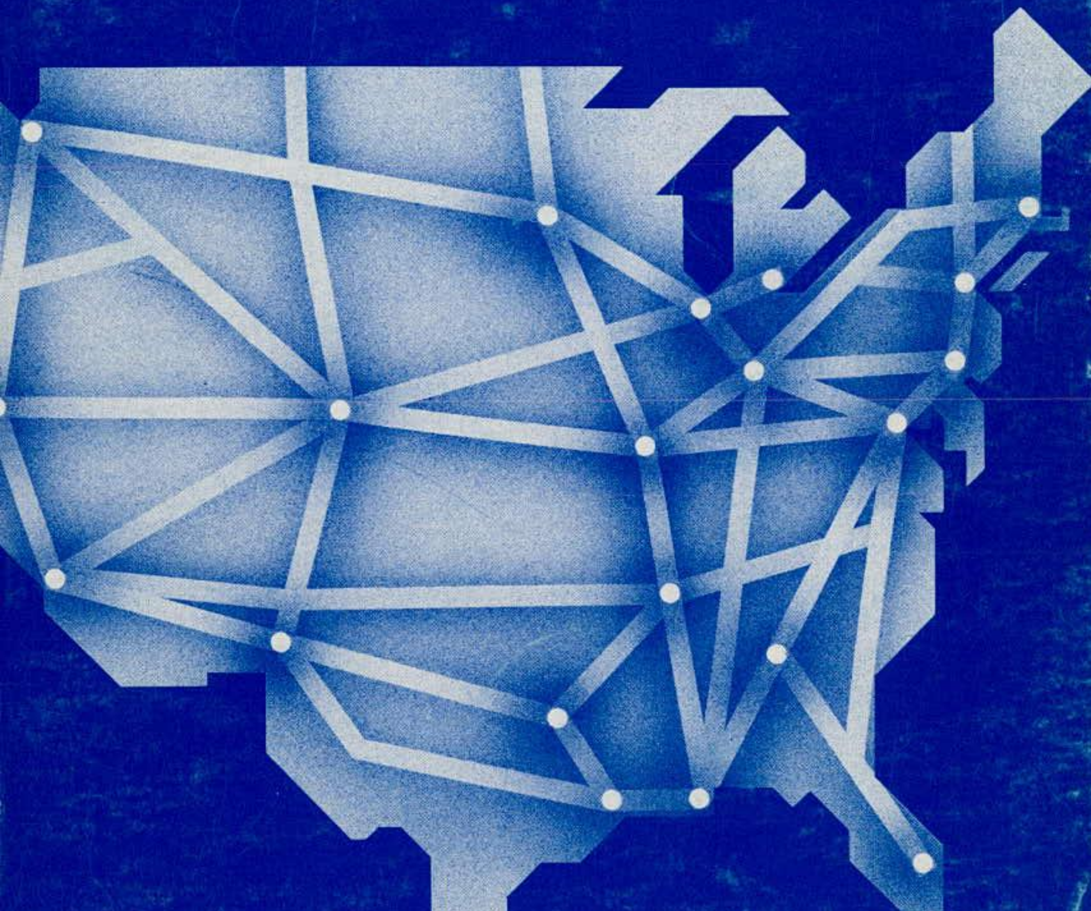
Special Report 202

America's Highways
Accelerating the Search for Innovation



TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

Special Report 202

America's Highways
Accelerating the Search for Innovation

Strategic Transportation Research Study: Highways

TRANSPORTATION RESEARCH BOARD
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NOTICE
The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

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.

The views expressed in this report are those of the authors and do not necessarily reflect the views of the committee, the Transportation Research Board, the National Research Council, or the sponsors of the project.

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Preface

The condition of America's highways is receiving intensive public and legislative attention. Most of this attention appropriately focuses on the scope of public programs that would be required to rebuild or replace these facilities or on the financing to support these programs. Nevertheless, financing alone cannot solve the problems of the nation's highways. Study after study has shown that needs far exceed the available resources. Innovation is the key to bridging this gap, and careful targeting of research can accelerate the search for innovation.

The Federal Highway Administration, in recognition of this need for innovation, commissioned the Transportation Research Board to study this problem, define the needs for research, and devise a plan for the implementation of a new strategic highway research program. This study focuses exclusively on public highway facilities. It is the first of a series of studies entitled the *Strategic Transportation Research Study* (STRS) that will examine transportation research from a new perspective. These studies will assess and recommend research priorities for various modes of transportation based on expected payoffs, prospects for success, and other concerns unique to each mode.

To provide a new perspective, this study approaches highway research from the vantage point of a unified industry, instead of by the present structure that involves every state, city, county, and toll highway authority, and thousands of contractors and suppliers.

The study describes the nature of this structure (Chapter 1) and examines current highway research programs (Chapter 2). From these reviews a strategy emerges for identifying neglected problems that might not be overlooked if highway responsibilities were more concentrated (Chapter 3). Using this strategy, the study identifies and defines six priority areas where concerted research could produce innovations that would greatly increase the productivity and safety of the nation's highways (Chapters 4–9). The study concludes with an examination of alternative institutional arrangements for managing research in these areas (Chapter 10) and a set of final recommendations (Chapter 11).

The Committee that performed this study was charged with developing a 5-year plan for strategic highway research. The Committee soon recognized that the proposed 5-year program would require additional start-up time and in the instance of long-term pavement testing a continuation well beyond the 5-year term. Nonetheless, the 5-year concept is considered to be an important feature of this strategic program. It defines the need for a time-specific, concentrated, short-term, and results-oriented research effort aimed at closing specific technological gaps that have impeded the effective advancement of the highway program.

The Committee included state transportation officials, corporate research directors, professors with expertise in specific highway research areas, and local officials, as well as liaison members from the federal government and the Congress. Over a period of about a year and a half, the Committee examined a diverse range of highway research activities and concluded that a unique opportunity exists to undertake a new approach in highway research by focusing on a limited number of major initiatives in a few critical areas. The program proposed in this report represents a significant departure from the past. The research plan envisions that there will be considerable transfer of information among the six research areas. This will require continuing coordination, cooperation, and feedback throughout the life of the program. It responds to critical national needs, has the potential for high payoffs, and has the necessary support of the important highway constituency groups. It has been designed to be practical and responsive to real problems.

The approach, however, goes beyond simple, immediate, pragmatic considerations. The Committee calls for the development of an innovative approach to highway research that will result in new techniques, new technologies, and new processes. Pragmatism and innovation are not incompatible, and the Committee recognizes both the opportunity and responsibility to understand the fundamental processes that affect the nation's highway system, both directly and indirectly. It is equally important to involve new participants in all aspects of the STRS program, to rebuild areas of neglected technical competence, to explore emerging technologies that will have an impact on the highway industry in the future, and to present new and different perspectives.

The committee has concentrated its major attention on the specific tasks to be undertaken and has reviewed only briefly the nature of the organization that might manage the STRS program. Although selection of the appropriate managing organization may be the most important decision affecting the success of the overall program, the Committee does not believe that its role is to recommend any specific organization. Rather, that decision should be made at a later time following careful consideration of all the issues involved. To aid in this decision, some guidelines and possible institutional arrangements for such an organization have been provided in Chapter 10. Of particular note, the STRS organization and its director should be competent in research and technical management, understand research deployment strategies, and envision how innovative approaches can be introduced into a large-scale research effort. A delicate balance must be maintained by the organization to satisfy the needs of the highway constituency and at the same time ensure that innovation, risk, flexibility, and new approaches are included in the process.

The momentum that has built throughout the highway industry during the course of the STRS study represents an important breakthrough for the highway system. In spite of its ambitious scope, the program recommended here focuses primarily on highway materials. There are numerous other areas in the highway field where research is vitally needed, and the Committee supports continuation of research initiatives in those areas. In particular, the planning of highway facilities and the management of the highway system continue to pose many questions that research can answer productively. The Committee is convinced that the STRS program, which concentrates on a few crucial problems that are not easily addressed by existing processes, must not divert attention from other valuable ongoing highway research efforts on management, financing, planning, traffic operations, and many other aspects of the nation's highway system. Not only should research in these areas continue, but it is recognized that the ultimate success of the STRS program is dependent on the ability of management, planning, and other functions to adjust to innovative materials and processes.

Safety has been emphasized as a key criterion in this study. Even so, it is clear that safety is of such paramount concern that it may warrant a separate, STRS-like reassessment of research priorities. Perhaps a future volume of the STRS series will be devoted to this important research area.

The Committee anticipates that as the proposed program of research is completed, other organizatons and individuals will follow its recommendations and implement its findings. Throughout the program, international collaboration will be necessary to exploit the technology being developed outside the United States and to share the results of this research program with the international community. In the end the success of the STRS program will depend on the extent to which innovation is transferred into practice. In this context, the Committee recognizes that its proposals are only one part of successful implementation. It seems certain that the widespread and effective application of innovative materials and techniques will also require changes in training, procurement practices, and other phases of implementation that cannot be thoroughly addressed until the findings of the proposed research are known.

This report represents the collective efforts of an effective and industrious steering committee, Transportation Research Board staff, consultants, workshop participants, and a host of highway agency and industry representatives who provided valuable data, ideas, and assistance to the study. The work was performed with the benefit of continuing personal guidance from both Dr. Thomas D. Larson, Secretary of Transportation for the Commonwealth of Pennsylvania, who served as committee chairman, and Thomas B. Deen, Executive Director of the Transportation Research Board.

The study was performed under the supervision of Dr. Damian J. Kulash, Assistant Director, and Robert E. Skinner, Jr., Program Manager, Special Projects Division of TRB. Valuable assistance in the preparation of the report was provided by Gary Byrd with contributions from Ronald W. Hudson, David W. Schoppert, Alan E. Pisarski, Ronald Duych, and Margaret Heckard.

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INTRODUCTION

At present state transportation agencies have a unique opportunity to make major improvements in the ways they build, maintain, and operate highways. Because of the infrastructure crisis, the public has awakened to its stake in the highway network. Over the years Americans have invested an astronomical $1 trillion in their highway system and are just beginning to realize that without a massive infusion of funds for rehabilitation and maintenance, the system will deteriorate rapidly. But merely replacing failing facilities will not solve the problem in the long run; better products and processes are also needed, and the research to create them is long overdue.

Research for improved highways has been seriously neglected by all measures. Relative to the size of the nation's highway expenditures, spending on highway research has fallen from 0.25 percent in 1965 to 0.15 percent in 1982. This 0.15 percent is far smaller than the research commitment of virtually all other industries: high-technology industries, such as semi-conductors or aerospace, spend 40 times as much on research; medium-technology industries such as the automobile manufacturing or chemical industries spend more than 20 times as much per dollar of sales. Even low-technology industries such as rubber, paper, and steel outspend highways by a factor of eight. Since 1973 state and federal governments have cut their highway research spending in half.

Why has not a system so crucial to everyday life, so large (4 million miles), and so expensive ($1 trillion) been supported all along by large-scale, long-term research? Chiefly because of the extreme fragmentation of the transportation industry. The U.S. highway system's operation is divided among thousands of federal, state, county, city, and private organizations.

In addition, these public agencies maintain complex contract arrangements with the private organizations that usually build or rehabilitate roads. Even routine maintenance is sometimes contracted out to private firms. Highway construction firms buy many materials locally. Both political pressure to favor local suppliers and the high cost of transporting bulky, low-value, construction materials dictate this practice. Thus an army of small, local suppliers supports many equally small, local construction firms.

This structure impedes innovation because it produces a situation in which no one organization has the resources or the incentive to undertake major research to increase facility life, reduce costs, or improve performance. Highway agencies face budgetary pressures and electoral priorities that favor short-term, highly visible projects. Further, high turnover in top management positions forces top officials to focus on visible current issues rather than on long-term functions such as research.

Despite this neglect thousands of improvements in the durability and safety of highway products have been made. For example, highway safety has been enhanced by breakaway sign posts, impact attenuators, and Jersey barriers. Increasing the life of bridge decks by the use of epoxy-coated reinforcing bars, and thousands of other product innovations make today's highways dramatically different from those of 50 years ago. Nevertheless, much more progress could be made in improving the nation's highways by devoting sufficient attention—both financial and managerial—to needed research.

A STRATEGY FOR SETTING PRIORITIES

The limited research in the highway area is largely directed at developing incremental solutions to current local problems. This is logical in view of the diversity of climate, soils, topographies, local paving materials, and traffic loadings throughout different states and counties. It is also top priority for the limited research funding available. The downward trend in research funding has caused the highway industry to overlook or neglect several of the big problems facing the industry as a whole. Research designed to fill these technological gaps must meet many stringent tests. This study outlines a strategy for screening potential research areas to identify the most promising for a national program. Specifically, this strategy involves answering the nine following questions:

1. *Will the research yield big payoffs if successful?*

Many areas of feasible highway research will potentially deliver payoffs far in excess of the necessary original investments. For example, even if research on better asphalt paving materials yielded only a 1 percent reduction in the cost of pavements, this reduction would save $100 million a year—far in excess of the total of $70 million or so now spent on research for highways. Much greater savings would probably result in view of the frequency of premature pavement failures and the ever greater demands that increased traffic and weights of vehicles make on pavements.

2. *Is the research area currently neglected?*

When measured against potential payoffs, virtually all highway research is neglected. However, some categories are funded much more inadequately than others. Research on asphaltic materials, for example, represents only a minuscule fraction of highway research, even though more than 93 percent of all paved roads and streets are surfaced with paving mixtures or surface treatments containing asphalt.

3. *Will the project deal with important research previously hampered by institutional or organizational barriers?*

Improvements in highway products and processes lag when procurement procedures (specifications and low bids) do not encourage the purchase of better products and processes. The profitability of proprietary products, the emphasis on life-cycle costs within procurement processes, and the pressure to buy local materials and services must be considered in choosing realistic research objectives.

4. *Can the research findings be used?*

Research often fails to change practice because of limited understanding, organizational inertia, inflexible standards, preoccupation with first costs, mistrust of change, or a desire to perpetuate jobs. A research program designed without taking into account such obstacles will fail. Nevertheless, determining what is achievable is probably the most difficult, albeit the most crucial, judgment in the entire research process.

Training requirements, organizational changes, investment in equipment, cash flow requirements, personnel implications, and legal liabilities of new approaches can make or break the acceptance of research findings.

Technical research personnel are not necessarily in a position to make these judgments, and, similarly, administrators and political leaders may not be fully aware of the technological options that might be developed. Both viewpoints are needed to identify promising research topics.

5. *Does the research require a large-scale effort?*

Most of the $70 to $75 million now spent on highway research is parceled out in problem-specific contracts of $30,000 to $300,000. Such small-scale efforts can be effective in addressing clear, well-defined problems. However, highway research funds are so broadly distributed that no single organization can attack the major problems that plague the industry.

Pavement performance, in particular, requires long-term research because of the long design life of pavements. The careful evaluation of paving materials and techniques under long-term field conditions could substantially reduce the life-cycle costs of maintenance and construction. Increasing fundamental knowledge of how pavements perform under diverse circumstances and using this knowledge to improve those pavements will require a substantial commitment of time, funds, and research direction.

6. *Does the research require an integrated or national approach?*

Existing highway research procedures are likely to overlook processes such as highway construction that include a sequence of distinctly autonomous steps, each managed by a different organization or unit. Because more than one organization is involved at each stage, none is able to evaluate and control the other stages. A prime example is the construction of an asphaltic pavement, which involves many major steps from mining crude oil to constructing the pavement and opening the road to traffic. The various links in the construction chain are managed by oil companies, refineries, batching plants, aggregate producers, construction companies, and federal, state, and local highway departments. Each depends on the work of the others, but none is able to control the others. However, research on improved binding materials could lead to products and specifications that stimulate more efficient use of resources by all of the organizations involved.

7. *Does the research respond to new and potential changes in national policy?*

Because of the immense variety in local materials, building conditions, and topographic features, the strong problem-solving research capability of state agencies is essential. At the same time this decentralized research structure can lead to duplication, particularly if shifts in national policy create new operational issues simultaneously in all states and counties (e.g. the 55-mph national speed limit or increases in truck size and weight limits). The most efficient and timely response to such changes is to create a coordinated research effort that can immediately address the operational implications of the policy change in all of the states.

8. *Does the research use or respond to other technological changes?*

Technological changes in highway vehicles, communications, materials, and other sciences bring new opportunities and new challenges to all states and counties. If research to tap this potential is too fragmented, it may be incremental and duplicative. Also, not all organizations have the resources or skills to monitor properly new developments in technology. Even more stable technologies, such as asphalt, are subject to far-reaching changes when shifts in petroleum distribution and refining processes occur. Various new technologies, such as miniaturized electronics generated in the space program, may have many more highway applications than are currently being explored.

9. *Will the research affect safety or the environment significantly?*

In addition to major cost savings, research also can help to save some of the 46,000 lives lost each year on the roads and to prevent the suffering of many of the more than 3 million persons injured. For example, research to prevent deterioration of bridge decks could reduce the hazard now posed by potholes and pavement irregularities on bridges and other places where there are no obstruction-free maneuvering zones.

A STRATEGIC RESEARCH PROGRAM

On the basis of the selection strategy discussed in the foregoing sections, six priority areas have emerged where it is believed that a concerted research effort can produce major innovations that will increase the productivity and safety of the nation's highway system. A program focused on these research areas could substantially alleviate the biggest, most pervasive problems now faced by the highway industry. Such a research program could be supported if states would allocate one-quarter of 1 percent of their federal-aid highway funds. The six components of this program are sketched below and organizational and financial implications are addressed in the closing section.

Asphalt

Asphalt use dominates the nation's highway industry. Highway agencies spend $10 billion a year on asphalt pavements—10 times as much as the nation spends on AMTRAK and 6 times as much as is spent on the entire intercity bus industry. Despite the huge sums it spends on asphalt, the highway industry has done very little research to improve this basic material or control its quality. As a result, the highway industry still suffers from premature, costly, and embarrassing pavement failures. Variations in asphalt cements caused by post-embargo shifts in sources of crude oil and new refining processes may have added to this problem. Pavement failures are also caused by substandard construction, faulty mixing, poor quality aggregates, inadequate pavement design, and other factors.

Stable, predictable, clearly specified asphalt cements could greatly reduce pavement failures. Even poorly constructed pavements could last longer if asphalt performance were better understood and if the specifications for this material were developed to compensate for possible failings at other steps of the paving process. Developing improved asphaltic products and specifications will require a closely coordinated research program to

1. Define properties of different asphalts,
2. Improve testing and measuring systems,
3. Determine relationships between asphalt cement and pavement performance,
4. Develop improved asphalt binders, and
5. Validate performance in the field.

The highway industry's use of asphalt is huge and growing. Research on this key product could result in substantial cost savings. But even very modest gains—such as a 1 percent saving in the cost of asphalt paving—would save the industry $100 million per year and more than pay for the research effort in less than 1 year. The five research tasks listed above would cost about $10 million per year for 5 years.

Long-Term Pavement Performance

The nation will spend about $400 billion replacing and rehabilitating pavements before the end of the century. Not only will the Interstate and primary systems need repair but also state, county, and local highways and city streets will require massive investments in pavement. Despite these immense expenditures, no comprehensive research on long-term pavement performance has been conducted since the AASHO Road Test—a large-scale field test completed in 1960. This was an accelerated test done under one set of climate and soil conditions. Fundamental questions concerning climatic effects, maintenance practices, long-term load effects, materials variations, and construction practices remain unanswered.

Answers cannot be found without intensive study of pavements under a large number of actual field conditions over many years. Such a large-scale research program (roughly $10 million per year) over such a long period (approximately 20 years) cannot be undertaken by any existing organization. It requires an unprecedented, long-term commitment that is largely incompatible with the short-run terms of public office and intense budgetary pressures. Nevertheless, the costs represent only about one one-thousandth of what the nation will spend on pavements during the 20 years that the field test would be conducted, and many early results could be obtained in time to reshape future pavement designs and expenditures. In additon, the pavement performance study could help cut the costs that motorists incur from driving on deteriorated highways. It could also help public officials make more informed decisions on axle load limits, cost allocations among various classes of highway vehicles, and restrictions on truck dimensions and configurations.

Maintenance Cost-Effectiveness

Maintaining the nation's 4-million-mile state and local road network currently requires more than one-third of the total highway budget, and the share of highway resources going to maintenance is growing. Despite this spending, continued deterioration of the nation's road systems indicates the need for more efficient and more effective maintenance. Methods, equipment, and materials have not changed significantly in recent years, although both the mileage and traffic volume of the highway system have increased significantly. The opportunity for major improvements through maintenance research is substantial: further mechanization, better repair materials, off-site prefabrication, and more efficient staffing and scheduling could all yield substantial savings.

Protection of Concrete Bridge Components

An epidemic of bridge deterioration has developed throughout the United States. Currently more than 132,000 bridges are classified as structurally deficient, and 3,500 more become deficient each year. About one-third of the structurally deficient bridges are so classified because of deck deterioration. Bridge deterioration will continue unless technology is developed to arrest the corrosion process in existing salt-contaminated bridge decks and other reinforced concrete structural members and to protect new and replacement concrete now being constructed from contamination or corrosion.

The procedures that appear to be the most promising for extending the life of bridge concrete are as follows:

1. Prevent deterioration of chloride-contaminated concrete through electrochemical removal of chlorides, impregnation of the concrete and upper steel, or cathodic protection; and
2. Prevent deterioration of new and uncontaminated concrete by using newly developed coatings for the reinforcing steel and external or internal sealants for the concrete surface.

In addition to the research on the protection of concrete from chlorides, research on alternatives to the use of chlorides for snow and ice control is proposed in another of the six program areas.

Cement and Concrete in Highway Pavements and Structures

The highway industry consumes more than $400 million of portland cement annually; this is about 13 percent of all portland cement made in the United States. Concrete is used for 85,000 miles of roads, thousands of miles of median strips, curbs, and virtually all sidewalks. Also most bridge decks, short-span bridges, and the supporting structures for thousands of bridges are made of concrete. Yet, cement and concrete research is diminishing just at the time when the quality, reliability, and utility of this basic building material are of the most importance.

A major cause for failure in concrete structures is deterioration of the concrete; therefore, research is needed to find ways to increase durability, particularly for structural uses.

Chemical Control of Snow and Ice on Highways

All but 7 of the 50 states can count on snow covering parts of their highway systems every winter. Salt was first used on intercity highways for snow and ice control about 50 years ago; by 1982 salt use had grown to 12 million tons a year. This heavy use of salt for snow and ice control exacts a price in vehicle corrosion, bridge deck and concrete pavement deterioration, and contamination of soils and waters. Two avenues of research could help to reduce the adverse effects of chlorides while maintaining the safe levels of service required on highways during winter storm periods.

First, the storing, handling, applying, and controlling of salt offer many opportunities for improvement, and research should be directed at better chemical management techniques. In addition, research should explore improvements in mechanical and thermal means of snow removal. Second, new chemicals with acceptable melting qualities and without adverse environmental effects should be developed for use in winter maintenance programs, and further assessment should be made of calcium magnesium acetate (CMA) as an alternative to salt.

CONCLUSIONS AND RECOMMENDATIONS

Each of these six proposed research areas represents an outstanding opportunity to fill in the gaps in highway research and make dramatic advances in transportation technology. An assessment of these high priority research areas in terms of the nine strategic criteria previously discussed is given in Table 1.

Together the six research components comprise a program of about $30 million per year for 5 years. This major funding requirement can be met by allocating one-quarter of 1 percent of federal-aid highway funds to research. This procedure would require no new money. Rather, a small fraction of today's program funds would be devoted to reducing tomorrow's program needs by developing better materials and techniques. The data in Table 2 indicate how these funds would be distributed. Cost savings of about $600 million per year could result from implementing new technology developed by this research effort. Although the savings would only be realized after the research results were put into practice, they would continue to accrue long after the research program is completed.

The strategic research plan described in this study is a practical approach to solving real-world problems and is carefully related to the materials and processes used to build and maintain the physical struc-

TABLE 1 Assessment of High-Priority Highway Research Areas

	Asphalt	Long-Term Pavement Performance	Maintenance Cost-Effectiveness	Protection of Concrete Bridge Components	Cement and Concrete in Pavements and Structures	Chemical Control of Snow and Ice
Probability of a big payoff	High	High	High	High	Medium	High
Has research on this topic been neglected in recent years?	Yes	Yes	Yes	No	Yes	Possibly
Degree to which organizational barriers now impede research	High	High	Medium	Low	High	Low
Likelihood that research findings will be usable	High	High	High	High	High	Medium
Scale of effort required for successful project	Large	Large	Small	Large	Medium	Medium
Does the research require greater unity of effort, now splintered?	Yes	Yes	Probably	Probably	Yes	Probably
Do changes in national policy create a common, multistate research need?	Possibly	Yes	Possibly	No	No	Yes
Do major technological changes require research here?	Yes	No	Possibly	Possibly	Possibly	Possibly
Likely magnitude of impact on safety and environment	Medium	High	High	High	Medium	Medium

TABLE 2 A 5-Year Strategic Transportation Research Program

Problem Area	Annual Expenditure ($ Million)	Total Expenditure ($ Million)
Asphalt	10.0	50
Long-term pavement performance[a]	10.0	50
Maintenance cost-effectiveness	4.0	20
Protection of concrete bridge components	2.0	10
Cement and concrete in highway pavements and structures	2.4	12
Chemical control of snow and ice on highways	1.6	8
Totals	30.0	150

[a]Continuation required for an additional 15 years at approximately $10.0 million per year.

tures of the highway system. It is tailored to focus on observed gaps in current research and the organizational structure and resources required to close these gaps. It advocates innovative approaches to down-to-earth problems. The plan can be characterized as follows:

- It is more sharply focused than current highway research efforts.
- It concentrates on a few specific, goal-oriented areas. It would exist for only 5 years (with the exception of the pavement field test, which would necessarily have to be longer).
- It represents a crash effort, a high concentration of time and money and technical expertise on crucially important and achievable targets.
- The staff should be independent of old allegiances thereby ameliorating some organizational barriers.
- It should include involvement by constituent highway operating agencies but insulate research efforts from special interests.
- It should have continuity both of staff and funding throughout its 5-year term and a strong central control.

Because of these special characteristics, no existing organization can simply absorb this strategic program. Various existing organizations could be modified to assume responsibility for this program, including the following:

- An American Association of State Highway and Transportation Officials (AASHTO) task force;
- A special-purpose unit of AASHTO, such as was created to oversee the AASHO Road Test;
- A new component of the National Cooperative Highway Research Program of Highway Research and Development (NCHRP);

- A new special project under the Federally Coordinated Program of Highway Research and Development (FCP);
- A modified Research Associate Program under the auspices of the National Bureau of Standards;
- A university research center or research institute; or
- A major private research organization.

Alternatively, a new organization, such as a special-purpose, chartered, nonprofit research agency, could be considered.

The current infrastructure crisis has reawakened the nation to the economic importance and the physical problems of its highway system. The appropriation by Congress in 1982 of $58 billion in federal aid for highways over 4 years must be matched by a serious, concerted research effort to find better ways to build, maintain, and operate the highway system of the future. Merely increasing support for current research activities will not focus the resources that are crucial to achieving that goal. The strategic research program proposed here is an efficient and productive way to initiate and monitor a concentrated research effort and it is well within the industry's financial ability. With the appropriate funding and institutional commitments, the strategic research program outlined here promises to make a monumental contribution toward improving highway technology.

PART I

Overview and Fundamental Approach

1
The Highway Industry

The need for a strategic assessment of the nation's highway research stems from the fact that the United States highway industry is large, fragmented, and lacks both the organization and the economic incentives to support needed research. Therefore progress in developing improved materials and methods of construction is too slow, uneven, and inadequate to cope with maintaining and replacing the rapidly deteriorating highway system. In addition to making essential repairs to the present highway system, national attention should be directed to research that will make it possible to build highways in the future that will last longer and be easier to maintain.

