two improvements or two improvements in addition to those defined in 1—The impedance saved for the two improvements is the total impedance saved for an interchange minus the impedance saved, if any, for those links defined in 2. A two-dimensional matrix of impedance saved by improvement number is created. The impedance saved in each cell is allocated to individual improvements in proportion to time saved per trip by improvement, determined from 1 and 3.
5. All other impedance saved that does not fall in the above categories—This is not evaluated, for it is insignificant by comparison (this assumption introduces little systemwide error).

Research Results

The series of programs developed was applied to the Hopkinsville test network. Travel time was used as the impedance. The 20-year skim trees were subtracted from the base year skim trees. The result was multiplied by the 15-year trip table to create a

Table 8. Time saved per unit cost.

Improvement	Time Saved: Categories 1 and 3	Category 2	Category 4	Total Time Saved	Cost (dollars)	Time Saved/ Cost
16	0	459.4	1.1	460.5	626,000	0.74
11	213.2	–	1,707.5	1,920.7	890,000	2.16
3	71.3	4,996.4	115.2	5,182.9	1,809,000	2.87
15	9,585.5	–	1,484.7	11,070.2	3,049,000	3.63
1	2,802.6	–	5,513.3	8,315.9	1,772,000	4.69
14	0	1,295.9	0	1,295.9	210,000	6.17
10	357.3	7,819.5	477.4	8,654.2	1,257,000	6.88
13	5.1	8,315.8	164.5	8,485.4	1,225,000	6.93
2	41.2	4,600.7	240.4	4,882.3	593,000	8.23
9	21.8	4,834.4	219.6	5,075.8	568,000	8.94
8	0	1,546.7	0	1,546.7	157,000	9.85
4	1,206.6	–	91.4	1,298.0	85,000	15.27
6	1,463.1	–	77.2	1,540.3	80,000	19.25
12	9,716.8	–	5,034.0	14,750.8	668,000	22.08
5	765.3	–	93.8	895.1	36,000	23.86
7	6,483.8	–	3,195.1	9,678.9	40,000	241.97
Total	32,733.6	33,868.8	18,415.2	85,017.6	13,065,000	6.51
Percentage of grand total*	34.6	35.8	19.5	89.9		

*Grand total is the total time for all categories.

Table 9. Analysis of predicted time saved.

Network ID	Actual Time Savings Lost (hours/day)	Predicted Time Savings Lost (hours/day)	Percentage Difference
2, 15	256	266	3.9
11, 15	188	217	15.4
14, 15	180	206	14.4
15, 16	162	192	18.5
2, 3, 11	213	200	6.1
3, 11, 16	122	126	3.3
3, 5, 11, 16	135	140	3.7
3, 6, 11, 16	127	151	11.0
3, 11, 14	138	140	1.4
2, 10, 11, 16	283	265	6.4
2, 10, 11, 14, 16	312	286	8.3
3, 10, 14	239	252	5.4
3, 11, 12	330	364	10.3
Average			8.3

matrix of total 15-year time saved. This matrix was processed through the various programs, which allocated the time saved to the various categories and improvements described. Improvement costs were entered, and data given in Table 8, ranked by time saved-cost, were produced. All time saved is in min/day. The 15-year network with the minimum amount of travel time, as defined previously, is one that does not include improvements 3, 11, and 16. The time saved procedure ranks these as the lowest. This procedure does determine the best 15-year network for Hopkinsville based on the selected criteria.

Although the primary interest was whether this procedure could determine the best network, another concern was the accuracy of the predicted time saved. To evaluate this accuracy, 13 reasonable 15-year networks were selected. The 15-year trip table was loaded onto each of these networks, and resulting total travel time was determined. These travel times were then compared to the total travel time of the 15-year trip table loaded on the 20-year network. This comparison yielded the actual time saved that was lost by eliminating improvements for each network. This value was then compared to the value predicted by the time saved procedure (Table 9).

CONCLUSION

The research reported here demonstrates the validity of both the effective speed approach and the time-saved approach to staging elements in a highway plan. Although neither approach is proposed as optimal, both were able to select the best staged plan for the Hopkinsville, Kentucky, network within the constraints imposed. Further understanding of the critical issues involved in the development of procedures for staging a recommended highway plan can be obtained by analyzing and testing a large-scale urban system with the two procedures developed in this research.

PRIORITY ANALYSIS PROCEDURE FOR RANKING HIGHWAY IMPROVEMENT PROJECTS

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This paper presents a priority analysis scheme for ranking highway improvement projects. The procedure is based on a scoring model approach that evaluates highway projects in terms of as many as 26 parameters that are divided into eight groups: need, deficiency, continuity, benefit-cost, local opinion, and economic, social, and environmental consequences. For each project, the individual parameters are evaluated and combined through a set of weighting factors into one or two indexes that can then be used to rank the projects. The selection of parameters and a set of weighting factors was determined from responses to questionnaires distributed to state transportation board members, department of transportation officials, and regional and local planners within the state of Georgia. The improvement projects are categorized according to 10 functional classes and nine improvement types. The projects are ranked within each category.

•MORE THAN $200 million was spent by the Georgia Department of Transportation (GDOT) in fiscal year 1972 for highway improvements. This amount, though large, cannot begin to fill the $10 billion worth of highway needs estimated for the years 1970 through 1990. To accommodate this scarcity of financial resources, means must be developed by which highway improvements can compete objectively for limited capital resources. Fundamental to every known capital allocation scheme is a procedure for ranking the criticality of highway improvement projects to maximize the use of available resources.

Currently in Georgia, as in many other states, priorities are assigned to improvement projects largely on the basis of subjective judgments developed from past experience. Priorities that are established subjectively run the risk of personal engineering bias, lack of comprehensiveness, and political bias. Furthermore, the increasing number, magnitude, and complexity of the programs will soon make subjective priority analysis unmanageable.

The priority scheme reported here was developed to satisfy GDOT's desire for a priority analysis procedure that recognizes needs and deficiencies and that also incorporates the following features: socioeconomic consequences, environmental consequences, continuity considerations, and state and local political reactions.

The new procedure should also be capable of rapid execution and be suitable for implementation in the immediate future without extensive changes in the existing data collection systems or in the existing planning process. Three general guidelines were established for evaluating a priority analysis procedure (6):

1. Objectivity—subjective judgments and opinions should be minimized so that answers can be defended;
2. Comprehensiveness—the procedure should be devised to permit the consideration of all projects; and

*Mr. Mak was with the Georgia Department of Transportation when this paper was written.

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3. Consistency—projects selected should be consistent between themselves and from year to year.

Most of the existing procedures meet these guidelines to some degree. However, the priority procedure presented has important elements that are not included in existing guidelines.

Social, economic, and environmental aspects of highway improvement projects have generally been omitted from priority analysis procedures, possibly because these aspects are intangible and require subjective judgments—a violation of the basic guideline of objectivity. However, recent emphasis on the social, economic, and environmental aspects of highway improvements dictates that, for certain types of highway improvements, they deserve equal, if not more than equal, consideration with the traditional need, deficiency, and service factors. A highway official (2) commented at a recent conference:

> The socioeconomic aspects of highway projects are becoming more and more important in priority programming. Some people believe that highways should be used primarily as an economic development tool to revitalize depressed areas, such as Appalachia, by providing access and mobility to and within these areas. Others are of the opinion that urban highways should only be developed when they are designed to achieve broader urban goals, such as better housing, more beautiful communities, or better recreational and social opportunities. Highways do contribute in greater or lesser degree to such objectives, and so decision makers are giving increased attention to such views, along with needs of the people for efficient motor vehicle transportation.

Federal legislation and guidelines, such as the National Environmental Policy Act and Federal-Aid Highway Acts of 1970 and 1972, require state highway or transportation agencies to prepare careful and thorough investigations of social, economic, and environmental consequences of federal-aid highway projects. These requirements have caused a substantial change in the planning process. The role of community participation in the planning process has also gained considerable momentum of late. It is, therefore, important to include such factors in the priority analysis process.

EXISTING PRIORITY ANALYSIS PROCEDURES

Priority analysis is the systematic process of ranking improvement projects according to certain criteria that measure their relative degree of need, urgency, or desirability. Over the years, many procedures have been developed for priority analysis (4, 5, 7-14, 22). Most of these are based on some form of sufficiency or deficiency rating. Conceptually, these procedures all consist of

1. A rating scheme to establish the relative degree of need, deficiency, or desirability of the projects by using quantitative and qualitative parameters that describe each project and
2. A ranking scheme to order projects in accordance with ratings and other qualitative inputs.

Although existing priority analysis procedures vary widely in detail, they can be divided into two broad groups: sufficiency ratings and economic analysis. Sufficiency ratings are composite ratings, in which a single composite score is calculated for each project and the projects are then ranked according to their scores [the procedure used by the Arizona Highway Department is a forerunner in this category (7)], or priority arraying, in which the projects are segregated into priority arrays or groups based on ratings of individual factors [Tennessee and Washington use procedures of this form (9, 10)]. In economic analyses, the projects are ranked according to their economic importance, expressed mostly in terms of benefit-cost ratio or rate of return. The Pennsylvania procedure is a prime example of this approach (11).

Without substantial changes, neither sufficiency ratings nor economic analyses are an adequate approach to priority rating. Sufficiency ratings measure the urgency for improvement, and economic analysis measures the benefit or importance of the improvement. Unfortunately, a project with a high degree of criticality may not have high economic importance, and a project with a high indicated economic return may not represent a critical need. The economic analysis approach also has drawbacks in estimating and quantifying benefits, which have prevented its widespread use. In the sufficiency rating approach and, to a lesser extent, the economic analysis approach, the rating is based on the need or deficiency of the road sections themselves, but it is the improvement projects that are assigned priorities.

Both of the approaches to sufficiency rating, composite score and priority arraying, are also open to criticism. Consider, for example, a project with a high score in only one element such as a road section with a critical structural deficiency and no functional or safety deficiencies, and another project with a low to moderate score in each of the three elements. A composite score cannot distinguish between the two projects. On the other hand, the priority arraying approach places all the weight on only one of the elements and fails to examine the overall situation.

An optimization approach has recently been proposed that is conceptually quite different from the existing procedures (14). The optimization approach combines the functions of priority analysis, program formulation, and project scheduling into one operation that produces the optimum schedule of available projects through the use of precise analytical techniques such as linear, quadratic, and dynamic mathematical programming. Linear programming is by far the most popular and most appropriate of these techniques. The optimization approach has many attractive prospects, but the difficulties encountered in the estimation and quantification of benefits and consequences cast some doubt on its practicality at this time. However, with technological advances in these areas, optimization may be the procedure of the future.

CONCEPTUAL FRAMEWORK OF THE PROPOSED PROCEDURE

A scoring model approach was chosen for the proposed procedure. This procedure can be implemented within the present state of technology. It also overcomes some of the shortcomings of the sufficiency rating and economic analysis approaches. The scoring model concept can be expressed mathematically as

$$S_j = \sum_{i=1}^{P} W_i R_{ij} \tag{1}$$

where

S_j = overall score or rating of project j,
W_i = weighting factor (relative importance) of the ith parameter,
P = number of evaluating parameters, and
R_{ij} = individual score or rating of the ith parameter of project j.

Equation 1 provides a basis for ranking projects with a similar or identical set of evaluating parameters and weighting factors. However, because of the wide diversity in highway functional classes and types of improvements, unlike projects must be divided into separate categories. A two-dimensional categorization was chosen that identifies each project by both a functional class and an improvement type. The functional class describes the level and use of the highway with which the project is associated, and the improvement type describes the nature of work to be done.

The scoring model is applied to priority analysis as follows.

1. Highway improvement projects are categorized according to their functional classification and improvement types so that they may be evaluated and compared under compatible sets of parameters and consequences.
2. The evaluating parameters and consequences that are pertinent to each category under consideration are identified.
3. The relative importance of the various evaluating parameters is determined through a set of weighting factors.
4. For each project in each category, the rating of each evaluating parameter is developed through objective, analytical methods where possible; otherwise, subjective judgments are made.
5. The overall rating of each project is developed by combining the individual parameter ratings into one or two indexes through the use of relative weighting factors.

The priorities of projects in each category can then be determined based on their overall index or indexes.

Categorization of Improvements

Improvements under different functional classifications and types of work should be evaluated under different but compatible sets of criteria. The first step of the priority analysis procedure is, therefore, to segregate the improvement projects into categories based on their functional classification and type. Categorization of improvement offers other significant advantages in addition to compatibility. Categorization provides a basis for legislative and administrative directives in terms of resource allocation, fund appropriation, policy making, and system priorities.

Ten functional classes of highways and streets were selected for use in the priority analysis procedure:

1. Urban Interstate,
2. Rural Interstate,
3. Urban principal arterial,
4. Rural principal arterial,
5. Urban minor arterial,
6. Rural minor arterial,
7. Urban collector,
8. Rural collector,
9. Urban local, and
10. Rural local.

The segregation of projects by improvement type is much less well-defined than functional classification. Nine types of improvements were adopted after careful studies of the nature of work involved, the funding sources, and the distribution of projects under the various improvement types. Table 1 gives the nine types of improvements and brief descriptions of each.

Identification of Evaluating Parameters

A set of evaluating parameters was developed to measure the significant impacts of all categories of highway projects. Parameters were identified from existing priority analysis and evaluation procedures (3-14, 17-21), and, where necessary, additions were made to provide adequate coverage of all significant impacts. The list of candidate parameters was reduced by analyzing the units of measure needed to evaluate the different parameters and the sources of data that can support the measures.

After careful study and review, 26 parameters were identified for which data are readily available. The parameters are grouped under eight broad headings:

Need factors
1. Need as identified by state, regional, or local transportation plans;
2. Need as identified by state, regional, or local officials;
3. Need as recommended by U.S. DOT officials evaluating the project;

Deficiency factors
4. Existing and projected traffic volume;
5. Existing traffic volume-capacity ratio;
6. Existing condition of highway facilities including pavement and structure;
7. Accident experience;
8. Deficiencies in roadway geometrics and alignment including roadway width, stopping and passing sight distances, horizontal and vertical curves, and horizontal and vertical clearance of bridge structures;

Continuity factors
9. Continuity with existing facilities;
10. Continuity and coordination with other improvements,

Highway-user-related factor
11. Benefit-cost ratio including the benefits of travel cost and time and accident potential and the costs of construction, operation, and maintenance;

Human factors
12. Local opinions from publications and hearings as well as requests (or complaints) from local civic groups and individuals;

Economic consequences
13. Desirability with respect to state, regional, and local community goals and long-range, land use, and economic development plans;
14. Effect on land value and development;
15. Effect on agricultural activities;
16. Effect on commercial and industrial activities;
17. Effect on local construction industry and employment;
18. Relocation of public utilities;

Social consequences
19. Disruption to community during construction;
20. Relocation of residential and commercial units;
21. Effect on neighborhood life and social patterns;
22. Preservation of historical, religious, and institutional areas;

Environmental consequences
23. Aesthetics and visual effects;
24. Air and noise pollution and vibration;
25. Water pollution and effect on drainage; and
26. Conservation of natural resources.

Not all parameters apply to every type of improvement. For example, relocation of public utilities is rarely of significance in a minor highway upgrading. Thus, we view the 26 parameters as the universe, and for each improvement type we select a subset of parameters that are significantly affected by the improvement type. It is assumed that all functional classes share the same set of evaluating parameters for a given type of improvement.

Units of measure and criteria values were established for each of the 26 parameters for each of the functional classes. The definition of units of measure and criteria values for tangible parameters poses little problem. However, for intangible parameters, their definition is of much concern and has to be established subjectively.

PREPARATION AND ANALYSIS OF QUESTIONNAIRES

To identify the pertinent parameters for each type of improvement and, at the same time, to establish the relative importance of the parameters in terms of weighting factors, a set of questionnaires was developed with the following objectives:

1. To serve as an identification process to select the pertinent parameters from the

Table 1. Improvement types.

