

DEVELOPMENT OF PROTOTYPE HIGHWAY ASSET MANAGEMENT SYSTEM

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ABSTRACT: A prototype methodology for integrating highway infrastructure management activities has been developed. This paper describes the analytical procedures and data integration and presentation methods as well as the geographic information system- (GIS-) based software system that ties together and implements the data and management procedures. Together these elements comprise the new methodology. There are four major areas of integration considered in the methodology: (1) Integrated computerized system; (2) network-level integration; (3) project-level integration; and (4) multiple performance measures. The network-level integration involves performing trade-off analysis to select candidate projects from various highway infrastructure components. The project-level integration includes identifying adjacent improvement projects from various infrastructure components that can be implemented simultaneously to reduce traffic disruptions. The project-level integration is performed in a spatial manner using GIS capabilities. The integrated system approach developed in this study for the management of highway assets was applied to five infrastructure components (pavements, bridges, culverts, intersections, and signs) of the state highway system in Champaign County in central Illinois. The sample highway application showed that coordinating project implementation is beneficial for highway agencies and users. It reduces disruption to normal traffic flow caused by rehabilitation and reconstruction activities in a 5-year program by 20%.

INTRODUCTION

Highway agencies are continually investing large sums of money to maintain the physical and operational quality of their infrastructure assets above minimum levels. A highway infrastructure network consists of many components that are normally owned and managed by the same agency (e.g., pavements, bridges, culverts, signs, intersections, and guardrails). Thus, it is logical to expect that managing these components in a coordinated manner is beneficial to both users and owners. Highway infrastructure management is essentially a set of activities associated with the process of maintaining, rehabilitating, and reconstructing/replacing highway assets in a cost-effective way. Thus, highway agencies need tools that allow them to perform coordinated management of their assets and that provide the services that the community expects of them within funding limits.

In many highway agencies, separate management systems are often incompatible in terms of location referencing systems, analytical procedures, and data input/output format. Thus, data sharing and communication among these systems become impractical and expensive.

The main objective of this research is to provide highway agencies at the state, county, or municipality with a methodology for developing tools that can be used to evaluate the trade-offs among various highway improvement projects and coordinate project implementation to reduce traffic disruptions. In other words, this prototype methodology can be used for managing various highway infrastructure components in a coordinated and cost-effective manner. The methodology consists of analytical procedures and data integration and presentation tools, along with the geographic information system-

(GIS-) based software (called InfraManage) that integrates and implements those procedures and tools.

METHODOLOGY DESCRIPTION

Significant efforts have been made to develop management systems to improve efficiency in utilizing limited transportation resources (e.g., pavement management systems and bridge management systems). However, there has been much less work done to develop a "total" highway infrastructure management methodology that ties these systems together. During the late 1980s, discussions began on the importance of a comprehensive system for managing highway infrastructure components such as pavements, bridges, culverts, and traffic control devices in a coordinated manner to improve managerial decisions. However, very few specifics have been stated in this regard.

One of the early efforts in the area of urban infrastructure management was made by the Urban Institute and the International City Management Association in the early 1970s to identify measures of effectiveness for basic municipal services (e.g., transportation, solid waste collection, water supply, sewage) (*Measuring* 1974). However, the real-world use of these effectiveness measures is still largely untested (Grigg 1988).

The need for a total highway management system and general guidelines for developing it were discussed by Sinha and Fwa (1989). Stephense (1987) described the approach taken by the city of Orlando, Fla., to develop integrated street infrastructure information systems that operate from a common street inventory. Similar systems are used by some municipalities to provide performance and inventory information related to urban infrastructures, such as pavements, sewers, gas, and electric (Person and O'Day 1986; Zhang et al. 1994; Lee and Deighton 1995). However, most of these systems do not have the necessary decision support analytical techniques, such as life cycle cost analysis, utility theory, and optimization techniques. These techniques are needed to perform reasonable integration of engineering as well as economic decisions.

One of the few efforts that established specifics for integrating highway infrastructure management systems is that of Harper and Majidzadeh (1993) to develop an integrated pavement and bridge management system for the kingdom of Saudi Arabia using fuzzy set theory to define optimal alternatives. The Finnish National Road Administration coupled bridge and

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pavement management systems into one infrastructure management system to optimize simultaneously bridge and pavement maintenance and rehabilitation activities under a single set of constraints and budget (Männistö and Tapio 1994). Other valuable efforts to integrate bridge and pavement management systems were made by Ravirala and Grivas (1995) using goal programming.