The material contained in this chapter provides background on the characteristics, capabilities, and limitations of the United States highway industry, highlights current significant trends in highway expenditures, and gives an indication of how these factors influence current research efforts.

CHARACTERISTICS OF THE HIGHWAY INDUSTRY

In this report the term *highway industry* refers to highway construction, maintenance, and operating activities performed by federal, state, county, city, and other operating units of government as well as toll-highway authorities. It also includes private firms that supply materials or services to the public agencies responsible for highways. This industry spent $43 billion in 1982—more than the steel, textile, or paper industries. It manages almost 4 million miles of roadways, of which about 75 percent are classified functionally as local roads.

It would be difficult to overestimate the importance of the U.S. highway industry to the nation's economy. Highway-based industries account for about 17 percent of the gross national product (GNP) and approximately 620,000 jobs are generated by highway construction and maintenance alone. The private sector dedicates more than 15 percent of its plant and equipment investments to transportation. Taxes paid by the transportation industry amount to 14 percent of all federal taxes and 23 percent of all state taxes.

Highway Administration is Dispersed

Although the federal government, through the Highway Trust Fund, provides capital funding for construction on the federal-aid system, the highway system is fundamentally administered and maintained by state and local governments. This decentralization of responsibility increases the sensitivity to local needs and issues as well as to regional topographic, climatic, and subgrade conditions affecting highway design and maintenance. It also results in a relatively large number of public agencies sharing authority and responsibility for keeping the highway system operating properly.

About 23,000 federal, state, and local agencies operate the nation's vast highway industry (see Table 3). Although the states account for about half of the industry in terms of spending, many other agencies and a large number of people are involved in road engineering, construction, and administration.

TABLE 3 Highway Mileage in the United States by Administrative Responsibility (*1–3*)

Administrator	No. of Agencies	Miles
Federal agency	5	262,403
State agency	50	934,696
County agency	2,500	1,577,420
City, town, and township	10,000	486,575
Other local (only residential streets)	25,000	605,153
Toll highway authority	35	4,773
Totals	38,000	3,871,020

TABLE 4 New Highway Construction: Top 10 Expenditure Categories (*4*)[a]

Industry Name	Percentage of Highway Industry Expenditures	Cumulative Percentage
Concrete products	13.30	13.30
Wholesale trade	9.05	22.35
Stone and clay mining and quarrying	8.30	30.65
Petroleum refining and miscellaneous products of petroleum and coal	8.20	38.85
Paving mixtures and blocks	6.06	44.91
Ready-mixed concrete	6.20	51.11
Fabricated structural metal	5.40	56.51
Motor freight transportation	5.00	61.51
Miscellaneous professional services	4.80	66.31
Retail trade	3.40	69.71

[a]Total number of industries represented here is 102; 49 of these are so small that together they represent only 0.25 percent of total purchases.

Diversity of Products Purchased by Highway Industry

Highway agencies purchase large quantities of products from firms in other sectors of the economy. Statistics show that concrete, wholesale trade, stone and clay mining and quarrying, petroleum refining, paving mixtures, and motor freight transportation sell substantial amounts of goods and services to government highway agencies.

Tables 4 and 5 depict the diversity of expenditures by the industry. Although paving materials represent the largest expenditures, purchases from other industries, such as explosives, lumber, and various metals, are also significant.

Diversity of Purchasers, Producers, and Suppliers

Some 23,000 public agencies are the purchasers and end users of these products. Most agencies contract out construction and major repair projects to private firms, who, in turn, buy products and services from numerous other suppliers.

Because most highway construction materials are bulky and low valued, the high cost of transporting them gives local suppliers an advantage. In addition, because county and state funds represent 73 percent of all public money spent on roads, political pressures frequently mandate the use of local firms or local materials. As a result of this diversity of local suppliers, the annual income of each firm tends to be small.

TABLE 5 Highway Maintenance and Repair: Top 10 Expenditure Categories (*4*)[a]

Industry Name	Percentage of Highway Industry Expenditures	Cumulative Percentage
Stone and clay mining and quarrying	16.9	16.9
Petroleum refining and miscellaneous products of petroleum and coal	10.3	27.2
Paving mixtures and blocks	9.7	36.9
Motor freight transportation	9.4	46.3
Wholesale trade	6.0	52.3
Ready-mixed concrete	4.9	57.2
Fabricated structural metal	4.0	61.2
Retail trade	3.8	65.0
Miscellaneous business services	3.4	68.4
Sheet metal work	2.9	71.3

[a]Total number of industries represented here is 113; the combined purchases from 56 of these represent only 0.87 percent of total purchases.

For example, a typical ready-mix company has annual revenues of only $1.5 million (see Table 6).

In short, the number of purchasers, producers, and suppliers is large; and the business of obtaining highway building materials is complicated. The use of portland cement concrete is a good example of this complexity. Portland cement concrete is a commonly used paving material and is an essential element in almost all bridges. It is made up of cement, mineral aggregates, and reinforcing steel. It may also contain additives to facilitate handling, control the rate of hydration, and increase the strength and the life of the final product. The purchasers and end users of portland cement are several thousand federal, state, and local agencies. The producers of the product are almost as numerous. About 60 companies make the cements; and more than 4,000 ready-mix companies produce concrete, using aggregates produced by the approximate 6,000 sand and gravel or crushed stone producers. Some of the 44,000 construction contractors involved in highway construction also mix their own concrete.

Highway Builders Lack Domination In Single Industry

Despite the importance of portland cement in road and bridge building, it is not used exclusively, or even predominantly, in highway facilities. Only about 15 percent of the concrete put in place each year is for

TABLE 6 Suppliers Share of Highway Industry Market (5)

Sector	No. of Firms	Total Market ($ Billion)	Average Share for Single Firm ($ Million)	Total Share for Top 50 Firms ($ Billion)	Average Share for Top 50 Firms ($ Million)	Share for Top 50 Firms (%)
Highway and Street construction contractors	14,354	16	1.1	2.8	56	17.5
Heavy construction, including dams, ports, tunnels, bridges, etc.[a]	40,000+	38.9	1	19.9	398	51
Ready-mix concrete	4,012	6.2	1.5	1.6	32	25.8
Concrete and gypsum products	4,461	6.0	1.3	3.2	64	53.3
Petroleum and Coal products (paving materials)	956	2.7	2.8	1.36	27	50.4
Petroleum refining[b]	130	131.5	1011.5	130	2,600	98.8

[a]The heavy construction industry is made up of approximately 1,000 firms primarily oriented to road structures. Their average annual receipts are slightly over $2 million.
[b]The top 4 petroleum refining firms account for 41 percent of the market; the top 8 firms account for 61 percent; and the top 20 account for 93.5 percent.

highway purposes. The remainder goes into private and public buildings, defense installations, dams and river channels, harbors, and airports.

The absence of an integrated effort noted in portland cement concrete production characterizes many of the products and services used by highway agencies. This lack of integration is noted even in the asphaltic cement industry where highway construction is the dominant user. The process of mixing and placing asphaltic concrete involves construction contractors, sand and gravel and crushed stone producers, and asphalt mixing plant operators, as well as equipment manufacturers, refiners, and many levels of government.

Although the highway industry makes large purchases of materials in dollars and tonnage, it is not a dominant buyer in any industry, except for asphalt. As noted, highway purchases represent a little more than 15 percent of cement production. Highway industry consumption of steel represents only 3 percent of steel production and 18 percent of structural steel. In mineral aggregates, highway use is about one-third of national consumption. Even in asphalt, where highways are the dominant consumer, asphalt is such a minor component of petroleum industry sales that it has little potential impact on the economic or research interests of the supplying industry.

Monopolistic Transportation Industry

Although the number of public agencies involved in the highway industry is large, each of them, typically, has a monopoly-like role in its "market area." This situation is similar to that of public utilities in which many utilities exist, but each has a monopoly in its area of operation. Although the number of private firms supplying products and services to the highway industry is large, the service area of each firm is often quite small. Only 12 percent of road construction contractors performs work outside their home state, and only half of the income for this 12 percent comes from out-of-state projects, according to the U.S. Bureau of Census. Thus the market in a given area will consist of a single buyer purchasing from a short list of suppliers in each industry sector.

The critical attribute of monopolies, for the purposes of this study, is their orientation to research. Because most monopolies are large, they are capable of supporting intensive research; however, their economic incentives to perform research are unclear. Usually research performed by a monopoly is incremental, conservative, and oriented to problem solving rather than to seeking cost efficiencies or alternatives to its product (*6*).

To the extent the highway industry is similar to a shared monopoly, such as the public utilities, its research activities would demonstrate the negative attributes of both small and large monopolies. Ironically, even with its monopolistic features, investor-owned public utilities spend over $600 million per year on research—more than 0.6 percent of their gross revenues. Much of this is devoted to basic research and large-scale, innovative projects managed by the Electric Power Research Institute. Thus, highway research may be even more incremental and conservative than that of other monopolies.

Highway research is also affected by the involvement of both public agencies and the private sector. As in other industries such as defense or mass transit, in which the government buys and the private sector sells, the procurement process tends to be based on the lowest bid for a given specification. As a consequence, a large part of the research burden falls on the buyer, which is the government agency. Sellers have an overwhelming incentive to do everything possible to bid the lowest. In the highway industry, where many of the purchased materials are low-value bulk products, this preoccupation with low bid is intensified. A further complication is that unlike many other public sector activites, buying is highly decentralized among many levels and units of government.

IMPLICATIONS FOR RESEARCH

A unique collection of public agencies, private organizations, activities, and expenditures comprises the system that plans, designs, funds, builds, and maintains highways. This uniquely linked industry has special characteristics that determine its research needs, research activities, and their implementation. The special attributes of the industry include:

- Large-scale expenditures—$40 to $45 billion per year and growing. This is larger than the air carrier industry ($30 billion) and the railroad industry ($30 billion).
- Dispersed responsibility—thousands of public agencies and supporting firms.
- Shared responsibility—federal, regional, state, county, and city governments are involved, jointly and continuously.
- Complex public and private relations—virtually all funds spent come from public organizations; most construction and repair work is done by private firms.
- Monopolistic control—a single agency controls any particular road, and bidding on related projects is generally done to a rigid standard.

The highway industry will spend over a trillion dollars in the remainder of this century; thus asphalt, concrete, steel, paints, and other products are important industries. Nevertheless, because of the large number of highway agencies, the market for highway materials and equipment is highly fragmented. Typically, highway agencies buy from relatively small, local suppliers and contractors.

If instead the highway industry were a concentrated industry with three or four firms—firms on the scale of $10 to $15 billion per year—it might behave differently. In particular, large competing firms would want to increase their share of the multibillion dollar market in bridges, pavements, and maintenance. Therefore, they would recognize the necessity of large-scale research into ways of offering better products and services. Hundreds of millions of dollars would be spent on research to support corporate strategies. Their marketing departments would be telling corporate management—

- More than $200 billion in expenditures will be guided by pavement management decisions in the next 10 years. Can we offer a better way to manage a pavement over its entire life cycle so as to reduce costs and enhance service? Research has shown that different management strategies can make big differences in life-cycle costs. A better product, that saves 10 percent, would be worth $20,000 million to our customers, and we could recapture much of this through profits on a better product. Is it worth $200 million to develop such a product? It's risky, but the payoffs could be much greater than the costs.
- About $25 billion will be spent by 1990 on bridge rehabilitation. If we could develop products to improve the maintenance of bridges, to locate decay and fatigue cracks sooner, before they expand, to mend such cracks more easily, or to protect concrete reinforcing steel more completely, then we might create a multibillion dollar market for those products during the next few years. How much should we invest in such research? Where? How can we capitalize on the obvious safety benefits involved?
- Many more billions of dollars will be spent on reconstructing roads to new safety standards. We know that broader lane widths, wider shoulders, wider medians, more guardrails, use of breakaway signs, and improvements to other geometric elements will increase safety. But our customers lack funds to buy all of these elements to top standards. Should we pitch our product development at specific elements? What traffic, topographic, and other conditions warrant improvements in specific elements? How much should we invest in research on such questions

to improve our profit potential, given the billions that are going to be spent on these various safety improvements?

However, in view of the nature of the highway industry who, if anyone, will ask such questions?

The small producers and suppliers, the small agencies, the lack of dominance in the marketplace, and the parochialism of local agencies all combine to produce a situation where there is neither the resources nor the incentive to undertake major research and development. Such research could lead to new products or processes that would increase facility life, reduce costs, or improve performance. Instead, research tends to be directed to incremental, problem-oriented tasks needed to streamline the industry's day-to-day operations.

This chapter has identified some of the key characteristics of the highway industry: most notably its fragmentation into many small, local buyers and sellers. This fragmentation of effort and scale is parallel to the industry's research activities, which are described in the chapters that follow.

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2
Highway Research Activities

ORIGIN OF HIGHWAY RESEARCH

Federally sponsored research on the nation's highways antedates the automobile age. In 1893 the U.S. Department of Agriculture established the Office of Road Inquiry to investigate the best methods of road-making and to help disseminate this information. "Good Roads Trains" were dispatched throughout the country to demonstrate new construction equipment and materials; and "Good Roads Days" were held in rural areas to demonstrate well-constructed road segments.

In 1900 a federal laboratory was created to evaluate highway materials (*1*). The desperate need for better roads and better road-building techniques was obvious. Europeans visiting North America at the time were struck by the excellence of the railroads and the inferiority of the roads(*2*). Indeed, the rise of the railroads and their spectacular contribution to commerce and economic development were the key reasons for the neglect of roads. Nevertheless, at the time awareness of the need for good roads began to intensify, the traffic on, and the responsibility for, these roads was primarily local. The federal government confined itself to research to aid local and state governments in finding better materials and methods for building roads.

Over the years, the federal government has maintained a strong interest in highway research. The Highway Act of 1921 authorized sustained support for highway research, and the Hayden Cartwright Act of 1934 provided that 1.5 percent of annual road appropriations to any state could be used for surveys, plans, or engineering investigations. The Federal-Aid Highway Act of 1944 broadened the uses of this 1.5 percent to include planning and research much as they are defined today, and the series of highway acts since 1944 has continuously provided the states with research funds through this program.

The current system of research activities and organizations that has evolved from these beginnings are described in this chapter. The description begins by recounting some of the products, now familiar, that resulted from research. Then the current context of this research, a comparison of highway research with that of other industries, and the highway research activities of other nations are presented. The conclusion is a program-by-program discussion of the major highway research activities now in place.

ILLUSTRATIVE ACCOMPLISHMENTS OF HIGHWAY RESEARCH

Every aspect of highway design, construction, maintenance, and operation has benefited from the past stream of highway research. In bridge construction, for example, dead loads have been steadily reduced by using high-strength steel reinforcing bars; by prestressing and posttensioning; by box girder designs; by cable-stayed spans; and by additives that make concrete stronger, easier to handle, and quicker to set.

Highways are safer because research developed less hazardous roadsides with flatter slopes, breakaway poles, impact attenuation devices, guardrails that redirect vehicles, and headlight screens. Pavement markings and delineation devices last longer and perform better in inclement weather. Signs are more legible, and construction zones are safer for workers and for motorists. Ramp metering, computer-controlled signals, variable message signs, and electronic monitoring devices reduce congestion on city streets and urban freeways. Pavement surfaces have much better skid resistance; grooved pavements have virtually eliminated tire hydroplaning on urban freeways. Planning methodologies are more comprehensive, flexible, and responsive.

Soils that were once unusable can now be stabilized; mineral aggregates can be evaluated more precisely; and in some instances mineral aggregates can be enhanced in strength and durability or, where they are not available in natural deposits, can be manufactured.

The environment benefits from highway research. Noise and air pollution caused by traffic are better understood, and the harm they do can be reduced. Also, planners can consider more fully the environmental consequences of various alternatives.

When high strength reinforcement was introduced in the building industry in the 1960s, engineers questioned the performance of such steel in bridges under heavy moving loads and hostile environments. Cost-shared research by the Federal Highway Administration and the Portland Cement Association indicated that the cost of reinforcing a bridge during construction would be 30 percent less if high strength steel were used. The result is that highway agencies and the public are saving about $30 million per year.

Breakaway poles and impact attenuation devices are the direct result of research conducted by several states and universities. Federal funds for highway safety improvements financed replacement of many existing poles and protection of fixed objects that could not be removed, resulting in a substantial reduction in accident severity. Changes in vehicle sizes and weights (smaller cars and larger trucks) may require new design standards in the future, and research will be essential in making those determinations.

When the National Aeronautics and Space Administration found that grooving of pavements reduced hydroplaning of aircraft tires on runways, highway research quickly developed similar solutions for roads. Improvements in rubber compounds and tire tread design have also reduced skidding.

In short, even at its relatively low level, highway research has made significant contributions.

CURRENT CONTEXT OF HIGHWAY RESEARCH

Continuous improvement of highways is evident in the comparison of the roads of the 1920s and 1930s with the superhighways of today. Similarly, recalling the relatively small trucks and low speeds of those early years emphasizes the extraordinary demands placed on today's roads. Despite the continuous improvements gained through highway research, financial support for this activity has never been a major component of total highway spending. At least in part, this is attributable to the historical context in which highway development has occurred and road building improvements have evolved. That context includes the following elements:

- Road technology evolved slowly, incorporating new technologies incrementally rather than through dramatic scientific breakthroughs.

- Historically road building began as the responsibility of the smaller units of government: cities, municipalities, and counties. In the latter part of the 19th century states began to play a role in road finance, and federal involvement dates from early in the 20th century. But even by 1921, the earliest year for comprehensive data, federal and state expenditures combined accounted for only 29 percent of highway expenditures.
- Roads are built by thousands of small, local contractors, each of which is involved in such a small part of the overall activity that there is little incentive for the contractor to perform his own research.
- Roads require large quantities of low-cost, bulk materials that have high transport costs; therefore locally available materials are used and research on alternative materials is inhibited.

Much of this historical pattern remains today. The major change is the continuing rise of the role of the federal and state governments. By 1981 the state and federal share of total highway expenditures had risen to 64 percent. This massing of funds in larger units provided greater opportunity for the development of research activities. But even with this stimulus and the additional stimulus of funding research through the Highway Planning and Research Program, spending for highway research has always been a fraction of 1 percent of highway expenditures.

Highway Research Spending Compared with Other Industries

The financial commitment to highway research also appears surprisingly low when compared with research funds invested in other sectors of the economy. High-technology industries, such as computers, aircraft, and chemicals, spend about 6 percent of their gross sales revenue on research (see Table 7). This level of research and development (R&D) expenditure, which is nearly 40 times greater than that of the highway industry, keeps these companies at the technological forefront, where they must be to survive. They realize that in 5 years half of their sales will probably come from products based on today's research.

Similarly, medium R&D-intensive industries spend about 3 percent of their sales revenue on research—still almost 20 times the corresponding percentage for highways. Even low-technology industries, such as building materials, metals and mining, paper, food and beverage, steel, and textiles, spend more than eight times as much on research, relative to their sizes, as does the highway industry.

The disparity in research commitment between the highway construction industry and other industries is indefensible. Yet throughout the

TABLE 7 R&D Funds as a Percentage of Sales for U.S. Industries: 1982 (*3*)

	Percentage	Average Percentage
High R&D Intensive Industries		
Semiconductors	7.8	
Information processing—peripherals, service	7.2	
Information processing—computers	6.8	
Drugs	6.0	6.2
Instruments	5.2	
Aerospace	5.1	
Information processing—office equipment	5.1	
Medium R&D Intensive Industries		
Automotive—cars and trucks	4.0	
Electronics	3.8	
Machinery—farm and construction	3.3	3.2
Chemicals	2.9	
Electrical	2.8	
Machinery—machine tools	2.6	
Low R&D Intensive Industries		
Tire and rubber	2.3	
Oil service and supply	2.1	
Building materials	1.3	
Metals and mining	1.2	
Paper	1.0	1.4
Food and beverage	0.7	
Steel	0.7	
Textiles, apparel	0.6	
Fuel	0.5	
All Industries (766 firms with 1982 sales of $35 million or more and R&D amounting to at least 1 percent of sales)		2.4
Highways[a]		0.17

[a]The estimate for highways is based on data presented in Figure 1.

automobile revolution, as automobiles and roads dramatically reshaped life-styles and the economy, old techniques were passed along; and research to find better techniques has been consistently shortchanged. The highway industry continues to work around fundamental, unanswered questions.

The reason roads have been shortchanged appears to be because they are so familiar. In 1896 one advocate of improved roads noted: "Roads appear, to those who do not know either their importance or the complicated nature of the problems involved in their structure and maintenance, to be such very simple things that, like other states of dust, such as the soil itself, there appears to be needed only a little ordinary practice to fit any dabster to deal with them." (*4*)

This perception of simplicity persists today. When members of the House of Representatives recently explored highway research in the light of the nation's highway infrastructure crisis, one member commented: ". . . [I]t seems to me like such a simple problem compared to many of the others like Medicare and other things we have to grapple with. . . ." Another member noted: "There has to be something hidden out there that just—it just seems to be too damn simple . . . it seems like everyone knows the problems and I can't believe the solutions are that difficult . . . we can put a shuttle into orbit. We can fly it across the Atlantic just to show it to folks in Europe, and we can't fix the potholes on the Wilson Bridge. It boggles my mind." (*5*)

Misunderstanding the Complexity of Highways

This public misperception of the complexity of highway construction and maintenance bodes ill for highway research. It is important to understand that research on the unglamorous or familiar is not automatically unnecessary or unprofitable.

IBM's Vice President for Research, Ralph E. Gomory, described a phenomenon in the computer industry that is applicable to highway research. The computer, he said, conjures up visions of exotic and difficult technologies. For example, "when you think of computers, you tend to think of semiconductor chips." However, Gomory added that impact printing is also an important component of a computer, albeit "a very crude technology . . . very much a mechanical thing. Impact printing, nevertheless, in spite of competition from the other exotic technologies, continues to improve . . . a deeper understanding of this crude mechanism results in progress. I only mention this because some people seem to think, 'Well, there's area A where you can make progress, there's area B where you can't.' I do not believe this—I am sure there are recalcitrant areas, but by and large my experience is that when you tackle an area—not always, but almost always—what technical potential of progress there is, is by no means confined to what is considered to be high technology." (*6*)

Public Spending Policies

Highway research is impeded not only by the misunderstanding of what research is necessary and its usefulness but also by public spending policies. Because most highways are constructed for governments—whether federal, state, county, or local—research on highways is subject to short-term governmental budgetary pressures. Highway research, which yields results that are distant, uncertain, and intangible, competes before legislatures with road construction, which produces visible and immediate results, and also competes with numerous other programs posing urgent demands on public spending. In a world of tight budgets, highway research appears continually deferrable. No competitor is poised to capture this market even if local products and processes are not the best, and no immediate calamity will result if research is put off. Public managers, unlike managers in private firms, do not view research as essential to survival. Compared to other priorities, it is too remote, too nebulous, and too uncertain. The long periods needed to reap the benefits of highway research put this activity at a disadvantage in budgeting decisions.

This disadvantage is exacerbated by the extraordinarily high turnover of top personnel in highway agencies. A recent survey by the American Association of State Highway and Transportation Officials reported that 20 of the 50 chief administrative officers in state departments of transportation have held their posts for 18 months or less. Preoccupied with decisions about new roads and bridges, widenings, unsafe segments, and many other frequently controversial issues, new top officials in highway agencies typically cannot focus on research programs immediately. Even when top officials do focus on highway research activities, in this environment they are likely to stress projects promising immediate results. As a result research activities may not be linked to the operational needs of agencies as closely as they might be; and research in general, particularly basic and long-term research, tends to be neglected.

Federal Highway Research Spending

During the decade from 1973 to 1982 annual federal outlays for highways declined from $12 billion to $11 billion, and the nation's total expenditures for roads fell from $53 billion to $43 billion per year, all in constant 1982 dollars. Even when the increased program resulting from the Surface Transportation Assistance Act of 1982 is implemented, real outlays for highways will be still lower than they were a decade ago because of inflation.

The Surface Transportation Assistance Act of 1982 broadened the funding base for each state's federal-aid highway apportionment, and the planning and research authorization increased proportionately. The effect of this increase is, as yet, uncertain. Research projects reported to the Highway Research Information Service (HRIS) at the Transportation Research Board (TRB) roughly doubled from 1982 to 1983 (from approximately 300 to 600 projects). Although 1983 was not so dismal a year for highway research as 1982, it was still inadequate with respect to past highway research spending levels, to the research expenditures of other industries, and, most important, to the great potential for eventual payoffs. From 1973 to 1982 expenditures for the nation's two leading highway research programs fell by half from $111 million in 1973 to $56 million in 1982 (constant 1982 dollars) (see Table 8).

The Highway Planning and Research (HP&R) program not only declined in absolute dollars, it also declined precipitously as a share of the total HP&R fund, falling from 22 percent to 15 percent during the last decade. The Federal Highway Administration (FHWA) in-house research activity declined from 0.33 percent to 0.20 percent of total FHWA expenditures in the same period.

Viewed as a share of total highway program expenditures by all levels of government, highway research spending has fallen from 0.25 percent to 0.17 percent between 1965 and 1982 (see Figure 1). Similarly, federal highway research spending has declined both as a share of U.S. Department of Transportation spending and relative to other federal spend-

TABLE 8 Major State and Federal Highway Research Spending: 1973–82, millions of constant 1982 dollars (*7*)[a,b]

Year	State	FHWA (Contract and Internal)	Total
1973	71.7	39.6	111.3
1974	65.1	37.6	102.7
1975	60.7	43.1	103.8
1976	53.0	46.4	99.4
1977	51.5	39.6	91.1
1978	50.4	35.6	86.0
1980	40.3	28.4	68.7
1981	35.9	20.5	56.4
1982	33.7	22.2	55.9

[a]These funds include federal HP&R funds of approximately $20 million, state matching funds of approximately $5 million, and additional state funds programmed for HP&R but not federally matched of about $10 million. They do not include any non-HP&R spending by the states.
[b]Dollar amounts from the original source were converted to constant 1982 dollars.

ing on research and development. In 1970 the U.S. Department of Transportation's funding level for R&D ranked fourth among federal agencies. By 1982 it had dropped to ninth with a total budget representing less than 1 percent of federal R&D expenditures.

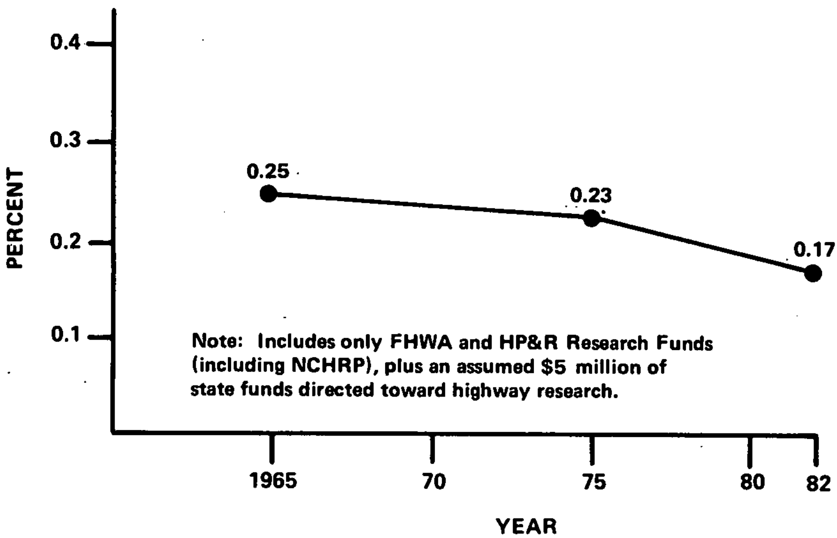

FIGURE 1 Highway research as a percentage of total highway program expenditures (*7,8*).