Improvement Type	Description
1. New highway construction	New highway construction and related engineering work
2. Reconstruction and major highway upgrading	Reconstruction, relocation, realignment, addition of lanes, and widening
3. Minor highway upgrading	Resurfacing, repaving, grading, drainage, paving shoulders, and surface treatment
4. New and replacement structures	Bridge structures, culverts, sign support structures, and special structures
5. Safety improvements	Safety projects, pedestrian overpasses, guardrails, medians, separator and sidewalk construction
6. Traffic engineering improvements	TOPICS, intersection improvements, traffic signals, flash and overhead signing, and street lighting
7. Beautification projects	Landscaping and acquisition of scenic rights-of-way
8. Railroad crossing projects	Railroad overpasses, signals, and crossing markings
9. Special projects	Projects that cannot be classified into any of the above improvement types, such as rest areas, weighing stations

Figure 1. Sample questionnaire rating form.

	FACTOR	IMPORTANCE SCALE (No Importance 0 – 10 Extreme Importance)
NEED FACTORS	Need as identified by state, regional or local transportation plans	0 1 2 3 4 5 6 7 8 9 10
	Need as identified by state, regional or local officials	0 1 2 3 4 5 6 7 8 9 10
	Need as recommended by DOT officials evaluating the project	0 1 2 3 4 5 6 7 8 9 10
DEFICIENCY FACTORS	Existing and projected traffic volume	0 1 2 3 4 5 6 7 8 9 10
	Existing traffic volume/capacity ratio	0 1 2 3 4 5 6 7 8 9 10
	Existing condition of highway facilities	0 1 2 3 4 5 6 7 8 9 10
	Accident experience (including hazard index)	0 1 2 3 4 5 6 7 8 9 10
	Existing deficiencies in roadway geometrics and alignments	0 1 2 3 4 5 6 7 8 9 10
CONTINUITY FACTORS	Continuity with existing facilities	0 1 2 3 4 5 6 7 8 9 10
	Continuity and coordination with other improvements	0 1 2 3 4 5 6 7 8 9 10
HIGHWAY-USER RELATED FACTOR	Benefit-cost ratio	0 1 2 3 4 5 6 7 8 9 10
HUMAN FACTOR	Local opinions from publications and hearings as well as requests (or complaints) from local civic groups and individuals	0 1 2 3 4 5 6 7 8 9 10
ECONOMIC FACTORS	Desirability with respect to state, regional and local community goals and long-range, land-use, and economic development plans	0 1 2 3 4 5 6 7 8 9 10
	Consequences on land value and development	0 1 2 3 4 5 6 7 8 9 10
	Consequences on agricultural activities	0 1 2 3 4 5 6 7 8 9 10
	Consequences on commercial and industrial activities	0 1 2 3 4 5 6 7 8 9 10
	Consequences on local construction industry and employment	0 1 2 3 4 5 6 7 8 9 10
	Dislocation and/or relocation of public utilities	0 1 2 3 4 5 6 7 8 9 10
SOCIAL FACTORS	Disruption to community during construction	0 1 2 3 4 5 6 7 8 9 10
	Dislocation and/or relocation of residential and commercial units	0 1 2 3 4 5 6 7 8 9 10
	Consequences on neighborhood life and social patterns	0 1 2 3 4 5 6 7 8 9 10
	Preservation of historical, religious, and institutional areas	0 1 2 3 4 5 6 7 8 9 10
ENVIRONMENTAL FACTORS	Aesthetics and visual effects	0 1 2 3 4 5 6 7 8 9 10
	Air pollution, noise pollution and vibration	0 1 2 3 4 5 6 7 8 9 10
	Water pollution and effect on drainage	0 1 2 3 4 5 6 7 8 9 10
	Conservation of natural resources	0 1 2 3 4 5 6 7 8 9 10
		No Importance … Extreme Importance

26 for each type of improvement and

2. To provide a basis for determining an initial set of weighting factors.

The questionnaires ask members of the rating panel to evaluate the importance of the 26 parameters for each of the nine types of improvements on a scale of 0 to 10. Zero denotes no importance or inappropriateness; 10 signifies extreme importance. A sample rating form is shown in Figure 1.

The rating panel was comprised of three groups of people, each with a direct concern over the selection of highway improvement projects in Georgia:

1. Georgia Transportation Board members, each of whom represents one of the 10 congressional districts in the state (the board members may be considered as the top-level decision makers because they give the final approval for each project);
2. Responsible Georgia Department of Transportation officials; and
3. Area planning and development commissions and urban area planning commissions.

The responses of the three groups were analyzed separately to determine whether the judgments of the groups differed significantly. Weighting factors were based on the overall judgment of the panel. When significant differences occurred between groups, weighting factors were sometimes adjusted on the basis of a logical rationale.

Overall, 57 of the 72 distributed questionnaires (about 80 percent) were returned with good balance for each group. For each parameter, the responses were tabulated, and the means and standard deviations of the importance ratings were computed for each group as well as for the three groups together. The differences among the means of the three groups were tested for statistical significance by using an F-test with one-way analysis of variance. These tabulations and calculations were repeated for each of the 26 parameters for each of the nine improvement types. The correlations and interrelationships between the parameters for each type of improvement were also evaluated by using correlation and factor analyses.

A parameter was deemed inappropriate for a given type of improvement if

1. Its mean importance rating was very low,
2. A significant fraction of raters considered it inappropriate, or
3. A relatively low mean importance rating was combined with a high standard deviation, which indicated widespread disagreement on the importance and appropriateness of the parameter.

Candidate parameters for exclusion were reviewed after data availability, cost of obtaining data, and pertinency of the parameters were considered subjectively.

The relative importance of pertinent parameters is expressed in terms of weighting factors that were based on the mean importance ratings. The initial set of weighting factors for each of the first eight types of improvements is given in Table 2. (The last type of improvement, special projects, was not included in the analysis because of the wide variation among projects.) Parameters deleted from the master list have zero weighting factors and are noted as not applicable.

FORMULATION OF PRIORITY ANALYSIS PROCEDURE

Two alternative approaches to the priority analysis procedure are shown in Figure 2. A proposed project is first assigned a category on the basis of its functional classification and improvement type. The set of pertinent parameters and their appropriate weighting factors are selected for the improvement type. Each pertinent parameter is then evaluated by using established units of measure and criteria values on a scale of 0 to 10.

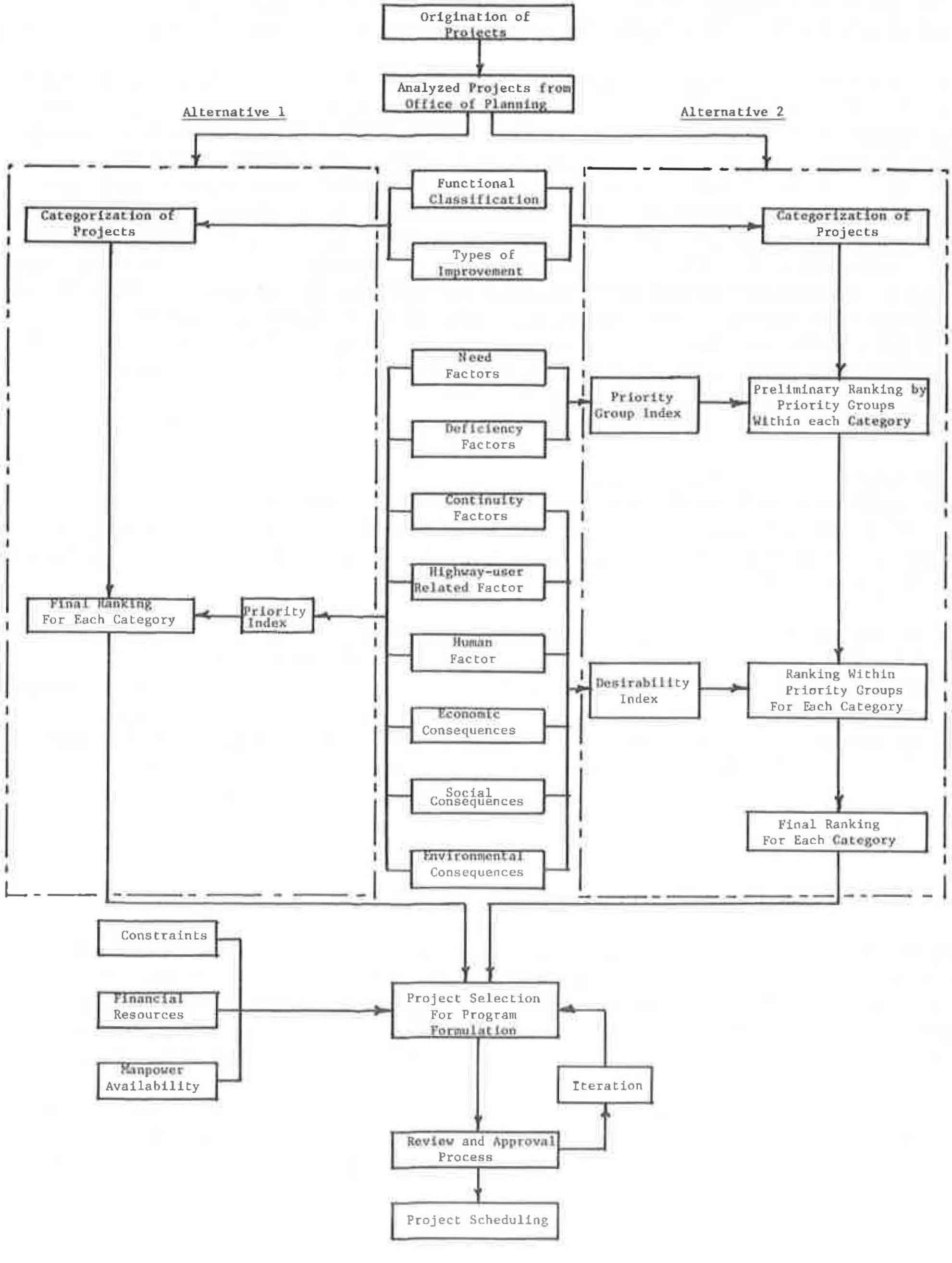
The individual ratings of the pertinent parameters are collapsed into one or two dimensions to provide a basis for ranking the projects. There are two approaches to this collapsing process. The first is to combine all parameter ratings into a single

Table 2. Initial set of weighting factors.

Parameter	Improvement Type 1	2	3	4	5	6	7	8	Parameter	Improvement Type 1	2	3	4	5	6	7	8
1	8.8	8.4	6.1*	5.4*	5.7*	7.2	5.1*	7.2*	14	6.1	5.7	4.2	NA	NA	NA	NA	NA
2	7.2	7.2	7.0	7.1	7.1	8.1	7.0	7.8	15	5.3	4.3	NA	NA	NA	NA	NA	NA
3	8.1	7.8	8.6*	9.0*	8.2	8.6*	7.0*	8.2	16	6.3	5.8	4.4	4.8	NA	4.2	NA	NA
4	8.1	8.1	6.7	6.6*	7.5	7.8	5.3*	8.3	17	4.2	3.8	NA	NA	NA	NA	NA	NA
5	8.2	8.3	6.5	7.9*	7.3	8.4	NA	6.6*	18	3.6*	4.3	NA	NA	NA	NA	NA	NA
6	7.1	7.5	8.7	8.7	8.3	8.1	NA	7.5	19	5.0	5.1	4.9*	4.8	NA	NA	NA	4.1*
7	7.5*	8.3	7.9	8.7	9.6	9.3	NA	9.7	20	6.6	6.2	NA	NA	NA	NA	NA	NA
8	6.9	7.8	5.7*	7.3	8.0	8.2	NA	8.3	21	7.5	6.2	NA	NA	NA	NA	NA	NA
9	7.6	6.9	4.7*	5.8	5.2*	6.8	NA	6.1*	22	6.8	6.8	NA	NA	NA	NA	7.0*	NA
10	7.9	7.7	6.0	6.4	5.8	6.8	4.8*	6.4	23	6.8	6.0	4.7	6.2	4.8	5.7*	9.2	4.5*
11	6.5	6.2	4.4*	4.2*	NA	4.3*	NA	4.6*	24	6.8	6.5	NA	NA	NA	NA	5.4*	NA
12	6.3	5.9	5.1	4.5	5.9	5.7	6.6*	6.8	25	7.8	6.6*	6.5*	7.0	NA	NA	6.2*	NA
13	8.9	7.6*	4.9*	6.2*	4.5*	NA	6.3*	5.7*	26	7.7	6.7*	5.0*	5.8*	NA	NA	6.9*	NA

Note: Asterisk indicates ajdustment in weighting factors because of significant differences between rating groups.

Figure 2. Proposed priority analysis procedure.



composite score or priority index. The second approach is to divide the parameters into two groups and to treat the groups independently.

First Alternative

In the first approach, the ratings for all pertinent parameters are collapsed into a single composite score, the priority index, which can be expressed mathematically as

$$P_j = \sum_{i \in M} A_i R_{ij}^{N_j} \qquad (2)$$

where

P_j = priority index for project j,
$i \in M$ = parameter i within the set M of pertinent parameters that have weighting factors greater than zero, excluding those with no available information,
A_i = normalized weighting factor for parameter i,
R_{ij} = rating of parameter i for project j, and
N_j = normalizing index for project j.

Equation 2 is essentially an extension of the basic scoring model concept. There are, however, three major modifications. The first modification is that a pertinent parameter with no available information for its evaluation is treated as if it is inappropriate, that is, as if the parameter has a zero weighting factor. This provides more flexibility in the model so that projects with only fragmented and incomplete information can be evaluated. The symbol $i \in M$ thus denotes those parameters within the set M of parameters with both the weighting factors greater than zero and information available for their evaluation.

The second modification follows from the first one. Inasmuch as some of the pertinent parameters with weighting factors greater than zero may not be applicable because of a lack of information, the number of evaluating parameters may not be the same for all projects within the same category. This variation in number of evaluating parameters poses a serious problem because the projects within the same category are no longer evaluated on the same scale or dimensions. The weighting factors must therefore be converted to the same scale or dimension to accommodate this variation.

The simplest approach to this problem is to normalize the weighting factors to a (0, 1) scale. This is accomplished by dividing each weighting factor by the sum of all weighting factors within the set M of pertinent parameters, which can be expressed mathematically as

$$A_i = W_i \Big/ \sum_{i \in M} W_i s \qquad (3)$$

where

A_i = normalized weighting factor for parameter i,
W_i = weighting factor for parameter i, and
s = a constant [multiplying by s converts W_i from a (0, 1) scale to a (0, s) scale; the value of s may be chosen as desired].

The third major modification is the use of a normalizing index as an exponent to the individual parameter ratings. (The normalizing index may alternatively be used as a multiplying factor to the individual parameter ratings.) The normalizing index is defined as

$$\text{Normalizing index} = 1 + \log\left(\frac{\text{projected traffic volume} \times p}{\text{estimated project cost}}\right)^{q}$$

where

log = logarithm to the base 10 and
p, q = constants.

The normalizing index is designed to incorporate the cost element into the evaluation process. This index may be viewed as an indicator of the importance of the number of users per unit of cost. This procedure favors improvements on highway facilities with high traffic volume and low capital cost. The constants p and q allow the index to be calibrated and adjusted. The use of the logarithm to the volume-cost ratio moderates the effects of extremely large or small ratios.

The ranking of projects in each category in the approach is based on the priority indexes of the projects. The project with the highest priority index is ranked first, the project with the next highest priority index is ranked second, and so on.

Second Alternative Approach

In the second approach, two indexes, a priority group index and a desirability index, are used to rank projects. The priority group index is determined by combining the parameter ratings on the need and deficiency parameters only. The remaining parameters of continuity, benefit-cost ratio, local opinions, and socioeconomic and environmental consequences are collapsed into the desirability index. The basic assertion for this two-index approach is that the 26 parameters can be separated into two groups: (a) the need and deficiency parameters, which evaluate the criticality or urgency of a project, and (b) the remaining parameters, which identify the importance of a project to a variety of interest groups.

The key to combining the two indexes is the relative significance, for priority determination, of the project urgency and project importance. For the purposes of this paper, urgency is placed ahead of importance for the following reason: Highways are at present the predominant mode of transportation and will likely remain so until satisfactory alternative modes are developed. To provide a sufficient level of mobility, service, and safety to the public, the existing highway network must be maintained to an acceptable quality standard. One of the main objectives of highway improvements is, therefore, to improve the highway network to a satisfactory level and to maintain it. A project that is in critical need should be implemented as soon as possible and thus should be given a high priority. For example, a bridge structure that is failing should be replaced or repaired as soon as possible, although it may have relatively little importance in terms of the second group of parameters.

