Use of Highway Performance Monitoring System and Bridge Needs and Investment Process for Reporting Conditions, Needs, and Performance Trends

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The estimation of current highway and bridge needs along with the future performance and conditional effects resulting from alternative policies and funding scenarios is an important engineering function. This function was accomplished in North Carolina by using the statewide data base and analytical procedures in the Highway Performance Monitoring System (HPMS). Various study applications of HPMS have been tested to verify and identify performance characteristics, operational statistics, trend lines, and improvement needs over time. HPMS studies were also used to establish investment-performance relationships for each highway functional classification. Collectively, HPMS study results provide a general assessment of the condition, safety, and service components for the North Carolina system of roadways and bridges for any given period of analysis. HPMS study findings also provide an important informational source for highway administrators and decision makers responsible for policy evaluation and improvement program development. For that reason, an HPMS-based administrative status report of performance characteristics is scheduled to be provided annually to North Carolina highway officials.

The use of the Highway Performance Monitoring System (HPMS) to study and analyze North Carolina highway and bridge systems relative to their physical condition, operational characteristics, and needs requirements is described. Study result summaries can give officials an important factual basis for assisting the development of a cost-effective highway improvement program. HPMS roadway analyses have been performed annually since 1980 and have focused on the existing arterial and collector systems. Local roadways were not analyzed because the HPMS data base did not contain samples of local roads and streets.

For more than a decade, HPMS could estimate both current and future roadway needs on existing collector roads and arterial highways as well as the operational effects resulting from different funding levels and scenarios. It could not be used for analyzing and estimating bridge needs, conditions, and funding level effects. Recently, however, FHWA developed the Bridge Needs and Investment Process (BNIP), which can be used to estimate the physical condition, safety, and operation of bridges.

North Carolina was one of seven states selected by FHWA to test the usefulness of BNIP for conducting a statewide bridge system analysis. Provided elsewhere (*1*) are the details for that testing and a description of how BNIP analytical procedures were subsequently used to perform needs and investment analysis of North Carolina bridge data as contained in the National Bridge Inventory (NBI) file. The BNIP study projected bridge conditions and needs from 1988 through 2000. Deficiencies were identified, improvements selected, and improvement costs estimated to maintain the 1988 level of service over the analysis period. Study summaries were constructed for the federal-aid and functional classification systems.

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DATA SOURCES

Data files that serve as input to HPMS and BNIP analytical processes are available from FHWA. State highway agencies and FHWA developed these files jointly and are responsible for their integrity, currency, support, and maintenance (*2,3*).

HPMS

The HPMS inventory files contains two types of data. They are usually referred to as "universe data" and "sample section data."

Universe data define the extent of roadway mileage by functional system and jurisdiction. Over and above the universe data are the sample section data, which are routinely collected on randomly selected sections from the complete arterial and collector highway systems. The sampled highway sections are spatially fixed over time and are homogeneous relative to highway geometric characteristics.

Individual sample sections are selected in accordance with the *Highway Performance Monitoring System Field Manual* and collectively provide the physical and operational data file from which the performance of the highway system can be evaluated (*2*). It is the only data file required as input to the HPMS models. State highway agencies are responsible for the annual update of the HPMS sample section data file (*2*).

BNIP

The NBI file is the primary source of data required by the BNIP. In addition to the NBI data file, the BNIP requires traffic growth rates and *K*-factors from the HPMS in order to predict bridge conditions and deficiencies.

The NBI file contains records for each bridge structure in the United States; it is kept current with data reported biannually by the states. NBI contains all state highway bridges and culverts but no tunnels. More than 16,000 highway structural records are contained in the file for North Carolina, and each record contains data that can be analyzed for structural, functional, and conditional deficiencies. State highway agencies are responsible for the biennial update of the NBI (*3*).

METHODOLOGY

HPMS

Several HPMS models may be used to perform analyses required for a particular highway study. These models have been designed to analyze the sample section data file and establish relationships between various levels of capital investment and the resultant performance of the highway system.