Foreign Highway Research

Not only are state and federal highway research programs declining, but they are also disproportionately small when compared with those in other countries. This is true despite the greater importance of roads to the U.S. economy and to the travel needs of the people than to other countries. Compared with the United States, the United Kingdom spends 10 times as much on road research, relative to program scale. Similarly, every country for which data could be obtained, with the exception of Japan, spends more than the United States on the same basis (see Table 9). Japan may be spending proportionally more; Table 9 gives data only for public spending and does not account for other sources such as joint public and private research encouraged by the Japanese government. Similar strong private-public support for research and development is typical among many of the European countries.

TABLE 9 A Comparison of Foreign and U.S. Spending for Highway Research Programs (*9*)

Country	Highway Spending at All Levels of Government ($ Million 1982)	Estimated Highway Research Spending ($ Million)	Research as Percent of Total Spending
United Kingdom	3,000	45	1.47
Japan	19,486	16.8	0.09
Australia	2,350	19	0.81
Federal Republic of Germany	9,800	20.5	0.20
Sweden	955	30	3.14
United States	43,278	72	0.17

These investments in road research by other nations appear to be productive. One measure of success is the flow of new road equipment, materials, and additives to the United States from Europe. Examples are Chem-Trite Silane, a product from the Federal Republic of Germany for protecting bridge reinforcing bars from corrosion; a Skega product from Norway for introducing rubber crumbs into asphalt pavements; Swedish made profilometer sensors; Japanese grinders for sign removal; and an electromagnetic gauge from the Federal Republic of Germany to measure paint thickness. Although the United States benefits from such foreign investments in research, it also pays for this through a negative balance of payments. In addition, the United States may be missing advances that are uniquely adapted to its own climate, soil, design, or traffic conditions.

MAJOR HIGHWAY RESEARCH PROGRAMS

The $70 to $75 million that the United States spends annually on highway research is disbursed through a variety of programs. The largest research program, state spending through the federally supported HP&R program, spent $30 million in 1982. Federal in-house and contract highway research programs cost $21.5 million in 1982, exclusive of the National Cooperative Highway Research Program (NCHRP). Together, the HP&R program and the FHWA spent 71 percent of all highway research funds. The remaining 29 percent was spent through independent state research programs, through the NCHRP, and through counties, other federal agencies, and highway-related industries (see Table 10). Each of these major highway research organizations and programs is discussed below.

Highway Planning and Research (HP&R) Program

HP&R funds are by far the largest source of support for highway research. Each state receives HP&R funding in the amount of 1.5 percent of its federal-aid highway apportionment. In addition some states elect to receive 0.5 percent available for urban highway planning and research activities.

State highway and transportation departments can divide HP&R money between planning and research as they see fit. Usually, about 15 to 20 percent of HP&R funds is spent for research, but some states spend as much as 55 percent for this purpose. State-sponsored research in the HP&R program may or may not be included in the Federally Coordinated Program of Highway Research and Development (FCP), depending on whether the research addresses objectives that are monitored in the FCP.

The states spend an average of about $30 million on research per year excluding the $4.4 million allocated for the NCHRP. Approximately $20 million comes from federal sources distributed through the HP&R program, and the remainder is state matching funds. States also spend about $5 million per year of their own funds on research independent of any federal program or matching funds.

The states, which are responsible for disbursing most of the highway funds in the country, face an immense variety of local problems. HP&R funding provides for correcting the unique problems associated with a state's climate, soil conditions, terrain, stone products, paving materials, traffic loadings, vegetation, and numerous other features. Unique or urgent problems can be tackled efficiently and directly through this structure.

This arrangement is not well suited, however, to stimulating research on large, national problems affecting many states. The costs of large research projects may be prohibitive for any single state; and the benefits may be national in scope, making it equitable for many states to bear the cost of the research. For these reasons, the states have created ways to pool their research funds to address common problems.

The National Cooperative Highway Research Program (NCHRP)

NCHRP emerged not long after construction began on the Interstate Highway System, when many states began to experience similar new problems related to the high-level design of that system. Instead of attempting to deal with the problems individually in each state, the states arranged through the American Association of State Highway and

Transportation Officials (AASHTO), the FHWA, and TRB to combine resources in a new research program created to address common problems.

In this grass roots program research is targeted at specific common problems and is initiated as follows:

1. Each member organization submits critical problem statements.
2. These problem statements are screened for mutuality of interest, immediacy of need, possible duplication of effort, and likelihood of solving the problem with a reasonable expenditure of time and money.
3. Those problems that pass screening process are further considered by the AASHTO Select Committee on Research, which recommends undertaking a new research project or summarizing related experience in a synthesis or tabling the idea.
4. The AASHTO Select Committee on Research puts new problem submittals in the order of highest priority and sends the list to the AASHTO Executive Committee.
5. The AASHTO Executive Committee decides on the final program.
6. After an advisory review by the TRB and the FHWA, the research program begins.

Since NCHRP was organized in 1962, 358 projects have been completed and 100 syntheses published. The program has been operating at a level of about $4.5 million per year but is expected to increase to about $6.8 million per year as a result of the increase in HP&R funds brought about by the Surface Transportation Assistance Act of 1982.

This problem-oriented process has effectively focused research on operational problems as they emerge. The extensive use of state personnel with operational experience ensures that the most urgent needs are addressed. The extensive review and screening processes avoid wasteful duplication of research and encourage new efforts to draw on previous and related research. The widespread participation not only assures that new or unusual problems do not go unnoticed, but also that program resources are spread across a varied mix of problems instead of being dedicated to a few significant research projects.

Federal Highway Administration (FHWA) Research

FHWA funds a broad array of research conducted by private contractors, consultants, universities, or FHWA staff. Many staff studies are continuing efforts in major research areas, but a significant portion of the research effort is in quick response to particular operational problems and preliminary investigations of new problems.

About 15 to 25 percent of FHWA research staff time is spent on research or development; the remainder goes to planning, administering, and monitoring sponsored research activities. Between 1970 and 1982, the number of researchers at FHWA was reduced from 257 to 165, and 44 of the remaining staff were involved in informing others of research results rather than performing research(*10*). Although FHWA's research expenditures have been roughly consistent over the past 5 years, inflation has reduced substantially the size of this program.

A key part of the FHWA research effort is the Federally Coordinated Program of Highway Research and Development (FCP) established in 1971 to coordinate federal and state activities. Recognizing that the states control the larger research efforts and also possess much of the talent needed to perform effective research, the FCP works with the states to coordinate four programs that are largely derived from federal funding—NCHRP and HP&R, discussed above, and the FHWA administrative contract and staff research programs. Because the states own and operate the majority of the highway system, they are closer to the operating problems and better positioned to try new concepts. Thus an effective R&D program requires substantial state participation; and the FCP seeks to achieve this. Virtually all work in the FHWA contract and staff research programs and approximately 70 percent of work in the HP&R and NCHRP programs are included in the FCP. The remaining 30 percent of the work in the HP&R program and that portion of the NCHRP committed at the discretion of the states are focused on local problems or national problems selected independently by the NCHRP program committee.

Other Federal Agencies

The National Highway Traffic Safety Administration (NHTSA) funds and conducts highway-related research on specific safety problems in addition to a substantial program of upgrading accident data records systems. It supports the Fatal Accident Reporting System (FARS) and the National Accident Sampling System (NASS), which permit increased understanding of accidents in relation to roadway and vehicle characteristics. NHTSA also funds the development of statewide accident reporting systems, including systems for improved identification of accident locations. Those systems provide an improved capability for research into accident causes, prevention, and loss reduction as well as the evaluation of highway safety programs. Over and above the support of data bases, some $2 million of research funded and performed by NHTSA is directly applicable to the design and operation of roads and streets.

Additionally, the Office of University Research of the U.S. Department of Transportation funds highway transportation research projects through a special grant program. The Urban Mass Transportation Administration (UMTA) has also funded highway research, particularly for urban street operations and transportation systems management techniques that directly relate to street design and operation. Policy research related to highways is performed from time to time by the Office of the Secretary of Transportation. Pavement-related research conducted by the Federal Aviation Administration (FAA) also can be applicable to highways. In the recent past, the Environmental Protection Agency and the Department of Energy funded staff and contract research in the general area of highway transportation with particular emphasis on environmental impacts and energy conservation techniques.

Both the U.S. Army Corps of Engineers and the U.S. Forest Service undertake research applicable to highway transportation. That research is usually directed to specific problems encountered in construction and maintenance programs or to economic analysis. The Forest Service builds and maintains a 320,000-mile road system nationwide, adding approximately 10,000 miles each year. It is the fourth largest road system in the world, and annual road-related expenditures are approximately $750 million.

The Forest Service maintains a small but productive R&D activity to reduce its construction and maintenance costs and to improve the performance of its road system. Expenditures for road materials R&D are between $0.2 and $0.3 million per year. Other road-related R&D, which is difficult to isolate in the total program of the Forest Service, and the materials program together probably do not exceed $1 million. Despite the size of this program, it is the central source of R&D in the United States for low-volume roads, which are a major part of the U.S. public roads system.

The U.S. Army Corps of Engineers manages an extensive program of research at a number of research laboratories in support of its own facilities and those of the military services. Some of this is applicable to highways, particularly that related to pavements, structures, loading areas, and airport runways. Its Cold Regions Research and Engineering Laboratory in New Hampshire provides research assistance to state highway agencies in surrounding states. Direct highway-related research expenditures of the Corps of Engineers are estimated at less than $1 million per year based on a 1982 program of approximately $1.3 million in the pavements research area, which includes rail and port related research. The U.S. Air Force and the FAA also perform research on runway pavements; perhaps $0.5 million per year of this is applicable to highways.

The National Bureau of Standards (NBS), through its Centers for Building Technology and Materials Sciences, focuses on the fundamental understanding of materials and developing testing methods. For the most part, their work on materials of interest to highway research is funded by other agencies as mentioned above. The Materials Reference Laboratory, part of the NBS' Building Materials Division, is supported by the American Society for Testing and Materials (ASTM) and AASHTO to assist highway related laboratories with improving the quality and uniformity of testing procedures.

The Counties and the Cities

Many county and city highway agencies perform or cooperate in highway transportation research. The major associations (National Association of Counties and National League of Cities) perform some research, develop problem statements, and disseminate research findings of interest to their members. Technology transfer, rather than pure research and development, is their principal activity. Counties and cities do participate directly by providing data and test beds for demonstrations of new products and methods.

Because most of the research by counties and cities is funded by other sources and participation is often in the nature of in-kind services, it is difficult to estimate expenditure levels; however, it appears that direct R&D expenditures by the counties and cities are about $1 million per year.

Private Sector Research

Highway-related research in the private sector is difficult to quantify for three reasons:

1. Many firms do not publicize the scale and focus of their research activities.
2. The number of firms in each sector of the industry is large; and no one, or number of, firm(s) represents a signficant proportion of sector activity. Thus development of an aggregate research value requires surveying a large number of firms.
3. In many sectors research is focused on a material, a process, or a product that may have applications in industries other than highways.

The major associations and institutes concerned with highways and highway construction have all curtailed research activities in recent years at least partly in response to declines in total construction activity during the recession. In testimony prepared for the Committee on Science and Technology of the U.S. House of Representatives, the President of the Portland Cement Association noted that cement use in 1982 was at its lowest point in 20 years. The long-term trend in the industry has also been downward. Construction, which accounted for 12 percent of GNP in 1950, has fallen to half that figure. In that period the major thrusts of capital investment (and presumably research) have been on meeting environmental standards and increasing energy efficiency. He stated: "In this kind of economic climate, it's little wonder that research was one of the extras that had to be sacrificed or curtailed pending a return to better times" (*11*).

These cuts have occurred both in the Portland Cement Association and in cement companies. Of 18 cement companies that once maintained their own research laboratories, only 6 laboratories remain. Within the Association, research funding has dropped to about $1 million a year, a third of the level a decade ago; 25 percent of this is highway related.

The Asphalt Institute also has seen budget reductions from $4.0 million in 1981 to $3.2 million in 1984 and field office reductions from 20 to 16, although the headquarters research staff of engineers has remained unchanged (*12*). The National Sand and Gravel and National Crushed Stone Associations have closed their laboratories.

Transportation Research Board (TRB)

The Transportation Research Board (a unit of the National Research Council, which is the operating arm of the National Academy of Sciences and the National Academy of Engineering) was organized in 1920 to stimulate, correlate, disseminate, and when appropriate perform highway research. During the 1960s TRB broadened its scope to encompass research in nonhighway modes and interactions between transportation and social, environmental, and economic issues.

TRB programs are carried out by some 270 committees, task forces, and panels comprised of more than 3,300 members from a wide range of scientific and technological disciplines. TRB spending is not shown in Table 10 because TRB is supported by the other programs shown in the table. State transportation departments, various administrations of the U.S. Department of Transportation, the Association of American Railroads, and many private companies and individuals pay a total of about $5 million a year (exclusive of NCHRP) to support TRB activities.

These activities include an extensive program for publishing research results, an annual meeting and many regional and special purpose meetings, technical information-exchange visits to transportation agencies, a computer-based information system covering recent and ongoing research projects, and various special projects.

TABLE 10 Spending for Highway Research by Major Sponsors, 1982

	$ Million
States	
Highway Planning and Research (HP&R)—1½ percent of funds allocated under various federal programs may be spent by the states on planning or research, usually some matching funds are required.	30.0
Independent Research—state financed highway research funded exclusively by states.	5.0
National Cooperative Highway Research Program (NCHRP)—state HP&R funds, not included above, that are contributed by the states to a common fund to address problems of mutual interest.	4.4
Federal Highway Administration	
In-house and contract spending on highway research.	21.5
Other Federal Agencies	
National Highway Traffic Safety Administration (NHTSA)—operates extensive systems to collect sample data on accidents, collects complete data on fatal accidents, and performs some highway-safety research.	2.0
U.S. Department of Transportation—through the Transportation Systems Center, the Office of the Secretary and the Urban Mass Transportation Administration funds research through programs for university research and transportation system management.	2.0
U.S. Army Corps of Engineers—performs research on pavements and structures and operates Cold Regions Research and Engineering Laboratory which aids highway agencies in surrounding states.	1.0
U.S. Forest Service—performs research related to the 320,000-mile road system that is built and maintained by the Forest Service.	0.3
Other—the Air Force, Federal Aviation Administration, National Bureau of Standards, and other agencies perform research related to pavements or other road materials; part of this can be considered highway research.	2.0
Cities and Counties	1.0
Private Firms, Industry Associations, and Other	2.0–5.0
TOTAL	70–75

NOTE: The Transportation Research Board is not listed separately because its $5 million annual budget comes from the research expenditures of several of the organizations already listed.

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3

Gaps in the Current System of Highway Research

Research should be directed to areas that are important, to elements that can be improved, and to results that can be achieved. Highway research is characterized by unique features that affect how this focus should be achieved. For example, highway research is highly decentralized among all levels of government and many private organizations. No single agency controls the majority of highway research spending. Also, the quality and safety of roads and the environmental consequences are as important as their costs.

These special features of highway research (need for large-scale integration and for safety and environmental considerations) combine with the requirements of all good research to form the basis of the following questions. Answers to these nine questions can pinpoint research areas with untapped potential.

1. Will the research yield big payoffs if successful?
2. Is the research area currently neglected?
3. Will the research investigate important issues previously slighted because of institutional or organizational barriers?
4. Can the research findings be used?
5. Does the research require an effort on a larger scale than can be expended by present programs and institutions?

6. Does the research require an integrated effort or national approach?
7. Does the research respond to new and potential changes in national policy?
8. Does the research use or respond to technological changes?
9. Will the research improve safety or the environment significantly?

Each of these questions is discussed below. This chapter concludes with a list of potential research projects that appear particularly promising with respect to these questions.

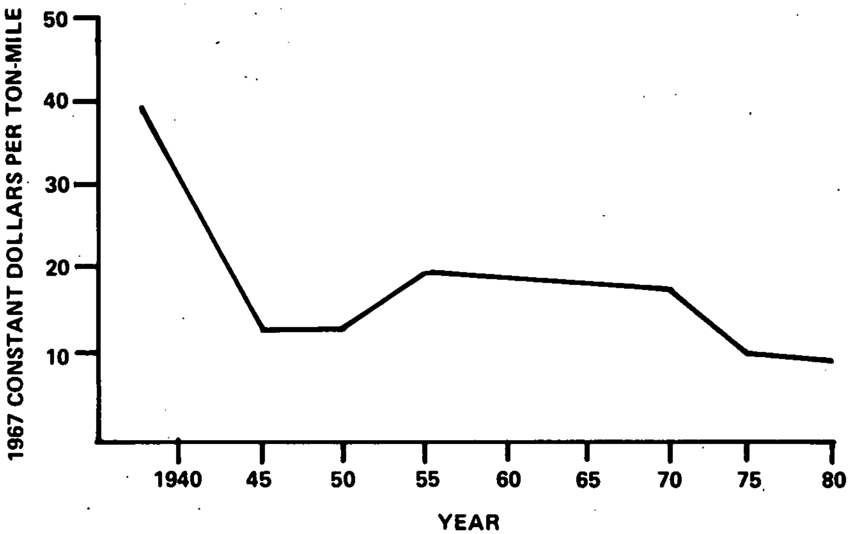
1. BIG PAYOFFS

The current investment in highway research is surprisingly low given the potential payoffs associated with more cost-effective, safer highways. Overall, the nation currently spends more than $40 billion per year on roads. A 1-percent cost reduction would save $400 million a year compared with the $70 million or so now spent on research in highways. Past improvements in highway productivity demonstrate that such a percentage improvement has been repeatedly achieved.

A good example of such improvement in productivity is the increased amount of freight moved over rural highways per dollar spent. Currently it costs about $12 per ton mile to transport goods that cost $20 per ton mile in 1955 (see Figure 2). These savings are partially the result of research-related improvements to rural highways. No doubt even greater payoffs would result from more intensive research. The potential payoffs can be gauged in part by examining federal, state, and local government plans for highway-related expenditures in the years ahead.

In 1983 dollars, the spending level for highways during the next two decades will be in the range of $1 trillion. Pavement-related spending will be about $400 billion based on expected allocations. Bridge repair and replacement activites will cost the nation upwards of $100 billion by the end of the century. Maintenance, grading, and drainage are also areas in which the nation will spend large amounts and research might make the largest contribution to reducing massive public expenditures.

Research can help to reduce these massive expenditures, but only if it can produce better, more workable products and processes. By its nature research looks into unknown areas, and the value of the results and findings cannot be guaranteed. Nevertheless, the inherent risks of research can be offset somewhat if major research activities are concentrated in areas in which the largest payoffs appear achievable.



Note: (a) Ton-miles of intercity freight as reported by the Interstate Commerce Commission *(1)*. (b) Expenditures on main rural highways are reported in *Highway Statistics (2)* and *Highway Statistics Summary to 1975 (3)*. (c) Expenditures have been deflated to 1967 dollars using *Price Trends for Federal-Aid Highway Construction* for capital expenditure *(4)* and *Cost Trend, Highway Maintenance and Operations (5)* for maintenance expenditures.

FIGURE 2 Total expenditures on main rural highways per ton-mile of intercity freight (*1-5*).

Corporations, in setting their research budgets, devote substantial resources to assessing the potential market for new products. Because the highway industry has a predictably important role to play in the nation's transportation future, it is spared much of the risk that private firms face when they spend funds for research on products that may be unpopular or rapidly superseded by competing technologies. Thus, highway research spending might reasonably be expected to be even more "bottom-line oriented" than private sector research, inasmuch as the composition of future spending appears relatively predictable. Nevertheless, this is not so.

2. NEGLECTED AREAS

Although spending for highway research across the board is low compared with spending for research by other industries and in other coun-

TABLE 11 Distribution of General Highway Expenditures Versus Distribution of Research Expenditures

Major Highway Spending Areas	Estimated Percentage of General Highway Expenditures	Estimated Percentage of Highway Research Expenditures[a]	Allocated Percentage of Problem Statements to AASHTO[b]	Percentage of Research Projects In Progress[c]
Pavements and Surfaces	27	10	9	19
Bridges (new and replacement, rehabilitation, and maintenance	9	14	9	Included in engineering
Grading and drainage	27	2	6	5
Traffic operations	4	11	11	24
Snow and ice and traffic control	6	2	13	4
Administration, planning, design, and right-of-way acquisition	16	19	34	47
Other (research dissemination, administration)	0	13	5	1
Safety, driver education, and enforcement	11	27[d]	12	

[a]Estimated from FCP program expenditures

[b]Allocation of annual AASHTO research statement submittals.

[c]Based on search of Highway Research Information Service, a TRB computerized data base.

[d]Actual safety funding averages 40 percent but is carried under other titles, e.g., traffic operations.

tries, some areas appear more neglected than others. One neglected area is grading and drainage. Although it accounts for more than one-fourth of all highway spending, only 2 percent of highway research funds is allocated to research in this area (see Table 11).

Similarly when research and program expenditures are compared side by side, basic paving materials research stands out as an area in which the immense payoff potential is not reflected in associated research spending. Pavements represent nearly one-third of all industry expenditures yet attract only one-tenth of industry research funds. When the future directions in spending, cited earlier, are taken into account, the disparity in research directed toward basic materials, paving technologies, and maintenance is further emphasized.

3. ORGANIZATIONAL BARRIERS

Without special effort some important research areas may never overcome the organizational barriers inadvertently erected by various highway groups. For example, a Martin Marietta Corporation executive, when asked about the low level of highway-related research in his company, responded that there is no incentive to do research on highways because rigid standards and low-bid procurement practices inhibit product innovation. Products whose first costs exceed those of competitors tend to be avoided, regardless of their life-cycle costs. Products of superior quality do not necessarily fare better in low-bid, set-standard procurement. As noted by another major manufacturer in a presentation to a congressional committee: "Today's highway purchasing standards are generally based on minimum specifications and low bids. There is little economic incentive for industry to provide added value, unless the specifications can be changed." The President of the Portland Cement Association has similarly argued that "the low first cost concept is a serious deterrent to new product development, quality improvement, and innovative technology."

Because the highway materials and services provided by private industry are purchased by tens of thousands of independent agencies and companies, materials standards and standardized tests are clearly essential for safety and cost efficiency. On the other hand, development of highway products could be left behind while other technologies advance if the procurement structure discourages the purchase of better products and processes. Standards that are more performance-oriented than today's could encourage more private-sector highway research. However, obtaining the factual basis for developing such performance-based standards will in many cases require major new research. Thus, current standards and institutional arrangements combine to impede research that could change standards, making some aspects of current practice self-perpetuating.

Obstacles also arise from within the highway agencies. Research often fails to change practice because of limited understanding, organizational inertia, inflexible standards, a preoccupation with first costs, a mistrust of change, or a desire to perpetuate jobs. A complaint commonly voiced by seasoned researchers is: "Why bother? We came up with a better way 10 years ago, and our operations people still won't use it. They won't learn how." Or, "They won't buy the equipment they need to do it." Or, "It costs too much at the beginning." Or, "It won't meet some dubious specification."

Sometimes the obstacle is a political need to use local products and suppliers. For example, in recent congressional hearings, Patrick J. McCue from the Florida Department of Transportation (DOT) recounted the difficulties his state was experiencing with limestone aggregate in pavement. Relative to the high-quality granite available in neighboring Georgia, Florida limestone lacks strength and thus pavements containing the material crack and wear much faster. Yet political realities made it futile to think about importing Georgia granite.

4. USABLE FINDINGS

If such political realities as the need for the Florida DOT to buy only Florida limestone are insurmountable, then research on issues such as the life-cycle cost-effectiveness of alternative aggregates in Florida might be an exercise in futility. Or, it could be instrumental in changing these political realities by demonstrating the indefensibly high costs of favoring in-state suppliers. Judging whether a research finding is politically or organizationally achievable is difficult and uncertain, but this is a key determinant of whether research changes practice. Determining what is achievable in each case is probably the most difficult, albeit the most crucial, judgment in the entire research process. The training requirements, organizational change, investment in equipment, cash flow requirements, personnel implications, and legal liabilities of new approaches are crucial aspects of a research result.

The usefulness of research results cannot be completely determined from laboratory results. Personnel adjustments, retraining, variable field conditions, and a host of other factors can inhibit the realization of a new product's potential. Some of these pitfalls can be avoided by linking research, product development, and product application activities. Nevertheless, translating a research result into innovative practice depends on behavioral and physical factors that are risky and partly unpredictable. Similarly, whether a research result will be economically achievable involves the shape of the learning curve, uncertain economics of scale, unknown side effects, and so forth.

Because political, organizational, technological, and economic factors can make or break potential innovations, assessment of research potential requires judgments about the factors. Research personnel well founded in technological understanding are not necessarily well positioned to make these judgments, whereas administrators and political leaders may not be fully aware of the technological options that might potentially be developed. Assessing whether an innovation is usable before investing the funds in the research to develop it requires judgments founded on the full range of affected interests.

5. LARGE-SCALE PROJECTS

Most of the approximately $70 million now spent on highway research is parceled out in problem-specific contracts of $30,000 to $300,000.

Analysis of the 1981 Federally Coordinated Program of Highway Research and Development (FCP) showed 7 projects below $250,000, 7 above $500,000, and 12 in between. National Cooperative Highway Research Program (NCHRP) projects show a similar pattern with the typical project in the $250,000 to $300,000 range. In the 20-year period from 1963 to 1983, only two NCHRP projects exceeded $0.5 million, and none exceeded $1 million. While frequently very effective, conducting research in many, small, relatively separate projects is not ideal for certain types of problems.

Long-term research projects need special emphasis to justify the substantial resource expenditures and to plan for the long-term commitment of funds and management. Because most funding for highway research is subject to short-term budgetary pressures at both the federal and state level, long-term research projects are at a particular disadvantage when they must compete with immediate, tangible needs. Moreover, turnover in the senior management of transportation agencies makes it difficult for such projects to receive continuing management attention and support.

Nevertheless, the national attention demanded by the nation's highway deterioration problem during the last few years reflects the logical consequence of this neglect of long-term issues. For example, when the AASHO road test was completed in 1960, the pavement experts suggested that a long-term field test embracing many climates, soils, construction techniques, and maintenance approaches would greatly improve the value and applicability of the road test results. The plan called for a series of satellite road tests to translate the findings to different regions of the country. The cost, when adjusted for inflation, would probably have been about $3 million, allowing for some costs that were not included in the original study design.

The plan was never implemented because the costs ($2 million in 1964) were too great and its payoff too remote (not until 1980). Ironically the highway deterioration that received such widespread media attention in 1982 might have been less severe had this research been done, and current highway funding could be more effectively spent if the results of that research were available. The problems of recent years promise to become a blueprint for the future unless the nation devotes enough resources to finding better ways to build and manage its investment in public works.

A good example of such a problem occurred recently on Florida's Interstate 10. Some 50 miles of I-10, mostly between Pensacola and Tallahassee, began pumping and faulting along the sides as a result of trapped water beneath the slab. These signs of pavement distress were unexpected on a road segment only about 8 years old. The highway's design life was 20 years, and a radical rehabilitation should not have been necessary for several years after that time.

Nevertheless, these circumstances forced Florida to rehabilitate its comparatively new highway. Recently Florida let a rehabilitation project at a cost of $6 million for an 8.6-mile segment. The engineers involved remembered: "We did everything by the book, and it still failed." Numerous federal and state auditors and other investigators corroborated this statement: I-10's design was "FHWA state-of-the-art." Neither the Florida DOT, its contractor, nor the FHWA had any way to know that the soil conditions of the area were incompatible with the special soil stabilization process they used.