Existing data collection and planning processes support a preference for urgency. Data for evaluating need and deficiency parameters are readily available and are collected on a routine basis for all types of improvements. On the other hand, data for the second group of parameters are not collected and evaluated on a routine basis and are often not available or are at best fragmented. For example, socioeconomic and environmental consequences are now evaluated only for proposed new highways and are not available for other types of improvements.

The need and deficiency parameters are also favored over the second group of parameters in terms of objectivity, one of the guidelines for a good priority analysis procedure. Evaluation of the need and deficiency parameters is largely objective and is based on well-established guidelines and standards. The parameters in the second group are generally evaluated on the basis of subjective judgments that may be biased and that may change appreciably from rater to rater. In addition, the impacts and significance of some of the importance parameters are still relatively unknown because these parameters have only been used to evaluate highway improvements for a short time.

The calculations used to determine the two indexes are very similar to those used for the priority index. The priority group index is formed by combining all parameter ratings of the need and deficiency parameters through the following expression:

$$PG_j = \sum_{i \in M_1} A_i R_{ij}^{N_j} \qquad (4)$$

where

PG_j = priority group index of project j, and
$i \in M_1$ = parameter i within the set M_1 of pertinent need and deficiency parameters that have weighting factors greater than zero, excluding those parameters with no available information.

The priority group index indicates the relative degree of urgency for a project. The larger the priority group index is, the more urgent is the need for such a project, and vice versa.

The desirability index is calculated by collapsing the parameter ratings of the remaining parameters of continuity, benefit-cost ratio, local opinions, and socioeconomic and environmental consequences. The equation for the calculation of the desirability index is again similar to that of the priority index:

$$D_j = \sum_{i \in M_2} A_i R_{ij}^{N_j} \qquad (5)$$

where

D_j = desirability index of project j, and
$i \in M_2$ = parameter i within the set M_2 of pertinent continuity, highway-user-related, human, economic, social, and environmental parameters that have nonzero weighting factors, excluding those parameters with no available information.

The desirability index indicates the relative importance of a project in terms of its benefits and consequences. The higher the desirability index is, the more important is that improvement, and vice versa.

The only significant difference among the calculations of the priority index, priority group index, and desirability index is the definition of the set of pertinent parameters, M, M_1, and M_2, which in turn induces changes in the normalized weighting factors.

The two-index approach is applied by first ranking the projects in each category in order of their priority group indexes or by the first criterion urgency. Several clusters, or priority groups, are formed from this list in such a way that the members of a priority group all have the same general degree of urgency. The priority groups are ordered on their degree of urgency. Projects in the first priority group are all ranked higher than those in the second priority group, which in turn are ranked higher than those in the third priority group, and so on. Within a priority group, projects are ranked in accordance with their desirability indexes or by the second criterion, desirability.

In addition to having a high priority group index, a project can be assigned to the top priority group for another reason. A project with one or more of its need or deficiency parameters rated critical, that is, assigned a parameter rating of 10, is immediately placed in the top priority group. The reasoning is that a project that is urgent enough to have one or more need or deficiency parameters rated critical demands immediate attention and should be placed near the top of the priority list.

It is premature to determine at this point which approach to priority ranking is more appropriate. Extensive testing is needed before any conclusions can be drawn about the relative merits of the two approaches. However, the two-index approach seems to offer more promise because it treats urgency and desirability separately and because it reflects urgent requirements.

COMMENTS ON THE PROPOSED PROCEDURE

The three basic guidelines of objectivity, comprehensiveness, and consistency are essentially satisfied by the proposed procedure. The comprehensiveness of the procedure is ensured by identifying parameters for each type of improvement from a master list of parameters that includes all of the candidates. Only those parameters that were given unfavorable responses by the raters were eliminated. Objectivity and consistency are preserved in the procedure through the need and deficiency parameters, which can be objectively evaluated through well-established guidelines and standards. The two-index approach places more emphasis on these need and deficiency parameters.

The biggest asset of the proposed procedure is the inclusion of intangible parameters. Socioeconomic, environmental, continuity, and state and local inputs are included. These parameters are sometimes more important than the tangible parameters in the evaluation of highway improvements. Their importance is expected to increase with time.

When intangible parameters are evaluated, objectivity and consistency are difficult to achieve. Subjective judgments, which are highly undesirable, tend to change and conform with the current trend of values. Although socioeconomic and environmental consequences have been considered only for about a decade, the impact of these considerations needs no description. The proposed procedure can adapt to value changes by modifying the definitions, units of measure, and criteria values of affected parameters. The weighting factors of the parameters can also be revised and updated to conform with a changing emphasis. However, some objectivity and consistency will have to be sacrificed when the intangible parameters are incorporated.

The fact that the procedure is flexible, simple to use, and adaptable to electronic data processing should not be overlooked. The number, magnitude, and complexity of present highway programs make the task of project programming a monstrous undertaking. Any technical assistance in simplifying this task should be of great help to the programming process.

The procedure also has the ability to evaluate improvements with only fragmented and incomplete information. Parameters that are pertinent but for which there is no available information are treated as if they are inappropriate and are given weighting factors of zero. Then, as additional information becomes available, the projects may be reevaluated based on the new data. The incorporation of traffic volume and estimated cost elements into the procedure is another small but significant addition to the process.

Some drawbacks observed in existing procedures also exist in the proposed procedure, but to a lesser degree. The obscuring of individual parameter criticality by a composite score is partially offset in the two-index approach. No such provision has been devised for the single-priority index approach.

The sufficiency rating approach as used in most existing procedures rates the deficiencies, or sufficiencies, of the highway facilities, but not the improvements themselves. On the other hand, the economic analysis approach rates the importance of the improvement but fails to identify the degree of urgency or criticality. The proposed procedure combines both these aspects by evaluating the criticality with the need and deficiency parameters and assessing the importance and impact of the improvement projects with the remaining parameters. Furthermore, parameters of conflicting interest may be evaluated simultaneously by the procedure.

The procedure may also be extended to include multimodal transportation improvements such as projects in public transit and airport development. The basic framework of the procedure may be retained. The major area of modification is in the redefinition of the evaluating parameters and probably the introduction of some new parameters. New sets of weighting factors, units of measure, and criteria values will also be needed for the evaluation of improvement projects in other modes of transportation.

CONCLUSIONS

A complete framework of a priority analysis procedure was developed. It is not possible to quantitatively evaluate the procedure until extensive testing and calibration have been completed. The procedure will also require considerable review and refinement before it can be fully implemented. Nevertheless, the authors feel that the procedure is good. It is comprehensive. It is certainly a step toward developing a sound priority analysis program.

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OPTIMAL HIGHWAY SAFETY IMPROVEMENT INVESTMENTS BY DYNAMIC PROGRAMMING

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Determining which projects to implement under a given budget and which to defer until later is central to the planning and management of highway systems. With a limited budget for construction, maintenance, and safety improvements, investments must produce optimal benefits. This paper discusses a dynamic programming procedure developed to select the optimal combination of safety improvement projects for a given budget. The type of dynamic programming considered is multistage, i.e., cost optimization of several projects, each with one or more alternatives. All safety improvement costs are dealt with in terms of present worth, and consideration is given to construction or installation cost, yearly maintenance cost, present interest rate, and expected life of the improvement. The option of staging safety improvements over a number of years was excluded from this analysis. All possible combinations of improvements were input as alternatives for each of the 61 projects involved in this study. The input consisted of the designated budget for the safety improvement program, the improvement cost, and the benefits derived from each improvement. The accuracy and reliability of dynamic programming depend on the accuracy of benefits and costs used as input. In a comparison with benefit-cost analyses, dynamic programming yielded a higher return for a given budget. An optimal allocation of funds will always be obtained if the individual project costs are multiples of the increment used in dynamic programming.

•THE PROCESS of determining which projects to implement under a given budget and which to defer until later is central to the planning and management of a highway system. Because the construction, maintenance, and safety improvement budget is limited, investments that will produce the optimal benefits must be chosen. This is often impossible to accomplish without the aid of a computer because of the complexity of the problem. Dynamic programming has been proved to be an efficient method for selecting priority projects to derive maximum benefits.

Dynamic programming is an optimization technique that transforms a multistage decision problem into a series of one-stage decision problems. The decision at each stage depends on the input to that stage, the feasible set of decisions at that stage, and the conditional set of decisions from the preceding stages.

There are three main reasons why dynamic programming is needed for transportation planning. First, dynamic programming is designed to provide the best plan over a period of time, inasmuch as the scheduling of a project is a critical variable. Second, dynamic programming makes it possible to obtain the best combination of projects where some approaches are inaccurate and trial-and-error methods can become an impossible task. Third, dynamic programming can determine the optimal investment plan when the usual benefit-cost, present worth, or maximum rate of return approaches are not practical. When the amount of money required for a single project is a large por-

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tion of the budget, the best projects are not necessarily those that would be chosen by the conventional means of priority selection. Benefit-cost and rate of return methods may not provide the best overall use of resources because an efficient implementation of results may not be possible. In addition, the benefit-cost method of selecting optimal alternatives does not always produce the best results because it focuses narrowly on immediate benefits and often precludes some future combinations of alternatives that are more desirable.

Many programs do not require detailed knowledge of the mechanics of dynamic programming. The input consists only of the costs and benefits anticipated for a project and the time required for completion. By taking all possible combinations into account, dynamic programming avoids the possibility of missing an optimal plan that will guarantee the best economic investment.

There are several approaches to priority programming as it relates to the capital allocation problem. Benefit-cost, present worth, and rate of return calculations have traditionally been used as an integral part of the transportation planning process. Performance bugeting has been proposed as a means of highway maintenance management (1). Construction and maintenance programs must continually be assigned priorities when funds are insufficient to complete all projects. Safety improvement programs, which were initially funded through the Highway Safety Act of 1966 and expanded through the Federal-Aid Highway Act of 1973, have become so large that they are unmanageable without a clear, concise means of priority allocation. Possibly the most comprehensive and accurate method of cost allocation for a constrained budget is dynamic programming. The term was coined by Bellman (2) in an attempt to simplify the phrase definition previously used: mathematical theory of multistage decision processes. He summarized dynamic programming applicability into three types of projects: single-stage, multistage, and multistage incorporating a time factor.

Single-stage dynamic programming is the evaluation of a single project with several alternatives as compared to multistage programming in which several projects with several alternatives are evaluated. Multistage with a time factor involves allocation of funds by dynamic programming in which several projects with several alternatives are subject to implementation over a period of time.

Johnson, Dare, and Skinner (3) presented dynamic programming as a means of selecting highway improvement projects to eliminate hazardous locations and therefore to maximize the annual cost reduction benefit. They suggested that use of dynamic programming ensures an optimal solution when several projects are being considered and construction funds are limited. de Neufville and Mori (4) dealt with a simplified procedure for determining the optimal construction schedule for additions to a highway or similar transportation network over time. They used only costs and benefits for each project as input to determine the optimum schedule. Funk and Tillman (5) used the systems approach to emphasize that the cost and benefits occurring to all parts of the system must be evaluated to establish the effect on a specific route under consideration. Dynamic programming was used to analyze the entire system such that construction was optimally staged.

Jorgensen (6) has done extensive work in identifying high-accident locations and developing methods for selecting improvements from among various projects. Jorgensen recommended use of benefit-cost, present worth, or rate of return calculations to determine which project yields the maximum difference between the annual investment cost and the annual expected safety benefit. Determining priorities with these methods is restrictive because they do not ensure the optimal combination of projects when the budget is limited. Lorrie and Savage (7) showed that, under a constrained budget, selecting a project with a large initial cost and a high ratio of present worth to cost may preclude the selection of several smaller projects that together yield a greater present worth. Another disadvantage is the inability of previously used methods to evaluate the relative merit of competing alternatives at varying investment levels.

Previous studies have dealt with highway budgeting in Kentucky (8, 9). Agent (10) evaluated the high accident location spot-improvement program in Kentucky and determined that the small investment in the program had returned significant dividends. It was felt that further study was warranted, and Zegeer (11) recently completed an investigation of the various methods for selecting high-accident locations. Favorable results from the studies by Agent and Zegeer, combined with an expansion of the spot-improvement program as a result of appropriations through the Federal-Aid Highway Act of 1973, have stimulated the development of an optimal method for allocating funds within the safety improvement program. Dynamic programming, as an optimal investment plan with a constrained budget, is presented here in a rather simplified but effective form for the particular problem.

The Alabama Highway Department has done considerable work in applying dynamic programming to the optimization of budget allocation for the spot safety improvement program (12). The Alabama program was modified significantly to evaluate the data available for the spot-improvement program in Kentucky.

PROCEDURE

In this study, multistage dynamic programming was evaluated as a means of assigning priorities and allocating expenditures for the spot safety improvement program in Kentucky. All safety improvement costs were dealt with in terms of present worth, and construction costs, maintenance cost, and the expected life of the improvement were all considered. The option of staging safety improvements over a number of years was excluded from this analysis. All possible combinations of alternatives were considered for each of the 61 projects involved in the analysis. For example, the safety of a curve where a large number of accidents occur may be improved in several ways, including realignment, resurfacing, signing, and delineation.

The problem of optimizing use of improvement funds can be divided into two distinct steps. First, the benefits associated with each proposed improvement are determined. Then, based on the costs and benefits for a set of improvements and a specific budget, the optimum combination of improvements to be implemented is chosen. A computer program[1] is used to calculate the costs and benefits in the subroutine COSBEN. These results are printed out and passed into the subroutine DYNAM along with the budget and output information. DYNAM then determines and prints out the optimum combination of improvements for the desired budgets. If no alternative emerges at a particular location, alternative O is printed. A range of budgets including the maximum budget available are considered. In this manner, an optimum budget is determined.

Calculation of Costs and Benefits Using the Present Worth Method

The following equations were used to calculate costs and benefits (13):

$$C = S + A[(1 - i)^L - 1]/i(1 - i)^L \qquad (1)$$

where

C = present worth cost of improvement,
S = construction cost,
A = yearly maintenance cost,
i = present interest rate = 10 percent, and
L = life of improvement.

[1]The original manuscript contained several appendixes giving the computer program, the subroutines, variables, and flow charts. These are available in Xerox form at the cost of reproduction and handling. When ordering, please refer to XS-67, Transportation Research Record 585.

$$B = \left\{ \frac{[(1+t)^{L+1}/1+i] - 1}{(1+t/1+i) - 1} - 1 \right\} \beta \quad (2)$$

where

B = present worth benefit,
t = exponential growth rate factor for traffic volume = 4 percent, and

$$\beta = \left(\sum_{m=1}^{J} \sum_{n=1}^{3} a_m N_{mn} \gamma_n \right) \Big/ T \quad (3)$$

where

β = benefit per year associated with the improvement,
T = time (years) of accident history,
J = number of accident causes associated with the location,
a_m = percentage of reduction of m th cause affected by the improvement,
N_{mn} = number of accidents associated with m th cause, and
γ_n = average cost of an accident (n = 1-fatality, n = 2-nonfatal injury, and n = 3-property damage only).

Dynamic Programming Algorithm

1. Step 1. Divide budget into N equal intervals.
2. Step 2. (Stage 1) Determine the best alternative at location 1 to maximize the return by using j increments, j = 1, 2, . . . , N; i.e.,

$$O_1(j) = R_1(j) \quad (4)$$

where

$O_1(j)$ = total optimum return after stage 1 for an investment of j increments,
$R_1(j)$ = return from location 1 for an investment of j increments, and
$D_1(j)$ = chosen alternative at location 1 for an investment of j increments.

3. Step 3. (Stages 2 through M) Repeat step 2 for each stage.

$$O_i(j) = \text{Max}\,[(R_i(k) + O_{i-1}(j-k)] \quad (5)$$

for j = 1, 2, . . . , N and k = 1, 2, . . . , j, where

M = number of locations considered,
$O_i(j)$ = total optimum return after stage i for an investment of j increments,
$R_i(k)$ = return from location i for an investment of k increments ($k \leq j$),
$O_{i-1}(j-k)$ = total optimum return after stage (i - 1) for an investment of (j - k) increments, and
$D_i(j)$ = chosen alternative at location i for an investment of j increments.