This paper describes a prototype methodology for managing multiple highway infrastructure assets in a coordinated and cost-effective manner. Key features of this methodology are summarized as follows:

- GIS-based software system
- Investment trade-offs (network-level integration)
- Coordination of project implementation (project-level integration)

This methodology also considers multiple performance measures in the selection of candidate infrastructure improvement projects. Spatial and statistical analysis of pavement condition, safety, and traffic data conducted on the state highway system in Champaign County, Ill., revealed that the integration of pavement, safety, and congestion management systems is particularly critical in urban areas (Gharaibeh et al. 1997).

Software System

An essential tool for applying the new highway infrastructure management methodology efficiently is a computer software system that includes a set of appropriate engineering, economic, and spatial methods, in addition to highway infrastructure data. This is a GIS-based single system architecture

that includes the combination of various highway infrastructure asset management systems. This system incorporates several tools (i.e., data, database management functions, analytical methods, and information presentation techniques). The potential value of each highway management system is extended beyond its individual scope by allowing engineers and engineering managers to coordinate decisions at the planning, management, and operational levels within the highway agency.

The InfraManage prototype GIS-based infrastructure management system is developed to manage five highway components (pavements, bridges, culverts, signs, and intersections) in a coordinated manner. The system design and operation procedure of the InfraManage software are summarized in Fig. 1. InfraManage was developed using version 7.04 of the ARC/INFO environment, a well-established GIS developed by the Environmental Systems Research Institute (*Understanding* 1994). Linear data in InfraManage is designed using the route-system linear data model. Milepost is the common location referencing system for all data. This model is used to represent linear features (called routes) and their associated attributes (called events) so that the dynamic segmentation mechanism can be utilized. Major advantages of an integrated infrastructure management software are as follows:

- Integrated database and common linear referencing system
- Compatible analytical procedures
- Compatible output presentation methods
- Potential for reduced software development, maintenance, and operation costs
- Potential for reduced training costs

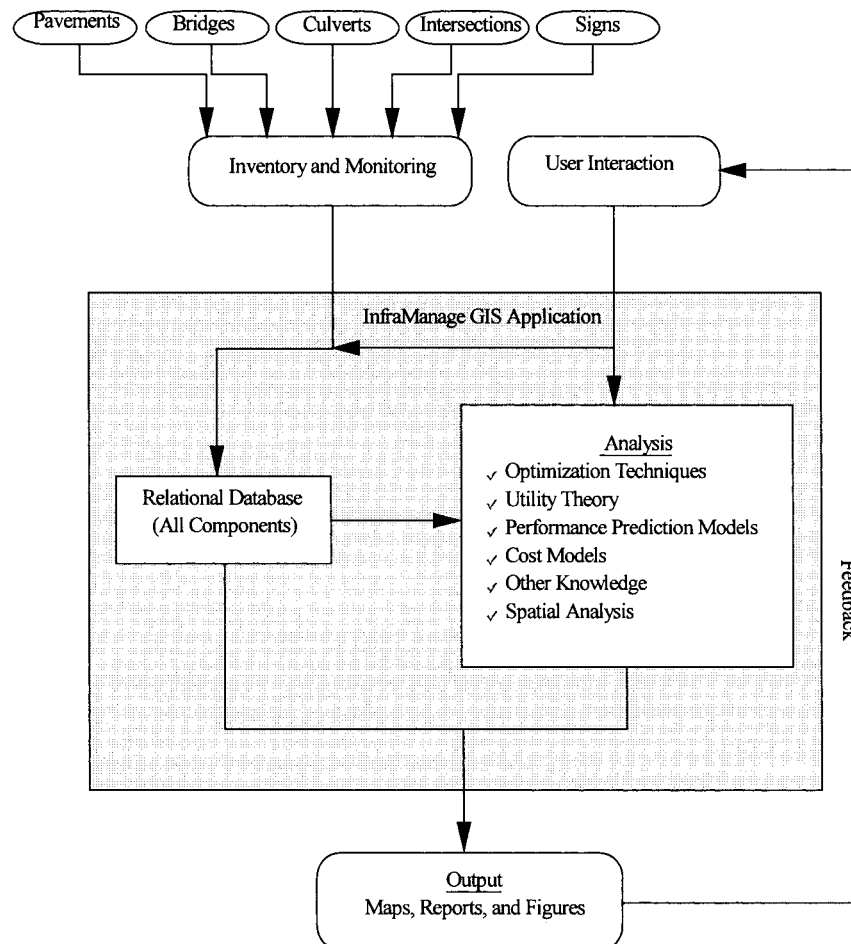


FIG. 1. System Design for Highway Infrastructure Management

Network-Level Integration

This is a trade-off analysis among alternative investment strategies that allows for the selection of improvement projects from various infrastructure components to maximize the overall performance of the highway network now and in the future, within funding limits. For example, to improve the overall performance of a highway infrastructure network, it may be more appropriate to shift a portion of the pavement funds to bridges, or vice versa. As can be seen from Fig. 2, the network-level integration is performed in two steps:

1. Allocate a total network annual budget across competing components
2. Allocate the optimum share of each component from the total budget across the competing projects within the component

To formulate the above procedure in optimization problems, it is necessary to measure the benefit of improvement for each infrastructure component, to develop a common infrastructure performance indicator for all components, and to develop mathematical relationships between investment level (i.e., budget) and infrastructure performance.

Measuring Benefits of Infrastructure Improvement

Vehicle miles traveled over adequate infrastructure (VMT-A) over the improvement life was identified as a reasonable measure of improvement benefits for linear highway features. Number of vehicles using an adequate infrastructure (VU-A) was identified as a reasonable measure of improvement benefits for point highway features. VMT-A and VU-A consider improvement life and traffic; for linear features, project length is also considered. Adequacy is defined based on thresholds of multiple performance measures. For example, a pavement section is considered adequate if the pavement condition, accident rate, and volume-to-capacity ratio (V/C) have not reached pre-specified thresholds.

Individual Investment-Performance Functions

The concept of "efficiency" was developed and used in this study as an infrastructure performance indicator. For linear features (e.g., pavement), efficiency is defined as the ratio of

the total VMT-A over the infrastructure life to the total VMT-A computed with an unlimited budget. For point features (e.g., intersections), efficiency is defined as the ratio of the total VU-A to the total VU-A computed with an unlimited budget. Efficiency is expressed in percentage units. Thus, with a highway infrastructure component of 100% efficiency, all users would be driving on or using infrastructure features in adequate condition for the longest possible period of time. On the other extreme, with a highway infrastructure component of zero efficiency, none of the users would be driving on or using infrastructure features in adequate condition. Percent adequate (e.g., 80% of the bridges in the infrastructure network are adequate) can also be used as a performance indicator; however, it is not discussed in this paper (Gharaibeh 1997).

To determine the optimum allocation of the total budget across the competing components, it is necessary to develop a mathematical model that represents the relationship between investment level and efficiency for each infrastructure component in every year of the improvement program. Using data for the state highway system in Champaign County, Ill., it was found that the exponential form is a reasonable and simple best-fit regression function for this relationship. Thus, the functional form of the investment-performance function is

$$\text{Performance} = a (\text{investment})^b$$

where performance is expressed in terms of efficiency or percent adequate, investment is expressed in terms of dollars, and a and b are regression coefficients.

It is necessary to note that the values of the a and b factors depend on the infrastructure condition in the current year and, consequently, on the investment levels and infrastructure condition in previous years. As the investment level in previous years increases and the infrastructure condition improves, the slope of the investment-performance curve in the current year decreases (i.e., a approaches 100 and b approaches 0). An example of the investment-efficiency function for pavements on the state highway system in Champaign County, Ill., is shown in Fig. 3.

Across Components Budget Allocation

This optimization problem is formulated as follows: If $\mathbf{G} = (g_1, g_2, g_3, \dots, g_n)$ is the vector of annual budget allocations to infrastructure components, then the across components