The following is an excerpt from the 1983 Florida DOT report to the Florida House Transportation Committee on Project Accountability:

> The most common causes of premature facility failures appear to result from the limitations of the transportation engineering technology existing at the time. Furthermore, today's technology is not yet refined sufficiently to assure freedom from occasional and often costly premature failures. The most critical need in this area seems to be for additional transportation engineering research.

This research is not being done because it requires a large-scale, long-term effort that exceeds existing institutional capabilities. Research funds are currently spread among the federal government and the states, and no organization has sufficient resources to take on a major new effort costing several million dollars a year without entirely discontinuing or substantially dislocating all of its other activities. Thus, in the search for areas where the current system of highway research may not be tapping all of its potential, special attention should be given to large-scale projects. Such projects are not inherently desirable; small-scale research involves smaller risks and fewer complications. But, large-scale long-term projects, which may result in the greatest payoff despite their cost and complexity, are most likely to be overlooked.

Highways, in particular, because of their long lives, place exceptional demands for long-term research. Some characteristics of materials can only be studied under long-term, actual conditions. Continuous attention—both funding and research direction—is needed to make progress in improving the life-cycle performance of highways.

6. GREATER INTEGRATION OF EFFORT

Because of the highly fragmented nature of current highway research activities, processes may be overlooked that operate through a sequence of distinctly autonomous steps, each managed by a different organizational unit. In such instances, each step in the process either depends blindly on the successful completion of earlier steps in the process or specifies, often through rigid standards, certain conditions that must be met at previous stages.

In either case improving the process as a whole requires determining exactly how each step should be accomplished, bearing in mind its implication on other parts of the overall process. However, different organizations are involved in each stage, and none of them is able to evaluate and control the others. An example of such a process is the construction of an asphaltic pavement, which involves ten major steps:

- Mining one of a wide variety of crude oils;
- Distributing the oil to a refinery, possibly combining it with other crude oils in the process;
- Refining the crude oil to produce gasoline, diesel fuel, residual oil, and so forth and asphalt;
- Possibly adding chemical additives to the asphalt;
- Quarrying the granite, limestone, or other aggregate to mix with the asphalt;
- Designing the asphalt mix;
- Mixing the aggregate with the asphalt through one of several available processes;
- Designing the pavement section to accommodate the soils, subbase, climate, and traffic involved;
- Constructing the pavement; and
- Opening the constructed road to traffic consisting of some combination of vehicle loadings.

The completed road is then subjected to varying levels and kinds of maintenance that are determined by management practices, budgeting constraints, and other needs.

These various links in the chain are managed by oil companies, refineries, chemical companies, mining companies, highway departments, mixing plants, and construction companies. Each depends on the work of others, but none is fully able to control the others. Improving the overall chain involves evaluating trade-offs among the links.

Consequently, coordinating research in the highway industry is achieved through many mechanisms—the FCP, the NCHRP, the American Association of State Highway and Transportation Officials (AASHTO), the Transportation Research Board (TRB), the American Society for Testing and Materials (ASTM), the American Society of Civil Engineering (ASCE), the Institute of Transportation Engineers (ITE), the

American Concrete Institute (ACI), the Asphalt Institute and many other professional and trade groups that highlight apparent coordination difficulties and use their broader organizational bases to develop solutions. Such grass roots coordination has been and should continue to be a key mechanism for integrating the activities of the diverse organizations involved in providing highways.

Informed, voluntary coordination is best suited, however, to correcting well-defined problems that occur between several adjacent links. Current coordination processes are unlikely to assess successfully whether the system as a whole can be improved through drastic reorganizaton of the parts or through substantial redefinition of the product. Such an overview requires more resources and stronger control than existing coordinating mechanisms can muster.

7. NATIONAL POLICY

The grass roots, bottom-up research processes now in place are ideally suited to addressing the specific problems associated with a particular climate, soil composition, local source of stone or sand, and so forth. Because of the immense variety in local materials, building conditions, structural requirements, and topographical features, each agency needs a strong, grass roots, problem-solving research capability to deal imaginatively and effectively with its unique problems. A different research approach may be warranted, however, when all states or all counties face a similar problem at the same time.

When the government changes federal regulations for vehicle dimensions, highway design, or other system features, many states may find themselves facing identical, unresolved questions. Recently changes in truck weight limits, regulations regarding the length and width of trucks, the imposition of a national maximum speed limit, and other legislative changes have directly affected how each state and county builds, maintains, or operates its highways. If the bottom-up research institutions are left to deal with such across-the-board shifts as they arise, some duplication of effort is likely despite coordination mechanisms such a FCP, TRB, and AASHTO.

Thus, in assessing opportunities for research, special attention should be given to the preformance of highway components that may be altered by shifts in national policy. For example, research on the effects of increased axle loads could systematically cover the range of soil types, climate conditions, construction techniques, maintenance practices, and traffic loadings present in various parts of the country. These could be tied into a single, carefully coordinated experiment in which coverage of each of these different conditions would permit meaningful comparisons.

Such coordination would greatly improve the transferability of results achieved by the present bottom-up system. Currently states, universities, and counties share their results; but meaningful comparison is impaired because not all relevant conditions have been explored, or because different studies used different measurement techniques, recorded different characteristics of the process, and so forth.

8. TECHNOLOGICAL CHANGE

Fundamental changes in technological capability affect each state and county, but research on some new technologies will be needlessly fragmented and duplicative if left to the various states and other organizations. Equally important, many of these organizations do not have the available resources and skills to monitor properly new developments in technology. In seeking innovative applications of exotic new technology to highways a centralized approach can be warranted. For example, if advances in computer technology make automated vehicle navigation or automated vehicle guidance feasible, the widespread potential for such an advance could justify a concerted national research effort.

9. SAFETY AND ENVIRONMENT

Despite the impressive continuous improvement in safety of the highway transportation system—fatalities are now at half the rate in the 1950s—safety continues to be a paramount concern. Even though the death rate on U.S. highways had declined to approximately 46,000 by 1982, this still is a staggering loss of life. Research has greatly improved and can continue to improve the safety of highway travel. The Interstate highway system, with its superior geometric features and access control developed through research, has less than one-half as many fatalities per vehicle mile as the primary system. During the past 29 years, virtually everything the driver sees from the road—from energy-absorbing bridge abutments to breakaway utility poles to deflective grading—has been improved by research to enhance safety.

Because safety is a top priority, the nation has developed an extensive data collection system that carefully monitors where the system is, and is not, performing safely. Two programs of the National Highway Traffic Safety Administration, the National Accident Sampling System and the Fatal Accident Reporting System, devote $15 million a year to collecting information that will improve understanding of highway safety and help identify the parts of the system most amenable to improvement. State programs have also given top priority to safety. State programs, such as those in New York, Michigan, Utah, and Washington have developed innovative information systems to track accident locations, law enforcement data, and highway systems data.

Although safety has accounted for the lion's share of research dollars (27 percent of all FCP spending is for safety research), continued financial support could lead to big payoffs. One promising area is the relationship between highway geometrics and safety. This issue has been receiving added attention as the nation turns increasingly to resurfacing, restoration, and rehabilitation (3R) of roads instead of constructing entirely new roads. Efforts to set national standards for 3R have failed repeatedly partly because of the diversity of local conditions that must be embraced by such standards and partly because of the lack of fundamental knowledge of how specific geometric features affect highway safety.

Other benefits to both the economy and the environment, items that never show up on a budget, can be attained through research. For example, deicing salt represents only about 10 percent of a highway department maintenance budget, even in a cold state such as New York. Nevertheless, the widespread use of deicing salt is estimated to cost the nation as much as $500 million per year in corrosion to bridges and reinforced concrete, to cost motorists as much as $4 billion per year in premature rusting and corrosion, and may cause environmental damage through runoff to wetlands and water supplies near salt-treated highways. Such nonbudgetary payoffs are another key determinant of where highway research spending might best be placed.

POTENTIAL RESEARCH AREAS

A list of six important, high-potential research projects has been compiled that fits the considerations discussed above. This list is the distillation of much discussion, redefinition, and evaluation. Ideas and suggestions came from highway practitioners, research personnel, previous research reports, and various other sources. Although the list is not comprehensive and other areas are clearly deserving of research, the six research projects selected were judged to be particularly demanding in their resource requirements and particularly promising in their potential payoffs.

This focus of resources on six particularly massive problem areas must not distract from the thousands of other areas where research continues to make progress; other research activities must continue. Nevertheless, the six areas given below stand out as promising large potential payoffs but large-scale investments will be required to achieve that potential.

Asphalt. An integrated evaluation that carefully monitors asphalt from various crude oil sources through to various field uses. At present, crude oil suppliers, refiners, mixing plants, contractors, state highway departments, and others participate fairly autonomously in a chain of events that takes asphalt from the ground and converts it to a paving material.

Most of these organizations cannot control what happens to this material at other points on the chain. Yet field experience suggests that huge variations in product performance are evident and that substantial improvements in performance might be possible if the entire manufacturing process—type of crude oil used, method of refining, additives, mixing process, pavement design, and construction procedures—were more carefully coordinated. Even a 1-percent improvement in product life would mean a saving of $100 million a year.

Long-term pavement performance. In spite of all the national concern about substandard highway condition, the United States has not systematically studied highway performance since the AASHO Road Test in 1958 to 1960. That test was a massive experiment that gave the nation, and indeed the world, its soundest understanding of the properties of pavement; nevertheless it leaves many unanswered questions.

By necessity this test represented only one climate, was conducted in an accelerated fashion, and incorporated some atypical maintenance procedures. A long-term field test that systematically covered a wide range of climate, soil, construction, maintenance, and loading conditions could substantially refine and expand the findings of the AASHO Road Test, thus yielding massive payoffs in terms of reduced construction and 3R expenditures.

Maintenance cost-effectiveness. Maintaining the nation's 4-million-mile state and local road network requires more than one-third of the total highway budget, and the share of highway resources going to maintenance is growing. In spite of this spending, continued deterioration of the nation's road systems shows the need for more efficient and more effective maintenance.

Methods, equipment, and materials have changed little in 20 years although the mileage and traffic volume of the highway system have increased dramatically. The opportunity for major improvements through maintenance research is substantial: further mechanization, improved repair materials, off-site prefabrication, or more efficient staffing and scheduling could all yield substantial savings.

Protection of concrete bridge components. An epidemic of bridge deck deterioration plagues the United States. Some 253,000 bridges are currently deficient, and 3,500 more become deficient each year. Bridge deterioration will continue unless technology is developed to arrest the corrosion process in existing salt-contaminated bridge decks and to protect from contamination or corrosion those new and replacement decks being constructed today.

Two areas of research seem promising in the search for ways to extend bridge deck life: preventing deterioration of chloride-contaminated decks through electrochemical removal of chlorides, impregnation of the deck and upper steel, or cathodic protection; and preventing deterioration of new and uncontaminated decks through newly developed protection systems for the reinforcing steel and external or internal sealants for the deck surface.

Cement and concrete in highway pavements and structures. The highway industry consumes more than $400 million of portland cement annually, which is about 13 percent of all portland cement made in the United States. Yet industry research is diminishing right at the time the quality, reliability, and utility of this basic building material are the most important.

Concrete is used for 85,000 miles of roads, thousands of miles of median strips, curbs, and virtually all sidewalks. Most bridge decks, short-span bridges, and the supporting structures for thousands of bridges are also made of concrete.

Because the single greatest cause for failure in concrete structures is deterioration of the concrete itself, research is needed into ways to increase durability, particularly for structural uses.

Chemical control of snow and ice on highways. All but 7 of the 50 states can count on snowstorms on parts of their highway systems every winter. Since the initial use of salt on intercity highways about 50 years ago for snow and ice control, its use had grown to 12 million tons in 1982. This heavy use of salt for snow and ice control exacts a price in vehicle corrosion, bridge deck deterioration, and contamination of soils and waters.

Two avenues of research could help to reduce the adverse effects of chlorides and maintain the safe levels of service required on our highways during winter storm periods. First, the storing, handling, applying, and controlling of salt offer many opportunities for improvement; and research should be directed at improved chemical-management techniques. Research should explore improvements also in mechanical and thermal means of snow removal. Second, new chemicals with acceptable melting qualities and without adverse environmental effects should be developed for use in winter maintenance programs.

Although other valuable improvements in highways require research in many areas beyond those highlighted here, a unique aspect of this study is the focus on innovations that promise exceptionally large cost savings and that are particularly likely to be overlooked by current practices and existing research organizations (Table 12).

Federal, state, and local governments will spend vast sums of money in these six areas according to FHWA's *Status of the Nation's Highways: Conditions and Performance*, 1983. This report indicates the shift that is already occurring from capital spending to maintenance and operations. For example, the timeliness of research on maintenance cost-effectiveness and such specific maintenance tasks as snow and ice removal is apparent.

In 1970 capital spending accounted for 55 percent of highway spending. This percentage declined over the decade, reaching 45 percent in 1982. In that same period, maintenance spending increased from 24 percent to 29 percent of total spending and highway patrol and safety expenditures increased from just over 6 percent to 10 percent. These trends, which are projected to continue, are shown in Figure 3. Noncapital expenditures are likely to increase from the present 55 percent of spending to 75 percent by 1995.

Enactment of the Surface Transportation Assistance Act of 1982 has momentarily arrested the trend toward decreased capital spending. However, FHWA forecasts of capital spending indicate that an important shift will occur from new construction to reconstruction of existing facilities. Federal-aid spending for new pavement will decline from 15 percent in the base period (1976-1978) to 5 percent in the forecast period (1980-1995) (see Table 13). Similarly purchases of right-of-way will decline from 13 percent to 6 percent. At the same time, pavement reconstruction spending will increase from 25 percent to 38 percent, and spending on structures will increase from 17 percent to 21 percent. These shifts indicate the importance of learning more about factors affecting the service life of pavements, particularly in the six areas identified in this report.

TABLE 12 Assessment of High-Priority Highway Research Areas

	Asphalt	Long-Term Pavement Performance	Maintenance Cost-Effectiveness	Protection of Concrete Bridge Components	Cement and Concrete in Pavements and Structures	Chemical Control of Snow and Ice
Probability of a big payoff	High	High	High	High	Medium	High
Has research on this topic been neglected in recent years?	Yes	Yes	Yes	No	Yes	Possibly
Degree to which organizational barriers now impede research	High	High	Medium	Low	High	Low
Likelihood that research findings will be usable	High	High	High	High	High	Medium
Scale of effort required for successful project	Large	Large	Small	Large	Medium	Medium
Does the research require greater unity of effort, now splintered?	Yes	Yes	Probably	Probably	Yes	Probably
Do changes in national policy create a common, multistate research need?	Possibly	Yes	Possibly	No	No	Yes
Do major technological changes require research here?	Yes	No	Possibly	Possibly	Possibly	Possibly
Likely magnitude of impact on safety and environment	Medium	High	High	High	Medium	Medium

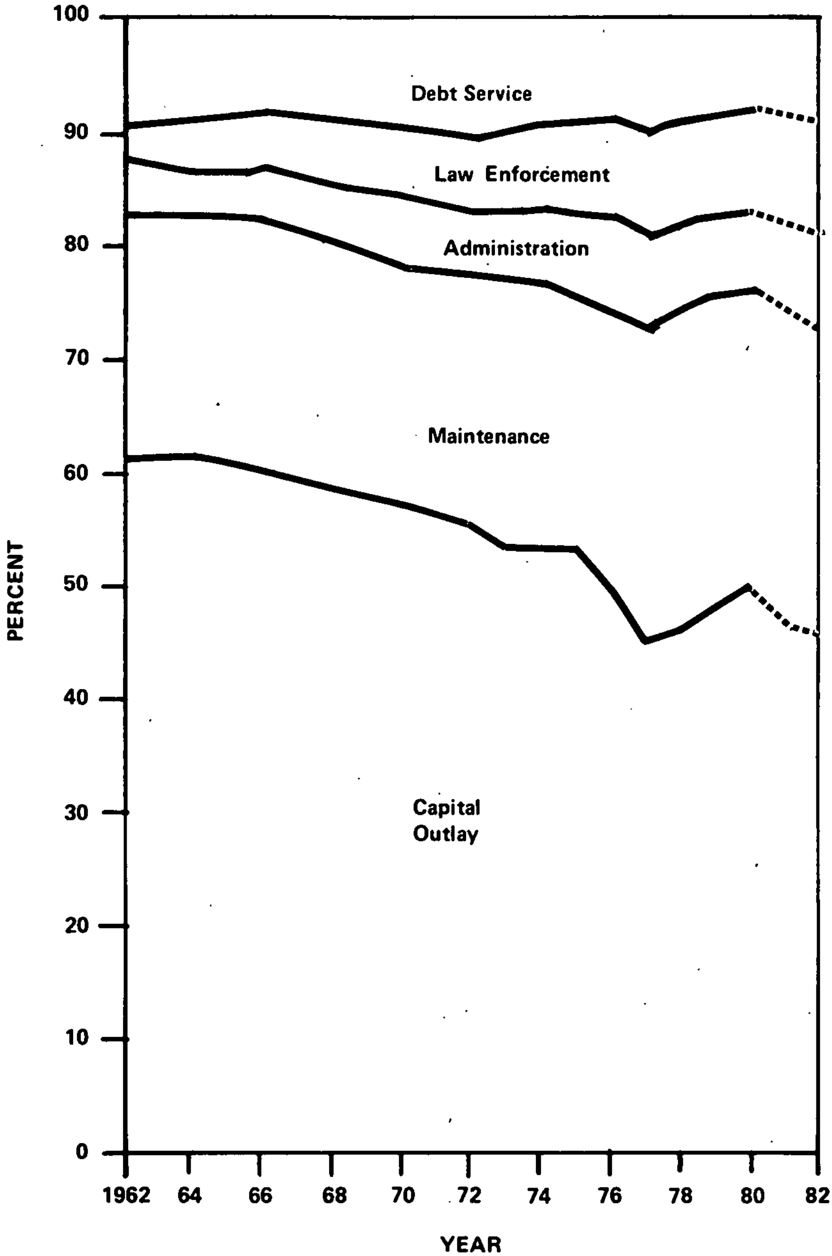


FIGURE 3 Distribution of total highway disbursements, 1962–1982 (*6*).

TABLE 13 Comparison of Past and Expected Future Federal-Aid Capital Spending (*7*)

Construction Type	Past (%) (1976–1978)	Future (%) (1980–1995)
Pavements		
New	15.0	5.3
Reconstructed	24.5	38.4
Total	39.5	43.7
Structures		
New	6.5	9.2
Replaced	9.3	8.6
Repaired	1.1	1.9
Total	16.9	19.7
Other		
Right-of-way	13.1	6.1
Grading	16.6	19.1
Other	13.9	11.4
Total	43.6	36.6

The trend toward increased spending is also supported at the state level and is embedded in existing legislation and spending programs. These trends can be expected to persist and dominate spending patterns through this decade and into the 1990s. Therefore, long-term research can expect to have a long period of application without fear of being made obsolete by a shift in public policy.

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PART II

Potentially Promising Areas of Research

4
Asphalt

Objective: To improve pavement performance through a research program that will provide increased understanding of the chemical and physical properties of asphalt cements and asphaltic concretes. The research results would be used to develop specifications, tests, and construction procedures needed to achieve and control the pavement performance desired.

INTRODUCTION

Asphalt, more than any other single product, sustains the nation's highway plant and facilitates the flow of commerce and personal mobility. Improvements in asphalt have contributed substantially to the productivity of the nation's transportation system, but the continuity of this success requires constant attention to the problems and promise of this vital material. As the nation increasingly focuses on the rehabilitation of roads, the number of dollars spent on asphalt and the importance of this product to the nation's economy and life-styles increase proportionally.

The introduction of larger and heavier trucks together with growing traffic volumes further increase the demands placed on pavements. As more and more is demanded of asphalt, costly and embarrassing failures continue to occur and defy explanation. The changing chemical composition of asphalt, caused in part by disruptions in world oil supplies, may contribute to those problems. The physical tests and specifications used to classify and control asphalt, some dating from more than 70 years ago, do not always control closely the performance of this material. Construction defects, which account for numerous failures, might be less costly if more reliable, durable asphalts were developed and functional specifications were drawn so that products were more forgiving of field errors. In spite of the immense potential for improving asphaltic pavements, relatively little research is being done. Day-to-day problems with asphalt receive close attention and often ingenious solutions are found, but these ad hoc approaches fall far short of what a well conceived, integrated, fundamental research program in asphaltic materials could achieve.

PROGRAM EVALUATION

Big Payoffs

Asphalt dominates the nation's highway industry. Ninety-three percent of all surfaced roads in the United States are paved with asphalt—some 2 million miles (*1*). About $10 billion per year are spent for asphalt pavements, which is about one-fifth of the nation's overall expenditures on highways. This share is growing as the emphasis of the nation's highway program increasingly turns to rehabilitation where asphalt has a particularly dominant role.

The asphalt paving expenditures of the highway industry, compared to total expenditures for other modes of transportation, are ten times the size of AMTRAK, six times the size of the intercity bus industry, half the size of the air carrier industry, and more than one-third the size of the entire rail industry.

In 1981 the highway industry purchased more than 17 million tons of asphalt cements, which is approximately 72 percent of all asphalt production; the remainder is used for roofing and industrial purposes (*2*). In 1983 the road paving demand for asphalt cements was in excess of 18 million tons; at current prices this is more than $2 billion. The asphalt cements account for between 25 and 30 percent of the cost of asphalt pavements. Traditionally, about half of these expenditures are for public roads and half are for private roads, parking facilities, and so forth. The recent federally funded increases for highway maintenance and restoration activities should increase the public share appreciably above 50 percent.

Because asphalt is one of the largest components of highway construction, improved asphalt pavements offer a large potential saving. Improved asphalt cements, which appear to be a key to achieving these savings, leverage the savings on the total pavement system. Because asphalt cement represents only 25 to 30 percent of the cost of the in-place pavement, the use of a better quality asphalt could help to avoid repaving costs that are four times as great as the asphalt cement itself.

Recently, many states have experienced costly and embarassing failures when asphalt pavements deteriorated prematurely, often only a few years after construction. The press is quick to seize on these failures, noting that extra millions of dollars must be spent to replace miles of failed pavement. These failures may result from many causes: some stem from inadequate materials, some have been traced to construction defects, and others are attributable to drainage, subgrade, and other factors. By understanding such failures pavement engineers may avoid them and save many millions of dollars per year.

Even well constructed pavements could be made to last longer if engineers understood more about how asphalt materials perform and how different combinations of materials respond under different conditions. Improved understanding of the basic materials could help to match the most appropriate type of material to a set of conditions thereby extending the expected design life. The annual costs of such longer-lived asphalt pavements would be correspondingly lower, again, potentially saving highway agencies millions of dollars per year.

Whether failures of asphalt occur prematurely or at the end of a design life, they require huge replacement costs that might be reduced through research to improve materials. The extraordinary potential of research in this area is not being realized because of the incentive structure embodied in current organizational arrangements and various other constraints. Recent changes in the composition of asphalt and the increased weight and traffic on asphalt pavements, however, demand that a comprehensive research program be established, as discussed in the following sections.

Neglected Areas

In spite of its large potential, research on asphalt has declined in recent years. Corporate research staffs working on asphalt have declined, both here and abroad, as private sector revenues from asphalt have declined. Major petroleum research groups in Europe have disbanded, and some domestic research groups have been discontinued or moved into other areas. The Asphalt Institute, which is the nation's largest industry association engaged in asphalt technical assistance and research, had its budget cut from $4 million in 1981 to $3.2 million in 1984. As a result of economic slowdowns in the early 1980s, asphalt handling and paving equipment manufacturers discontinued most of their research on asphalt.

Asphalt cement is produced by petroleum companies, which generate about $3 billion per year through asphalt sales to users in the highway industry. When the costs of aggregates and construction are added to the cost of the asphalt cement, the $10-billion value of asphalt pavements laid by highway construction each year equals about one-fifth of all funds spent on roads—the largest single expenditure. From the petroleum companies' perspective, asphalt brings $3 billion per year into an industry whose gross annual revenue is about $500 billion in the United States. In other words, asphalt generates less than 1 percent of the annual revenue earned by the U.S. petroleum industry. In addition asphalt has traditionally been a residual product, which is sold as a by-product for whatever it will bring after the high-volume, high-markup products have been produced and sold.

Because asphalt has traditionally been a waste product of the petroleum industry, it is not surprising that this industry devotes relatively little research to its improvement. Indeed, as petroleum research identifies other refinery products that will be more profitable than asphalt, both the quality and quantity of the waste product could be impaired. Over the years, the price of asphalt has risen sharply with the price of crude, but asphalt is generally priced just at or even below the cost of crude oil. It is hardly surprising that petroleum refiners seek to convert this low-value by-product to more high-value products wherever market conditions and refining technologies permit. Recent petroleum industry research has been aimed at achieving a higher yield in primary products per barrel of crude oil and corresponding reductions in the residual asphalt by-product.

Nevertheless, research on asphalt has advanced through small but effective programs of the Federal Highway Administration (FHWA), states, petroleum companies, and materials and equipment manufacturers. Although such research efforts have declined sharply in recent years, a few still continue. For example, a 1981 study by FHWA of data on 97 asphalts collected by states throughout the United States found that statistically significant changes in asphalt properties occurred between 1950 and 1980 (*3*). Another recent study, funded jointly by 17 states, is using liquid chromatography analyses to attempt to tie the chemical characteristics of asphalt with desired pavement performance (*4*). These two studies verify that asphalt products are changing and that chemical analysis techniques can identify 160 types of changes.

Activities in this type of research fall far short of determining which chemical mixes are most appropriate in highway application and which products have those properties. Answers to such questions could save hundreds of millions of dollars, but the current understanding of asphalt cement is so inadequate that these savings elude us. Over the years there have been efforts to study the chemical nature of asphalts. In the 1940s and 1950s research was conducted by Shell Oil Co. in Emeryville, California, and in Amsterdam. The work by Corbett at Exxon resulted in adoption of a current American Society for Testing and Materials (ASTM) procedure for asphalt testing. More recently, work at Pennsylvania State University (5) and Western Research Institute have evaluated chemical and physical properties of apshalt.

Only $1 to $2 million per year have been spent in recent years on asphalt research. The largest recent Federally Coordinated Program of Highway Research and Development (FCP) studies related to asphalt include a fiscal year 1983 study for $575,000 on "Substitute and Improved Materials to Reduce the Effects of Energy Problems on Highways (Sulphex)." NCHRP problem statements on asphalt for fiscal year 1984 include

- Design of Joint Systems for Flexible Pavements,
- Energy/Economic/Environmental and Materials Aspects of Asphalt Pavement Recycling, and
- Field Evaluation of Sulphur Extended Asphalt (SEA) Pavements Constructed from 1975 to 1981.

The FCP has made progress in evaluating the effectiveness of sulphur and other substitutes and additives, recycling technologies, effects of new mixing plant processes, and the development of data banks on state experimental road sections.

Although these ongoing research efforts are valuable, they are not adequate to meet the needs for asphalt research. The research currently devoted to asphalt is less than proportional to its current financial importance and far less than the amount needed to make the significant breakthroughs that appear to be within reach.

Organizational Barriers

Currently public highway agencies place great stress on low-bid procurement. Standards are selected, and the provider that can furnish the specified product most cheaply gets the business. Low-bid procurement is intended to save public agencies from paying unnecessarily high unit costs for their materials and services. It also provides a formal, standardized way to translate complicated engineering knowledge and research results into specifications and bidding requirements. Such procedures are essential to the smooth operation of the nation's highway industry, which involves thousands of agencies and hundreds of thousands of suppliers.