4. Step 4. The optimum alternative at each location can now be obtained by determining the best alternative for location M at stage M with N increments. The remaining increments can now be used at stage (M-1). Therefore,

$A_M = D_M(N)$, leaving N_M increments,
$A_{M-1} = D_{M-1}(N_M)$, leaving N_{M-1} increments,
$A_{M-2} = D_{M-2}(N_{M-1})$, leaving N_{M-2} increments, and

$$A_i = D_i(N_{i+1}) \quad (6)$$

where A_i = alternative chosen at the i th location.

Development of Benefit and Cost Values

Some of the major inputs to the dynamic programming model are the benefits assigned to each improvement at a location. For example, the effect on accident patterns of upgrading a traffic signal at an intersection will be different from that of installing channelization. To quantify the effect of various improvements on accidents, 447 improvement projects in Kentucky since 1968 were studied to determine the accident reduction (or increase) associated with each at various location types.

Various improvements on curves, intersections, and other (general) locations are given in Table 1. The total accident reduction value (in percentage of reduction) at each location under consideration was used to calculate an approximate benefit. Accidents unrelated to the location caused by brake failures, drunk driving, tire blowouts, and the like were disregarded. Associated with the high accident locations were 447 improvement projects. Many of the improvement projects included a combination of the various improvements listed in Table 1. Therefore, an alternative that was input for the dynamic programming model may be a combination of several types of improvements with respective adjustments in the percentage of accident reduction. To make the data manageable for this evaluation, 61 improvement projects were selected as input.

The subroutine COSBEN was used to compute monetary benefits from expected accident reductions. Accident costs used were recent National Safety Council values (14):

Accident Type	Cost (dollars)
Fatality	45,000
Injury	2,700
Property damage only	400

The accident occurrence at each location is multiplied by the expected percentage of reduction for the improvement alternative. The cost of accidents is then multiplied by the expected accident reduction to give annual benefits. These annual benefits are then multiplied by an exponential growth, present-worth factor (equation 2) to obtain the benefits for the entire service life of the improvement.

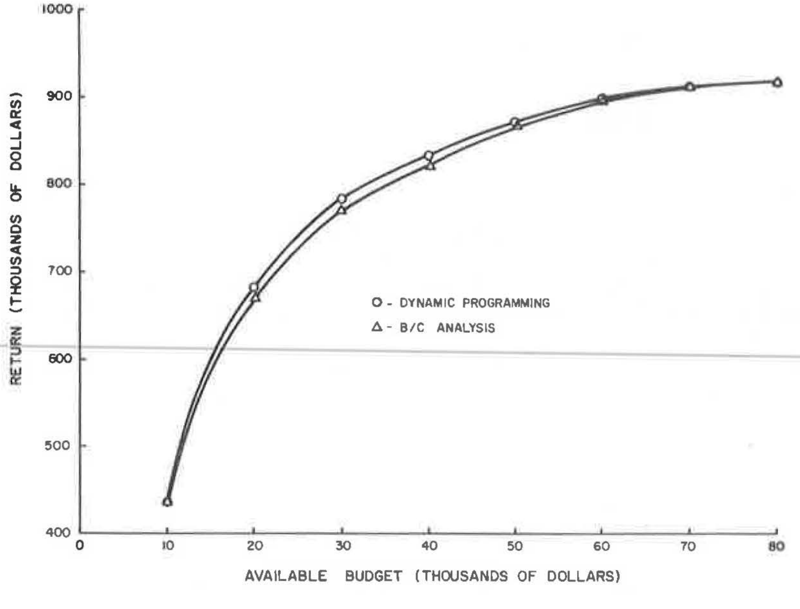
The costs used in the calculations are the sum of the improvement cost for each project and the maintenance cost. A present-worth factor (equation 1) was used to adjust the maintenance cost from a future date to the present.

Accurately estimating benefits and costs can be very difficult. Even with a large sample of before-and-after data for locations that have been improved, accident reduction estimates may be inaccurate. This is partially attributable to the varying characteristics of specific highway locations. Randomness in accident occurrence makes it impossible to accurately predict future accidents. Predictions of expected accidents after a particular improvement should be based on large samples combined with care-

Table 1. Summary of improvement costs and benefits.

Location	Type of Improvement	Number of Projects	Total Accident Reduction (percent)	Service Life (years)	Annual Maintenance Cost (dollars)
General	Signs and markings	9	36	3	25
	Warning signs	23	35	5	25
	Regulatory signs	16	22	5	25
	Guidance signs	10	14	5	25
	Sign combinations	16	20	5	25
	Markings	8	16	2	0
	Sight distance improvements	9	28	2	50
	Post delineators	3	25	5	20
	Combination delineators, markings, signs, and maintenance	11	22	5	25
	Shoulder improvements	7	23	10	100
	Combination resurfacing, patching, drainage, deslicking, culvert	22	16	10	100
	Rumble strips	8	29	5	0
	Removal of median crossovers	2	29	20	0
	Lighting	1	-58	10	500
	Lighting and rumble strips	1	17	7	300
	Rumble strips and beacon	2	32	7	50
	Side road sign only	31	19	5	25
	Prepare for sudden stop sign only	19	25	5	25
	Side road sign and warning sign	15	27	5	25
Curves	Signing	34	30	5	25
	Post delineators	4	32	5	25
	Signs and delineators	16	28	5	25
	Signs and maintenance	6	47	3	25
	Combination delineators, markings, signs, and maintenance	16	24	5	25
	Resurfacing, patching, drainage, deslicking, culvert, guardrail	22	33	10	100
	Realignment (relocation)	3	32	20	100
Intersections	Signs and markings	21	24	3	25
	Warning signs	11	27	5	25
	Regulatory signs	5	48	5	25
	Regulatory and warning signs	20	16	5	25
	Markings	17	16	2	0
	Marking, maintenance, and signing	9	35	5	25
	Channelization, storage lane	13	15	10	100
	Channelization and signs	2	37	7	75
	Install beacons	13	2	10	100
	Upgrade beacons	10	5	10	100
	Installation of signals	10	23	10	300
	Upgrade signals	2	18	10	250
Total		447	24		

Figure 1. Expected return versus available budget for dynamic programming and benefit-cost analyses.



ful engineering judgment. Dynamic programming can give near-perfect results if all input is correct. However, if benefit and cost input is carelessly or incorrectly estimated, results of dynamic programming will be equally in error.

RESULTS

A group of 61 high accident locations previously improved under the Kentucky spot-improvement program was selected as test data for the dynamic programming model. Accident reports at each location were reviewed, and improvement alternatives were actual improvements made at the locations. Input to the computer program for each alternative at each location consisted of accident data, expected accident reduction, project costs, service life of improvement, maintenance costs, and interest rate.

The dynamic programming model computed benefits for each alternative. Then, as the available budget was varied from $10,000 to $80,000, an optimal scheme of alternatives was generated for each budget. For an available budget of $50,000, the computer processing time was 38 sec on an IBM 360 computer at a cost of $5.86. The computer storage required for the 61 improvement projects and increments of $250 was 268 K.

A similar calculation of return and benefit-cost ratio was made by using a benefit-cost analysis. There was very little difference between the benefit-cost analysis and the dynamic programming analysis for the test locations. This is shown in Figure 1 where expected return versus available budget is plotted for both dynamic programming and benefit-cost analyses. Details of the data used to plot Figure 1 are given in Table 2. The insignificant difference between benefit-cost analysis and dynamic programming can be attributed to the fact that the priority allocation of funds by benefit-cost is a very efficient method in many cases. However, there is no guarantee that benefit-cost will always assign priorities that will yield the greatest return for a specified budget. Comparison of dynamic programming and benefit-cost, presented below, shows the weakness of the benefit-cost method for certain situations.

Comparison of Dynamic Programming and Benefit-Cost Ratio

Theoretically, dynamic programming computer techniques will produce a scheme for allocating funds under a fixed budget that will provide the optimal return. Testing the computer model showed that this is true as long as each project cost is an exact multiple of the budget increment. For example, if computer storage constraints permit increments of $250 for a budget of $100,000, then the cost of each improvement should be a multiple of $250 if the optimal improvement scheme is to be obtained. An increment was defined as some fraction of the budget used in the computer analysis for weighing benefits against costs. In general, the smaller the increment is, the better the solution obtained will be. The number of increments into which the maximum budget may be divided, however, is largely governed by the computer storage capacity and computer time required. Practically, then, the increment cannot be made as small as desired.

A simplified example (Table 3) was developed to demonstrate how the monetary return using dynamic programming techniques will exceed the return from a benefit-cost analysis if project costs are multiples of the increment. As shown in Figure 2, the dynamic programming return is the best at nearly every budget level from $5,000 to $34,000. Although the two are fairly close at some points, the return from the benefit-cost curve is inferior to that of the dynamic programming curve by about $50,000 at a budget of $20,000 and by $40,000 at a budget of $30,000. The two curves are equal at budgets of $25,000 and $34,000. In this example, the $34,000 budget was divided into 34 increments of $1,000 each. Each project cost is a multiple of $1,000.

A more detailed explanation of the logic used in the comparative example of benefit-cost versus dynamic programming may be enlightening at this point. With reference to Table 3 and Figure 2, a budget of $15,000 will produce a greater return by using dy-

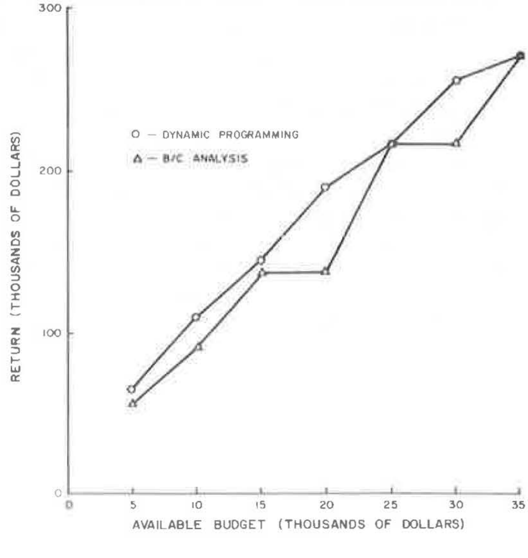
Table 2. Input data for comparison of dynamic programming and benefit-cost analysis.

Location Number	Location Name	Alternative Number	Cost (dollars)	Return (dollars)	Benefit-Cost Ratio
1	63-25-10.9	1	1,500	7,620	5.08
2	30-60-15.1	1	4,250	158,707	37.34
3	30-60-15.2	1	2,000	11,385	5.69
4	54-41A-12.0	1	500	9,792	19.58
5	73-45-6.5	1	500	973	1.95
6	73-45-7.2	1	500	0	0.0
6	73-45-7.2	2	500	0	0.0
6	73-45-7.2	3	750	6,726	8.97
7	48-421-14.4	1	500	0	0.0
7	48-421-14.4	2	500	588	1.18
7	48-421-14.4	3	750	0	0.0
8	20-51-1.1	1	750	2,987	3.98
9	102-25-9.2	1	1,000	3,365	3.37
10	102-25-54	1	500	226	0.45
11	30-60-15.2	1	500	16,145	32.29
11	30-60-15.2	2	4,750	3,524	0.74
11	30-60-15.2	3	5,000	31,866	6.37
12	72-641-8.5	1	750	40,588	54.12
13	30-60-4.1	1	1,250	814	0.65
14	39-I71-63.7	1	4,500	26,029	5.78
15	79-641-18.9	1	750	3,548	4.73
16	54-41A-12.4	1	500	14,598	29.20
16	54-41A-12.4	2	500	3,442	6.88
16	54-41A-12.4	3	750	18,040	24.05
17	24-68-9.1	1	500	814	1.63
17	24-68-9.1	2	500	916	1.83
17	24-68-9.1	3	1,000	1,729	1.73
18	114-31W-16.2	1	500	2,649	5.30
18	114-31W-16.2	2	500	1,422	2.84
18	114-31W-16.2	3	750	4,071	5.43
19	63-25-16.0	1	500	966	1.93
19	63-25-16.0	2	500	1,272	2.54
19	63-25-16.0	3	750	2,238	2.98
20	106-6-3.2	1	500	373	0.75
21	37-127-8.7	1	750	2,348	3.13
22	47-31W-26.0	1	2,250	24,654	10.96
23	30-54-12.6	1	750	4,290	5.72
24	114-31W-16.1	1	1,750	256	0.15
25	41-22-11.3	1	500	5,765	11.53
25	41-22-11.3	2	500	5,765	11.53
25	41-22-11.3	3	500	39	0.08
25	41-22-11.3	4	1,000	11,530	11.53
25	41-22-11.3	5	750	5,855	7.81
25	41-22-11.3	6	750	5,855	7.81
25	41-22-11.3	7	1,250	11,620	9.30
26	73-62-17.8	1	500	424	0.85
26	73-62-17.8	2	500	0	0.0
27	73-45-6.5	1	750	824	1.10
28	73-62-16.9	1	2,000	7,039	3.52
28	73-62-16.9	2	1,250	5,246	4.20
28	73-62-16.9	3	3,000	12,286	4.10
29	63-25-10.8	1	750	746	0.99
30	54-41A-12.2	1	500	4,528	9.06
30	54-41A-12.2	2	500	3,985	7.97
30	54-41A-12.2	3	750	8,513	11.35
31	72-641-8.5	1	500	10,565	21.13
31	72-641-8.5	2	1,500	13,357	8.90
31	72-641-8.5	3	2,000	56,100	28.05
32	56-I65KTP-130.1	1	1,500	11,711	7.81
33	63-25-10.9	1	750	746	0.99
33	63-25-10.9	2	1,250	0	0.0
34	41-I75-155.6	1	4,000	152,094	38.02
35	51-41-20.0	1	2,000	1,678	0.84
36	051-41-20.0	1	500	4,699	9.40
37	82-31W-1.1	1	500	17,168	34.34
38	84-68-18.5	1	1,000	34,486	34.49
39	120-60-12.6	1	500	9,008	18.02
40	82-60-12.3	1	500	11,078	22.16
41	10-60-8.3	1	500	593	1.19
42	79-641-13.0	1	500	1,064	2.13
43	51-60-20.3	1	750	86,411	115.21
44	70-60-11.4	1	750	412	0.55
45	82-US60-12.7	1	750	9,097	12.13
46	82-US60-12.7	1	1,750	4,488	2.56
47	82-31W-1.0	1	500	922	1.84
48	30-60-15.0	1	4,250	2,792	0.66
49	10-60-9.2	1	500	2,664	5.33
49	10-60-9.2	2	750	3,196	4.26
49	10-60-9.2	3	750	5,860	7.81
50	79-641-12.5	1	500	8,710	17.42
50	79-641-12.5	2	750	5,784	7.71
50	79-641-12.5	3	1,000	17,152	17.15
51	79-641-12.5	1	1,000	26,532	26.53
52	70-US60-11.3	1	500	626	1.25
52	70-US60-11.3	2	750	1,649	2.20
52	70-US60-11.3	3	1,000	366	0.37
52	70-US60-11.3	4	2,000	1,465	0.73
52	70-US60-11.3	5	1,750	8,021	4.58
52	70-US60-11.3	6	4,000	13,348	3.34
52	70-US60-11.3	7	4,250	14,447	3.40
53	47-31W-23.3	1	2,000	4,894	2.45
54	63-25-10.4	1	500	4,735	9.47
54	63-25-10.4	2	500	5,380	10.76
54	63-25-10.4	3	1,000	10,115	10.11
54	63-25-10.4	4	1,500	1,889	1.26
54	63-25-10.4	5	1,750	10,200	5.83
54	63-25-10.4	6	2,000	11,334	5.67
54	63-25-10.4	7	2,250	19,645	8.73
55	102-25-11.9	1	500	3,934	7.87
56	82-31W-2.2	1	2,500	6,780	2.71
57	51-41-20.0	1	500	10,792	21.58
58	82-31W-1.2	1	500	1,921	3.84
59	30-60-16.4	1	500	1,731	3.46
59	30-60-16.4	2	500	3,338	6.68
60	22-60-26.2	1	750	221	0.29
61	63-25-10.0	1	500	287	0.57
61	63-25-10.0	2	500	326	0.65
61	63-25-10.0	3	1,000	613	0.61
61	63-25-10.0	4	1,500	114	0.08
61	63-25-10.0	5	1,750	618	0.35
61	63-25-10.0	6	2,000	687	0.34
61	63-25-10.0	7	2,250	1,191	0.53

Table 3. Example input data for comparison of dynamic programming and benefit-cost analysis.