Figure 1 shows a hierarchical listing of HPMS models that have been used in North Carolina for base year and investment-performance analyses. Study references provide for a complete documentation and description of these models, ranging from an overview of their use in yielding performance information to a detailed discussion of their analytical potential as policy planning tools (*4*).

BNIP

The BNIP contains several model types that may be used to perform analyses required for special bridge studies. The BNIP consists of a main computer program (BRIDANAL) and five subprograms (BRIDEDEV, BRIDNEED, BRIDIVST, BRIDDRCS, and BRIDCTAB) that are dynamically called by user-supplied options. Such user options determine the number and sequence in which the subprograms are called.

Base Year Analysis
- ■ Complete Index Analysis
- ■ Multiple Deficiency Analysis
- ■ Impact Analysis

Investment/Performance Analyses
- ■ Investment Level Analysis
  - ▲ Needs Analysis
  - ▲ Investment Analysis
- ■ Funding Period Analysis
  - ▲ Needs Analysis
  - ▲ Investment Analysis
- ■ Summary Analyses
  - ▲ Composite Index Analysis
  - ▲ Deferred Cost Analysis
  - ▲ Multiple Deficiency Analysis
  - ▲ Impact Analysis

FIGURE 1 HPMS analytical process hierarchy (*4*).

The subprogram BRIDEDEV must be called initially to accept input records from the NBI file and create the master bridge file called BRIDMAST. Other BNIP subprograms can analyze BRIDMAST for a particular time period and output a systemwide estimate of highway bridge needs along with the investment level required to address those needs.

Specific information relative to the function and philosophy of the BNIP is explained elsewhere (*5*), with an executive summary for that process (*6*).

DEFINITIONS

The performance of a highway system can be defined in terms of the safety, economy, and efficiency of the flow patterns resulting from the movement of people and goods on the system. A measure of highway performance is defined to be an indicator of highway service derived from the condition, usage, operation, and physical characteristics at a particular point in time (i.e., past, present, or future).

Important examples of highway performance measures are speed, volume-to-capacity ratios, pavement condition, roadway cross sections and alignments, system mileage and travel, accidents, and user costs.

EXTENT AND USE OF NORTH CAROLINA HIGHWAY SYSTEM

As stated previously, the basic function of any highway system is to provide for the safe and effective movement of people and goods. It follows, then, that a highway system must be planned and designed with that function in mind. Several measures of effectiveness (MOE) including safety, convenience, efficiency, economy, mobility, and accessibility should be monitored closely to determine if the system is optimally serving its purpose. Such indicators are now being monitored conveniently on the North Carolina highways by the HPMS.

Mileage and Travel

HPMS estimates of mileage and travel on North Carolina's 1989 highway system are presented in Table 1. Data in this table are stratified by the federal functional classification system (*7*); they show that there were 149,266,000 daily vehicle miles traveled (DVMT) distributed over 94,619 highway-mi. It should be noted that the distribution of travel is not directly proportional to mileage. For example, Table 1 shows that rural highway mileage is nearly 80 percent of the statewide total but only 60.3 percent of the total travel.

The percentage of rural and urban travel is expected to change in the next few years. It is anticipated that urban travel will increase and rural travel will decrease. These changes will be due primarily to the redefinition of rural to urban areas in the 1990 census. The HPMS is useful in tracking such jurisdictional changes in mileage and travel over time.