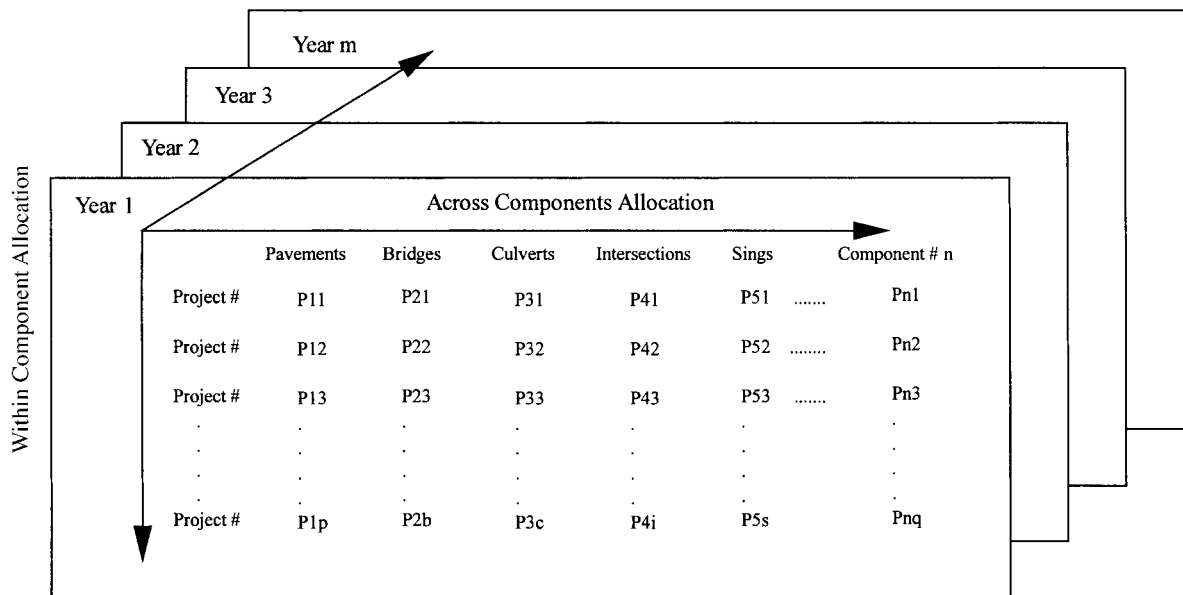


FIG. 2. Network-Level Integration Approach Used in Prototype Methodology

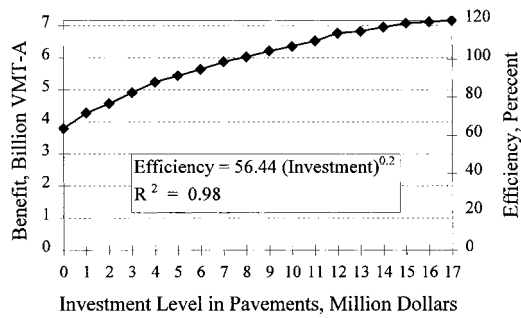


FIG. 3. Pavement Benefit and Efficiency versus Investment Level (Champaign County, Year 1996)

budget allocation problem is to determine the optimum value of g for each component. The budget portions must add up to the total network annual budget or less. The optimization problem is to determine the optimal budget allocation for the highway infrastructure components that maximizes the total performance function (i.e., the objective function) considering budget constraints. Thus, the optimization decision problem is formulated as follows:

$$\max \sum_{i=1}^n p_i$$

subject to

$$\sum_{i=1}^n g_i \leq G; LB_i \leq g_i \leq UB_i$$

where p_i = infrastructure component performance indicator (e.g., efficiency) expressed as a function of investment level (i.e., budget) of highway infrastructure component i ; g_i = investment level (or budget) of highway infrastructure component i ; G = total highway infrastructure network budget; n = number of highway infrastructure components considered in the analysis; and LB_i and UB_i = lower and upper bounds of the budget of component i .

In this study, the individual budgets' lower bounds are set to zero, and the upper bounds are set at the budget level at which efficiency reaches 100%, when the investment-performance curve starts to flatten out. However, the decision maker can set the budget bounds (LB_i and UB_i) as desired. The reverse marginal analysis optimization algorithm, developed by Basu and Batra (1984) for advertising budget allocation purposes, is used to solve the optimization problem. The algorithm consists of two stages, described as follows.

Stage 1—Total budget constraint ignored. For each highway component i , the budget g_i is increased in small steps of Δg_i to maximize p_i until the maximum value of p_i is reached. Δg_i is a prespecified small positive quantity between LB_i and UB_i [$\Delta = (UB_i - LB_i)/10,000$, where LB_i and UB_i are in million dollars]. Let g_{\max_i} be the value of g_i that maximizes p_i . For a continuously increasing function, $g_{\max_i} = UB_i$.

Stage 2—Total budget constraint satisfied. This stage consists of the following steps:

1. If $\sum_{i=1}^n g_{\max_i} \leq G$ (where G is the total network budget), set $g_i = g_{\max_i}$ for all i and stop. Otherwise go to Step 2.
2. Find the highway component j that has the minimum marginal performance for an additional budget dollar (i.e., the partial derivative of the investment-performance function with respect to investment) as follows:

$$\left. \frac{\partial p_j}{\partial g_j} \right|_{g_j=g_{\max_j}} \leq \left. \frac{\partial p_i}{\partial g_i} \right|_{g_i=g_{\max_i}}, \text{ for } i = 1, \dots, n$$

3. Decrease g_j to $g_j - \Delta g_j$ (i.e., set $g_j = g_j - \Delta g_j$).
4. If $\sum_{i=1}^n g_i \leq G$ (where G is the total network budget), stop. Otherwise go to Step 2.