Location Number	Alternate Number	Cost (dollars)	Benefit (dollars)	Benefit-Cost Ratio
1	1	1,000	20,000	20
2	1	1,000	15,000	15
3	1	1,000	12,000	12
4	1	3,000	30,000	10
5	1	5,000	45,000	9
6	1	10,000	80,000	8
7	1	1,000	7,000	7
8	1	9,000	54,000	6
9	1	2,000	6,000	3
10	1	1,000	2,000	2
Total		34,000	271,000	

Figure 2. Example problem of expected return versus available budget for dynamic programming and benefit-cost analyses.



namic programming than by using benefit-cost. The benefit-cost procedure permitted a sequential selection of projects in the order of decreasing benefit-cost ratios and a corresponding total of accumulative costs and benefits. Those projects whose costs would make the total exceed $15,000 were omitted, and the procedure was continued until the available budget was reached or the projects were exhausted. From Table 3 and based on this logic, locations 1, 2, 3, 4, 5, 7, 9, and 10 with an available budget of $15,000 would be selected. Therefore, by using benefit-cost analysis and a $15,000 budget, the improvement costs would be $15,000 and the return would be $137,000 in benefits.

The dynamic programming procedure is not constrained by the benefit-cost ratios and may search throughout the list of projects for those projects that provide the greatest return for an available budget. In this case with the $15,000 budget, dynamic programming would select locations 1, 2, 4, and 6. These selections would provide a return of $145,000 for improvement costs of $15,000.

From Figure 2, it is obvious that there is a great difference between the respective returns at an available budget of $20,000. This is because, for the benefit-cost procedure, no additional projects were added to the preceding $15,000 budget inasmuch as the remaining projects had costs of $9,000 and $10,000. An addition of either would have exceeded the available budget of $20,000. In contrast, dynamic programming was able to use all of the available budget because it was not constrained by limits similar to benefit-cost analysis. The respective benefits at an available budget of $20,000 were $137,000 with benefit-cost methods and $190,000 with dynamic programming.

Benefits from benefit-cost techniques may sometimes equal benefits from dynamic programming. In addition, when it is impossible to arrange the project costs such that they are an exact multiple of the budget increment, the benefits from benefit-cost may exceed those from dynamic programming because of rounding errors. However, dynamic programming will always produce the optimal scheme if project costs are expressed as multiples of the increment. For these reasons, it is suggested that both benefit-cost and dynamic programming be tested when it is not feasible to express project costs as multiples of the budget increment.

Use of Dynamic Programming

Application of dynamic programming techniques to the highway safety improvement program in Kentucky involves several steps. First, a list of potentially hazardous locations, based on accident data, is identified. A recommended location-identification procedure for Kentucky identifies hazardous 0.3-mile (0.5-km) spots and 3-mile (5-km) sections based on fatal accidents, total number of accidents, accident severity rating (the equivalent-property-damage-only number), and accident rate (applying quality control techniques). Locations should be identified based on 1- and 2-year time intervals. Also, locations identified by citizens, engineering personnel, and state police should be considered. All locations identified as possibly hazardous should then be reviewed. Locations considered worthy of a field inspection should be investigated for possible corrective measures.

The proposed program requires that all warranted minor improvements such as signs, paint striping, flashing beacons, and delineators be implemented without dynamic programming considerations. Major improvements such as resurfacing, bridge widening, realignment, and intersection channelization should be selected by dynamic programming techniques.

Project costs, expected benefits, maintenance costs, and expected service life of the improvement should be determined for each alternative at every location to be considered under dynamic programming. After the warranted minor improvements are considered, the remaining money should be budgeted for use in other projects where the dynamic programming may apply. An optimal set of improvement alternatives would then be generated.

SUMMARY AND CONCLUSIONS

The objective of this study was to develop or adopt appropriate dynamic programming methods that would assist in establishing optimal budgeting procedures for various highway programs. Dynamic programming is a multistage operation that involves evaluating several projects with several alternatives. The option of staging safety improvements over a number of years was excluded from this analysis. A dynamic programming procedure was developed to select the optimal combination of safety improvement projects for a given budget. Findings and procedures are summarized below.

1. Use of dynamic programming is relatively simple. Input consists of the budget, costs, and benefits. Estimating the benefits derived from a particular improvement presents the most difficulty.
2. Table 1, which gives accident reduction by type of improvement for past safety improvements, was developed from past accident experience for use in estimating savings.
3. The accuracy and reliability of dynamic programming depend on the accuracy of benefits and costs used as input.
4. Requisite to using dynamic programming for the safety improvement program is an efficient method of systematically identifying locations based on accident data. In-depth field investigations are also needed so that only necessary improvements are recommended as input for the dynamic programming model.
5. All possible combinations of improvements were included as alternatives in the model for each of the 61 projects.
6. Safety improvement costs were dealt with in terms of present worth, and construction or installation cost, yearly maintenance cost, present interest rate, and expected life of improvement were all considered.
7. Improvements selected by dynamic programming can yield a higher return for a given budget than those chosen entirely on the basis of benefit-cost ratios (Figure 2).
8. If individual project costs are multiples of the increment used in the dynamic programming, the optimum allocation of funds will always be obtained. In general, the smaller the increment is, the better the solution obtained will be. However, use of a smaller increment is restricted by available computer storage.
9. Both benefit-cost and dynamic programming should be tested when it is not possible to express project costs as multiples of the budget increment.
10. Applicability of dynamic programming to budget allocation in transportation planning is practically unlimited. In addition to highway safety improvement investments, optimal investments in maintenance and construction programs and eventually the entire transportation field can be determined through dynamic programming.

ACKNOWLEDGMENT

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MANAGEMENT BY OBJECTIVES PROGRAM OF THE FLORIDA DEPARTMENT OF TRANSPORTATION

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During the last few years, the Florida Department of Transportation has been engaged in a comprehensive management improvement program. Key improvements made include (a) establishment of a management systems coordination unit, (b) implementation of a sophisticated management and scheduling system for program development, (c) design of a conceptually advanced financial management system, (d) implementation of a maintenance management system, and (e) acquisition of data processing hardware. In July 1973, the department undertook a new phase of management improvement based on the concepts of management by objectives. This phase was preceded by a series of management seminars for some 270 top and middle managers. To date, a top management planning and decision-making system has been developed and implemented. Implementation required a statement of the department's mission, goals, and objectives; development of an annual plan and calendar for top management decision making; incorporation of strategic planning and decision making into the top management system; and implementation of operation procedures for the system, including those to achieve completed staff work. The elements are described as are the processes used by top management to develop the structure of the mission, goals, and objectives.

•AFTER governmental reorganization in 1969, the Florida Department of Transportation began a comprehensive program of management improvement. The key actions taken include

1. Establishment of a function for coordinating management systems,
2. Development and implementation of a management and scheduling system,
3. Design of an advanced financial management system built around a common data base,
4. Development and implementation of a maintenance management system, and
5. Acquisition of data processing hardware whose capabilities enable implementation of a comprehensive management information system built around a common data base.

In August 1972, the department initiated a program to develop a management system built on the established data base. The aim was to implement a system that was well-conceived, integrated, and understood and accepted throughout the department. Also, the system was to be based on the concepts of management by objectives (MBO). Figure 1 shows a general outline of the management improvement program and strategy.

PROGRESSION OF PROJECT PLAN

The project advanced in several distinct phases (Figure 2), each of which is briefly described below.

Publication of this paper sponsored by Committee on Management Review.

Figure 1. Basic mission of Florida Department of Transportation.

TO PROMOTE, PLAN, DEVELOP, MAINTAIN, AND OPERATE A SAFE, EFFICIENT, BALANCED, AND INTEGRATED STATEWIDE TRANSPORTATION SYSTEM ADEQUATE TO MEET PRESENT AND FUTURE NEEDS TO MOVE PEOPLE AND GOODS.

X X X X X X X X X X X X X

BASIC STRATEGY TO ACCOMPLISH MISSION

DEVELOP AN ORGANIZATION--BUILT ON SYSTEMS CONCEPTS--WHICH IS DYNAMIC, OBJECTIVE, CREATIVE, INNOVATIVE AND, ABOVE ALL, COMMITTED TO ACCOMPLISHMENT OF THE DOT MISSION.

X X X X X X X X X X X X X

MAJOR ELEMENTS OF THE BASIC STRATEGY

ORGANIZATION

DEVELOP AND MAINTAIN A DOT ORGANIZATION WHICH IS:

+ ORGANIZED AND OPERATES TO ASSURE THAT CLEAR-CUT OBJECTIVES ARE ESTABLISHED ON A CONTINUING BASIS FOR EACH UNIT IN THE ORGANIZATION.
+ OPERATIONALLY GEARED TO ACCOMPLISH ESTABLISHED OBJECTIVES EFFECTIVELY.
+ OPERATED IN SUCH A FASHION THAT MUTUALLY SUPPORTIVE RELATIONSHIPS EXIST AMONG ALL UNITS AND AMONG PEOPLE IN THESE UNITS.

PEOPLE

DEVELOP AND MAINTAIN A MANAGEMENT TEAM CHARACTERIZED FROM TOP TO BOTTOM:

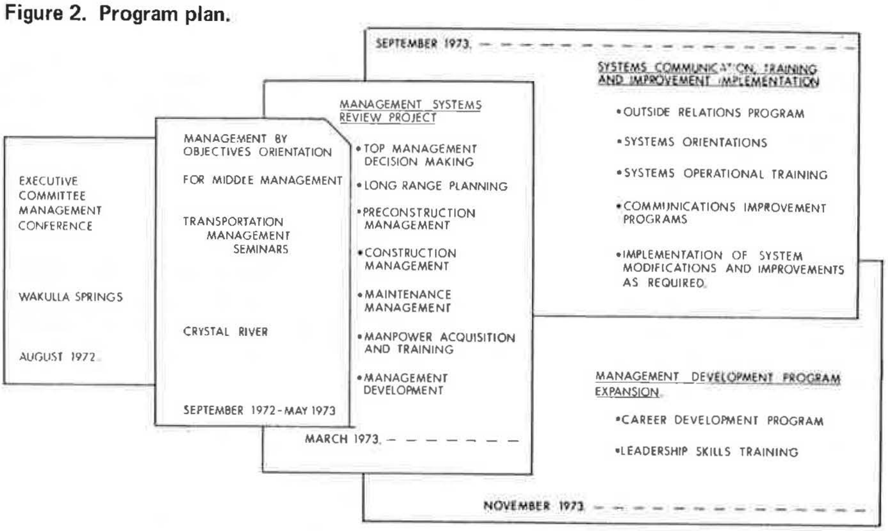
+ BY HIGHLY QUALIFIED, ENERGETIC, AND CREATIVE INDIVIDUALS COMMITTED TO EFFECTIVE ATTAINMENT OF ESTABLISHED OBJECTIVES.
+ BY A CLIMATE CONDUCIVE TO SELF-DEVELOPMENT, OPPORTUNITIES FOR SUCH DEVELOPMENT, AND SUPPORT OF SELF-DEVELOPMENT EFFORTS.

COMMUNICATIONS

DEVELOP AND MAINTAIN AN EFFECTIVE MANAGEMENT INFORMATION AND COMMUNICATIONS SYSTEM WHICH WILL:

+ ASSURE CLEAR COMMUNICATION OF OBJECTIVES TO EACH UNIT AND PERSON AND THE INFORMATION NECESSARY TO EFFICIENT ACCOMPLISHMENT OF OBJECTIVES.
+ PROVIDE FEEDBACK INFORMATION TO MANAGERIAL PERSONNEL AT ALL LEVELS TO PROVIDE A BASIS FOR EVALUATION AND APPRAISAL OF PERFORMANCE AS WELL AS A BASIS FOR DECISION-MAKING.

Figure 2. Program plan.



Management Seminars

Nine management seminars were conducted from August 1972 to May 1973. The seminars were generally patterned after those jointly sponsored by AASHO and the Highway Users Federation for Safety and Mobility since 1957. The seminars emphasized MBO concepts and practices as applied to departments of transportation.

The first seminar in the series was for the department executive committee and selected staff and lasted 3 days. The next five seminars were 1 week long and were attended by approximately 150 middle managers and 25 FHWA personnel assigned to the Florida division office. Three more seminars, each 3 days long, were conducted for middle managers and were attended by approximately 90 department managers and 15 FHWA managers.

Systems Review

After the seminar series, an assessment was made and some general conclusions were drawn. One conclusion was that the processes by which top management provided unified direction and control needed major improvement. Another was that the various functional systems operating in the department needed to be analyzed and integrated.

In July 1973, the executive committee adopted a management by objectives model to serve as a framework for implementing MBO concepts and practices and developing the overall transportation management system (Figure 3).

Several task forces were created to review and analyze various management processes to determine where improvements were needed and make recommendations to the executive committee. The task forces reviewed the following processes: top management decision making, long-range planning, preconstruction management, construction management, maintenance management, and manager development.

As a result of task force efforts, the transportation management process was viewed as a total process and characteristics of subprocesses that needed improvement were identified. Most of the recommendations for improvement made to the executive committee were approved for additional research, development, or implementation in accordance with general plans drawn up by key task force personnel in conjunction with the consultant.

TOP MANAGEMENT DECISION-MAKING SYSTEM

The top management decision-making task force recommended improvement of top management direction and control processes, and the recommendation was approved by the executive committee. Development and implementation were directed toward a top management decision-making system.

Top Management Emphasis

Figure 4 shows the role and responsibilities of top management developed by the task force and approved by the executive committee. As shown, top management is responsible for providing (a) central, overall, unified direction and (b) central, overall review, appraisal, and evaluation of results of operations. As the figure also shows, top management should direct major attention to

1. Defining, clarifying, and communicating the mission, goals, and objectives of the department;
2. Creating and maintaining a sound plan of organization;
3. Ensuring that competent persons are placed in all key positions; and
4. Creating and maintaining an effective means of direction, evaluation, and control of operations.

Top management must direct department activities within a framework of legislative and executive branch missions, goals, and objectives. Furthermore, top management should concentrate its attention on program development rather than project definition, scheduling, and progress. Figure 5 shows the general MBO-program management hierarchy developed to provide a framework for top management decision making.

Top Management Work Program

Top management needed an annual work program to guide its planning and decision making. An annual calendar of major planning and decision areas geared to the department's procedures for program development and approval and to state administrative procedures for budget development and submission was developed (Figure 6).

Figure 3. Florida Department of Transportation management by objectives model.