Performance Relative to Condition, Safety, and Service

Performance of the North Carolina highway system is related to many physical and operational characteristics. Some of

TABLE 1 North Carolina Highway System Mileage and Travel in 1989

Functional Classification	Miles	% of Total Miles	Daily Vehicle Miles Traveled (DVMT)	% of Total DVMT
Rural				
INTERSTATE	621	0.7	16,297,000	10.9
OPA	2,061	2.2	15,881,000	10.6
MA	2,047	2.2	8,985,000	6.0
MAJ COLL	10,473	11.1	29,107,000	19.5
MIN COLL	9,058	9.5	10,191,000	6.8
LOCAL	51,140	54.0	9,606,000	6.5
Subtotal	75,400	79.7	90,067,000	60.3
Urban				
INTERSTATE	226	0.2	9,655,000	6.5
OF&E	213	0.2	6,198,000	4.2
OPA	1,732	1.8	24,338,000	16.3
MA	2,193	2.3	14,443,000	9.7
MC	1,370	1.5	3,224,000	2.1
LOCAL	13,485	14.3	1,341,000	0.9
Subtotal	19,219	20.3	59,199,000	39.7
Total	**94,619**	**100.0**	**149,266,000**	**100.0**

these characteristics are relatively fixed (e.g., lane width and alignment), and some can change rapidly (e.g., pavement condition). HPMS data that can be used to define performance are organized into the categories of condition, safety, and service. Condition data contain information on pavement type, pavement condition, and drainage adequacy. Safety data contain information on the adequacy of roadway cross section (i.e., lane, shoulder, and median widths) and alignment. Service data contain information on volume-capacity ratios and access control.

The HPMS analytical models provide information on highway system performance by measuring and reflecting changes in the system condition, safety, and service performance indicators that over time provide the factual basis for trend-line analysis.

Needs Estimate

The three interrelated variables of present conditions, future travel, and investment levels will determine future needs and conditions on the existing arterial highways and collector roads. These variables can be used in HPMS analyses as a basis for establishing investment-performance relationships. The HPMS user can tailor analyses for the evaluation of specific policies and situations by selecting appropriate minimum tolerable conditions (MTCs), construction improvement types, design standards, travel projections, and funding strategies (*5*).

Several types of analyses and studies have been performed on the North Carolina highway system; they include the estimation of needs, development of investment-performance relationships, and determination of future cost of travel as a function of investment.

Needs Determination

HPMS defines needs on the existing arterial highways and collector roads in terms of the funding level required to maintain a highway system equal to or above MTCs. Dropping below the chosen MTC values implies a state of deficiency. The level of funding necessary to correct all deficiencies as they occur is called full needs funding. The HPMS needs model determines full needs funding by first identifying deficiencies and then simulating the type and cost of capital improvements required to correct those deficiencies. Such funding level estimates are objectively based on a cost to maintain the highway system level of performance defined by MTC values.

TABLE 2 Other Principal Arterial Needs (1989–1998)

	Backlog (1989) Miles	Backlog (1989) Cost	Accruing (1990-98) Miles	Accruing (1990-98) Cost
Reconstruct to Freeway	107	281,904	300	856,357
Reconstruct w/more Lanes	0	0	0	0
Reconstruct w/wider Lanes	52	53,266	13	16,613
Pavement Reconstruction	1	417	0	0
Pavement Reconstruct w/Align	1	270	0	0
Major Widening(add lanes)	24	48,908	27	48,217
Minor Widening	12	6,225	0	0
Resurfacing w/Shoulder Improv.	47	12236	323	75593
Resurfacing	41	8879	327	73422
Resurf w/ Align & Shoulder Improv.	3	2027	76	62194
Resurfacing w/Align Improv.	2	1344	22	25424
Total	**289**	**415,476**	**1,087**	**1,157,820**

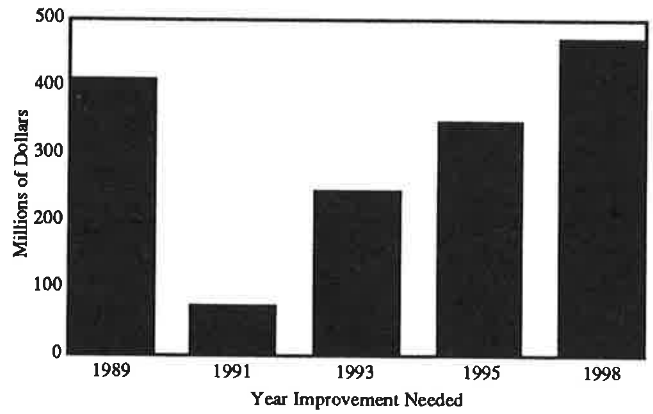

FIGURE 2 Rural OPA needs (1989–1998).