The setting of standard specifications, however, carries enormous implications. Petroleum companies and other suppliers of asphalt may be discouraged from producing higher quality products if such products are not specified and cannot command a higher price. Bidding regulations prohibit highway agencies from paying more than the minimum price for products above standard quality. Because of such forces, the procurement process for asphalt has reached a sort of equilibrium that began more than 70 years ago. A selected set of physical properties is used to specify asphalt that can be obtained within a predictable price range. This process does not accommodate improved adhesion, wetting, and oxidation characteristics that might ideally be obtained. In any event, the current knowledge of such desirable properties, including where they may be found and what they would cost, is not sufficient to be able to incorporate them in a procurement specification.

As a result, trade-offs with service life or maintenance needs are not usually considered in procurement; thus, industry suppliers have little incentive to provide an improved product. If an asphalt with longer life expectancy or lower maintenance costs were available at a slightly higher price, it is not clear that it could or would be purchased under present organizational practices.

Expensive materials that might prove more cost-effective in the long run are specified infrequently, because of the long time periods required to verify expectations and the inadequacy of predictive tools. The lack of apparent demand for a better product, particularly given the procurement procedures involved, has suppressed the research that might lead to the development of superior products. In summary, organizational barriers will have to be overcome along with technical challenges. Changes in specifying and purchasing practices could result in major reductions in life-cycle costs.

Usable Findings

To achieve the benefits of research on improved asphalt materials, several things must happen. First, substantial funding must be available for a concentrated effort in asphalt research. A simple scale-up of the incremental research that has previously been conducted will not be sufficient. Second, the research must be successful in developing new tests, analyses, and procedures to identify fully those more durable, robust asphalts. Third, the results must be disseminated in a usable form to the organizations that build the nation's roads. If successful this effort could give state and federal highway agencies an ability to specify, and an economic incentive to use, better quality asphalts and pavement designs; and it could provide an economic incentive for industry to develop and supply better quality materials.

It could be argued that the failure to take these needed steps in research during the entire history of the modern highway program suggests that they are not achievable. Such a view would find support inasmuch as some key questions that were unanswered 70 years ago still remain unanswered today. Research on the scale discussed here, however, has never been tried in the area of asphalt. Incremental research has yielded incremental savings. The last large-scale project attempted in pavement research—the AASHO road test of 1958-1962, which cost the equivalent of $90 million in today's dollars—was viewed as an overwhelming success. Its results have determined how pavements costing billions of dollars have been built in the United States. It has had an equally large impact abroad. There is nothing in the historical record to suggest that asphalt is particularly recalcitrant to research.

Useful results are particularly likely to be achievable because of the concentration on the material itself rather than construction processes. Undoubtedly substantial reductions in asphalt pavement problems could be gained by optimized error-free construction practices. Yet sustained improvements in those practices, long recognized to be desirable, continue to elude us. The prospects of developing a material that is more forgiving and durable appear to be more promising than the likelihood of altering the underlying human behavior and field conditions responsible for construction defects.

Large-Scale Projects

Research on chemical and physical properties of asphalt requires a large-scale, fundamental research program. The numerous, valuable, and often ingenious solutions that have been discovered by current practitioners in different parts of the asphalt paving industry will provide a valuable basis for this research. But meaningful answers to the most basic questions such as—What chemical properties are desirable in asphalt? How much better will materials with those properties perform? and How can realistic specifications be set to achieve them?—will not be found unless research into asphalt is pursued at a scale and comprehensiveness far beyond that currently practiced.

Is such an ambitious research effort worth it? How much might it cost? Would it repay its costs? Firm answers cannot be given at this stage because research on asphaltic materials, like any research, involves some risk. These risks appear worth taking when the scale of the potential rewards is taken into account. The U.S. government will spend over $200 billion on asphalt pavements before the end of the century. A $50-million research project would repay its costs in 6 months even if it achieved a reduction of only 1 percent in asphalt pavement costs. Similarly, a $50-million research project spread over the next 5 years would repay its costs even if it only achieved a 0.1 percent reduction in costs. Moreover, in view of the incremental component-by-component research that has characterized asphalt throughout the years it has been used in highways, substantial payoffs far in excess of 1 percent might come from well-integrated, in-depth research on this material.

The fertile payoff potential of asphalt research depends on an integrated effort. Crude oil used in asphalt production now comes from 200 different sources. It is refined by numerous refineries and refining processes; combined with numerous additives, cutbacks, and emulsifiers; mixed with a wide variety of aggregates using one of several mixing processes; and constructed according to different designs. Construction takes place under many temperature and weather conditions; and constructed pavements must withstand different traffic and loading mixes under different climates and atop different base soils. Even if only five alternative conditions are considered at each of these stages (crude source, refinery, additives, aggregates, mixing processes, construction design, construction conditions, loadings, and climates) the resulting number of combinations is almost two million. The real number of combinations of pavement conditions associated with current practice may be far larger. Two implications become apparent when this vast number of combinations is recognized.

First, asphalt-materials research geared to represent actual conditions must incorporate a wide spectrum of variables at different stages of the process. For this, a large-scale, multimillion dollar research program is essential. Second, even a large-scale research program must be carefully focused. Otherwise, it will be spread too thin over the huge number of combinations that are implicit in an across-the-board approach.

Greater Integration of Effort

Part of the failure to see the potential of asphalt research stems from the lack of a single clear beneficiary. None of the industries involved in asphalt at each of the various stages of production can control or specify what happens at other stages. The asphalt pavement industry includes petroleum companies, refiners, mixing plant operators, road contractors, and various levels of government. Many of these participants are small, local companies typically operating solely within one state with annual revenues averaging $1 million. Indeed, the asphalt industry has virtually no vertically integrated companies. The crude oil supplier, the refiner, the asphaltic concrete plant operator, the contractor, and the highway agency (which is usually also the designer and maintainer) are unique, separate, and independent organizations. Each controls only one link in the production chain; and antitrust laws, procurement regulations, and geographic and operational requirements of the industry are likely to keep it this way. No part of the industry is clearly responsible for the end product and no part has sufficient incentive to seek major improvements in the process as a whole.

Research into problems in asphalt reflects this institutional fragmentation. Each sector of the industry has focused on its own area. Little cross disciplinary or integrative work has been done. Some state departments of transportation have effectively coordinated a few segments of the overall process, but these efforts represent a limited attack on a pervasive problem. Until an integrated effort brings together the disparate parts of the process, major fundamental improvements in asphalt will not be found.

Although improvements in mix design, careful application of sound construction techniques, and many other steps could greatly improve the overall asphalt paving process, the key research task is to gain an improved understanding of the asphalt cement itself. Construction defects may account for many observed asphalt pavement failures, but research on improved construction practices may not yield realistic, achievable solutions. Indeed, given that some corner-cutting in construction will occur even under the most carefully controlled conditions, a more promising approach may be to develop materials that are sufficiently forgiving to perform acceptably over a wider range of variations in mixing and paving applications or misapplications.

Forgiving characteristics that might be sought in asphalts include

- A tolerance for a wide range of mixing temperatures and physical and chemical properties of aggregates used in the mix;
- Sustained adhesion to aggregates of different composition, temperature, and dryness;
- Stability under varying asphalt cement proportions in the mix;
- Stability under high ambient temperatures;

- Long-term retention of adhesion;
- Flexibility under low temperatures and over a long service life of exposure to atmosphere, sunlight, dust, moisture and traffic; and
- Recyclability.

National Policy

The value of a carefully focused, integrated approach to research will increase in future years because several recent legislative actions have intensified the demands that will be placed on the asphalt industry and increased the size of the federal highway program to deal with this and other needs. The Surface Transportation Assistance Act of 1982 increased the funding for most federal highway programs, particularly those that finance resurfacing, rehabilitation, restoration, and reconstruction (4-R). These are the areas where the greatest percentages of program funds are spent for pavements, so asphalt will increase in financial importance.

The Act also increased the maximum truck gross vehicle weight limits that states must allow on the Interstate system. Although only three states had their maximum weight limits increased directly in response to this change, the volume of heavy trucks in many states will increase as a result. The three states involved previously formed a barrier to Interstate traffic, and heavy trucks now allowed in these three states will presumably also travel through adjacent states. The 1982 Act also permits double-trailer combinations to be operated nationwide over the Interstate system and on designated sections of the primary system. Calculations based on the axle-load equivalencies found by the AASHO Road Test indicate that pavement damage by these configurations may exceed that caused by conventional trailers carrying similar cargo.

Pavements can be built to accommodate these additional loadings. Previous research convincingly shows that increasing the depth of the pavement section greatly increases its load bearing capacity. But increasing the depth of pavements may not be an efficient way to meet current or future demands, which historical trends suggest will be even greater. As traffic loadings push asphalt pavements closer to the limits of historical test results, new materials breakthroughs could permit the building of better roads rather than simply building them heavier.

Technological Change

In addition to new demands being placed on asphalt pavements by heavier traffic, the asphalt material used in highway construction is changing, thereby adding to the uncertainty about how best to use it. Asphalt is changing because of shifts in where refiners get their crude oil as well as the introduction of new refining processes. Following the Arab oil embargo of 1973, disruptions in the international flow of crude oil caused numerous shifts in the supply line to refineries. Refineries that previously processed a single type of crude increasingly found themselves required to deal with other types and were often having to change from one to the other. Because the amount and quality of asphaltic content vary widely from one type of crude oil to another, the shifts in supply lines led to asphalt product variations that had not previously been experienced.

Further, the rapid increase in crude oil prices that occurred during the 1970s raised the price of all refined petroleum products, including asphalt. As a result, other petroleum products increased in financial importance relative to asphalt, which has traditionally been produced from the residual that remains after other lighter (and usually higher valued) products have been extracted. As new economic conditions make it profitable to produce more and more of the light petroleum products, a smaller percentage ends up in the residual from which asphalt is produced.

In short, the Arab oil embargo stimulated the production of asphalt from different crude oils and through different refining processes. But the product specifications used for asphalt do not adequately ensure satisfactory performance when applied to changing or unknown sources. Since the early days of modern paving, engineers have recognized that asphalt obtained from one source performs differently from that of other sources and that the several physical tests and specifications used (then as well as now) do not guarantee adequate performance. For example, writing in 1913, one expert noted (*6*):

> Such tests [penetration, float, viscosity] can only be of maximum value, however, when applied to a specific type of bituminous material and when considered in connection with other tests which, by themselves, may not directly indicate suitability. Thus, for a certain type of bituminous concrete pavement the proper penetration limits at 25°C for a California asphalt may lie between 7.0 and 9.0 millimeters, while the proper penetration limits for a fluxed Bermudez asphalt to be used in exactly the same type of pavement and under the same conditions, may be entirely different, say, from 14.0 to 16.0 millimeters. It is evident that to attempt to cover the penetration limits for both materials under one specification would be useless.

States have adjusted ingeniously to the limitations of current product specifications by modifying specifications and testing procedures to offset known variations in certain sources of asphalt. In spite of such ingenuity, shifts in product sources and refining processes together introduce many potential variations in product performance. The extent to which such variations in asphalt cause premature pavement failure or other problems is unclear; failures commonly attributed to construction defects cannot be completely isolated from shortcomings of the materials. Regardless of the extent to which past failures can be attributed to the asphaltic cement, the challenge is to make this material sufficiently robust so that it performs well even in the face of construction defects. A forgiving asphalt—one that maintains its adhesion and durability even if it is too cold, too wet, or too poorly mixed when it is put in place—might avoid the costly and embarrassing failures that now occur.

Developing such a forgiving product will require a major, coordinated research effort. Which asphalts are most robust? Which are the binding, adhesion, wetting, and oxidizing characteristics that make them robust? How can these be obtained from various crude oils and refining techniques? What functional characteristics can be specified for a forgiving asphalt within constraints of economic possibility? Answers to such questions could profoundly reshape the properties of asphalt, the priority attached to it by producers, and the price paid by and the performance experienced by users. These questions cannot be answered by casual experimentation with current product offerings. Answers require fundamental research on the properties of asphaltic materials.

PROJECT DEFINITION

The central goal of the proposed research project in asphalt will be to identify and define the chemical and physical properties of asphalts and asphaltic concretes that affect pavement performance and to develop tests, specifications, and construction procedures to establish and control the performance standards desired. The research effort involves questions of fundamental materials science. What are the chemical properties of asphalt? How are these properties affected by varying sources of crude petroleum and by varying refining processes? How do these variations in product affect pavement mix design and the paving process itself? How do other factors such as the selection of aggregates, paving conditions, and location affect variance of the product? How do these variables affect pavement performance?

The argument can be made that asphalt is only one component in the pavement system. Performance also can be influenced by the variability of the mix design, the pavement (cross section) design, the aggregates, the batch plant operations, the paver operations, and the traffic and environmental condition under which the pavement serves. Research must continue to address each of these elements in the pavement system. The question is more one of research strategy than of the span of the problem.

Because of its key role as the binder in the pavement system and because of the new and unknown variability of this key element, the strategic research program should focus on an expansion of basic knowledge of the chemical and physical properties of this strategic material. This proposed asphalt research would be a first step in understanding and improving asphalt pavement performance. The chemical and physical characteristics of asphalts would be a basic input to the long-term pavement performance studies discussed in Chapter 5 where mix design, aggregate characteristics, the effects of loads, aging, and environmental factors will be studied. The long-range pavement performance studies would make it possible to verify or modify laboratory findings in actual pavement sections.

This project requires research on the fundamental characteristics of materials and involves disciplines such as molecular chemistry, materials science, and engineering science. The results must be developed in a form that would permit specific changes or additions to specifications for asphalts.

RESEARCH OBJECTIVES

The research program would have five main objectives:

1. Identify and describe asphalt properties. Research would be directed at better identification and description of the chemical and physical properties of asphalt cements and their interrelationships. Chemical analyses would determine the chemical characteristics of asphalts by using the most modern chemical and instrumental techniques available. Chemical characteristics would be correlated with existing and newly developed measures of the physical characteristics of asphalt cement. The research would be used to identify the characteristics of, and ranges of variation in, crude petroleums and assess the effects of these variations on asphalt properties. It would also be used to analyze existing and prospective refining processes in terms of their effects on asphalts.
2. Design improved testing and measuring systems. Weaknesses in the asphalt pavement design and construction process are in part attributable to the limited ability of outdated testing and descriptive meth-

ods to identify the characteristics of asphalts. The investigations would be used to develop totally new tests that are not tied to colligative properties of asphalt to determine the physical characteristics of asphalts and that would reflect the more realistic temperature ranges of asphalts in the field.

3. Determine relationship of asphalt cement and pavement performance. Physical testing of asphalt cement performance in paving mixes would be performed using mechanical testing devices to simulate loads, wear, and environmental conditions at normal and accelerated rates. Validation of these test results would be sought through field testing of in-service pavement sections, using existing old pavements where adequate historical data are available and new pavement sections as required.

The pavement testing phase of the study would be in part incorporated with the long-range pavement performance studies that are a separate part of the strategic highway research program. The research would include evaluation of both the micro- and macro- conditions affecting performance. Consideration would be given to materials, placement, homogeneity, and other factors. The study may include fracture mechanics and the mechanisms of degradation. The opportunity to use state-of-the-art computer analyses and artificial intelligence concepts in addressing the extensive data and correlation of variables would be considered.

4. Analyze the desired characteristics of a pavement material. The research would identify the key characteristics required for asphalt paving materials using measures and criteria developed in the study to define asphalts more precisely and predict service more accurately.

5. Develop model asphalts. Research would be performed to separate asphalt cements into their basic molecular structures and reconstitute them as artificial asphalts with the desired properties. Model asphalts would be determined or hypothesized for various regions of the nation. Asphalt cements modified by polymers, sulfur, rubber, and other additives would be studied as candidates for improved asphalt cements.

A work flow diagram of the asphalt cement study design is shown in Figure 4.

PROJECT ORGANIZATION

When the project is begun it should have adequate incentives in place to assure maximum private sector support. Private sector involvement would be important in several areas:

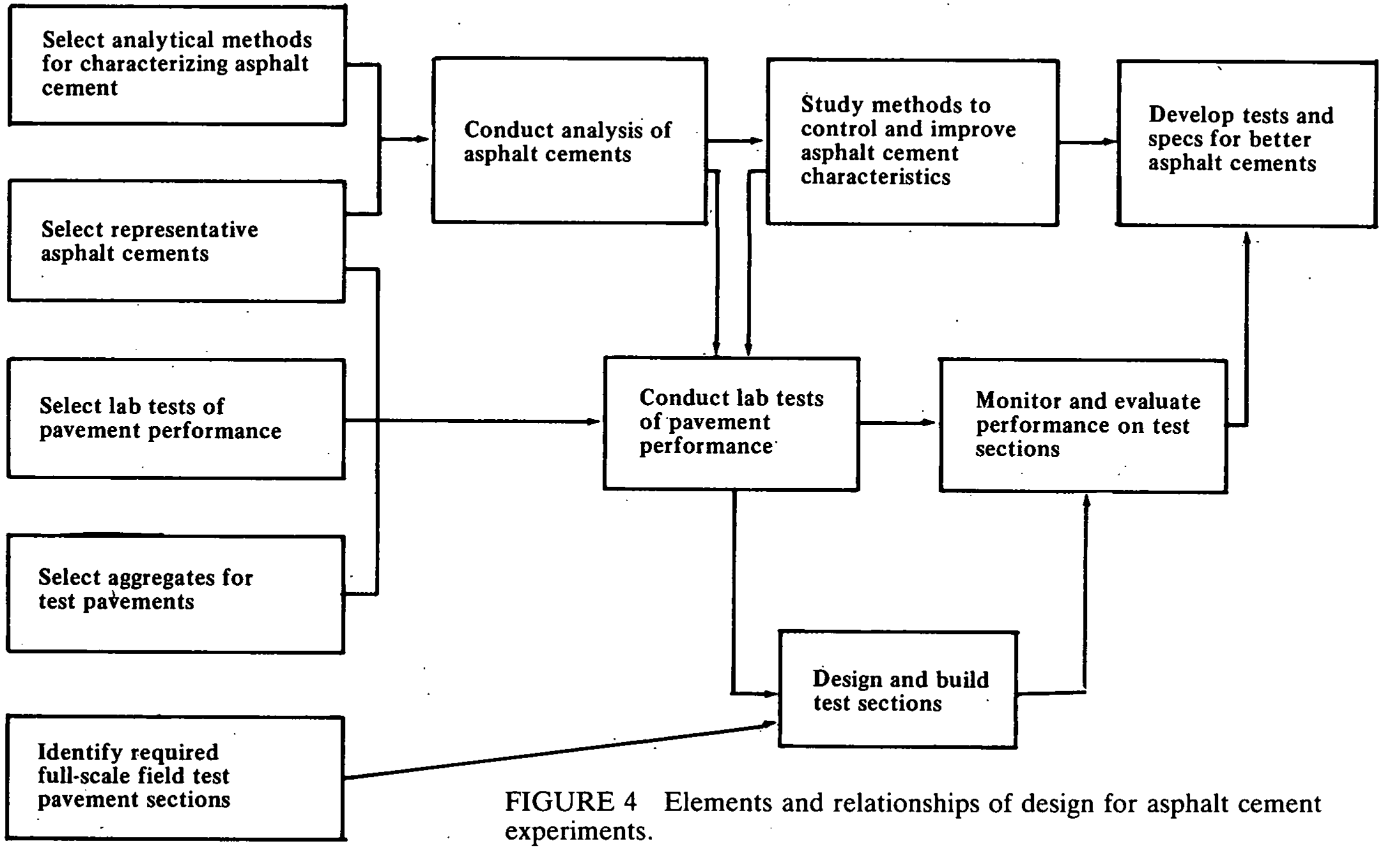

FIGURE 4 Elements and relationships of design for asphalt cement experiments.

- Petroleum industry responses to new product demands;
- Chemical industry responses to new product attributes;
- Equipment manufacturer responses to new processes, procedures, and material handling requirements; and
- Road contractor responses to new processes, procedures, tests, and specifications.

Key incentives to private industry would be

- Markets for newly designed products,
- Retained markets under new standards and specifications, and
- Responsive procurement procedures.

FUNDING

In order to carry out the proposed program of research with the intensity necessary to realize significant breakthroughs in the chemical and physical characterization of asphalt cements, a major laboratory effort with state-of-the-art-equipment is required.

Approximately $4 million per year will be required to maintain an adequate laboratory research team of professionals with support staff and facilities. Development of suitable physical testing equipment and its operation for pavement mix testing during the project term is estimated at $2 million per year. Field validation of laboratory data and physical testing will require an estimated $3 million per year. Data processing, analyses, and reports for the massive testing program should be budgeted at an additional $1 million per year.

In summary annual costs are estimated to be

	$ Millions
Laboratory	4
Physical tests	2
Field validation	3
Analyses	1
Total	10

Such a level of investment is readily achievable in an annual highway program of over $30 billion. The potential for return on investment exceeds that for almost any other expenditure being made today on streets and highways.

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5
Long-Term Pavement Performance

Objective: Increase pavement life by the investigation of long-term performance of various designs of pavement structures and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soils, and maintenance practices.

INTRODUCTION

There was an assumption that the highway problems would be solved when most of the nation's highways were in place . Such is not the case, of course, because pavements wear out, sometimes much faster than expected. Why do pavements wear out prematurely? What is the most cost-effective strategy for pavement maintenance? Why does a year of extra harsh weather cause such a large increase in pavement maintenance costs? How does the pavement behave and perform under various traffic conditions, environmental conditions, and maintenance programs?

Unfortunately all the answers to these questions are not known. Although engineers have been building and maintaining pavements in North America for more than 100 years and although road tests and laboratory analyses have given insight to improved design and performance of pavements, much remains to be learned. A proper analysis of actual performance and behavior of a portion of our highway network over a 10- to 20-year period could provide solutions to many costly problems that are currently unresolved.

The interaction of maintenance and repair programs with pavement performance needs to be studied. The relative effects of alternative maintenance strategies—types of preventive or corrective maintenance and timing or threshold levels for taking maintenance action—need to be evaluated for their influences on pavement performance and life-cycle costs under various loading and environmental conditions. Such information is vital to the successful operation of pavement management programs.

Other specific questions relate to (a) climatic effects on pavement performance, (b) effects of repeated heavy loads on pavement life, and (c) interaction of these two damage factors and the resulting assignment of costs. Other complex and difficult questions relate to the projected life of new materials, new rehabilitation techniques, recycling methods, and related new technologies. What are the real benefits of these new technologies? Are they cost effective?

Effects of Climate

A particularly important question that has not been adequately resolved is the effect of climate on pavement performance and life. It is known in general that pavements in wet rainy areas deteriorate more rapidly than those in dry areas, and pavements that suffer many cycles of freezing and thawing each year seem to have a shorter life than those with no frost effects. A quantitative comparison of these effects could be extremely cost-effective. Knowledge of climatic effects on pavements, when translated into design requirements, could permit optimum pavement designs for the environmental conditions to be encountered. This could result in substantial savings through a reduction in pavement failures in severe environments and a reduction of overdesign of pavements in mild environments.

Effects of Heavy Load

Although many benefits accrue to the economy from large, heavily loaded vehicles, doubling the axle load of a vehicle increases pavement damage from four to ten times or more. It would be valuable to evaluate this damage factor in more detail, particularly in various climatic zones, so that effects of the interaction of load and environment could be ascertained. This information is important not only to the design and rehabilitation of pavements but also to the equitable allocation of costs to highway users.

PROGRAM EVALUATION

Big Payoffs

A better understanding of pavement performance through research could have an important impact on the total cost of replacing and rehabilitating the nation's highway infrastructure, which is estimated to be between $1 trillion and $3 trillion. The need for rehabilitation and new pavement construction extends far beyond the Interstate or the primary highway system to state, county, and local roads and city streets. Thus the total cost is unknown.

Would it be possible to increase the life and effectiveness of the pavement network? An increase in effectiveness of 1 percent from the research proposed here would result in a direct savings of $10 to $30 billion. In reality the payoff could be considerably greater because this estimate includes only the agency costs for highways. The user costs associated with damaged highways, particularly in high-volume urban areas that must be closed and rehabilitated prematurely because of a lack of knowledge about the problem, could equal or even exceed the agency costs by an order of magnitude.

Can such benefits be expected? A number of experienced pavement engineers have estimated that additional pavement life of 3 to 5 years can be gained for initial pavement construction and for pavement overlays if the pavements are properly designed, constructed, and maintained. If only one additional year of life could be gained from improved pavement performance, significant cost savings would be realized. Table 14 compares the cost savings that would accrue for additional life gains of 1, 3, and 5 years for current estimated performance life ranging from 10 to 40 years for existing pavements. Many studies of the actual overlay and rehabilitation history of portions of the Interstate highway system indicate that a pavement life of 10 to 20 years is all that currently can be expected in most cases.

A typical 20-year pavement (see Table 14) with an additional 3-year gain in service life shows a discounted savings of 3.35 percent, or $369 million, for an annual pavement program of $11 billion. Where shorter pavement life is being experienced, even greater savings would be realized by the same 3-year gain in service life. Thus a potential saving at a discounted value of 1 percent, or $110 million, is a conservative estimate of the potential payoff of pavement research.

TABLE 14 Benefits Derived from Increased Pavement Life

Estimated Current Performance Life (Years)	Additional Life Gained (Years)	Lifetime Cost Savings (%)	Percent Savings in Present Value[a]	Annual Program Savings in Present Value ($ Million)[b]
	1	10	3.50	385
10	3	30	8.69	956
	5	50	11.97	1,317
	1	6.6	2.18	240
15	3	20	5.40	594
	5	33	7.43	817
	1	5	1.35	149
20	3	14	3.35	369
	5	25	4.62	508
	1	4	0.83	91
25	3	12	2.08	229
	5	20	2.87	316
	1	3.3	0.52	57
30	3	10	1.29	142
	5	16.6	1.78	196
	1	2.5	0.20	22
40	3	7.5	0.50	55
	5	12.5	0.69	76

[a]At 10 percent interest rate.
[b]Based on an annual paving program of $11 billion.

Further benefits from long-term pavement observations would include better understanding of the technology involved and would increase the ability to make rational analyses and decisions about questions such as axle load limits, cost allocations to various classes of highway users, and an improved evaluation of the overall national economics of relative vehicle sizes and weights.

Also important is the value of the improved knowledge of long-term pavement performance for the U.S. military requirements, the Forest Service, the National Park Service, airport authorities, private agencies, and many foreign governments. Clearly the findings of the proposed study could have favorable impact on all future spending relative to roads, airfield pavements, vehicles, and associated costs.

Conscientious long-term pavement performance observations would provide an extensive continuing payoff. The longer the observations were continued, the more significant and complete would be the answers provided to the questions of pavement performance, load, and environmental effects and interactions. These could be obtained by a careful statistical analysis of the important variables observed. There also would be, however, significant payoffs in the intermediate period and even in the short-term. It is important to examine all three levels.

Long-Term Payoff

This long-term experiment would consist of pavements constructed of various materials on a variety of subgrades in a range of climates. Twenty years of observing these experimental pavements would yield a much more complete understanding of the interrelationships of the effects of load, environment, and maintenance on various types of pavement. A good definition of the pavement structure as-built including material properties would be essential. Regular observations should include traffic volumes and loads, pavement roughness, serviceability, rutting, cracking, damage and patching, and maintenance activities and costs. Weather and environmental factors must also be recorded.

The performance histories of pavements in such an experiment could be examined in terms of relative loads at various levels of maintenance and rehabilitation. The knowledge of these factors would enable greatly improved decisions on cost allocation among various classes of users and also development of improved design methods and materials for use in pavement construction, rehabilitation, and maintenance.

The dollar values of these payoffs are treated separately. The technical payoff would be the ability to answer effectively the questions relative to pavement longevity, the effects of repeated loading, load-environmental interactions, and the effect of use (traffic) and environmental pavement damage. It would be possible to assess the cost, benefit, and effect of both various maintenance strategies and pavement rehabilitation methods and various materials and construction techniques. Information would also become available on the effect of recycling materials, sulphur-asphalt mixtures, and other new or modified materials.