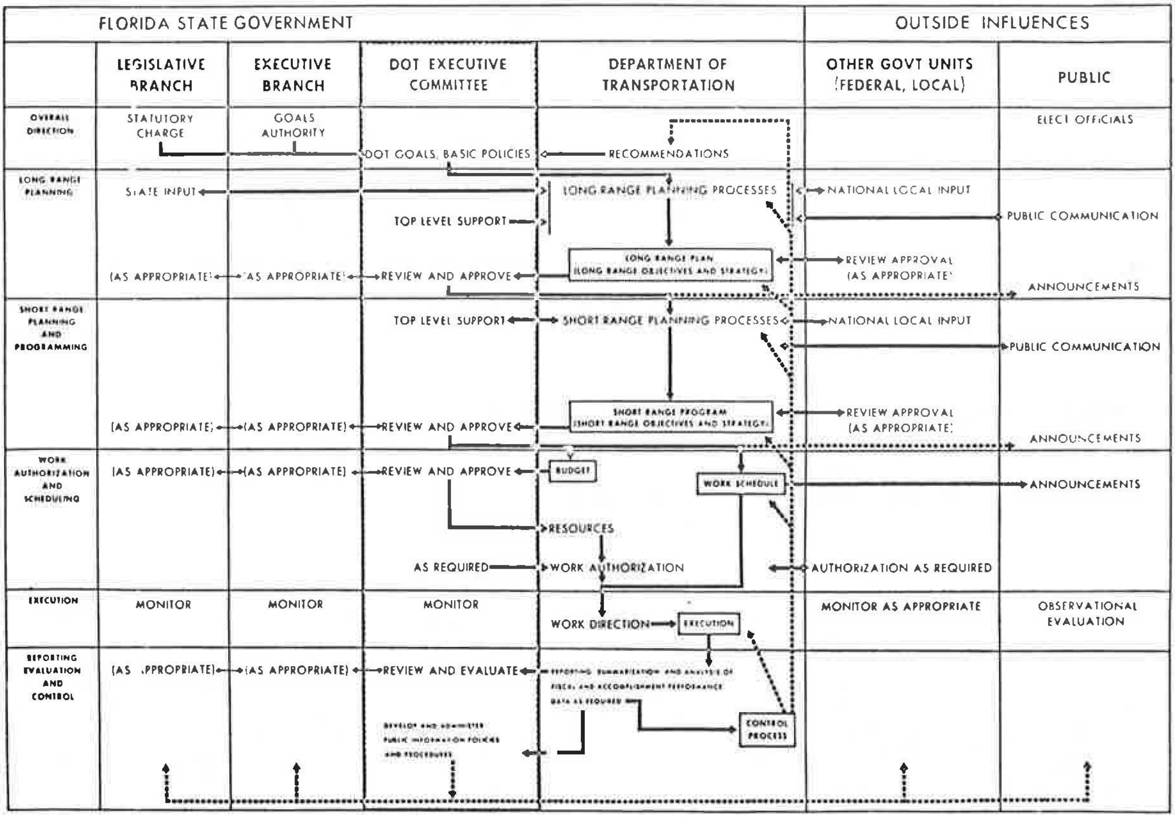


Figure 4. Role and responsibilities of top management.

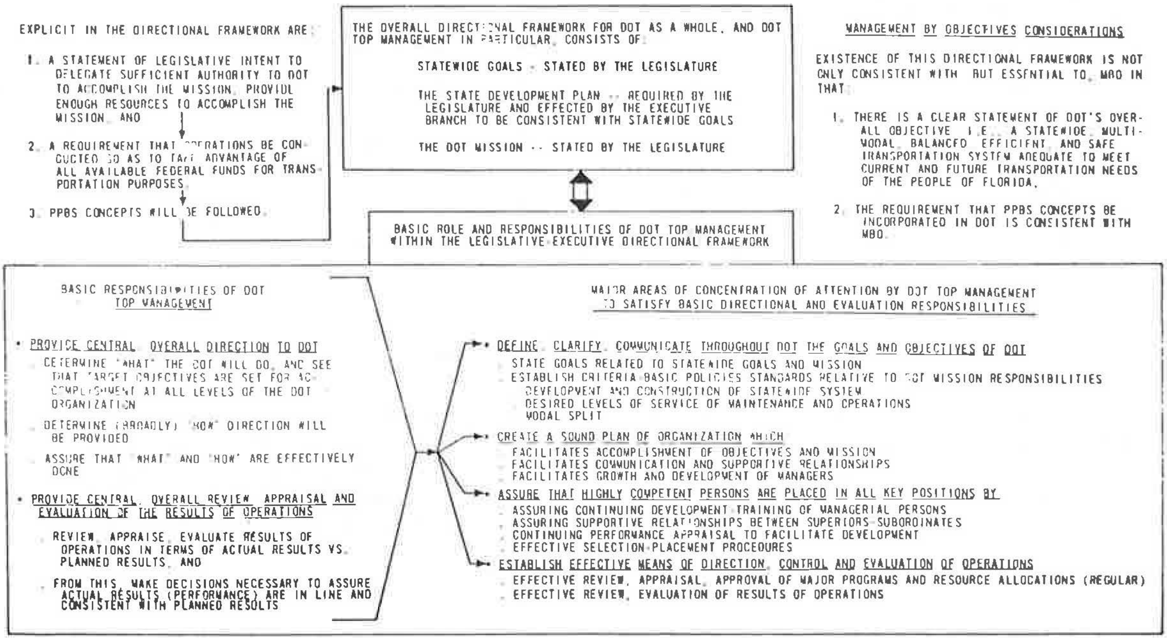


Figure 5. General MBO-program management hierarchy.

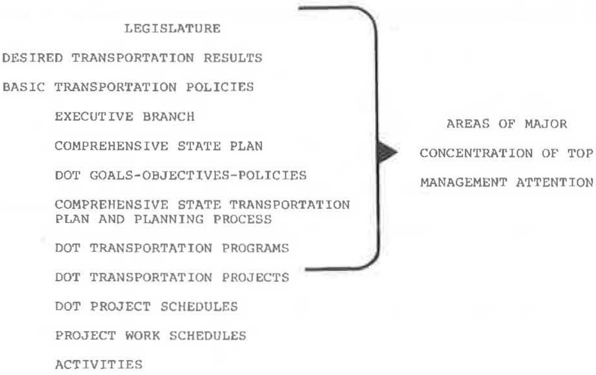
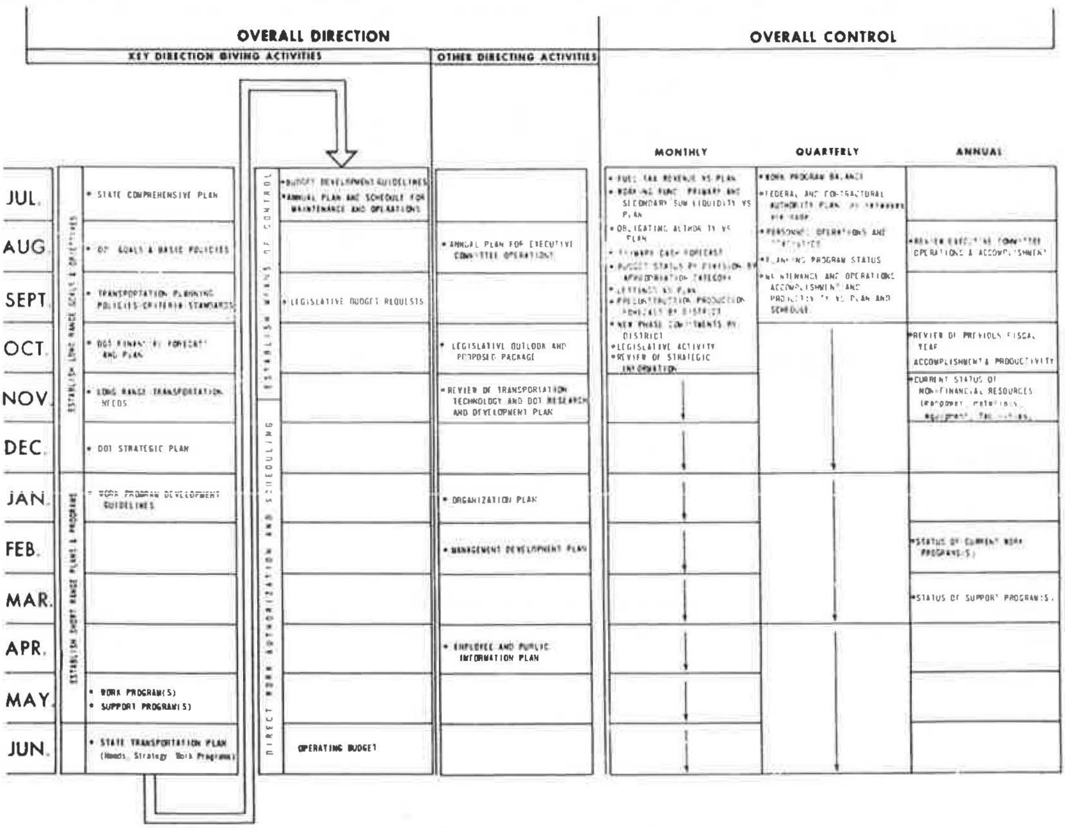


Figure 6. Annual plan for decision making by executive committee.



The work elements of the annual plan are geared to the two basic responsibilities of top management, direction and control. The basic idea is that someone on the executive committee will be assigned responsibility for each key decision activity on the plan. Analyses and alternative decisions will be presented to the executive committee in accordance with the schedule. The control items shown will be reviewed as scheduled.

Figure 7. Overall strategic planning and decision-making process.

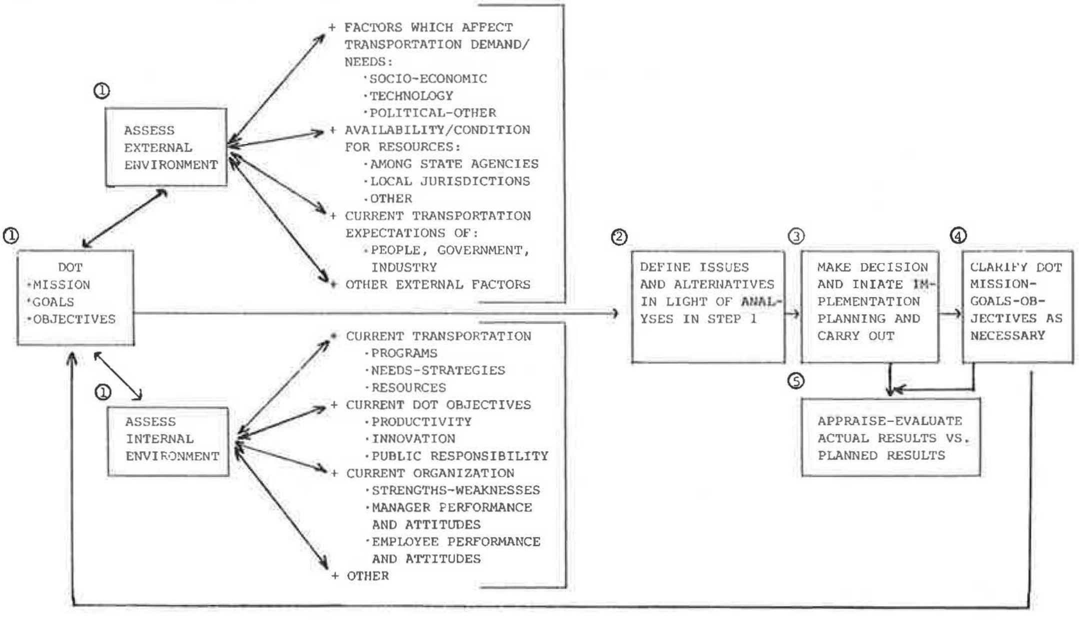


Figure 8. Process and procedure for staff work to support top management decision making.

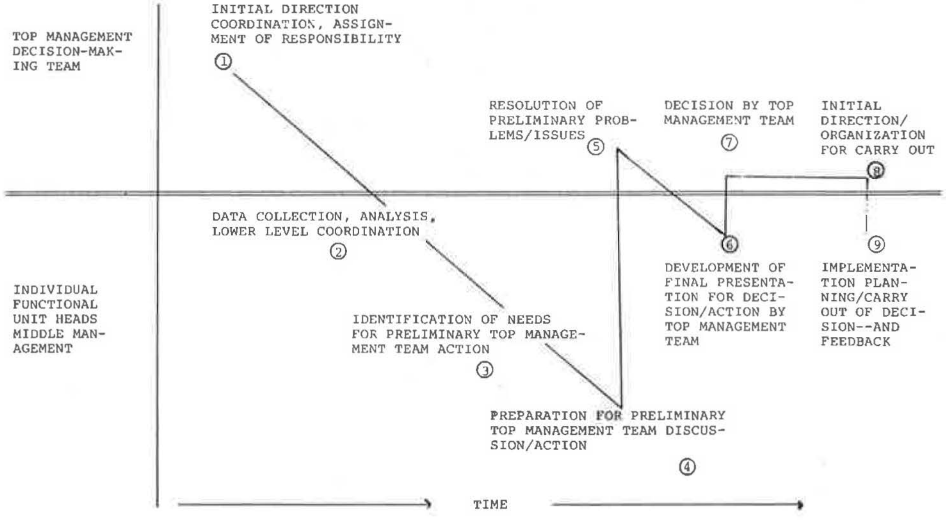
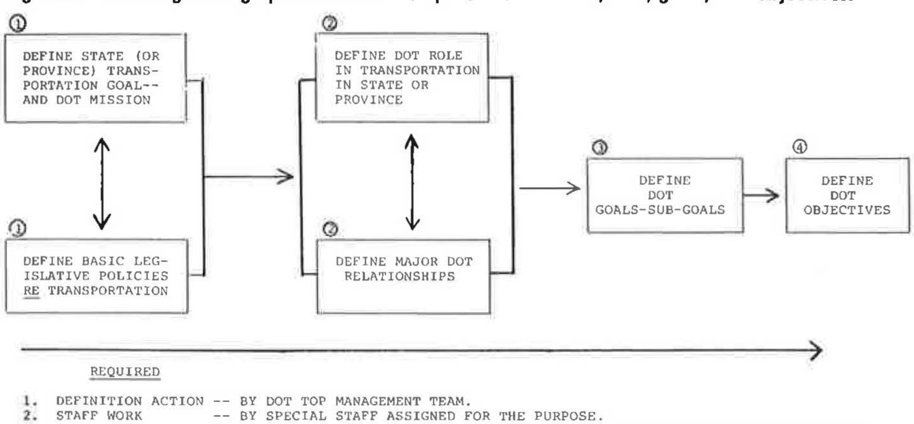


Figure 9. Thinking through process for development of mission, role, goals, and objectives.



REQUIRED

1. DEFINITION ACTION -- BY DOT TOP MANAGEMENT TEAM.
2. STAFF WORK -- BY SPECIAL STAFF ASSIGNED FOR THE PURPOSE.
3. TIME -- SEVERAL ONE TO THREE DAY MEETINGS OF TOP MANAGEMENT OVER A PERIOD OF 5-7 MONTHS. MORE TIME BY STAFF-CATALYTIC AGENT BETWEEN MEETINGS.
4. CATALYTIC AGENT -- TO PROVIDE GUIDANCE, COUNSEL, DIRECTION, MODERATION.

Figure 10. Basic structure and definitions of mission, goals, and objectives.

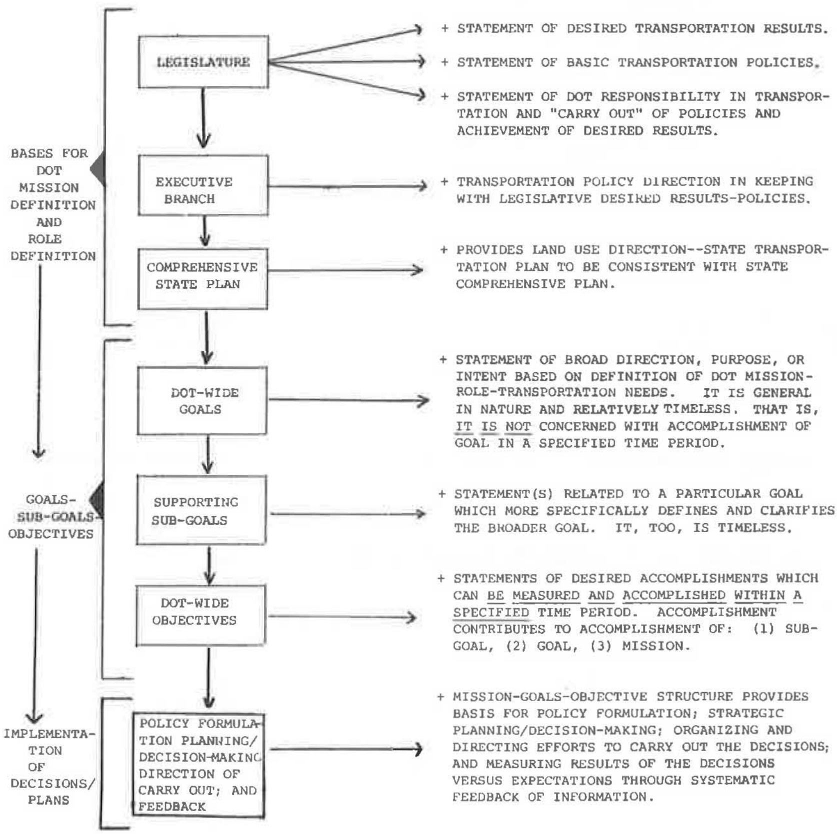
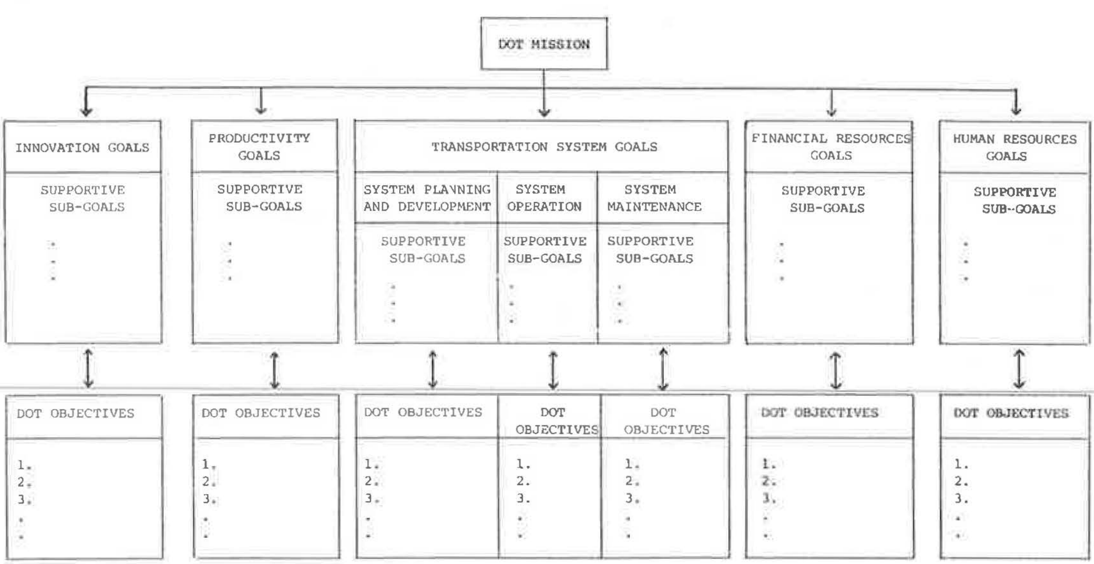


Figure 11. Structure of mission, goals, subgoals, and objectives.