The needs model requires three major types of look-up tables. These tables contain MTC values, design standards, and costs for right-of-way and construction. System default values and standards are national averages. System default values are used for the North Carolina study.

An example of the output of an HPMS roadway needs study is presented in Table 2 and graphically shown in Figure 2. The costs shown are in 1989 dollars. It should be noted that HPMS needs assessment is accomplished without regard to revenue availability, user cost distribution, jurisdictional responsibility, or other subjective factors that actually determine highway program direction and investment levels. It should also be noted that the assessment of needs is the first step to be accomplished in investment-performance analyses.

Development of Investment-Performance Relationships

Highway investment-performance relationships output by the HPMS analytical procedure are based on theoretical and empirical research conducted by federal and state governments, AASHTO, and several leading universities (*4*). These relationships permit modeling of future highway system performance when given investment patterns and levels, future travel estimates, and applicable design standards. Such investment-performance models can be developed for each functional class system from the HPMS investment-level analyses.

The two types of investment-performance analyses that HPMS can accomplish are known as investment level and funding period. Both types were used in the North Carolina study. Investment-level analysis was used to determine total highway needs on the existing arterial and collector road systems and to estimate base year conditions and vehicle performance impacts. Funding-period analysis was used to forecast target year conditions and vehicle performance impacts.

It should be noted that either base or target year conditions can be analyzed by the impact model but that target year conditions and impacts can be analyzed only during a funding-period analysis (*4*).

The HPMS investment-level model simulates seven funding levels ranging from full needs investment to no investment at all. The full needs investment (or 100 percent funding) level simulates highway system effects for all improvements selected by the needs model. In terms of full needs investment, the next six funding levels simulated have the respective percentages of 80, 70, 60, 40, 10, and 0. The lower funding levels simulate only a portion of total required improvements, depending on the relative amounts of funds available. The zero funding level simulates the effect of making no capital improvements during the analysis period, which can be a maximum of 20 years.

After completion of the investment-performance analysis, the HPMS models output seven coordinate points for each of the safety, service, condition, and composite curves. The shapes of these curves are discretely and uniquely determined by those point sets.

Investment-performance graphs are developed by plotting the composite index values versus the dollars allocated for each of the funding levels (i.e., 100, 80, 70, 60, 40, 10, and 0 percent). Such graphs are being used by the North Carolina Department of Transportation (NCDOT) to answer many highway programming and budgeting questions. For example, management may desire an estimate of how anticipated funding changes could affect the safety, service, condition, and composite performance indicators over time. The investment-performance models can be used to answer that question.

Investment-performance models have been prepared for each functional classification in the North Carolina highway system and will serve as the basis for evaluating the future impact of different funding strategies and improvement programs.

Highway User Costs as Function of Highway Performance

Changes in pavement conditions, traffic congestion levels, vehicle operating characteristics, and roadway geometry affect the costs of using the North Carolina highway system. Costs for using that system can be estimated from data output by the HPMS simulation procedures for vehicular operation (*8*). The procedures simulate the way that highway conditions affect vehicle performance.

HPMS simulation results are expressed as vehicle performance indicators, which include speed, fuel consumption, operating costs, emissions, and accident rates. With the exception of accident rates, all of the performance measures are summarized by vehicle type.

Vehicle performance indicators provide a flexible means by which cost of travel estimates can be compared for different highway program, policy, or investment strategy scenarios. For example, vehicle performance indicators can be converted to user costs units and (a) compared between base (or existing) and target (or forecast) years to obtain the effects of a single program over time or (b) compared at the target year with alternative improvement programs to obtain relative cost of travel differences.