Intermediate-Term Payoff

Although ultimate answers would derive from long-term observations, major payoffs should accrue within 10 years. Improved pavement behavior theories or models can be developed from observations of pavement performance over 10 years. For example, the reduction in present serviceability index (PSI) over a 10-year period could be analyzed for each test section and can be related to load, environment, pavement structural, and material variables. Similar studies could be made of cracking, rutting, and other distress conditions. The results would be precursors of the long-term results but would provide less confidence than would be gained over a 15- to 20-year period.

Short-Term Payoff

An early payoff could result in the first 5 years of this project from the comparison and selection of the design, construction, rehabilitation, and maintenance methods that would be applied to the test sections. The study of existing variations among the participating states could result in improvement in the policies and activities of the individual participants. The resulting synthesis of information would have early benefits in improved pavement design, construction, maintenance and rehabilitation, and in improved estimates of the relative effect of load and environment on pavement performance.

It is also important to note that the results of this study could have a favorable impact on three other research areas: (a) asphalt, (b) cement and concrete, and (c) highway maintenance. All three of these research areas are integral parts of the pavement problem. Undoubtedly observations obtained in the short run from this study on pavement performance would have significant impact on the findings and ultimate payoff of the other three related studies. For example, observations from the first few years of the long-term study would yield useful information about the oxidation and fatigue life of asphalt, the weathering and D-cracking of portland cement concrete, and the benefits and life of various maintenance techniques and materials. Thus, even in the short run the long-term performance study would yield a data set against which these other research areas could be examined and tested.

Neglected Areas

A recent evaluation of AASHO Road Test satellite and environmental studies (*1*) points out that many pavement observations that started after the AASHO Road Test have been discontinued and did not provide the continuity and uniformity of measurements necessary for reliable analysis on a national scale.

During a recent 2-year period, the Federal Highway Administration (FHWA) conducted a pavement monitoring program in which eight pilot states entered into a contract with FHWA to collect standardized condition, operation, and environmental data for selected test sections of existing highway pavements. Conferences have been scheduled in 1984 to evaluate these efforts and to consider an expanded national program.

It is essential that a direct and continuous program be established if this initiative is to be successful over the long term.

The FHWA pilot study monitoring program and selected observations of test sections in satellite environmental studies carried out by 19 states are the only significant work in this area at the present time. Because the independent state programs sometimes lack adequate funding for a continuing effort and do not use the same procedures for collecting data, they do not satisfy the vital needs for pavement performance data on a national scale over a long term.

Earlier pavement performance studies using field observations of selected or constructed test sections were successful in advancing pavement design and construction technology in the United States. Organized field observations of pavement were first obtained in the 1920s from the Bates experimental road financed by the Illinois Division of Highways and from the Pittsburg, California, test track built by the Columbia Steel Company with private funds. These experimental studies and observations of pavements in a real environment served as the basis for early design methods.

In an effort to obtain better information about pavements under actual test traffic, a number of state highway departments sponsored the Maryland Road Test (*2*), which was carried out near La Plata, Maryland. The test was initiated in 1949 by the Interregional Council on Highway Transportation. It was conducted under the direction of the Highway Research Board on behalf of 12 state highway departments and the Bureau of Public Roads as well as a number of commercial sponsors. The total cost of the project then was $245,000 and involved up to 238,000 applications of four test loads. Both single and tandem axle loads were applied to four test sections of 10-year old portland cement concrete pavement existing on U.S. 301.

In 1950 as a follow-up to the Maryland test, the states in the Western Association of State Highway Officials along with the U.S. Bureau of Public Roads undertook the WASHO Road Test at Malad, Idaho (*3*). This test investigated the destructive effect of axle loads ranging from 18 kips on a single axle to 40 kips on tandem axles applied to a total of 46 test sections that were constructed of granular base and asphaltic concrete of varying thicknesses. The test was conducted from November 1952 to May 1954.

After the Second World War great efforts were expended to reconstruct major highway arteries in the United States that had deteriorated as a result of wartime traffic. In addition major efforts were undertaken to expand the U.S. highway system. The Federal Aid Highway Act of

1956 initiated efforts to design and construct the 41,000-mile Interstate highway system. Early designs for these pavements were based largely on empirical methods such as the California Bearing Ratio test and related design methods. Portland cement concrete pavement design was based on a slightly more rational method of analysis, proposed by Westergaard (*4*). These methods were largely empirical and were applicable to relatively low traffic volumes and light loads.

With the Interstate highway program underway, there were major needs for improved information related to pavement design. There was also a Congressional mandate to produce information relative to cost allocation among various classes of highway users (*5*). Thus, the American Association of State Highway Officials and the U.S. Bureau of Public Roads undertook the AASHO Road Test in Ottawa, Illinois. Traffic began on this test in October 1958 and culminated in 1960 after a total of 1,117,000 test load applications were applied to surviving sections. A total of 836 test sections were tested; of these, approximately 60 percent were asphaltic concrete surfaced and 40 percent were portland cement concrete surfaced.

The preliminary results of this road test were used by the AASHO Committee on Design and the Pavement Design Task Force to produce the original AASHO Interim Pavement Design Guides for Flexible and Rigid Pavements, published in 1962. Thus the Maryland Road Test, costing $245,000 in 1949; the WASHO Road Test, costing $890,000 in 1952 to 1954; and the AASHO Road Test, costing $31 million in 1958 to 1960, represented a series of major pavement research studies in a period of significant advances in highway technology. In the more than 25 years since that time, however, no pavement research of comparable magnitude has been carried out.

The AASHO Interim Design Guides clearly recognized the limitations of the AASHO Road Test, and these limitations were overcome to the extent possible by practical experience and applicable theoretical knowledge. The AASHO Committee admitted the gaps and strongly supported research on environmental and soil support factors. Furthermore, the need for additional study and research was fully recognized by the AASHO Road Test staff and the supporting committees, which involved more than 300 professionals from highway agencies, universities, and pavement related industries in all areas of the United States. At the end of the AASHO Road Test, funds obtained from the sale of test vehicles and other residual equipment and facilities were used to establish the National Cooperative Highway Research Program (NCHRP). Some of the early projects associated with NCHRP were aimed at extending the

AASHO Road Test results to other climates, longer time and traffic periods, and a wide variety of subgrade conditions.

Out of the data and the capabilities developed in the road tests and provided to pavement design engineers and maintenance engineers have emerged the principles used to manage major networks of highway pavements. At present, pavement management systems offer processes for understanding and integrating all aspects of pavement design, construction, maintenance, and rehabilitation to fulfill the needs of a highway system at minimum cost and to evaluate, on a life-cycle costing basis, the effects of increased axle loads, increased environmental effects, and alternative maintenance and rehabilitation strategies.

To be functional, however, the models in the pavement management systems must be based on empirical data or theoretical models that best describe the behavior and performance of pavements of various types under various conditions. The proposed long-range pavement performance studies would provide essential field data needed to refine and validate the relationships modeled in pavement management systems.

Organizational Barriers

The long-term research that would yield better pavement performance would include many different climates, soils, loadings, materials, and locations. This would require that many individual state highway agencies be involved to obtain the needed test sections that must be dispersed in a variety of settings around the country.

Such a broad and complex program would undoubtedly place extraordinary demands on the agencies and organizations involved. To be useful, the measurements and observations taken across organizational or state boundaries must be comparable and must be collected and treated in a similar fashion. Obtaining such uniformity over a variety of state highway agencies presents a formidable and challenging task.

In addition to the long-term need for funding and coordination, there is the continuing need to maintain an established experimental design and an established direction for the program. It is important that once the guidelines and the sections for the project are established, continuity be maintained and priority be given to continuing the observations and maintaining the sections as a part of the experiment.

Usable Findings

Improved pavement performance and load carrying capacity are achievable technologically. It would, however, require significant political, organizational, and economic effort and coordination to achieve the results. The technology currently exists to carry out the studies needed. It has existed in large measure since 1960 but improvements have been made that would make the payoff more rapid than would have been possible in the 1960 to 1980 time frame. These improvements include better instrumentation such as surface profilometers, improved deflection devices, and microcomputers for data handling.

The organizational and political problems might be the most severe. The industries served by highways or whose materials and products are used on the highways must have input to the experiment but not influence the findings. However, pressures from such industries have always existed and were successfully handled at the Maryland, WASHO, and AASHO Road Tests. Many special interest groups were brought in and participated effectively in those studies, both technically and financially.

The research results, once obtained, should help in overcoming local political and lobbying pressure to use poor materials, to accept unjustified load increases, or to neglect needed maintenance programs.

Large-Scale Projects

The pavement performance research would require a large-scale, long-term commitment that is beyond the limitations of local governmental organizations and state highway agencies associated with the problem. How large would the project be? It should involve a variety of climatic regions and soil and material characteristics from across the United States. A maximum of 20 test sections per state should be sufficient. It is not essential that all states be involved, but some benefit would accrue to each state that is involved directly with the project.

The cost of providing load applications over a time period of up to 20 years makes it most practical to test pavements under normal or real traffic conditions rather than under traffic conditions created by special test vehicles. The cost of special test vehicles and the associated labor and operating cost over a period of up to 20 years could be prohibitive.

Greater Integration of Effort

As shown by the Maryland WASHO, and AASHO Road Tests, an integrated approach to the problem of long-term pavement monitoring is essential. The variability observed in the field with natural pavement materials is quite large. A carefully planned experimental design and carefully selected pavement sections are necessary to obtain the number of observations required to provide the data needed over a long period of time. The problem involves geography, administration, time, and general understanding of the theory and analysis techniques involved.

Because the effort outlined here would involve many states and many years, it is important that an integrated approach be taken that would centralize and standardize staff, planning, section selection, equipment, operation, data storage, data processing, and data analysis. A specific, unique and complex research methodology is needed. The methodology includes a thorough understanding and application of statistical principles as well as scientific knowledge of measurement accuracy and analysis. Such technology requires a trained research staff that includes instrumentation experts and statisticians as well as pavement specialists. The integrated approach needed would call for a staff to be assembled and maintained with continuity and integrity.

National Policy

The proposed long-term pavement performance study is directly related to some of the most critical and controversial national policies currently being debated by national political and transportation industry leaders. Some of these issues are truck size and weight restrictions, use of multiple-trailer trucks, restriction of large trucks to Interstate and designated primary routes, the impact of trucks on maintenance programs and costs, cost allocation formulas for highway user taxes, funding alternatives for restoration of the deteriorating infrastructure, the impact of deferred maintenance on life-cycle costs, the relative costs and values of alternative pavement designs and alternative pavement materials, and an array of additional issues.

Essentially, these policy questions revolve around incomplete or statistically inadequate information about the real-world performance of highway pavements under a variety of design, construction, environmental, loading, and maintenance conditions.

Changes in national policy with respect to highway funding, cost allocation, and decisions to maintain, rehabilitate, reconstruct, or construct new pavements would have tremendous impact on the various states, counties, and cities of this country. Knowledge gained from the proposed observations would have an important direct impact on such policies within 3 to 5 years and would provide a continuing and strengthening basis for future national policy decisions.

Safety and Environment

The long-range pavement performance study could contribute to saving many lives and dollars. Improved pavement performance has several important direct impacts on safety.

The most obvious impact is the effect of pavement condition on the driver's ability to control the vehicle. Rough, irregular surfaces affect steering and cause vehicles to bounce and sidestep. Surface irregularities retain water, which splashes in warm weather or freezes in winter weather. Ruts may cause vehicles to "track" rather than steer freely. Worn, polished surfaces lose skid resistance and encourage skidding.

Pavement conditions may affect the way the driver must maneuver the vehicle. Deteriorated pavement edges cause drivers to move toward the center of the pavement. Potholes and irregularities cause drivers to attempt to avoid them, often by abrupt lateral movements of the vehicle.

In Phoenix, Arizona, a section of concrete pavement on I-17 became so rough with time that a significant increase in lost-load accidents (in which all or part of the commercial vehicle load spilled or shifted violently) occurred as shown in Figure 5. By grinding the surface to restore ride quality, dry-weather accidents were reduced by 15 percent (*6*). Because the old pavement surfaces had also polished, the grinding resulted in a 40 percent reduction in wet weather accidents as well.

In addition to the effect of the pavement on safety, the process of repair creates many hazards that would be reduced or eliminated by long-lived pavements. Maintenance and repair work sites on the pavement are extremely hazardous for maintenance workers. Such work sites represent unexpected obstacles to traffic, and the resulting turbulence in the traffic stream is an added hazard to motorists.

Thus, research that improves the long-term performance of pavements also reduces the accidents resulting from pavement roughness, defects, and work sites—with a direct payoff in lives saved and injuries prevented.

PROJECT DEFINITION

The purpose of this study would be to provide information on the long-term performance of various pavement structures under different maintenance programs, loads, climatic factors, and subgrade soils. The performance of various rehabilitated pavements and the interaction of maintenance, rehabilitation, and initial design along with load and climate would be the major concerns of the project.

The project would observe pavement performance in the field for a long period. The pavement would be tested under real traffic conditions. This means that it would be necessary to integrate the test sections into the existing highway network either by careful selection of existing pave-

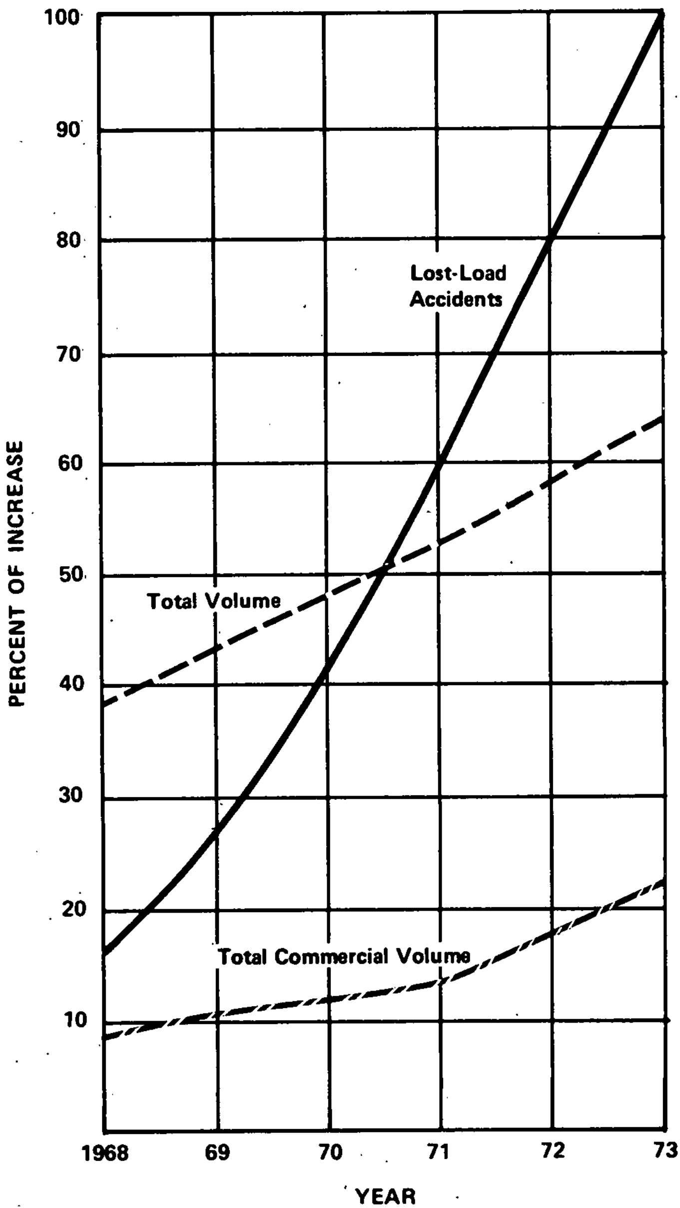

FIGURE 5 Traffic volume and lost-load accidents on I–17 milepost 195.0 to 210.0, Phoenix, Arizona (*6*).

ments or by special construction. This subject has been treated at length in other studies that can be used as a basis for this experiment with relatively modest additional development (*7, 8*).

RESEARCH OBJECTIVES

The basic purposes of the study would be to develop a data base for pavement performance over a wide range of conditions and service life factors. The data base can then be used to answer the following important questions about pavement management and design:

1. What are the proper design and construction procedures for pavement rehabilitation and overlays to provide economical renewed pavement life?
2. What are the effects of various types and levels of pavement maintenance on pavement life and performance? What is the cost benefit of pavement maintenance?
3. What is the cost of deferred maintenance and the ultimate effect on the life of the highway?
4. What are the effects of climatic and environmental variables on pavement life and pavement performance?
5. Are the long-term load effects (load magnitude, type, frequency, and summation of loads) now correctly evaluated for pavement design and construction methods?
6. Is it necessary to reevaluate the load equivalency factors developed from the AASHO Road Test in order to apply them over a wide variety of pavement strengths, material types, and environments?
7. What are the relative effects and interactions of load and environmental (climatic) variables on pavement deterioration, performance, and service life?
8. What are the effects of varying subgrade material types and strengths on pavement construction requirements and ultimate performance?
9. What is the load-carrying capacity of a pavement when the design life is reached?
10. What are the effects of alternative drainage designs on pavement performance and service life?

In addition to answering the questions above, the data base could provide data for long-term proof testing and comparisons of

1. Asphalt cements and modifications of asphalts;
2. Improved portland cements and related materials;

3. Pavement recycling agents and recycling techniques;
4. New pavement materials that offer promising improvements in pavement performance, such as polymer concrete, sulfex, and sulphur asphalt; and
5. Pavement sealers, patching mixtures, and other pavement maintenance materials and processes.

PROGRAM ADMINISTRATION

An advisory task force should be established to outline the research objectives in detail before the study is undertaken. It is important that the organization for such a study be long term and free from special influence by any individual or agency.

It would be important that the project or program staff carefully document the activities, undertake educational and reporting programs to sponsors, and carefully strive to produce results in the short, intermediate, and long term as previously outlined.

The advisory committee should represent sponsoring agencies, state DOTs, the FHWA, the academic community, and industry. Individual advisory panels and working groups should be set up to function as needed to provide individual advisory services. The AASHO Road Test provides a basic model that could be followed. The difference between this new project and previous work is the longer term and the much larger geographic scale. However, the longer term can be handled by proper overlap, transition, and selection of personnel for committee or work terms with 5 years as a basic term of appointment for members. With a broadly based group, it should be possible to maintain continuity over the longer term.

FUNDING

The funding requirements for this project can be divided into three parts: initiation, construction, and monitoring. Initiation includes developing a research staff, purchasing special research equipment, establishing supporting advisory groups, and obtaining computer and analytical resources. The construction portion of the funding relates to the selection, construction, rehabilitation, and maintenance of pavement test sections. The monitoring part covers the annual data collection and analysis requirements after the test sections are established.

It is estimated that funding for the initial phase would require about $5 million per year for the first 5 years of the program. A major research report should be produced in the first 2 years designating (a) the experiment design, (b) the proposed analysis, (c) the detailed selection of test sections, and (d) the conceptual plans for construction of test sections. Following this keystone documentation, one or more reports on the major analyses would be produced. Short-term reports of study results should be produced at the end of the first 5 years.

The test sections would encompass the natural variability of pavement materials, construction, traffic, climate, and other variables. In view of the number of variables involved, approximately 20 test sites per state would be required to yield an adequately strong predictive model capable of detailing the results required. It is estimated that an average of $25,000 per test section would be needed to (a) define existing material properties and structure at each test site, (b) evaluate traffic volumes and loads, (c) purchase, install, and calibrate instruments and equipment to evaluate pavement behavior, distress, and performance. Using $25,000 for each of 1,000 sections yields the estimate of $25 million. These costs would set up a strong, well-defined pavement experiment that could be observed over the long term.

The funding for construction and maintenance of the test sections on the highway system would involve some major costs that would not be chargeable to research. Instead, the experiment would rely on operating highway sections that would continue to serve as a part of the highway network during and after the test period. Only a portion of the total project construction costs, averaging about 10 percent, would be uniquely associated with the research program. The remainder would be normal construction or rehabilitation expenditures. The total of about $25 million of research funds over a 3-year construction period would be required for special construction controls, documentation, and other research-related construction costs.

Annual data collection costs could be about $10 million per year. The experiment would be spread over a large geographical area. This dispersion is required to get the variety of climate, weather, materials, and traffic loads needed for the study. The work items and measurements would include (a) deflections, (b) condition surveys, (c) roughness measurements, (d) materials strength, (e) data processing, and (f) data handling and storage. Data collection would involve seasonal variations, perhaps four rounds per year. Assuming that 100 measurements or operations per round would yield 400 operations per section per year, for 1,000 sections this equals 400,000 operations. At an estimated $20 per operation, the cost would be $8 million per year. Allowing for general administrative costs to set up and support advisory groups of

$2 million per year, this implies a total cost of about $10 million per year.

In summary, the estimated funding requirements are

Year 1 to 5	Part I, Initiation	$25 million
	Part II, Construction	$25 million
Year 6+	Part III, Monitoring	$10 million per year

The proposed long-term pavement performance research represents an investment of about $10 million per year, and promises to yield an annual saving in paving programs that is almost 40 times greater than the investment. It promises to provide vital data for some of the most critical transportation policy issues facing the nation today; and it promises to advance the technology of pavement design beyond that point where it has rested for almost 25 years. Long-term pavement performance studies are a key element in the strategic highway research program.

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6
Maintenance Cost-Effectiveness

Objective: To improve the cost-effectiveness of maintenance through research that will provide technological improvements in equipment, materials, and processes and will improve the administration of maintenance programs in the areas of budget development, program management, and resource allocation.

INTRODUCTION

National attention, resources, and interests are being directed toward the problems of restoring and protecting streets and highways. State and local governments spend $15 billion annually to maintain the nation's 4-million mile network. Yet less than 1 percent of the Federally Coordinated Program of Highway Research and Development (FCP) is directed toward maintenance technology (*1, 2*), and state-funded research on maintenance amounts to less than the federal effort.

Maintenance research has not kept pace with the need for new technology for three key reasons. First, maintenance lacks the glamour necessary to attract a spontaneous constituency in the research community. New technology and materials research is directed primarily at new construction programs rather than the patching, painting, and preserving of existing facilities. Second, maintenance presents a wide array of research topics that tend to diffuse rather than focus attention and emphasis on this important research. Third, maintenance is a perpetual activity that demands attention and resources on a continuing basis—long after the excitement and financial commitments given to building a new facility have faded from public view. Furthermore, the fact that state and local maintenance budgets are typically inadequate for the basic task leaves little room for research activities.

It is obvious that the national program of highway maintenance is inadequate for the task at hand. The methods, equipment, and materials being used represent a state of the art that has changed slowly over the past 20 years, whereas the size of the highway system and the work load it is performing have increased significantly in that same time period. Thus, a high priority, major research program in highway maintenance is urgently needed to protect the highway system and the commercial and social structure it serves.

PROGRAM EVALUATION

Big Payoffs

The current national highway maintenance program costs about $15 billion annually (*3*) and is increasing each year. Three major factors drive highway maintenance costs upward.

First is the changing size and complexity of the physical plant. The highway system is not increasing significantly in centerline miles; but the increase in lane-miles of paved surface and the number and complexity of appurtenances such as signs, signals, lighting, electronic detectors, guardrails, and energy attenuation devices is increasing rapidly. Today highway maintenance may include anything from patching a center lane of pavement in an eight-lane, high-speed expressway or repairing a transmitter in an electronic traffic detection and control installation to the more prosaic jobs of cleaning, painting, mowing, collecting, sweeping, adjusting, and plowing.

Second, maintenance costs are driven—or should be driven—by maintenance needs. As the highway system ages and traffic and the environment cause wear and failures to increase, the maintenance workload and costs also increase. During the 1950s and 1960s the nation was building at a rapid pace and adding to the physical plant. During the 1970s and 1980s, it is experiencing an aging of that plant at the same time that the size, weight, and volume of traffic served is increasing. The compound effect of age and service is increasing maintenance needs and maintenance costs.

A third major influence on maintenance costs is the effect of inflation on labor, materials, and equipment. Maintenance is a labor-intensive activity, and labor is sensitive to inflation even though labor rates in public agencies tend to lag behind the rate of inflation in the national economy. The trend toward using contractors for many maintenance activities is adding the influence of contract labor costs, which are more sensitive to inflation.

In summary, the opportunity for big payoffs in maintenance research is substantial. A 1 percent increase in maintenance productivity or reduction in current maintenance expenditures would represent an annual saving of $150 million. The development of mechanization, better repair materials, off-site prefabrication, optimized staffing, and scheduling could produce savings well in excess of 1 percent.

Neglected Areas

Maintenance programs represent nearly one-third of total annual expenditures on highways today. The allocation of less than 1 percent of the FCP research effort to maintenance clearly shows that this is a neglected area and one that merits new emphasis and funding levels proportionate to its value in the highway program.

Two modest but important efforts have been made in the last decade to redirect attention and resources to maintenance research. Both were needs studies funded by the Federal Highway Administration (FHWA) and performed by the Transportation Research Board (TRB), first in 1975 and again in 1980 (*4, 5*). The 1975 study recommended a $9.1 million program to be conducted over a 5-year period. Projects recommended for the program were grouped as winter maintenance, work-site evaluations, management systems, quality of service, new concepts, structure maintenance, pavement repairs, roadside maintenance, and equipment development. The proposed research program was developed through a series of workshops employing the Delphi technique, drawing upon almost 500 experts and practitioners to evaluate elements of the program. FHWA adopted the study recommendations as part of the FCP but was able to fund only a $5.2 million program or 57 percent of that proposed in the study.

In the 1980 study a 5-year program costing $11.9 million was developed through regional and national workshops. Major emphasis was given to developing a system for managing pavement maintenance, developing procedures to optimize the allocation of resources to maintenance, and improving technology transfer. Elements of this program have been incorporated in the FCP and the National Cooperative Highway Research Program (NCHRP) for current or future consideration, but no clear, continuing commitment at the required level of support is yet evident.

Organizational Barriers

Maintenance of streets and highways in the United States is performed by many separate state, county, city, authority, or agency departments. The maintenance programs are independently funded and managed. This fragmentation of maintenance responsibilities has both positive and negative effects on the introduction of new technology and incentives for research. On the one hand, it fosters the introduction of new ideas on a limited basis (somewhere, someone will try them out). On the other hand, it inhibits nationwide acceptance of proven new technology. Technological improvements are likely to be implemented somewhat sooner in maintenance than in major new construction programs, but the acceptance of new maintenance technology systemwide is likely to be slower than for new construction. Several factors influence this process.

First, the Federal-Aid Highway Program administered by FHWA does not cover routine maintenance programs. These are carried out by the state and local governments using their own funds and policies (*6*). As a consequence, there is more flexibility in most state and local programs for incorporation of new technology but less uniformity in its acceptance.

Second, individual maintenance activities are very small compared to new construction programs. The risk involved in trying new materials, equipment, and procedures is easily limited and controlled.

Third, most maintenance programs are performed by agency employees on the basis of internal work orders or verbal instructions. Also a maintenance work program is easier to alter, modify, or supplement to take advantage of new technology than a construction contract, which requires plans, specifications, and competitive bids.

Conversely because maintenance is performed by many small organizational units under informal or at least internal direction without national or federally imposed standards and specifications, technology transfer is a slow and difficult process. Thus, organizational barriers do not threaten systemwide improvements, but organizational fragmentation does pose a challenge to systemwide implementation of research results.

Usable Findings

Because maintenance encompasses a varied program of processes and resources, the research program also should address a variety of areas for improvement. Although areas such as improved pavement patching are more promising than others (such as silent concrete pavement cutting), usable results can be realized for the spectrum of research activities proposed in this program.