Basu and Batra (1984) compared the reverse marginal analysis algorithm with several other optimization algorithms and concluded that it always gives the best solutions.

Within Component Budget Allocation

This problem focuses on the optimum allocation of each component's annual budget (a portion of the total budget) across the competing projects within the corresponding component. In other words, the optimization problem is to select

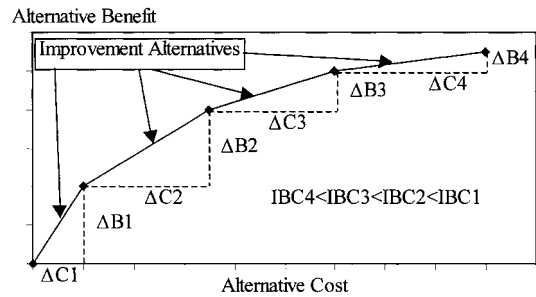


FIG. 4. Arranging IBCs of Improvement Alternatives for Deficient Feature

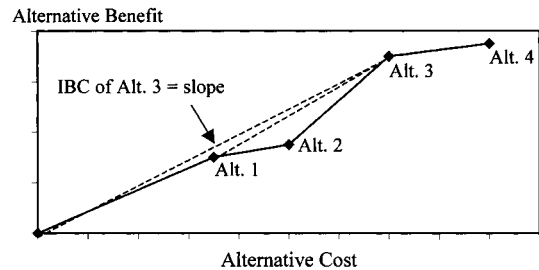


FIG. 5. Converting Concave Up Project-Level Graph to Concave Down One

TABLE 1. Performance Measures Thresholds

Measure (1)	Threshold (2)
(a) Pavement	
CRS	6
IRI	2.52 m/km (160 in/mi)
V/C	0.95
PAR	10 accidents/mi/year (6.2 accidents/km/year)
(b) Bridge	
DKR	6
SBR	6
SPR	6
VUCLr	4.69 m (14.08 ft)
BAR	1 accident/million vehicles
(c) Intersection	
CRS	6
V/C	0.95
IAR	2 accidents/million vehicles

Note: BAR = bridge accident rate (number of accidents/million vehicles entering bridge); CRS = condition rating survey (1-to-9 scale); DKR = bridge deck rating (0-to-9 scale); IAR = intersection accident rate (number of accidents/million vehicles entering intersection); IRI = international roughness index [m/km (in./mi)]; PAR = pavement accident rate [number of accidents/km (mi)]; SBR = bridge substructure rating (0-to-9 scale); SPR = bridge superstructure rating (0-to-9 scale); V/C = volume-to-capacity ratio; VUCLr = bridge vertical under clearance [m (ft)].