For comparison purposes, the HPMS analytical procedures produce highway travel cost components for both base and target years. Costs components reported by these procedures are average travel speed, accidents, and operating costs. The respective measurement units for these components are miles per hour, accidents per 100 million vehicle-mi traveled (VMT), and dollars per 1,000 VMT. These units can be equated to the single unit of money and subsequently combined to yield an economic basis for comparing alternative highway improvement programs.

The task of assigning money values to the variables of travel time or accidental death and injury is usually very difficult and subjective in nature. This task must be accomplished, however, before conducting any analysis designed to yield total user cost differences among highway improvement program alternatives.

Future Costs of Travel as Function of Investment

From a cost/benefit perspective, the most interesting and useful study using the HPMS had the objective of estimating the future cost of travel on the North Carolina highway system as a function of funding level. The study objective was accomplished in two steps.

First, the vehicle performance measures were determined by simulation for the target year for each of three funding levels. The second step involved calculating the total cost of travel based on the vehicle performance measures as determined in the first step. The methodology used to calculate those costs is outlined in the appendix cited elsewhere (*9*); the study results are also reported elsewhere (*8*).

NORTH CAROLINA HIGHWAY BRIDGE CONDITIONS, NEEDS, AND INVESTMENT REQUIREMENTS

The BNIP was conceptually designed as an analytical tool that could assess the operation, safety, and physical condition of highway bridges at the state or federal level. North Carolina was one of several states chosen to field-test and evaluate the analytical potential for that system.

Computer runs thoroughly tested each type of analysis including base year, full needs, and investment level. Each testing scenario was developed by selecting specific user options relative to analysis type, investment levels, design standards, and MTCs. User control statements may be used to specify a particular type of analysis and optionally override system default values (*5*).

BNIP testing results were compared with output data from the North Carolina Bridge Management System (*10*). The bridge needs and condition trends output by the two systems were very similar.

Evaluation of the testing showed that the BNIP provides a powerful analytical method for determining existing or future highway structure conditions, estimating backlog needs, and predicting investment requirements on a statewide basis. The analytical results can be output for either the federal-aid or the federal functional systems. Therefore, for a given period of analysis, bridge conditions for the base year can be compared to those in the target year to provide an estimate of conditional effects for different funding levels. In addition, BNIP summary tables can be conveniently used for trend-line analysis.

The versatility and usefulness of BNIP for determining bridge needs and condition trends on the highway system was clearly demonstrated by the study. Subsequently, it was decided to use the system to perform a statewide structure investment analysis and study to determine the annual funding required to maintain the 1988 base structure conditions through the year 2000. The findings, conclusions, and recommendations from that study are given in another paper (*1*).

TABLE 3 1988 Bridge Conditions on North Carolina Highway System

Federal-Aid System

	Number of Bridges				Condition
Classification	STR DEF	FUN DEF	FUN ADE	Total	Index
Interstate	37	199	560	796	7.3
Primary	113	195	1,355	1663	7.0
Secondary	507	386	1,314	2,207	6.5
Fed-Aid Urban	133	132	604	869	6.7
Non Fed-Aid	3,075	4,080	3,274	10,429	6.1
Grand Total	**3,865**	**4,992**	**7,107**	**15,964**	**6.3**

Federal Functional Classification System

	Number of Bridges				Condition
Rural	STR DEF	FUN DEF	FUN ADE	Total	Index
Interstate	11	109	328	448	7.2
Prin.Arterial	25	61	656	742	7.2
Maj. Arterial	49	66	309	424	6.7
Maj. Collector	523	397	1,338	2,258	6.5
Min. Collector	870	327	667	1,864	6.2
Local	1,994	3,461	1,983	7,438	6.0
Total	3,472	4,421	5,281	13,174	6.2