Significant achievement may be realized by the transfer and adaptation of existing technology from other fields to highway maintenance. For instance, the Department of Defense has important research underway to develop materials and methods for rapid repair of war-damaged runway pavements. The potential application of this technology to rapid pavement repair on urban expressways should be explored.

Politically highway maintenance has achieved important recognition in recent public discussions of the aging infrastructure (*7*, *8*). The recently enacted federal-aid legislation for bridge replacement and resurfacing, restoration, rehabilitation, and reconstruction (4-R) programs indicate that political leaders are willing to support maintenance and rehabilitation. This same political awareness of the growing public concern about the condition of streets and highways should translate into political support for a major research effort in maintenance.

Large-Scale Projects

The earlier efforts (1975 and 1980) to identify and fund needed research programs for maintenance through existing organizations and resources clearly document the need for a new approach. Only 1 percent of the already inadequate FCP funds was recommended for maintenance research as a result of those efforts and less than one-half of the recommended funding was provided.

Already $15 billion per year are committed to the maintenance of highways, and simultaneously they are deteriorating at an unacceptably high rate. The choice is not whether the funds will be used but how they will be used in the maintenance program.

If the big payoffs discussed earlier are to be realized, a large-scale effort is needed—not because of a few major problems requiring massive funding but because of a massive number of problems, each requiring modest but adequate funding. A commitment to maintenance research is essential to the success of this vital program.

Greater Integration of Effort

Current programs are fragmented as well as inadequately funded, and the probability of making a major contribution to national needs is low under the present organizational structure. Although there are many maintenance tasks, tools, materials, equipment, and procedures that lend themselves to small, independent research efforts, there are several major maintenance research needs that require a single, coordinated, comprehensive research effort to achieve results.

Most maintenance functions are performed as a part of a system. A system for pavement repair might include drilling holes and pumping grout into voids beneath the pavement or locating deteriorated pavement, removing old material, cleaning and preparing the area, placing new material, compacting or curing the new material, and restoring pavement markings (*9*). Research activities are needed that attempt to improve the system as a whole rather than each incremental step.

An example of an improved system is provided by a concrete pavement repair technology developed in Germany and used experimentally by the Michigan Department of Transportation. Rather than performing research on the incremental steps in concrete repair (such as new patching materials) the German technology employed an entirely new system. The system consisted of completely removing old broken concrete slabs by crane after sawcutting the perimeter and replacing them with precast slabs lifted into place fully cured and ready for traffic. The technology may still need some development, but the concept of research directed toward the full system rather than toward small steps in an old process is the key point. This concept can best be achieved—and perhaps only achieved—by a well-funded, integrated approach to the research.

In all instances it would be most effective to have a common program under one management to direct the effort, allocate the resources, control the quality and reliability of the results, and integrate the findings to achieve implementable new technology.

National Policy

The recent national policy changes (and potential future changes) in the size and weight of vehicles permitted to use the highways will have a direct effect on pavement and structure maintenance programs. These changes and the debates they generate demonstrate the need for further research in this area. The AASHO Road Test established the relationship between axle loads and the service life of a pavement; however, the influence of maintenance on that service life and the optimum level of maintenance effort required to yield the greatest service life return per maintenance dollar expended has not been adequately researched. Also, the influence of new vehicle sizes and weights on the relationship between pavement service life and maintenance effort requires study.

Policies on environmental issues also affect maintenance activities. Air and water pollution policies have affected the use of cut-back asphalts that permit volatiles to escape into the atmosphere; the use of certain herbicides for vegetation control on rights of way; the use of lead-based paints on structures; the sand-blast cleaning of lead-based paint from old structures that span rivers and lakes; and the control of dust, smoke, spray, or fumes in other operations. Substitutes such as zinc-rich paints are being used in greater quantities. Noise pollution policies have affected the use of, or required the modification of, equipment such as air compressors and pneumatic tools. Restrictions on the disposal of waste materials also will affect maintenance by adding incentives to reuse and recycle materials.

The Occupational Safety and Health Act (OSHA) has necessitated the use of breathing masks and other safety clothing for workers, back-up horns for vehicles, and new safety provisions in work procedures. Much study remains to be done to provide safety and efficiency for maintenance activities.

In summary, national policies have and will continue to have a direct effect on many maintenance activities. A major national research effort could respond effectively to the continuing need for technological change to match policy change.

Safety and Environment

Highway maintenance work is classified as one of the most hazardous occupations in the nation and is outranked only by refuse collection and disposal work, according to the National Safety Council. Approximately 500 maintenance workers are killed each year. Maintenance activities are hazardous for the highway user also. Although traffic accident statistics are inadequate to quantify the problem, the growing necessity to repair existing pavements and structures while maintaining traffic flow makes maintenance work site safety an increasing concern to workers and highway users. Much progress in work site safety has been achieved over the past decade. Much more is needed.

In the 1975 Highway Maintenance Research Needs report, safety was specifically addressed in project statement R5, which proposed research to develop and evaluate the effectiveness of improved traffic control devices and procedures at maintenance work sites. FCP studies completed in this problem area have included the preparation of a two-volume supplement to the Manual on Uniform Traffic Control Devices to be used as a guide in setting up work site traffic controls and a report on breakaway barricades. This research has already resulted in greatly expanded use of Jersey barriers, new and better arrow boards, and other safety devices. Safety has improved but costs have escalated. Continuing improvements in temporary pavement markings, portable signs and devices, and in design concepts are needed.

Maintenance operations have a direct effect on highway safety in such obvious areas as snow and ice control and pavement maintenance to maintain adequate riding quality and skid resistance. Traffic sign and signal maintenance; guard rail, energy attenuation, barricade, and breakaway post maintenance; mowing for sight distance; control of pavement edge drop-off; and a variety of other activities are also necessary to retain the safety features designed into the highway.

Research that reduces roadway occupancy time by maintenance crews, reduces the cost of managing traffic during maintenance, improves the characteristics of the repaired highway, and extends the time between required maintenance activities will have a significant effect on safety for workers on and users of the highway system.

PROJECT DEFINITION

The objective of this study is to increase the cost-effectiveness of maintenance through research on

1. Management information systems that will provide better capabilities for developing budgets, administering programs, and allocating resources.
2. Technological improvements in equipment, materials, and processes that will increase productivity.

Program Administration

This area of study promises important gains in cost-effectiveness through improved maintenance program administration. Over the last 20 years successful research and development has produced management information systems that are now installed and used by maintenance program managers in 46 states. The systems typically capture unit cost information for units of work performed on standard maintenance activities and monitor progress against budgets and schedules. This growing resource of performance data now offers researchers the opportunity to evaluate alternative maintenance programs, procedures, equipment, and materials and to identify opportunities for important improvements.

Comparative analyses are needed to evaluate the responsiveness and cost-effectiveness of contract maintenance, to identify the areas and activities best served by contractors, and to establish practical processes for contract administration. The performance indicators developed from these analyses would help management to optimize the blend of force account and contract activities in a balanced program.

Improvements in Productivity

Research should be directed toward developing materials, equipment, and methodologies that improve the productivity of maintenance activities. This research should emphasize those activities that require on-the-road performance. Reducing maintenance time and thus maintenance costs also may have significant benefits in reduced delay time for motorists and in increasing safety for maintenance crews and motorists.

Principal activities performed on the roadway that are to be studied include pavement repairs, bridge deck (patches) repairs, crack and joint sealing, and pavement marking. Major activities performed contiguous to the pavement area include turf and vegetation maintenance, maintenance of appurtenances, and drainage maintenance. Snow and ice control materials, activities, and systems relevant to winter maintenance are discussed in Chapter 9.

RESEARCH ORGANIZATION

A special task force should be created to develop the detailed research programs and monitor and coordinate the effort. The task force should have as its members knowledgeable maintenance managers representing highway agencies in each major region of the country supplemented by representation from the federal government, the research community, and industries serving the maintenance market.

The need to create an integrated approach to highway maintenance research is based on a need for a single, dedicated, well-funded team to manage the research program. Because of the varied equipment, materials, and procedures to be studied, the program may require a diverse group of research agencies and disciplines. The key to the success of this effort will rest in the management of the program in such a way that each effort contributes to a common goal with a minimum of duplication or gaps and with a maximum of synergism.

FUNDING

The maintenance research program should be funded at approximately $20 million over a 5-year period. Substantially all of the program lends itself to contract research in the developmental phase and demonstration or training programs through state highway agencies (with contracts for support services by private agencies, as required) in the implementation phase.

Although a new program management organization will be required to administer the program, the research effort is readily achievable through existing research organizations. FCP, NCHRP, and HP&R programs can accommodate a major portion of the research projects. The key to the success of the program, however, will be the new organizational unit required to direct, administer, and coordinate the program.

Because the potential benefit from the research is likely to exceed the costs by a factor of ten or greater, the economic justification for the effort is not difficult to establish. However, the obvious need for federal funds for the maintenance research program requires another analysis. Because maintenance dollars are not presently provided by federal programs, the economic justification for federal research funds lies in the capability of improved maintenance technology to increase the service life of the system, for which more than 50 percent of the construction costs was provided by the federal government.

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7
Protection of Concrete Bridge Components

Objective: To prevent the deterioration of chloride-contaminated concrete components in existing bridges and to protect new, uncontaminated bridge components from chlorides.

INTRODUCTION

Since 1970 all bridges on the federal-aid system have been inventoried and inspected periodically. The Surface Transportation Assistance Act of 1978 (P.L. 95-599) added all bridges not on federal aid routes to the inventory and inspection system. The latest comprehensive survey conducted (as required by the federal legislation) revealed that as of December 31, 1982, 26 percent of the federal-aid system bridges and 60 percent of all other bridges were deficient (*1*).

Few problems in the operation of the nation's highway system aggravate drivers more than this epidemic of deterioration of bridge decks, parapets, piers, abutments and other concrete components. The repair or replacement of deficient bridges will demand greater expenditures over the next decade than any other single requirement of the highway system.

The federal definition of "deficient" includes both structurally deficient and functionally obsolete bridges. The 1982 status report shows that deficient bridges are almost equally divided between these two categories (*2*). In both cases, there is a major program underway to repair or replace the bridges; repair almost always includes a new bridge deck.

Beyond the major problem of deficient bridges, however, lies an even greater challenge in protecting 74 percent of the federal-aid system bridges and 40 percent of the other bridges not yet classified as deficient. These structures and especially the newer ones are built with concrete bridge decks. If they are in the 32 states having regular winter snow and ice storms, they are vulnerable to the elements and snow melting chemicals that cause deterioration (*3*).

The phenomenon of concrete bridge component deterioration is well understood and well documented by experience (*4, 5*). In the post World War II highway building boom of the 1950s and 1960s, thousands of concrete bridge components were constructed using cast-in-place concrete heavily reinforced with steel. On most decks the upper steel reinforcing bars were designed to be positioned 2 inches or less below the top concrete surface. However, the concrete covering was often less than the design minimum because of imperfect placing of the steel (or displacement of it while casting the concrete) or other construction related imperfections.

Many of these concrete components have developed fine cracks or capillary passages from the surface to the underlying steel. Water and contaminants, particularly brines from rock salt and calcium chloride used to melt snow and ice, penetrated the concrete and initiated corrosion of the steel. Lenses of oxidized steel generate pressures within the concrete that exceed the tensile strength of the thin concrete cover, causing the concrete to spall over the steel. Spalled areas provide free access to moisture and brines thus accelerating the destructive processes cased by moisture, corrosion, freeze-thaw cycles, vibration, and impact loadings from traffic. The bridge building boom of the 1950s and 1960s, then, has generated the repair and replacement crisis of the 1980s. The crisis presents a challenge to prevent a repeat of the cycle for the next generation.

There are two parts to the challenge, both representing urgent needs for immediate programs. There is a need to design and construct new or replacement decks and other components using technology that will protect them from premature failure. There is also a need to protect or counteract destructive action underway on existing decks and other components so that they will not have to be rebuilt prematurely. These two research areas are part of a common problem. They should be addressed in a coordinated effort to share as much as possible the technological development that serves both.

PROGRAM EVALUATION

Big Payoffs

It is estimated that $48.9 billion in current dollars will be required to repair or replace the 253,196 bridges classified as deficient at the end of 1982. Additionally the Federal Highway Administration (FHWA) estimates that about 3,500 bridges will become deficient each year (*6*).

Progress in addressing the problem has been slow. From 1970 through 1978 only $816.5 million was made available for the Special Bridge Replacement Program by the Congress. In 1978 Congress authorized $4.2 billion for bridge replacement and rehabilitation for the 4 years through 1982. Last year Congress authorized $7.05 billion for 4 years through 1986. Thus $11.25 billion have been committed to the bridge program in 8 years. More than $37 billion is still required to correct current deficiencies and the need is increasing at a rate of 2.5 percent per year in 1983 dollars.

Although bridge decks are designed to serve without major repairs for about 40 years, unprotected concrete decks subjected to salting during winter storms often require major repairs within 5 to 10 years and replacement after only 15 years of service. Of the 32 states reporting moderate to major bridge deck deterioration, 27 reported that unless repairs are completed within 3 to 5 years, currently repairable decks will require complete replacement.

In 1978 FHWA estimated that $6.3 billion was required to restore decks on federal-aid system bridges. Multiplying 1978 dollars by a factor of 1.4 to account for inflation, 1983 deck restoration would represent $8.8 billion or about one-third of the $26.7 billion needed for bridge repairs in the federal-aid system. If that same ratio holds for bridges outside the federal-aid system, an additional $7.3 billion would be required for deck restoration. This represents a total cost for all highway bridge deck restoration needs of about $16.1 billion, and this cost is increasing at the rate of $402 million per year. Protection systems that could extend the performance of decks and other concrete bridge components from 15 to 20 years (only half the theoretical design life) would have a payoff in excess of $2 billion.

Neglected Areas

Although no research commitment made to date in bridge deck protection approaches the effort warranted by the magnitude of the problem, within the funding levels and programs available effective research activity has been underway and meaningful progress has been made. New designs for bridge decks that promise resistance to reinforcing steel corrosion have been developed under the Federally Coordinated Program of Research and Development (FCP). Today most design standards incorporate epoxy-coated reinforcing steel and more than 2 inches of high-cement-content, dense concrete covering the upper steel. An alternative design uses latex-modified concrete for the surface cover.

Continuing study is underway of materials effective in reducing or eliminating water-absorption and chloride-intrusion characteristics of concrete. Membranes and penetrants have been studied and evaluated for this purpose, and several have been accepted by FHWA.

Cathodic protection systems have been shown to be effective in stopping corrosion in salt contaminated concrete. Recently much research has concentrated on this technology. Under the National Cooperative Highway Research Program (NCHRP), a current project includes laboratory investigations of cathodic protection systems that use conductive coatings as secondary anodes (*7*). Recently published NCHRP reports discuss methods of polymer impregnation of concrete and electrochemical removal of chlorides.

For fiscal years 1979 through 1984, the FCP budget (including staff studies, contracts, HP&R, and NCHRP) for research in the area of bridge deck protection totals about $4.741 million or about $790,000 per year. Although this effort has made a significant contribution to the advancement of needed technology, the magnitude of the problem far outweighs the research investment made to date.

Organizational Barriers

Unlike most production items used in new highway construction, the materials and processes used in repairing or protecting existing concrete bridge components are largely custom designed or selected for each unique application. As a consequence, the problem of the standard specification, low-bid barrier to innovation and use of research results is eliminated or greatly reduced. Instead the highway industry is seeking new materials and methods to meet the need for protecting bridge decks.

Where private industry encounters barriers in marketing the results of their research, it is usually because they are unable to persuade a public agency to test the product. The proliferation of sealants and membranes developed and offered by industry—at times with limited qualities but extensive claims—have made state departments of transportation reluctant to undertake unlimited testing of every material offered. However, when reliable industries develop materials with documented effectiveness, both federal and state transportation agencies usually are willing to evaluate the materials.

Another potential barrier exists when a proprietary material or process has been evaluated successfully and accepted for use on the highway system but cannot be used because of the low-bid, specification-controlled procurement procedures. Generally, however, specialized, quality-sensitive applications like bridge deck protection systems pose less of a problem for suppliers of proprietary items. Federal and state procurement procedures usually include either performance specifications or reference to proprietary items (or equal) in such cases. Philosophically most public agencies accept the limits initially imposed by such specifications and rely on the competitive drive of the marketplace and the ingenuity of private industry to restore competition over a period of time. For example, latex-modified concrete mortar was developed by one company and marketed successfully as a proprietary material for several years; now it is supplied competitively from several sources.

Usable Findings

Major achievements have already been realized in improving new bridge deck durability, and ongoing research clearly indicates that systems can be developed and implemented that effectively arrest corrosion and protect existing concrete. Several years ago, FHWA adopted several "nonexperimental" membrane systems, epoxy-coated reinforcing bars, high-cement, low-slump concrete overlays, and latex-modified concrete overlays. Protective systems are now required for all new federal-aid bridges. Thus, the new technology is achieving success and promises to continue to do so.

Despite the progress that has been made, more research is needed to provide the technology to protect all bridge components adequately. The challenge to researchers lies in developing new technology as quickly as possible. The immediacy and magnitude of the bridge deck deterioration problem and the major increase in bridge replacements and repairs funded by the 1982 Federal-Aid Highway Act of 1982 require equally immediate achievements from research. Such achievements can be realized in the short term only by means of a well-funded, high-priority research effort.

Large-Scale Projects

There are strong arguments for a large-scale effort in this research area. First, of the more than one-half million highway bridges in the United

States, about 250,000 are deficient and about $49 billion will be required to repair or replace them. The magnitude of this problem and the immediacy of the need for solutions require a prompt, large-scale research effort.

Second, the research must be field oriented and field tested to be useful. Highway bridges are massive, dynamic structures. Experimental installations of concrete protection systems are costly, sensitive operations that must be repeated many times in many locations if the research is to be complete and the results reliable and implementable. Such a program must be large-scale if it is to make a meaningful and early impact on bridge concrete technology.

Greater Integration of Effort

Bridge decks are complex structural systems incorporating reinforcing steel, concrete, joint devices, and structural support elements (floor beams, girders, etc.). To be successful, the research must be an integrated effort addressing the full system because the interaction of the component parts is a basic consideration in deck performance and durability.

Currently research on this problem is divided into two basic areas: extending the life of existing bridge components and designing and building more durable new components (*8*). Within these two problem areas research projects are addressing a range of solutions including

- Rapid assessment of existing deck conditions,
- Removal and replacement of deteriorated concrete,
- Impregnation of deck and other concrete surfaces,
- Construction of membranes,
- Use of epoxy-coated reinforcing steel,
- Cathodic systems for electrochemical removal of chlorides, and
- Cathodic protection for stopping or preventing corrosion in the presence of chlorides.

Research on bridge decks has been and will continue to be performed by the public sector. Highway bridges are designed and built almost exclusively by public agencies using basic materials for construction. (The need for research in cement and concrete is discussed elsewhere. Improvement of basic construction materials may contribute to the durability of bridge decks, but the thrust of this research effort must be in the functioning of the bridge deck system, as it uses those basic components.)

Industry has an opportunity to play a role in the research effort. The need for effective penetrants, sealants, and membranes for bridge concrete has been recognized by industry, and private research and development has produced a number of candidate materials and processes for this purpose. For example, epoxy coating protection systems used for coating reinforcing steel were developed under the FCP, and industry has taken a supplementary role in developing and improving production procedures for applying the coatings (*9*).

National Policy

The Surface Transportation Assistance Act of 1982 and the national policy changes it has brought about are having a significant impact on research for bridge deck protection. The Act provides $7.05 billion to be spent on bridge repair and replacement over the next 4 years. However, this authorization combined with that for 1978 is $37 billion short of the estimated $48.9 billion needed to repair and replace all bridges classified as deficient at the end of 1982. Therefore the $7.05 billion should be spent in such a way that it will achieve a full design life for deck systems that serve in a hostile environment. The 1982 Act added to the work load on bridge decks by requiring all states to permit 80,000 lb. g.v.w. vehicles on the Interstate highways and double-bottom trucks on the Interstate and selected primary routes.

The national bridge inspection standards require that all bridges be inspected at 2-year intervals and sufficiency ratings computed. This inspection and rating policy provides a current and continuing measure of the magnitude of the bridge problem. It could also provide an additional opportunity to observe and record other bridge concrete conditions and rates of change. When these ratings are correlated with alternative designs for protection systems, work loads, and environmental conditions, the knowledge of bridge concrete performance and bridge protection systems can be expanded significantly.

Technological Change

Research in bridge concrete protection systems is not dependent on or driven by technological changes. It is, however, poised to take advantage of new materials technology such as epoxy coatings, concrete penetrants, latex modification of concrete and new energy sources (for cathodic protection) such as solar panels and fuel cells.

Safety and Environment

The deterioration of concrete represents a major safety hazard to highway users. In the late summer of 1983, the Cabin John Bridge carrying I-495 traffic on the beltway around Washington, D.C., suddenly developed a major deck failure of several feet in diameter in one westbound lane. One vehicle was damaged and disabled when a wheel dropped into the void. Thousands of vehicles were delayed in the resulting traffic backup, and several rear-end collisions resulted from the unexpected halting of traffic on the travel lanes. The personal injuries and property damage were not great; but the potential was great for loss of life and catastrophic damages.

Because bridge decks do not have obstruction-free maneuvering zones and often lack full shoulder sections, the presence of pavement irregularities and potholes or voids represents an even greater hazard than on roadway sections. Research that significantly reduces bridge deck deterioration will contribute directly to highway safety.

PROJECT DEFINITION

The ongoing research efforts in the area of bridge-deck protection represent a multipronged attack on this problem. Each area is an important part of the total research effort. As noted earlier the research may be divided into two study areas. One would be directed toward preventing deterioration of existing bridge concrete already exposed to salt brines for several seasons and badly contaminated with chlorides. The other would address the protection of new and uncontaminated concrete.

The key problem, however, is the need to develop economically feasible methods of saving the thousands of bridge decks built before the use of present-day protective systems. The undersides of decks over saltwater bodies in coastal areas are deteriorating. Pier caps and columns are deteriorating from exposure to saltwater that seeps through deck joints or from traffic spray.

Preventing Deterioration of Chloride-Contaminated Decks and Components

Most existing concrete bridge decks and pier caps are contaminated with chlorides. Those that are currently sound are facing inevitable premature deterioration unless the corrosive process already underway can be halted or reversed. Current research shows promise in the following areas:

Electrochemical removal of salt. A direct electrical current is applied between the top reinforcing steel and an electrode on the concrete surface. The chloride ions are driven to the surface electrode and the level of chloride contamination in the concrete is reduced below the threshold level for corrosion. Apparent increases in the permeability of the concrete may be of concern unless the treatment includes subsequent impregnation of the surface with an inert sealant.

Although this concept holds promise, a full field evaluation is needed. If found feasible and economical, the system needs development as a practical, reliable process for implementation.

Impregnation. A range of processes have been considered and tried on a limited scale. These processes are designed to penetrate and seal the surface concrete to prevent intrusion of moisture and chlorides, and to encapsulate the upper mat of reinforcing steel or permeate the concrete surface with corrosion inhibitors.

Field testing of the most promising systems is needed. Application techniques, such as grooving or scarifying, need to be assessed. Resistance to freeze-thaw cycles and the development of galvanic corrosion cells need to be thoroughly studied.

Cathodic protection. The application of cathodic protection systems to bridge concrete has been under development in California for several years and more recently has been studied by the NCHRP. The process involves reversal of the galvanic corrosion in chloride contaminated concrete surrounding reinforcing steel. This is accomplished by two possible methods: in one, the anode, placed on the deck surface, is a sacrificial metal such as zinc or magnesium and the flow of current is induced by galvanic action; in the second, a current is impressed between the reinforcing steel and an anode on the surface that is not sacrificial. The anode arrangement for either method must provide a uniform current flow to the reinforcing steel mat.

Continuing study is required to develop an electrically conductive mat for the deck surface that also provides durability and stability as a part of the wearing surface. The selection of materials and positioning of anodes require further study. Also the performance of the total systems under long exposure to weather and traffic needs to be studied and economic evaluations made.

Preventing Deterioration of New and Uncontaminated Decks

An expanded set of options is available to the researcher in studying methods of protecting new concrete. These include alternative materials or coatings for the reinforcing steel and internal or external sealants to prevent penetration of moisture and chlorides into the concrete. Successful research during the 1970s and subsequent field verification has led to specifying epoxy-coated reinforcing steel by more than 40 state highway agencies. Use of high-cement-content, dense concrete or latex-modified concrete to cover top reinforcing steel in bridge decks has also become a standard practice in most state highway agencies. Continuing refinement of these technologies through research and development is warranted. The primary research need, however, lies in the area of evaluation.

In spite of the progress made in bridge concrete protection systems, very limited performance data are available on the effectiveness of these systems. There is a need to develop methods to evaluate existing conditions and to understand the relationship of measured conditions and concrete durability. Research is needed to

- Quantify the oxygen level necessary to support corrosion of steel embedded in concrete,
- Develop a method or tool to determine the rate of corrosion of reinforcing steel in existing concrete, and
- Develop a tool for measuring the permeability of in-place concrete to penetration by moisture and chlorides.

Also a long-term data collection and evaluation program is needed. The program should be organized on a national scale for a term sufficient to make valid assessments of the performance of deck protection systems. Probably 20 to 25 years would be needed to capture data covering the useful life of the systems. Data should include design and construction information; annual information on environmental and operational conditions under which the concrete performed; measures of permeability, corrosion, equipotential contours, concrete soundness, and chloride content in the concrete; and other applicable conditions. In addition to a unique and comprehensive inventory for planning and scheduling purposes by individual states, the resulting data bank would provide extensive opportunity for evaluation and correlation of data related to design, operating conditions, and performance. This major effort will require substantial funding to

1. Develop the data collection program;

2. Conduct the data collection and enter the data into computer storage files;
3. Monitor the quality and completeness of the data received; and
4. Evaluate, analyze, and report on the findings at appropriate time intervals.

RESEARCH ORGANIZATION

Most of the successful research performed on bridge concrete protection has been under the FCP, some by in-house staff of FHWA, some by state agencies using HP&R funds, and some under NCHRP contracts. This effort has been effective and this organizational structure should continue.

A long-term data collection program would require a special effort that would be best accomplished through a contract with a firm qualified to manage research. Data collection could be accomplished by the individual state agencies under a cost reimbursement contract arrangement with FHWA. Data monitoring, evaluation, and report preparation could be performed by a special in-house team assigned exclusively to this project, or by a research management organization under contract. In any event, this project should be given a priority research area status with an adequate, qualified, and continuing staff assigned to its accomplishment.

FUNDING

The current level of funding in this research area, which has averaged less than $800,000 per year, has produced a slow but valuable rate of improvement in the technology of bridge deck protection. However, the magnitude and urgency of the need, particularly to prevent or stop corrosion on existing sound concrete decks, mandates a substantially increased research effort.

To conduct concurrent major research studies on impregnation, electrochemical systems, evaluation tools, and a national data collection program, a funding level of $2 million per year will be required for an initial 5-year program. Continued funding of the national data collection program beyond the 5-year term should be contemplated at a rate of about $1 million per year in 1983 dollars.

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8

Cement and Concrete in Highway Pavements and Structures

Objective: To improve the economy, versatility, and durability of concrete in highway pavements and structures through an increased understanding of the chemistry of cement hydration and the properties of concrete.

INTRODUCTION

Concrete is the most widely used man-made construction material in the world today. Concrete has several advantages over most other construction materials. It is derived from widely available, low-cost raw materials, and it has the ability to incorporate waste and by-product materials without serious deleterious effects on its performance (*1*).

The highway transportation industry is a large user of cement and concrete; it consumes about 16 percent of the portland cement used for construction in the United States. This translates into 7 to 8 million tons of cement per year, costing about $65 per ton. Roughly 85,000 miles of roads and streets are paved with portland cement concrete (PCC), which is also the most commonly used material for curbs, sidewalks, and median dividers. Two-thirds of the short-span bridges currently being built in the United States are constructed of concrete. Almost all bridge decks are made of concrete as are piers and abutments, even where steel is used for the superstructure.