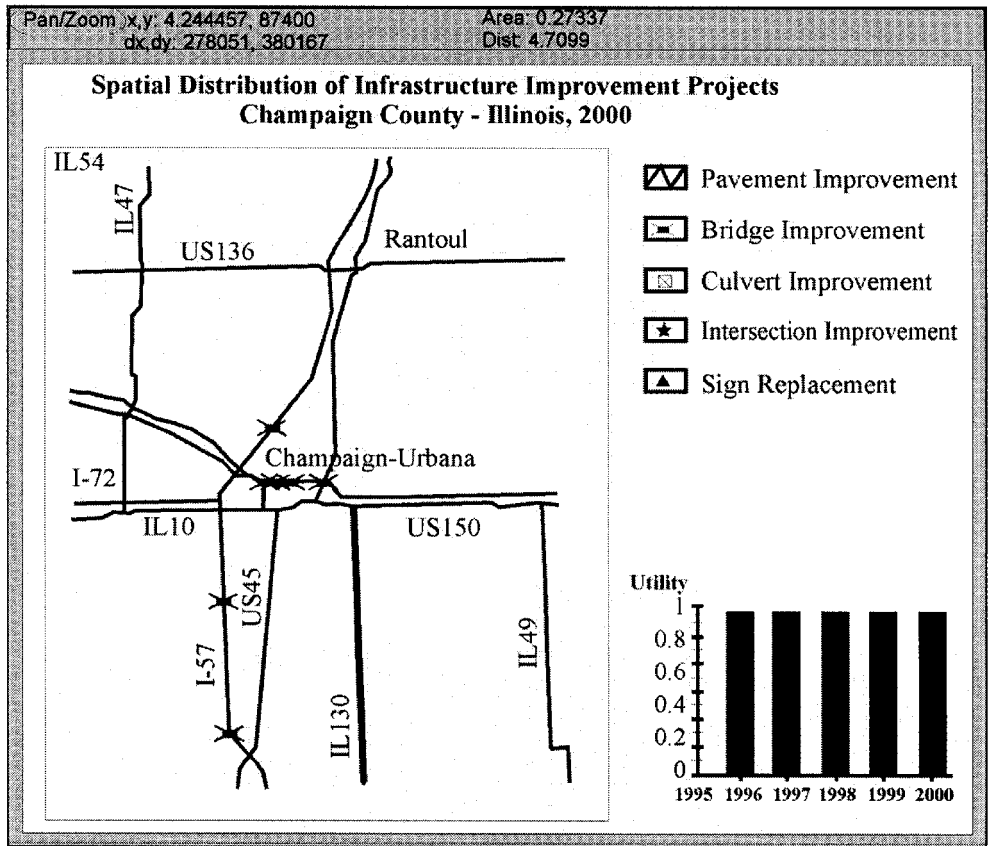


FIG. 6. Example Spatial Distribution of Candidate Improvement Projects (Year 2000)

improvement projects of the infrastructure component under consideration that yield the maximum benefits expected within the available budget.

Incremental benefit cost (IBC) analysis is employed to solve this optimization problem such that a collection of annual projects is selected that yields the highest benefits (VMT-A or VU-A) of each infrastructure component expected within the available annual budget. The IBC method requires the following input data to solve the “within component budget allocation” problem:

- Identification of potential improvement alternatives for each deficient feature.
- Equivalent uniform annual cost (EUAC) of every improvement alternative for each deficient feature.
- Numerical value of benefits expected from every improvement alternative for each deficient feature (In this methodology, VMT-A and VU-A over the improvement life are used for measuring benefit.)
- Annual budget.

The IBC algorithm process projects cost and benefit data to select a collection of projects that maximizes the total benefits in a particular year within the available budget using the following procedure:

1. For each alternative improvement, the EUAC and benefits are calculated.
2. For each deficient feature, improvement alternatives are sorted in the increasing order of their EUAC.
3. The incremental cost and benefit of improvement alternative i are calculated as follows:

$$\Delta C_i = EUAC_i - EUAC_{i-1}$$

$$\Delta B_i = B_i - B_{i-1}$$

4. The IBC ratio of alternative i is calculated as follows:

$$IBC_i = \Delta B_i / \Delta C_i$$

Any alternative with a negative IBC ratio is eliminated from any further analysis.

5. For each deficient feature, the costs and benefits of every improvement alternative are arranged as shown in Fig. 4. The project-level graph should be concave down; that is, the IBC ratios must be in descending order (Shahin et al. 1985; Mohseni et al. 1992). If there is a concave up portion in the graph, a new IBC ratio for the alternative with the highest cost within the concave up portion (call it alternative j) is computed as follows:

$$\text{New } IBC_j = (\Delta B_j + \Delta B_{j-1}) / (\Delta C_j + \Delta C_{j-1})$$

The new IBC ratio ensures that the IBC ratios are in decreasing order. The concave up situation is explained

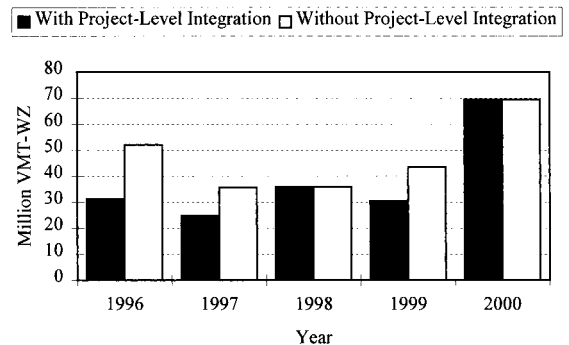


FIG. 7. Annual Amount of Travel Through Work Zones with and without Project-Level Integration

in Fig. 5. The process of converting a concave up graph to a concave down one is explained in the following steps:

- a. The beginning and ending points of the concave up portion of a project-level graph are connected by a straight line.
- b. The IBC ratio of the alternative with the highest cost within the concave up portion (alternative 3 in Fig. 5) is set equal to the slope of the new line developed in Step a.