	Number of Bridges				Condition
Urban	STR DEF	FUN DEF	FUN ADE	Total	Index
Interstate	26	90	230	346	7.3
Free/Expressway	27	63	213	303	7.1
Prin. Arterial	58	76	538	672	6.9
Min. Arterial	101	105	320	526	6.6
Collector	41	30	97	168	6.6
Local	140	207	428	775	6.3
Total	393	571	1,826	2,790	6.7
Grand Total	**3,865**	**4,992**	**7,107**	**15,964**	**N/A**

Condition of North Carolina Highway Bridges in 1988

A BNIP analysis was used to determine highway bridge conditions that existed in the 1988 inventory year. The subprogram BRIDNEED first determined the number of structural, functional, and conditional deficiencies from the input NBI file. BRIDNEED summarized the frequency of condition values for the deck, superstructure, substructure, culverts, retaining walls, and safe load capacity. Summaries of the number of structurally deficient bridges that are open to all traffic, load- or speed-posted, or closed to traffic are also provided by BRIDNEED. The subprogram BRIDCTAB tabulated the structure condition summary tables for either the federal-aid or the functional classification systems. Results of the 1988 BNIP base year analysis of conditions and deficiencies for North Carolina bridges are presented in Table 3.

North Carolina Highway Bridge Needs from 1988 to 2000

BNIP will determine future bridge needs up to 20 years. After identifying the structural, functional, or conditional deficiencies by use of the MTC method, other subprogram models will select an improvement type that is dependent on the deficiency category. For example, if a bridge is structurally deficient, then the improvement type selected to correct that deficiency is "replacement." If a bridge is functionally deficient, the improvement type selected may be "widening" or "replacement." The bridge improvement type for a conditional deficiency is "rehabilitation."

After selecting the improvement type, BRIDNEED estimates improvement cost, assuming unlimited funding. Finally, the model determines future physical conditions and operational characteristics as if the simulated structural improvement were to be made. The results from the analysis of bridge needs for the North Carolina highway system from 1988 to 2000 are presented in Table 4.

North Carolina Highway Bridge Investment Analysis from 1988 to 2000

A BNIP investment analysis can be used to determine the funding level required to simulate improvements (i.e., as identified from the needs analysis) necessary to accomplish a future level of service for the highway bridge system.

The subprogram BRIDIVST will evaluate the future physical condition and operational effects that different funding levels would have on highway bridge structures. BRIDIVST accomplishes such an evaluation by building on output from the BRIDNEED model and priority ranking the improvement as a function of constrained investment levels specified by the engineer/user. Based on user funding specifications and time horizon, the subprogram BRIDIVST will produce future bridge condition values summarized by either the federal-aid or the functional classification system.

Investment analyses have been performed to determine an annual funding level that would maintain the 1988 bridge conditions until 2000. Four analyses were performed over that period using the respective yearly investment levels of $35 million, $55 million, $85 million, and $110 million. Condition values resulting from each of those investment levels are graphically illustrated in Figure 3.

TABLE 4 Number of Deficient Bridges and Costs by Improvement Type and Year of Deficiency (In Millions of Dollars)

	Backlog		1989-1993		1994-2000		Total	
	No. of Bridges	Cost	No. of Bridges	Cost	No. of Bridges	Cost	No. of Bridges	Cost
RURAL								
Rehabilitation	3	0	31	4	278	70	312	75
Widening	398	30	14	2	17	2	429	34
Replacement	7,331	1,112	20	7	149	129	7,500	1,248
URBAN								
Rehabilitation	8	1	23	8	326	97	357	104
Widening	45	5	1	1	2	0	48	6
Replacement	749	280	13	8	101	59	863	347
Total	**8,534**	**1,428**	**102**	**29**	**873**	**357**	**9,509**	**1,814**