Strategic Planning and Decision Making

Before initiation of the implementation program in July 1973, the need for formalization of a strategic planning process was discussed. Recognition of the need had derived from the increasing complexity of the environment of the department and the many factors that affect accomplishment of the department's mission, goals, and objectives. The strategic planning and decision-making process involves continual review, analysis, and evaluation of the external and internal environment of the department and identification of factors that affect accomplishment of the mission, goals, and objectives of the department.

These factors are defined as strategic issues and submitted to the executive committee for acceptance or rejection. Once accepted, responsibility for any further analyses and definition of alternatives is made, and the issue is scheduled on the agenda.

Figure 7 shows major elements of the strategic planning and decision-making process. The office of strategic planning, a small unit acting in a staff capacity to the executive committee, is responsible for steps 1 and 2. Issue definition (step 2) is coordinated with affected units of the organization. Steps 3, 4, and 5 are the exclusive process of the executive committee.

Completed Staff Work

The top management decision-making system depends on effective completed staff work. Middle managers must be involved in the analysis and definition of alternative decisions. Figure 8 shows the basic procedure for staff work to support the system.

DEFINING MISSION, GOALS, AND OBJECTIVES OF THE DEPARTMENT

Planning and decision making by top management cannot occur in a void. There must be explicit knowledge of what the department intends to accomplish and a commitment to accomplish it. The department made this knowledge explicit by developing statements of its mission, goals, and objectives in a logically arranged structure.

Development of the mission, goals, and objectives required a rigorous thinking through process (Figure 9). The end result of the process is, of course, department objectives established within a logical framework. It is to accomplish these objectives that resources must be allocated and organizational efforts focused.

Figure 10 shows the structure and definitions of the mission, goals, and objectives adopted by the executive committee. It clearly shows the expected result: conversion of objectives into action.

Managing a complex transportation department today involves balancing a variety of needs and demands. It requires multiple goals and objectives, not just one. The executive committee adopted the multiple goals and objectives areas shown in Figure 11. The starting point was to define the mission of the department and the leadership role it was to take in transportation.

Initially, explicit statements were developed for transportation system goals and objectives.

Currently, the executive committee is in the final stages of converting several objectives into specific plans, schedules, and targets and assigning responsibility for them. The process includes establishing systematic feedback to provide a basis for appraising results.

After departmentwide goals and objectives have been established, the department will be in a position to extend the MBO process into lower levels of management. The overall goals and objectives will provide the necessary framework within which to do so.

ENGINEERING RESOURCE PLANNING AND USE IN THE STATE OF WASHINGTON

Donald R. Anderson and Gerald E. Goetz, Washington State Highway Commission

After a management system for maintenance was successfully implemented, Washington State initiated a program to develop a manpower management and information system to assist the work of its engineers and right-of-way personnel. The system is based on the basic functions of planning and scheduling, measuring and comparing, and acting and reacting. The development effort was performed by a team of Washington State Department of Highways personnel with maximum participation by all levels of engineering classifications. The system centers around the development of performance standards and flow-time standards. These are applied to components of a work plan, including schedules, to determine manpower requirements. The system will eventually be automated but has been successfully used manually in its initial phases. The cost of developing the system is expected to be amortized in 2⅓ years, when increased efficiencies will result in lower operating costs.

•THE Washington State Department of Highways has been acutely aware of the need for an effective manpower management program since the mid-1960s. Early in 1967, the department began the development of the maintenance control system. This system was designed to respond to the requirements for better highway maintenance and to consider human and financial resource needs. It was developed in 18 months and implemented by 1969. Some of the benefits of the maintenance control system are

1. Increased productivity that resulted in a direct or indirect savings of approximately $1.7 million per year,
2. A performance budgeting system acceptable to and understood by the legislature and the state budgeting agency,
3. Better scheduling of time and assignments by employees and managers,
4. Continued evaluation of accomplishment as related to budget expenditures of both human and monetary resources.

In 1972, approximately 27 percent or 1,250 of 4,600 highway department employees were working under the maintenance control system requirements. Encouraged by the system's success, the department began considering a similar system of resource management for its engineers and technicians.

As in most states, highway construction in Washington is decreasing and is being influenced by many outside factors. Department managers were faced with the possibility of having excess personnel for preliminary and construction engineering. The effect of this excess could be eased if a system could be developed that anticipated and accounted for most influencing factors in the planning process.

Washington legislators were also interested in the productivity and use of the department's engineering employees. At its last regular session, the legislature required the department of highways to develop and implement nonexpenditure workload performance criteria for approximately 2,000 engineering and right-of-way personnel.

Publication of this paper sponsored by Committee on Construction Management.

Fortunately, the manpower utilization program, which the department had decided to develop, could be adapted to fulfill this requirement.

At the beginning of the manpower utilization program, the department had the basic scheduling and data collection systems to develop a comprehensive program. These systems needed to be tied together and expanded or modified to fit the needs. This new program was identified as the manpower management and information system (MMIS). The unit to develop the system was organized, funded, and staffed with six full-time department employees in July 1972. A comprehensive work plan outlined the functional tasks and activities to be undertaken in developing the system. The work plan included the services of an engineering management consultant in an advisory capacity and extensive contributions by many engineering disciplines within the department. The work plan was ambitious in that it affected engineering work activities for preconstruction, construction engineering, and right-of-way. The work plan involved refinements of project scheduling systems, development of labor standards, development of flow-time standards, and design of an automated data processing subsystem to satisfy management information needs. Development of the system was complicated by the fact that the department's organizational structure is decentralized.

The overall project is guided by an advisory board. The board consists of the deputy director, two district engineers, four assistant directors, the state director of personnel, and a union representative. The advisory board reviews policy determinations and makes recommendations to the director of highways regarding policy matters.

MANPOWER MANAGEMENT AND INFORMATION SYSTEM

The system contains elements with which district and headquarters administrators can plan, organize, direct, and control the day-to-day efforts of their staff. It provides major input into an annual performance budget for the highway construction program. It relates elements of construction programs to labor requirements and will ultimately provide the information needed for cost comparison purposes.

Maximizing use of engineering personnel requires realistic planning and scheduling, immediate and continued visibility of actions taken, and response to deviations from the plan or schedule. Simply stated, MMIS is based on planning and scheduling, measuring and comparing, and acting and reacting. The system recognizes the human factors vital to the success of this type of project. The importance of the understanding and cooperation of workers is a basic factor contributing to increased efficiency. A totally mechanical approach to improving work procedures will not guarantee desirable results. Worker cooperation and motivation, even if combined with relatively ineffective work methods, will frequently give better results than impersonal automated control in which the worker has no input. It is only through consideration of the worker as an individual that a work improvement or management program can be effective.

In addition to benefits to management, benefits should also accrue to employees under the system. The system will provide a way by which projects can be rescheduled to use the department's staff effectively. Personnel will then be ensured of a continuous work program and employment. The system also has features that can motivate the employee to establish goals to guide his career development and everyday activities.

In development of the system, an engineering management consultant was used in an advisory capacity and engineering employees contributed extensive input. Employee expertise was focused through three active working committees plus ancillary teams. One committee was an 18-man team of district and headquarters personnel who coordinated the efforts of the MMIS project. Another 12-man team of engineers and technicians developed task definitions in the area of preconstruction engineering. An eight-man team was used in a similar capacity in the area of construction engineering. Other teams of engineers and technicians in districts and headquarters were trained to conduct the long cycle time and work sampling studies. In addition, the MMIS project staff carried out personal interviews with 75 percent of the department's project engineers and support group managers.

The system can best be symbolized as a pipeline with a funnel at the beginning. The

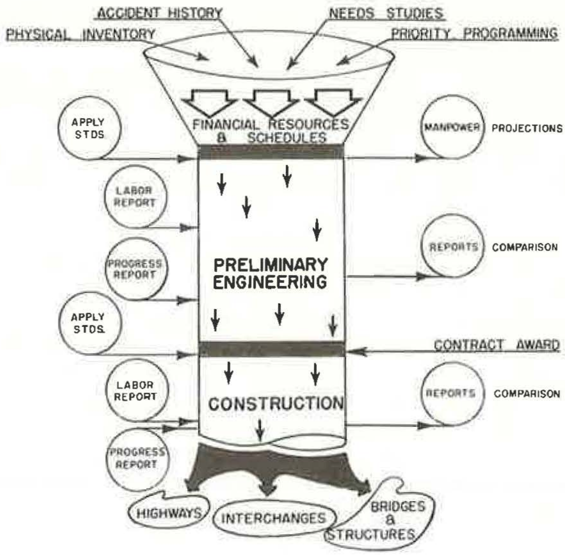


Figure 1. Highway project planning process.

Figure 2. Project input information for design.

Project Number: 11123B-201

Sign Route: 002 MP 147.96 to MP 148.44

Project Title: SUNSET INTERCHANGE

Project Type (Select One):	Length of Project:
[X] Major Construction Rural	0.48
[ ] Major Construction Urban	

Project Features:	Unit of Measure	Quantity
[X] Action Plan Group 1	/////	/////
[ ] Heavy Vegetation	/////	/////
[ ] Mountainous Terrain	/////	/////
[ ] ◊ Interchange	Each	
[X] Major Interchange	Each	1
[X] Intersection	Each	3
[X] Frontage Road	Mile	2.0
[ ] Rest Area	Each	
[ ] Weigh Station	Each	
[ ] Railroad	/////	/////
[X] Access Points	Each	1
[X] Photogrammetry Products	Sq. Mile	3
[X] Special Studies	Each	2
[X] Landscaping	Acre	10
[X] Noise Study	Mile	0.48
[X] Air Study	Each	1
[X] Biological Study	Each	1

funnel represents the planning process through which a project is conceived (Figure 1). A wide range of information is combined to form the basis of a single project as it passes through the pipeline. The system considers the results of continuing needs studies, public input, traffic data analysis, and legislative direction. When a project prospectus is determined, it enters the pipeline and is processed through the scheduling system. Manpower projections are made for each activity by applying the standard data included in the work criteria for these activities. As each milestone is reached, the project can be reevaluated and new personnel requirements can be projected.

As the project becomes refined, the work criteria become more finite, and more accurate manpower projections can be made. After the project arrives at the advertising stage, construction labor standards are reapplied to the components of the project and construction engineering requirements are projected. Thus, engineering costs can be identified more accurately. The present method of estimating engineering cost in Washington is to assign a percentage of the estimated construction costs. The system will provide planning for multiple projects and control of individual projects.

Input to the system must begin at the lowest level of management and must be summarized for all levels. Because of the detail involved in multiproject scheduling, the system should be automated so that the effect of changes resulting from high-level decisions or unavoidable delays due to outside factors can be rapidly identified.

In the system, control input comes from the field or operating forces through the payroll reporting subsystem. One copy of these data is used for payroll purposes and another for management purposes.

Monthly reports will provide each project manager a status report for each project under his control. These reports will compare his crew's work output of the past month to the work planned for that month. Thereby crew performance can be measured and corrective action can be taken if the scheduled performance is compromised. Factors that delay the construction program can be identified and equated to time and money. This output will help top management make decisions that will minimize the effect of delays. The ultimate result of the successful implementation of the MMIS will be that engineers and project managers will become actors who anticipate and prevent problems rather than merely reactors to situations as they occur.

WORK STANDARDS

The backbone of the MMIS is the person-hour work or performance standards and flow-time or long-range planning standards. These standards were specifically developed for work performed during preconstruction, right-of-way, and construction activities. A person-hour work or performance standard is the criterion on which actual performance is evaluated for quality, quantity, and productivity. A flow-time or long-range planning standard prescribes the number of days allowed to complete an activity, milestone, or project.

Each preconstruction engineering activity was defined early in the project development. There are 140 work activities identified as preconstruction engineering and 60 as construction engineering. Each activity is described in a specific work control statement. The work control statement gives the scope of the work involved, the purpose, significant decisions needed, and the necessary staffing by number and skill level. Work performance standards and flow-time standards were developed for each activity. These standards are stored in the computer and are the basis for resource calculations when the construction program is developed.

Examples of typical planning inputs to the automated system shown in Figures 2 and 3 demonstrate the use of work performance and flow-time schedules and the development of manpower forecasts. These figures show the design and construction phases of a project. Similar input is required for other preconstruction phases. Descriptions of the project type and project features key the computer to calculate an estimate of planned person-hours. The input to the computer also keys a calculation to produce a scheduling network. This becomes the basis to calculate and spread the person-months required to complete the phase. Planning reports similar to those shown in Figures 4,

Figure 3. Project input information for construction.

Project Number: 11123B-501

Sign Route: 002 MP 147.96 to MP 148.44 Working Days: 240

Project Title: SUNSET INTERCHANGE

	Project Type	Unit of Measure	Quantity
☐	Reconditioning	Rdwy Mile	______
☒	Major Construction	Rdwy Mile	2.35
☐	Structures	MSF Deck	______
☐	Safety (General)	-----	///////
☐	Safety (Special)	-----	///////
☐	Stockpiling	M Ton	______
☐	Bridge Painting (Misc.)	$ Contract	______
	Project Features		
☐	(M) Urban	Rdwy Mile	______
☒	(M) Earthwork (Embankment)	MCY	100
☒	(M) Structures (Bridge)	MSF Deck	10.5
☒	(M) Retaining Walls	CLF	5
☒	(M) Existing Alignment under Traffic	///////	///////
☐	(M) No Surfacing & Paving	Rdwy Mile	______
☐	(R) Pit	Rdwy Mile	______
☐	(R) Multilane and/or Urban	Rdwy Mile	______
☐	(R) Shoulder Rebuilding	Rdwy Mile	______
☐	(R) Automatic Grade Control	Rdwy Mile	______
	General Features		
☒	Lane Markers, etc.	Rdwy Mile	2.35
☒	Channelization, etc.	Rdwy Mile	2.35
☒	Guard Rail	MLF	0.45
☐	Impact Attenuators	Install.	______
☒	Drainage (30" & Under)	Install.	10
☒	Drainage (Over 30")	Install.	1
☒	Illumination	System	5
☒	Sign Structures	Each	3
☒	Sign Illumination	Each	3
☒	Erosion Control	Acre	40
☐	Aggregate Production	M Ton	______
☒	Federal Aid	///////	///////

Figure 4. Project engineer manpower plan.