The above process is repeated until the whole project-level graph becomes concave down. For example, in Fig. 5 it is repeated twice.

6. All improvement alternatives for all deficient features are arranged in descending order of the IBC ratio to determine the steepest path. This is sometimes called the network IBC curve (Mohseni et al. 1992). In selecting projects for implementation, the steepest path is followed until the budget is consumed.

Project-Level Integration

This aspect of integration includes identifying adjacent improvement projects from various infrastructure components in a particular year that can be implemented simultaneously to reduce traffic disruptions. In the absence of coordination, conflicts in project implementation are likely to occur. For example, pavement rehabilitation activities may be performed on a section, and then a few months later rehabilitation activities are performed on a culvert located within the pavement section. Obviously, such uncoordinated projects increase both agency costs and user costs.

In InfraManage, the GIS performs the project-level integration in a spatial manner using the "event overlay" function available in ARC/INFO through the dynamic segmentation process. The adjacency criteria currently available in InfraManage are described as follows:

- All bridge, culvert, and intersection projects within a pavement section that is scheduled for improvement in a

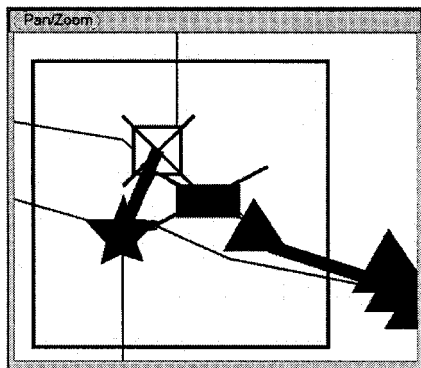
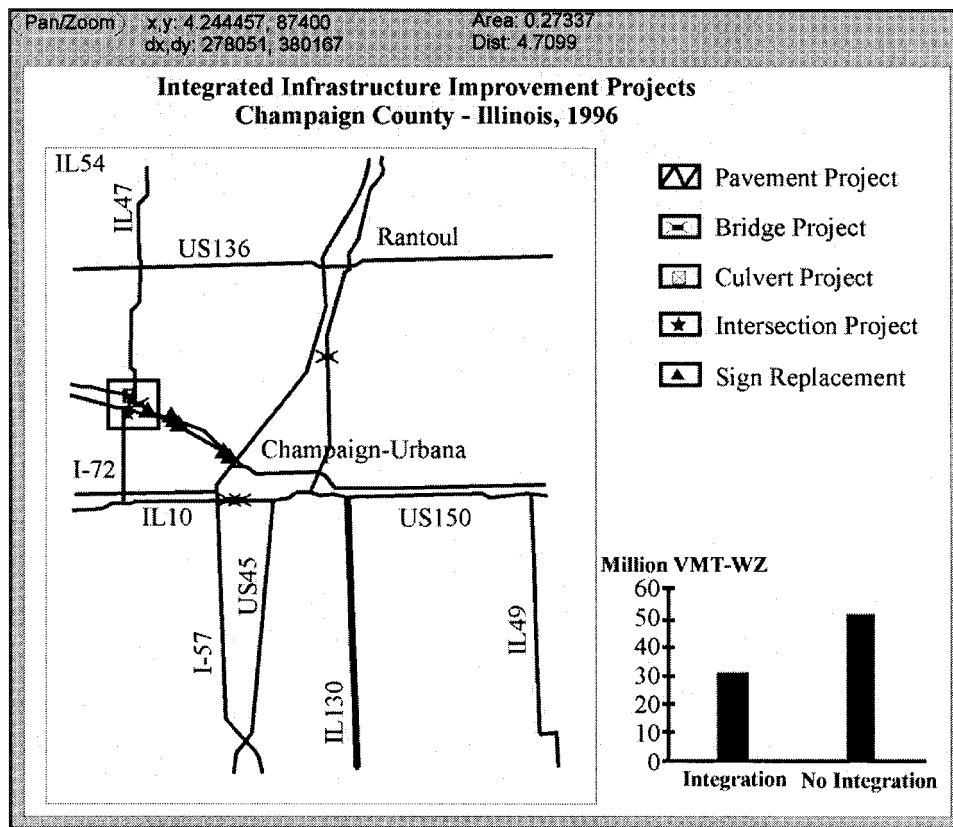


FIG. 8. Spatially Integrated Improvement Projects in 1996

particular year are identified as integrable with the pavement project.