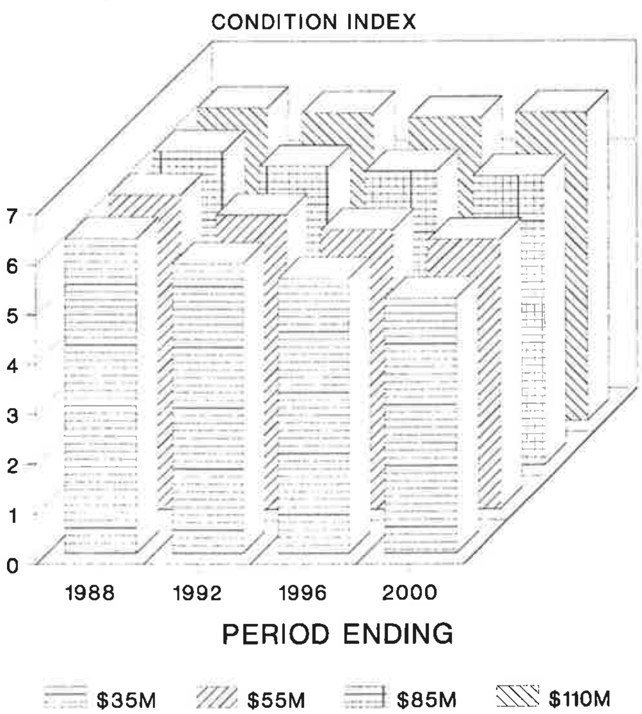

FIGURE 3 Bridge condition index as function of funding level (1988–2000).

ANTICIPATED USE OF HPMS DATA AND ANALYSIS PROGRAMS

The NCDOT business plan completed in 1990 recommended that the department produce a periodically updated report on statewide transportation needs. It also recommended that a committee be formed of representatives at the working level, drawn from participating groups, to make decisions on report format, report content, schedule, and participating group responsibilities. The committee would make decisions on modal and service coverage, standardization of forms and time periods covered, technical problems with information and data resources, and coordination between responsible groups.

In March 1991 NCDOT staff met to discuss the production of the annual report. Major conclusions from this meeting were as follows:

1. The annual report should be initiated as a report on the status of the highway system.
2. The HPMS analytical package had been run on the HPMS data set for each year beginning with 1982. This would provide a means for selecting key data to be portrayed in the report. The first report will illustrate what has been happening with the highway system during the 1982–1991 period.
3. Data from the bridge analytical package would also be incorporated into the report.
4. Data to be presented should be easily understood by lay persons.
5. The report should be short.
6. The Statewide Planning Group, Planning and Environmental Branch will have responsibility for producing the report. The research unit of the Planning and Environmental Branch will assist in developing the first report.
7. The first report should be completed by December 1991.

SUMMARY

There is a national recognition of the necessity to assess highway and bridge systems periodically relative to their extent, physical condition, efficiency, economy, and safety. In addition to such a general assessment, it is sometimes desirable to evaluate the effects that various highway programs and policies may have on those systems.

The HPMS analytical process has been used to assess needs on the existing arterial highways and collector road system and evaluate the effects that different levels of investment would have on the highway system for particular time horizons. However, bridges could not be analyzed in an analogous manner and provided some of the motivation for developing the BNIP.

The NCDOT was among the first to test the analytical capability of BNIP and evaluate its potential for performing bridge needs assessment and for predicting bridge conditional and operational characteristics as a function of constrained funding. Testing and evaluation showed that BNIP could provide a powerful yet convenient method for analyzing bridge conditions, operational characteristics, and bridge needs on a statewide basis.

The proper management of highway systems requires that administrators have current estimates of system conditions, performance, and needs. The decision maker should also be given estimates of the impact of different investment levels and strategies on the performance of roadways and bridges over time. It has been concluded that these two systems can provide an informational support basis to help management evaluate policy, analyze need, develop improvement programs, and allocate money to maintain optimally the North Carolina highway and bridge systems.

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