ORG 442501 J. JONES

PROJECT NUMBER	PROJECT ******DESCRIPTION******	F.Y.	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	TOTAL
			********** PLANNED MAN MONTHS **************												
11012H-401	FREEDOM TO WATT ROAD	76	F	F	2.0	4.0	5.0	5.0	6.0	3.0					25.0
	SR 195 MP 003.09 - 005.94	77													
	GR, DR, STR, PAV	78													
11012H-501	FREEDOM TO WATT ROAD	76									3.0	3.0	4.0	6.0	16.0
	SR 195 MP 003.09-005.94	77	6.0	6.0	6.0	6.0	6.0	3.0	2.0	2.0	3.0	3.0	4.0	6.0	53.0
	GR, DR, STR, PAV	78	3.0	2.0											
[illegible]H-501	SNAKE RIVER TO DUSTY	76	15.0	15.0	15.0	15.0	8.0	6.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	144.0
	SR 127 MP 079.26-085.77	77	15.0	15.0	15.0	15.0	10.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible] DR, PAV, SIGN, ILL	78	6.0	4.0											
11123B-501	SUNSET [illegible]	[illegible]													
	SR 002 MP 147.96 - [illegible]	[illegible]												7.0	7.0
	GR, DR, PAV, RAMPS, SIGN, ILL, G.R.	78	12.0	15.0	15.0	15.0	15.0	12.0	10.0	10.0	12.0	15.0	15.0	15.0	161.0
ORG. 442501 J. JONES		***** 76	17.0	18.0	20.0	23.0	23.0	21.0	20.0	22.0	27.0	29.0	28.0	30.0	278.0
		* TOTAL * 77	29.0	26.0	26.0	26.0	21.0	16.0	13.0	16.0	21.0	21.0	22.0	28.0	265.0
		***** 78	21.0	21.0	15.0	15.0	15.0	12.0	10.0	10.0	12.0	15.0	15.0	15.0	176.0

5, and 6 are generated.

The input information on the construction phase includes the project type and features. These data key the computer to calculate the planned person-hours for the construction phase of each project. A calendar predicting manpower needs is stored in the computer and is used to allocate the manpower over contract flow time. Another innovation of the system is the use of predetermined flow-time percentages of the total project for each functional activity.

The control aspects resulting from the use of these standards provide the individual manager the opportunity to measure and compare his schedule accomplishments and person-hour expenditures with the original plan. An example of this tool is shown by the project status and expenditure report (Figure 7). The information displayed in the report identifies potential future impacts and isolates specific problem areas.

WORK PLANNING AND SCHEDULING

The system of planning for work uses a critical path scheduling network for all projects and work activities involved in preconstruction engineering. Unfortunately, all projects cannot be planned the same way because of differences in project characteristics. Therefore, each project is planned independently by considering the factors that make each project unique. The final estimate for engineering resources will depend on the project location, environment, sociopolitical influences, and many other considerations.

Development of MMIS was based on the premise that there may be five stages or phases involved in planning, designing, and constructing a highway project. These phases are shown in Figure 8.

Using a critical path scheduling network to develop engineering manpower requirements has been contested by many in the highway field. The primary argument is that, because preconstruction engineering work is so strongly influenced by public reaction, environmental impacts, and dynamic changes in general, it is difficult to determine a final design and schedule; therefore, it is impractical to develop a manpower management system. We take exception to that argument. Changing conditions in planning for construction projects actually justify the development of a manpower management program becuase it becomes more essential to maintain control and direct the efforts being expended.

Six steps describe the operation of MMIS: evaluation of alternatives, balancing district resources, statewide planning and coordination, budget approval, development of operational plan, and direction and control of project.

Evaluation of Alternatives

The policies and goals established by the legislature, highway commission, the director, and other top department officials establish the scope of the highway construction program. Initial decisions on program development are controlled by ongoing needs studies, priority programming, accident histories, physical inventories, and so on.

District Resource Balancing

Headquarters is responsible for estimating future revenue and for preliminary allocations of money to each district. The districts generate a preliminary work plan for a specified period of time by selecting and identifying projects from a 6-year program. After all data related to this program are input to the computer, the resources necessary to accomplish the program are determined. If the results of these calculations are different from the known condition, the program is reiterated until available resources and plans are balanced.

Each project is considered as a MMIS work package that is subdivided into phases

Figure 5. Project schedule and manpower plan.

ORG. 442501 S. JONES

PROJECT # 41001A-201
GEORGE CR. VIC. TO MARTHA LAKE
SR 090 MP 100.56 - 106.87

ACT #	ACTIVITY TITLE	FLOAT DAYS	EARLY START	LATE COMPLETE	WORK DAYS	SUPPORT ORG.	***MAN-HOURS*** HDQTR SUPPT	DIST. SUPPT	PROJ ENG	**** MAN-HOURS BY SKILL LEVEL *** ENGR AD	LEVEL 5	LEVEL 4	LEVEL 3	LEVEL 2	LEVEL 1
201	SCHEDULE & BUDGET DESIGN	0	02/13/76	03/18/76	25	442001		24	24	24	0	0	0	0	0
203	TRAFFIC DESIGN DATA	1	03/19/76	05/12/76	39	442001		8	34	8	10	16	0	0	0
						333321	168								
204	BASE MAPS & PHOTO	0	03/19/76	05/12/76	40				262	0	22	84	52	52	52
230	FHWA APPROVAL	0	11/18/76	12/02/76	15	322232	16		0	0	0	0	0	0	0
						322250	32								
			* DIRECT TOTAL *				225	190	750	157	120	255	75	68	75
			* INDIRECT *				25	20	156						
			* TOTAL *				250	210	906						

Figure 6. Three-year district planning schedule.

PROJECT NUMBER	PROJECT *****DESCRIPTION*****	ASSIGNED PROJ ENG	FTBP (MO)	FISCAL YEAR	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	TOTAL
41001A-502	JEFFERSON COUNTY LINE TO FORKS SR 006 MP 184.62 - 191.07 C, G, GR, DR, S, PAV CONTRACT $'S = 706,000 (FA)	444301		76	24.0	20.0	20.0	3.0	3.0								60
41001A-503	BOGACHIEL RIVER BRIDGE & APPR. SR 00. MP 185.58 185.64 GR, S, PAV, STR CONTRACT $'S = 760,000	------	10	76	F	F	F	F	F	3.0	3.0	5.0	10.0	12.0	7.0	7.0	47
				77	6.0	6.0	3.0	3.0	3.0								21
	* * * WORK PACKAGE # 41001A TOTAL *		**	76	24	20	10	3	3	3	3	5	10	12	7	7	107 *
				77	6	6	3	3	3								21 *
42023B	JCT. SR 5 TO JCT. SR 8 SR 101 MP 367.26 - 381.70	442502		76	7.0	7.0	8.0	6.0	2.0								30

Figure 7. Project status and expenditure report.

ORG. 444304 T. JOBEY

PROJECT # 43001B-501
SR 395 TO HILLYARD JCT.

WORK ORDER # 0L5823

ACT #	ACTIVITY TITLE	SUPPORT ORG	***START DATES*** PLANNED	ACTUAL	*COMPLETE DATES** PLANNED	ACTUAL	PLAND WORK DAYS	********* MAN-HOURS ********** CUR MO	TO DATE	TOTAL	BALANCE
415	CONTRACT PLAN DRAFTING		4/15/76	4/15/76	12/17/76		120		136	136	
422	FIELD ESTIMATES & COMPILED PSE		10/12/76	11/11/76	4/15/77		120		40	35	5
424	DISTRICT OFFICE - PS&E	442202	5/1/77	6/1/77	6/15/77	7/15/77	30		56	60	4
428	HEADQUARTERS - PS&E AND PIH	322222	8/1/77	8/15/77	9/1/77	9/5/77	20	8	49	60	11
		322232							8	8	
		325530						10	10	10	
433	PROJECT ADVERTISEMENT	327720	9/5/77	9/12/77	9/20/77		10	7	7	24	17
	***** TOTAL PROJECT # 43001B-501 ****		4/15/76	4/15/76	9/20/77		360	25	306	333	27

Figure 8. Highway project stages.

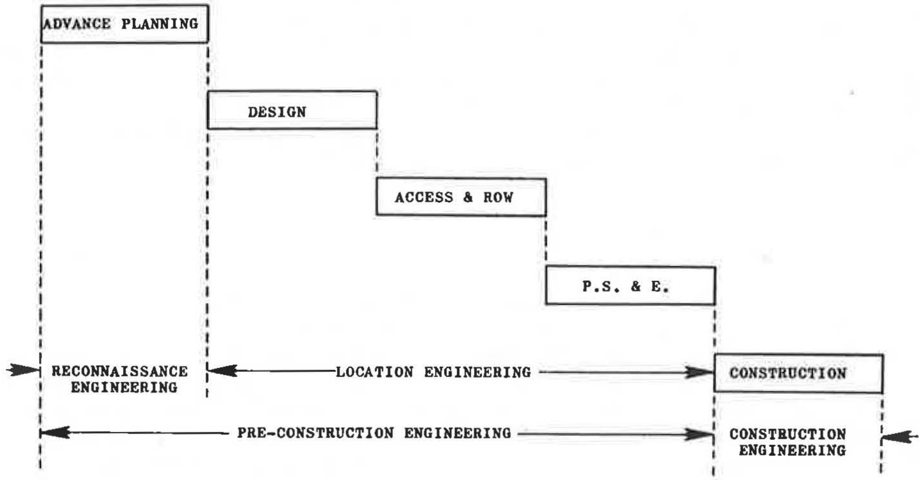
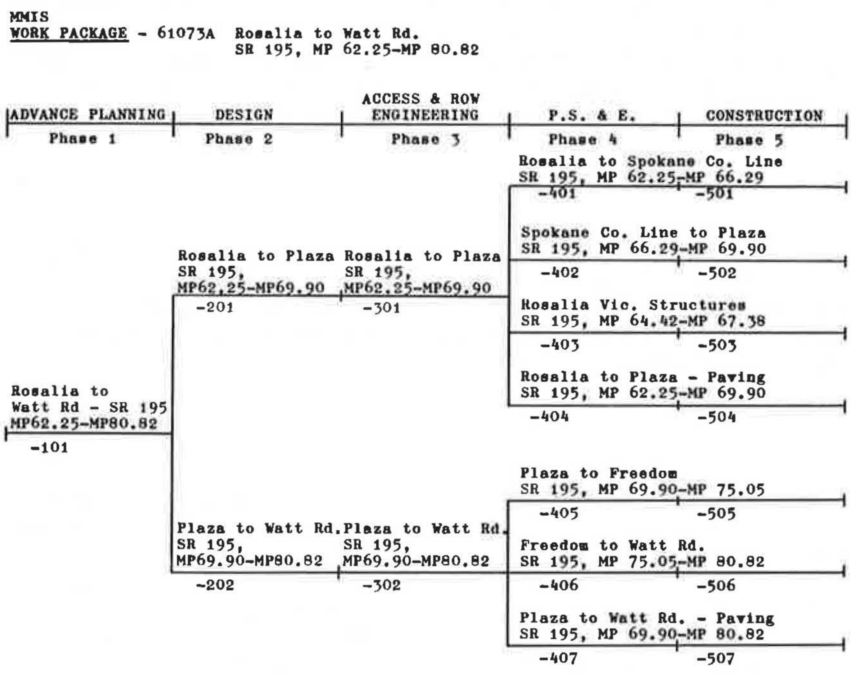


Figure 9. Highway project fragmentation.



and into its most probable project fragmentations. A typical fragmentation of a work package is shown in Figure 9.

These preliminary planning data are input to the system so that work package planning schedules may be developed. Manpower standards and flow-time standards are stored in the computer as base data. These data are used to calculate preliminary schedules and manpower requirements for individual projects at the district level. The output data are reviewed by top-level district management to ensure that financial and manpower resources are balanced. This review allows the district work plan to be formulated with as many reiterations as necessary. A typical planning report resulting from this procedure is the 3-year district planning schedule shown in Figure 6. This and other reports are distributed only to the district engineer and his planning staff. The purpose of these reports is to review schedule feasibility and to show project start and completion dates. They are also used for balancing manpower resources and as an aid in assigning projects to respective project engineers. They are updated and produced once a year and are the basis for the yearly operational plan.

Statewide Planning and Coordination

The district preliminary work plans are transmitted directly to headquarters for processing, review, and subsequent approval. When the preliminary work plans are received, the data are consolidated and formatted in accord with existing policies and procedures. The projects included are input to the computer. Schedules and manpower output reports are reviewed by the organizational units affected. Each unit makes adjustments to ensure that the best balance of human resources is attained on a statewide basis. This is accomplished by personal and telephone contacts between units.

The statewide planning and coordination may require several iterations. After a balanced program has been achieved within each district and supported by the affected headquarters units, the recommended plan is presented to the approving authorities. A typical balanced planning report resulting from this procedure is shown in Figure 4.

This and other reports are distributed to the appropriate organization in the districts and headquarters. The district reports are forwarded to the district engineer and his planning staff, project engineers, and support group managers. The headquarters reports are forwarded to the appropriate support group managers and assistant directors.

Budget Approval

When headquarters has received all recommended program plans, the pertinent information is extracted and summarized in a prescribed format for review and approval. Upon approval by appropriate authorities, headquarters allocates the financial and human resources to the various districts and headquarters support groups. These allocations are related to the approved program.

Operational Plan Development

After the program is approved, district and headquarters units are furnished an operational plan from the MMIS control group. Computer printouts of the plan provide project schedules and manpower requirements that are within the scope of the approved program. The operational plans come in two formats: the project schedule and manpower plan (Figure 5) and the support group activity schedule and manpower plan.

The project schedule and manpower plan is the project engineer's yearly operational plan. The project engineer uses this report in conjunction with the project engineer manpower plan (Figure 4) to schedule day-to-day operations and coordinate support work performed by other organizational units. The operational plans are updated and furnished once a year or on a demand basis if projects have been rescheduled.

Before work can be performed in the operational plan, the district staff must ensure that funds are available for work in progress. If new projects are planned, a new fund and work order authorization request must be prepared.

Project Direction and Control

When work is performed by highway employees on projects appearing in the operational plan, their labor time charges are reported through the regular accounting labor reporting system. These charges are coded to report the actual type of work accomplished by each individual. The project engineer or support group manager is responsible for the reporting of key activity completions. The scheduling and planning efforts expended in the operational plan development process result in a series of management reports. Management at all levels have the opportunity to monitor, compare, and evaluate the progress and performance of planned accomplishments and expenditures. A typical report that provides management with progress and performance is the project status and expenditure report (Figure 7). This and other monthly reports are distributed to management levels within districts and headquarters that have a need for them.

SUMMARY

The Washington State MMIS development is nearly a reality. Development of labor standards has been instrumental in helping the district and headquarters management to better predict engineering manpower requirements for the 1975-77 period. The labor standards were initially applied manually for fiscal year 1975 so that standards could be tested prior to the 1975-77 period. Revamping the scheduling system has introduced a new dimension into the area of project planning by isolating the work into specific phases of preconstruction and construction engineering.

The work remaining on the project involves testing labor standards, completing the data processing system design, programming, and testing. The total system is planned to be operational soon.

This project has attempted to consider every facet of preconstruction and construction engineering activities. These range from establishing standards for survey crew sizes to involving interdisciplinary teams associated with the action plan. Although reluctance on the part of employees to accept the system was anticipated, it never materialized. This can be attributed to the deep involvement of many department employees who directly contributed to the development of the system. The commitment of top management to support development costs on this project was based on the premise that the benefits would far outweigh the development costs. Management is still holding to this premise.

Should other transportation agencies consider the development of a similar system, information on the Washington experience is available. For those who are interested in costs, the MMIS 3-year development and implementation will cost $700,000 when fully implemented. The total cost will be distributed as follows:

Item	Percent
In-house labor	53
Data processing design, programming, and testing	35
Consultant	7
Miscellaneous	5

As was demonstrated by the development of the Washington maintenance control system, the total development costs are expected to be recovered rapidly and should be related directly to increased productivity. Our goal is to realize a cumulative 5 percent improvement in productivity and employee use for at least 5 years. We expect to break even in 2⅓ years.

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