- All bridge and culvert projects within a user-defined distance [e.g., 83.3 m (250 ft)] from the center of an intersection that is scheduled for improvement in a particular year are identified as integrable with the intersection project.

The effect of project coordination on highway users is measured in terms of number of vehicle-miles driven through work zones (VMT-WZ). This indicator is a surrogate for several user cost components such as delay costs and vehicle operating costs that result from driving through construction zones. VMT-WZ is computed for a particular year as follows:

$$\text{VMT-WZ} = \sum_{i=1}^n \text{AADT}_i * \text{WZL}_i * \text{DC}_i$$

where VMT-WZ = total number of vehicle-miles driving through work zones; AADT_i = annual average daily traffic at project i (vehicle/day); WZL_i = work zone length of project i (mi); DC_i = total days of construction for project i ; and n = total number of infrastructure improvement projects. The above equation was used by Wang (1995) to measure highway unavailability for users.

SAMPLE APPLICATION

The state highway system in Champaign County was used to demonstrate the prototype system and to conduct the necessary analysis. Champaign County is located in east central Illinois in the wet-freeze climate of the United States. The state highway system in Champaign County consists of three interstate routes (I-57, I-72, and I-74), three national routes (US-45, US-136, and US-150), and five state routes (IL-10, IL-47, IL-49, IL-54, and IL-130).

The following five components of the sample infrastructure network are considered in the application:

1. Pavements: 148 pavement sections (620 lane-miles of rigid, flexible, and composite pavements)
2. Bridges: 128 concrete and steel bridges
3. Culverts: 64 concrete culverts
4. Intersections: 11 major intersections (where any two or more of the considered highways intersect)
5. Signs: 660 signs (only signs on the interstate highways are considered)

Table 1 shows the performance measures and their default thresholds for pavements, bridges, and intersections considered in the InfraManage software and used in the analysis. Signs were visually inspected at night and assigned a rating on a 0-to-9 scale to measure their night visibility performance. This measure is called sign condition index. A sign condition index threshold of 6 is used in the analysis. Also, the performance of culverts is measured using a rating on a 0-to-9 scale and a threshold of 6. This measure is called culvert condition index.

A 5-year infrastructure improvement program (1996–2000) was developed for the sample highway network using performance, monitoring, inventory, and cost data for 1995 and a total annual budget of \$6,500,000. The network-level integration procedures were implemented to allocate the total budget and identify candidate projects. For example, the map in Fig. 6 shows candidate infrastructure improvement projects for year 2000 that are selected using optimization and presented using GIS.

Fig. 7 illustrates the effect of project-level integration on the total annual VMT-WZ throughout the sample network. The

largest annual reduction in VMT-WZ due to project-level integration is about 21,000,000 or 40% (31,300,000 versus 52,100,000) and occurs in the first year of the improvement program (1996). This is due to the large number of projects from all infrastructure components scheduled for 1996. In 1998 and 2000, there is no effect of the project-level integration on VMT-WZ because no adjacent projects are scheduled for these years. Over the 5-year program (1996–2000), project-level integration reduces the total VMT-WZ by about 20% (191,900,000 versus 236,600,000).

Project-level integration is performed using spatial analysis capabilities of GIS. For example, the map shown in Fig. 8 identifies adjacent projects scheduled for implementation in 1996 that should be implemented in a coordinated manner.

SUMMARY AND CONCLUSIONS

A prototype methodology was developed for the management of various highway infrastructure components in a coordinated and comprehensive manner at the network and project implementation levels. The methodology is, in principle, applicable to any number of highway infrastructure components. A GIS-based infrastructure management software system was developed using the concepts of the new integrated methodology. Key features of the new methodology include (1) investment trade-offs (network-level integration); (2) coordinating the implementation of highway infrastructure improvement projects (project-level integration); (3) comprehensive evaluation of highway infrastructure performance (multiple concerns and performance measures); and (4) a single system architecture software that ties together the data and engineering, economic, and spatial analytical procedures.

Applying the methodology to the state highway system in Champaign County in central Illinois showed that integration is beneficial to highway users and agencies. Over a 5-year program (1996–2000), project-level integration reduces the total VMT-WZ by about 20% (191,900,000 versus 236,600,000).

GIS, particularly when using dynamic segmentation, is a powerful tool for (1) integrating, managing, and displaying transportation data; (2) displaying the geographic distribution of improvement projects and deficient features; (3) displaying spatial relationships among performance measures; and (4) spatially analyzing transportation data. Various analytical procedures were integrated with GIS to perform engineering and economical analyses in addition to spatial analysis and visualization.

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