About 50 companies produce cement in the United States. Of these about 40 belong to the Portland Cement Association (PCA), which performs basic and applied research on the manufacture and use of cements. The Association also represents the industry before regulatory agencies, committees that formulate standards, and consumer groups.

The PCA is a leader in basic research in cement. Other centers known for cement and concrete research are the National Bureau of Standards, Lehigh University, Purdue University, The University of California, Pennsylvania State Univeristy, and The University of Illinois. The American Concrete Institute and committees of the American Society for Testing Materials and the Transportation Research Board are active in identifying and disseminating the results of cement and concrete research. The PCA research program tends to concentrate on cement rather than additives although they have addressed additives such as fly ash and blast furnace slag. Additives, however, appear to have considerable potential for improving the strength and durability of concretes. About $1 million per year is spent on cement research in the United States.

As the cost of energy has risen, the cement industry has focused on research and capital investment to reduce the amount of energy used. It is estimated that a modern plant can produce cement for $10 per ton less than the older plants. Other countries are well ahead of the United States in plant modernization, in the use of additives, and in research on the basic process of hydration (*2*).

Research on cement and concrete is financed by a variety of industry and government sources. The cement industry concentrates on portland cement production; the construction industry concentrates on construction methods; the sand and gravel and crushed stone industries on aggregates; and the chemical industry on additives. None of the research efforts is of adequate scale, and their effectiveness is further limited by the absence of integration.

A coordinated effort is needed to provide the funding and direction for research in cement and concrete for structures. With leadership and adequate resources, a renewed research program can improve the applications, durability, and economy of this basic building material.

PROJECT EVALUATION

An evaluation of the proposed study of cement and concrete in highway pavements and structures follows.

Big Payoff

Portland cement represented 6.2 percent of total highway construction costs in the 1979 federal-aid highway program. Of the $16.5 billion capital outlay for streets and highways in 1979, more than $1 billion was spent for portland cement.

Deterioration of concrete is a problem in highway bridge decks, pier caps, and other exposed structural components. Research is needed to improve the flexural strength, volume stability, resistance to sulfate, and thermal expansion of concrete pavements. Research that leads to increased durability of concrete in the highway environment can provide savings to local, state, and federal agencies that fund street and highway programs. The Federal Highway Administration (FHWA) estimates an annual accruing bridge deficiency (in 1980 dollars) of $2.3 billion and a total expenditure for bridge repair and replacement from 1981 through 2000 of $102.6 billion as shown in Table 15 (*3*). Reducing the cost of the highway bridge program by 1 percent as a result of cement and concrete research would amount to a saving of more than $1 billion during the next 20 years.

Neglected Areas

Because cement and concrete are commodities, there is little incentive for private companies to invest in long-range research to improve them. When compared with other nations, the U.S. investment in cement and concrete research is low and declining. The concrete construction industry is not on the Securities and Exchange Commission list of firms that spend 1 percent or more of revenues on R&D. Cement industry records show that expenditures for research are less than 0.03 percent of gross sales, which is even less than the 0.15 percent spent for R&D by the total highway industry. A recent comparison of published papers and presentations at the International Congress on the Chemistry of Cement shows that those for Japan and the Soviet Union outnumbered those for the United States. These trends show not only neglect of needed research in the United States but strong indications that the position of leadership in cement and concrete technology is being usurped by other nations. The loss of technological leadership is generally followed by a loss of market position as the steel, electronic, and automotive industries well understand.

Instead of investing in research, cement manufacturing companies are investing in badly needed modernization of plant processes and equipment, modifications to meet strict environmental requirements, and

TABLE 15 Estimated Annual Accruing Bridge Deficiencies, in 1980 dollars (*3*)

	Bridges Eligible for Replacement	Estimated Replacement Cost ($ Billion)	Bridges Eligible for Rehabilitation	Estimated Rehabilitation Cost ($ Billion)	Total Annual Cost ($ Billion)
Federal-Aid					
Interstate	270	0.285	196	0.084	0.370
Primary	592	0.476	476	0.196	0.672
Urban	418	0.475	437	0.209	0.684
Secondary	535	0.153	553	0.120	0.273
Total	1,815	1.389	1,662	0,609	1.999
Other	1,581	0.245	790	0.066	0.311
Total	3,396	1.634	2,452	0.675	2.310

NOTE: The total bridge needs for 1981 to 2000 is $102.6 billion, which is the sum of backlog and accruing needs plus the $8.8 billion ineligible deficiencies.

improvements to decrease energy requirements. Financial support for in-house R&D and that done through the PCA (see Figure 6) is currently small and no increase is indicated in the present economy (*4*). This important industry needs a significant national research program.

Organizational Barriers

The organizational barriers represented by the low-bid procurement process in public works affect cement and concrete research as they do research on asphalt and other basic highway materials. Cement and concrete products usually are provided to highway agencies by contractors as a part of construction contracts. Construction specifications control the procurement process by setting minimum materials characteristics and as-built requirements. To be competitive, contractors strive to meet but not exceed minimums. Specifications change slowly, usually after substantial laboratory and field evidence indicates the superiority of alternative materials, tests, or procedures.

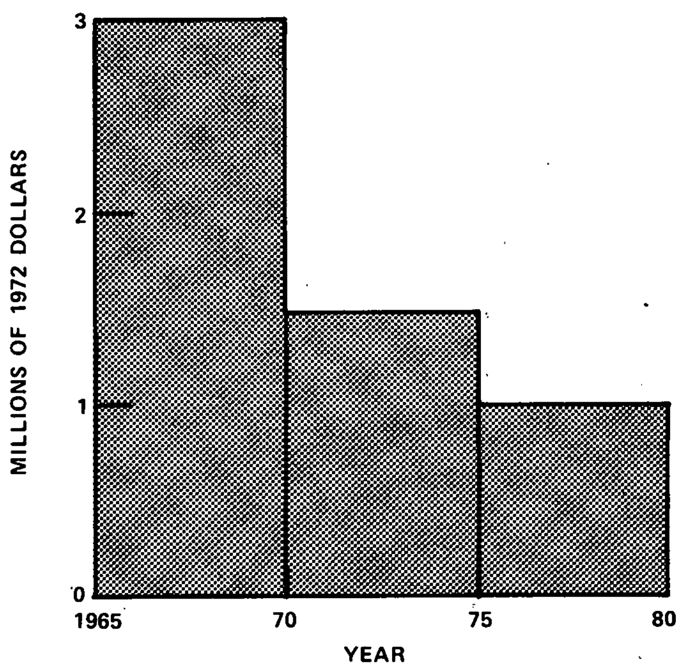

FIGURE 6 Average annual research expenditures by PCA from 1965 through 1980 (*4*).

In testimony before the House Committee on Science and Technology (*4*), William J. Young listed three "structural deterrents" to higher levels of cement research by industry:

> 1. It is traditional for public construction contracts to be awarded to the low bidder. While this practice historically has been considered necessary to the public interest, the universal application of the low-first-cost concept is a serious deterrent to new product development, quality improvement, and innovative technology. In construction, as in most activities, quality demands a premium.
> 2. Cement is actually a commodity, and every manufacturer makes essentially the same product. For this reason, new developments in cement or concrete technology cannot be proprietary—they must be disclosed openly so that public agencies can include them in product specifications which must be followed by all competitive bidders. This is a further deterrent to materials research by individual companies because the benefits of innovation are so difficult for the innovator to capture.
> 3. A third major structural deterrent is the one I alluded to earlier. It is the *owner* of the highway or bridge—in other words, the American taxpayer—that is the major beneficiary of new developments—not the cement producer. The cement producer, because the benefits are not quantifiable over the short term, has little incentive to invest heavily in the type of proprietary research that is the lifeblood of companies in other industries that make high-technology proprietary products.

Industry then would have to make a substantial front-end investment in research, wait a long time for acceptance of results, and still face a low-bid market for the improved product. These incentives are insufficient to motivate industry. The fragmentation of the industry and current antitrust laws that restrict industry-wide cooperation are further barriers to industry-funded research efforts.

Usable Findings

Remarkable improvements in concrete performance have recently been obtained through the use of superplasticizers and microsilica in the concrete. This strongly suggests that the performance of concrete could be significantly improved without an exorbitant increase in cost. Research for improving the performance of concrete would be expected to have a significant effect on the highway and bridge program.

Opportunities for advances in concrete technology are arising because of new possibilities for application of (a) materials science to concrete engineering, (b) new instruments and computers for research on concrete materials, (c) artificial intelligence to aid in the use of the best existing knowledge in decision making, and (d) diagnostic techniques for assessing the condition of concrete and other structures (*5*).

The continuing development of scientific instrumentation can be applied to an increased understanding of cement hydration and concrete production as well as to better methods of nondestructive testing of existing concrete. One research objective would be to develop or improve instruments for on-site nondestructive testing of existing concrete structural members. This may be achieved by applying or modifiying existing technology to this specific need. Candidate technologies in this area include X-ray, electrical resistivity, and sonic wave measurement (*6, 7*). Because quality control of cement and concrete production and inspection of existing concrete structures are performed primarily by trained technicians or professional engineers and scientists, the probability of acceptance of new technology in this area is high provided it is reliable, practical, and efficient.

The magnitude of the research effort requires a greater commitment of funds than can be provided by private cement and concrete firms under current economic climates. Therefore the research project is economically achievable only if there is a substantial commitment of public funds. The level of funding required is small when compared with the potential value of improvements in structural concrete where the problems of deterioration are significant. A major portion of the current federal bridge replacement and rehabilitation program, which is budgeted at $7.05 billion for fiscal years 1984 through 1986, will be spent on structural concrete. A modest investment in cement and concrete research could result in much longer service before future expenditures are needed for repair of these bridges in the future.

Large-Scale Projects

Although the needed research program is not large in the context of the industry it serves, it represents a requirement greater than any previously met by the cement and concrete industry. The industry is unlikely to make a commitment for a large, integrated research effort specifically addressing the improvement of quality, testing, and durability of cement and concrete. It faces major needs for plant modernization that challenge available resources; it realizes a low rate of return on investment compared with other industries; it has no tax or market incentives to invest in product improvements when existing products meet market-place specifications and when low-bid procurement characterizes the major public works buyer.

If cement and concrete technology is to advance in the United States in keeping with the increasing challenges in the highway industry, a large commitment of public funds to a national research program will be required.

Greater Integration of Effort

A cement and concrete research program is needed to keep the United States competitive in world markets, to meet new design and application challenges, and to advance the quality, reliability, and utility of this basic building material. The physical and chemical instrumentation available and required for a major research effort is extremely costly and currently scattered among a few well-funded research organizations. Cement materials research involves a number of technical disciplines, including chemists, physicists, geologists, crystallographers, and chemical, civil, and ceramic engineers.

The main source of engineering specialists in cement and concrete research are the civil engineering departments of the universities where the study of cement and concrete as basic building materials generates an interest in research. However, the chemists, physicists, and those in other specialized disciplines must be recruited or assigned to the study area because they are not drawn to cement and concrete research by education or professional practice.

Cement research and concrete research have been approached as separate and distinct when there are many justifications for an integrated research program that includes both. Although much of the fundamental research could be performed by individual researchers at various locations, there is a need for the interactions of a multidisciplinary team having broad tangible goals to which all may contribute. This approach has proved effective for national R&D efforts in defense and space.

In summary, the chances that research in this area would contribute to decreasing the hazards and costs associated with deteriorating cement and concrete would be enhanced by an integrated effort by an established research team in well-equipped facilities.

National Policy

There are several points of national policy that cement and concrete research must address.

Recycling of materials. Research is needed to determine the opportunity for and applicability of using recycled materials such as crushed concrete in producing new concrete products (*8*).

Noise and air pollution. Technological improvements are needed to reduce the noise and air pollution produced by cutting, removing, or shaping existing concrete. (This is important in high density urban areas and has lead to research studies by the Gas Research Institute using a very high pressure water jet for concrete cutting.)

Shortages of quality aggregate. As land development, environmental concerns, and use deplete the high quality aggregate resources in regions of the United States (see Figure 7), other options will have to be evaluated such as using beneficiated aggregate, alternative materials (such as slag), or lower quality aggregates in selected applications.

Energy conservation. Current and future national policy on energy conservation will necessitate research in cement and concrete technology to respond to several needs. The emphasis on conserving energy has created a need to reduce the amount of energy used in cement production. New and increased applications for concrete will be needed to replace or supplement high energy materials such as asphalt and coal tar.

Safety and Environment

Serious failures of concrete structures under construction occur with sufficient frequency to warrant concern by safety officials. Causes of failure often are attributable to improper construction practices, such as inadequate form supports, or to premature dependence on newly cast concrete. The ability to measure and monitor precise strength and bond development in in-place structural concrete, as it cures, could contribute significantly to safety during construction.

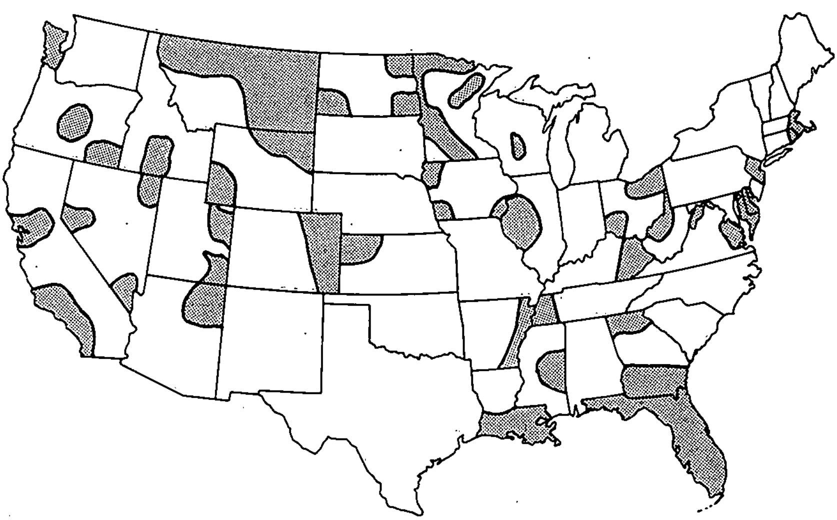

FIGURE 7 Areas where quality aggregate is being depleted, as reported by state highway departments (*9*).

The deterioration of existing concrete under wear and environmental stresses does not usually result in structural failures except in cases of extreme neglect. However, concrete wear and deterioration do cause safety problems that could be eliminated or deferred by research leading to improved durability of concrete. Such problems include surface polishing that causes loss of skid resistance on concrete pavements and bridge decks; and the presence of scaled, spalled, cracked, or eroded areas on concrete paved surfaces that cause drivers to make sudden evasive maneuvers, brake suddenly, or lose control of the vehicle momentarily.

Another emerging area of safety consideration in structural concrete is in monitoring the service life of structural elements such as precast, prestressed concrete beams and concrete box girders. Fully reliable nondestructive testing equipment capable of measuring the strength and condition of the concrete, embedded reinforcing steel, and stressing cable strands could advance the state of the art in inspecting concrete structures and computing load ratings.

PROJECT DEFINITION

Cement and concrete research should be addressed in three phases: (a) the manufacturing processes and materials used to produce cement; (b) the processes for evaluating, controlling, measuring, testing, and placing cement and concrete; and (c) the engineering design of structural elements, joints, fasteners, and other components made of or interfacing with concrete. It is the second of these phases that is proposed for attention in this research program.

This program will have as its primary goal the increased understanding of the chemistry of cement hydration, the properties of concrete, and the performance of concrete in the highway environment. Several specific objectives will be addressed to improve the economy, versatility, and durability of concrete in highway pavements and structures. These are as follows:

The mechanisms of setting and strength development in concrete. Although research in cement hydration chemistry has received more support than any other cement research activity in the United States, the basic knowledge necessary to characterize the anhydrous materials present at the start of hydration is still lacking. Cement should not be considered a given in the equation.

A better understanding of the mechanisms of setting and strength development and the chemical processes during hydration should improve the ability to predict, control, or change the performance of cement and to correlate performance with material properties. The relationship of hydration products to cement paste, to aggregate bond, and to the effects of curing on cement paste structure needs to be studied to improve curing methods. Research is needed also to identify and quantify the changes that occur in concrete when recycled, crushed concrete is used as an aggregate and when pozzolans, fly ash, gypsum, and other energy saving components are used (*10*).

Improving production, placement, quality control, nondestructive testing, and durability of concrete. An increase in the use of high-strength (10,000 psi) concrete for structures has increased the need to study mixing and placing methods. Methods such as shotcreting and dry packing offer opportunities for high payoff in repair of existing concrete structures.

Concrete properties and test methods need to be studied. Methods should be developed for monitoring the properties of concrete during its production, placement, and curing. Also more information about heat evolution and thermal stresses in nonmassive concrete and better alternatives to the slump cone test method for controlling the properties of fresh concrete are badly needed. A major effort is needed to develop and improve effective nondestructive testing methods for existing concrete structures. As existing bridges and buildings age, inspection and testing will require new technology to evaluate strengths, defects, and other characteristics important to the safety of the structures.

Although the durability of concrete has received much study in recent years, this property is critical and still merits a concentrated and continuous research effort. Durability failures account for the greatest loss in concrete highway structures. The separate and combined effects of freeze-thaw cycles, vibration, traffic impact loadings, reinforcing steel corrosion, and other factors require greater understanding (*11*).

RESEARCH ORGANIZATION

A special advisory committee made up of representatives from producers, consumers, and advisors should be named to serve as a counseling group to the project staff. This committee would be an advocate for the project while it was ongoing and for the implementation of the findings as they were confirmed. The committee should include representatives from each of the following groups: cement producers, additive manufacturers, ready-mix concrete suppliers, concrete highway designers, highway construction contractors, highway design and operating agencies, universities, and nonprofit research agencies. The proposed research requires a substantial well-equipped laboratory with facilities for controlled-environment and natural exposure (outdoor) studies. Special modern instrumentation such as electron spectroscopy, Auger spectroscopy, low-angle X-ray scattering, and Moessbauer spectroscopy will be desirable for the study of cements. Structural testing equipment for large structural concrete components will be required.

FUNDING

The proposed 5-year program should be funded at a level to provide (a) $2 million in capital costs for instrumentation and modifications as required to carry out the program; (b) $5 million in research project team staffing costs; and (c) $5 million for contract research activities by uniquely qualified research agencies.

In the search for new technology it is easy to neglect the basic components that have served and sustained the highway system for many decades. Cement and concrete are two such basic components, and the potential for improvement through research is great.

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9

Chemical Control of Snow and Ice on Highways

Objective: To avoid costly deterioration of bridges, pavements, and vehicles and other adverse environmental effects by reducing the dependence on chlorides for snow and ice control; improving mechanical, thermal, and other removal techniques; and producing environmentally safe alternative chemicals.

INTRODUCTION

The dependence of the nation's economy on the year-around use of the highway system has required highway maintenance forces to battle winter storms with chemical as well as mechanical means of snow and ice control. Rock salt (sodium chloride) has been the principal chemical used. Calcium chloride in lesser amounts, because of higher costs and more difficult storage and handling characteristics, is the other primary chemical used on highways to melt snow and ice and to prevent or break bonding of packed snow to pavement surfaces. Because both chemicals present problems in storage and use, research into new substances is needed.

PROGRAM EVALUATION

Big Payoffs

Snow and ice control is a major program for U.S. highway agencies. All but seven states (Florida, Georgia, Hawaii, Alabama, Mississippi, Louisiana, and South Carolina) can count on snowstorms affecting parts of their systems almost every winter. Occasionally the remaining seven may encounter snow or ice on their highways. Since the initial use on intercity highways about 40 years ago, salt applications have increased to an annual rate of about 12 million tons (at $36 per ton this equals $432 million) in 1978-1979 but dropped to 6.9 million tons in 1981-1982 and 8 million tons in 1982-1983. Although some of this reduction reflects the relative severity of the winter weather in those years, a portion of the reduction is due to an increasing awareness of the problems of heavy salt use and better management of chemical programs.

If, in addition to the cost of materials, one considers the equipment and labor costs of winter maintenance programs in the United States, the total expenditure exceeds $1 billion each year. By its nature, snow and ice control is a demand-responsive maintenance activity. As such, certain inefficiencies are inherent in the program. However, the problems associated with storing, handling, and applying salt offer significant opportunities to reduce rates of application, improve effectiveness, prevent leaching and losses, and evaluate alternative or combined snow removal processes. Solutions to these problems could result in savings measured in direct reductions of materials costs and requirements for labor and equipment.

Structural corrosion of vehicles was a problem for the highway industry in the 1970s. This problem has been almost eliminated by using galvanized steel and other kinds of treated steel, but according to corrosion authorities (*1*) cosmetic corrosion is becoming a serious problem. Dr. Robert Baboian of the Electrochemical and Corrosion Laboratory of the Texas Instruments Company says the problem is the combined effect of road salt and acid rain from industrial pollution of the atmosphere.

Studies in Minnesota (*2*) have estimated that the cost of protecting vehicles from corrosion ranges from $4.50 to $30.00 per vehicle per year, based on estimated costs for corrosion protection over a 10-year life. Up to 50 percent of the corrosion, however, may be caused by atmospheric conditions. One could factor the vehicle population by the cost of corrosion protection and claim a potential payoff from research leading to the substitution of a noncorrosive chemical for rock salt on highways.

Such savings are unlikely to be realized, however, even if corrosion-free chemicals are developed. Automotive manufacturers are unlikely to abandon established technology and processes for corrosion protection because vehicles are subjected to hostile environments caused by seawater in coastal areas, industrial chemicals in heavily developed areas, agricultural chemicals in rural areas, and the drippings and abrasive contaminants on the pavement surfaces in all regions of the nation. The savings, then, are more likely to be measured in the reduction of cosmetic corrosion of vehicles and the resulting increase in value and appearance during the service life of each vehicle.

The other payoff potential, and perhaps the largest, results from the effect of salt on bridge deck durability. It has been estimated that during the 1970s salt damage to bridge decks cost in excess of $200 million annually. Significant research has been conducted in bridge deck protection. Today new bridge decks have epoxy-coated reinforcing steel and dense, high-cement-content concrete or latex-modified concrete surfaces with a deeper minimum cover over the top lift of steel. Such decks are much less vulnerable to salt damage. The threat to existing older bridges continues, however, and the option to replace concrete decks on all of the 500,000 existing bridges in the United States is not economically possible in the near term.

Neglected Areas

Research activity in chemical control of snow and ice has centered on three areas: reducing the amount of chemical used; physical alternatives to chemicals; and alternative chemicals to replace sodium chloride and calcium chloride. The U.S. Army Cold Regions Research and Engineering Laboratory is conducting studies on optimum use of chemicals. The Federally Coordinated Program of Highway Research and Development (FCP) has a continuing research project on calcium magnesium acetate (CMA) that addresses environmental acceptability, manufacturing technology, and technical evaluation of this new deicer (*3*). A pooled fund research study of CMA involves 23 states. A 2-day research workshop on Noncorrosive Winter Maintenance was held in Minnesota in October 1983.

Although this important research area is not currently neglected in terms of the range of activities underway, it is important that a major national research effort be applied to this problem.

Organizational Barriers

Snow and ice control programs are usually administered at the lowest local organizational level. To minimize response time and address unique local storm conditions, each local municipal government and each district or section of state government is responsible for local operations. Thus, operations are highly fragmented.

Aside from relatively simple specifications governing the gradation, purity, and (where applicable) noncaking additives for rock salt, snow and ice control programs are administered under internal policies and instructions; these are often of an informal character whether written or unwritten.

The research effort directed toward developing CMA as an alternative to rock salt is unlikely to result in a material that has either the same melting power per ton of material or has a comparable or lower unit cost. Consequently, in terms of incentives to the actual user (i.e., the maintenance organization and crews), CMA will probably require more material and a substantially higher unit cost to achieve the same results now being achieved with salt. The foregoing circumstances can generate organizational barriers in accepting and using CMA if it is fully and successfully developed.

A second barrier is the need to achieve a transition from an experimental prototype production program funded and operated by the public sector to full scale production, marketing, and delivery by private industry. Unless innovative arrangements for licensing and marketing are developed and incentives are adequate, private industry will not invest in the production and marketing of CMA.

Also, current suppliers of 12 million tons of salt annually to the highway program may prove to be an organizational barrier. However, based on current estimates of CMA production costs, it is unlikely that rock salt will be fully displaced by CMA in winter maintenance programs. A more likely development may be the use of CMA on a selective basis in areas where there is great sensitivity to structural corrosion or to environmental problems and the continued use of salt in most other areas.

Usable Findings

As discussed earlier in this chapter, improvements to existing snow and ice control measures are an ongoing effort, applying new technology from many fields. This phase of the research is achievable technically and faces no political or economic barrier.

The replacement of salt by another chemical capable of snow and ice removal without adverse environmental or corrosive effects faces a major economic barrier. If CMA increases winter maintenance material costs by 20 times and doubles material handling costs, it will require substantial justification in terms of savings from reduced corrosion and environmental benefits.

Because most winter maintenance programs are controlled by local highway departments, implementation of research findings will be slow and may not be universally accepted. Federal money does not go into snow and ice control (except on federal forest and park roads). National maintenance policies set by the Federal Highway Administration (FHWA) for state and local federal-aid highways are only advisory because 100 percent of the maintenance funds are supplied by the state and local governments.

In summary, the development of CMA is technically achievable but economic and operational achievement is not assured. The improvement of chemical management systems, mechanical and thermal removal of snow and ice, and other alternative winter maintenance systems promise economic and operational gains.

Large-Scale Projects

When considering the scale of the proposed research program, several assumptions should be made. First, the research program would address improvements in the chemical snow and ice control program that reduce or eliminate the undesirable features of the heavy use of rock salt, i.e., corrosion and brine contamination of soils and water. Second, it is not probable that a manufactured melting agent would ever be as economical in material costs as an abundant natural material such as rock salt. Third, current technology applied to engineering design and construction makes new highway bridges and pavements less vulnerable to damage by snow and ice control salting. Fourth, carefully designed and covered salt storage facilities and well-managed salting programs have reduced the problem of soil and water pollution in most areas where good practice prevails.

The scale of the research effort, then, cannot be based on potential savings in the snow and ice control programs because such programs are likely to be more costly if manufactured chemicals are used. Savings may be realized by a decrease in problems associated with corrosion on older existing bridges, but this would apply only if the chloride content in the bridge decks had not already reached a critical level. Savings might be realized by eliminating some of the new protective measures (epoxy coated re-bars and dense concrete surface cover) on future bridge decks. Such reductions in quality standards are unlikely to be adopted, however, because of the continuing potential for corrosion in bridge deck systems due to other elements and contaminants that would still be present in the environment even if salt were not used.

Measures of scale, instead, must be based on the research task required and the return on investment in terms of environmental protection. Generally the FCP and pooled fund activities that address the development, evaluation, and, eventually, the production of CMA appear to satisfy the requirements for an integrated effort in this study area. Over the past 5 years approximately $1 million has been invested in investigating alternative chemicals; this research led to the emergence of CMA as the prime candidate. An allocation of approximately $10 million over the next 10 years will be required to explore the full potential of this material.

Continuing independent studies by state highway agencies to improve snow and ice control procedures, funded by Highway Planning and Research (HP&R) funds, also are needed. Resources are available for this research activity from the new revenue flowing into HP&R from the Surface Transportation Assistance Act of 1982.

Greater Integration of Effort

Two types of activity should be considered when assessing the need for an integrated approach to this research area. Operations is the first activity to be studied. Examples are calibration of equipment, design of storage facilities, planning of snow and ice control, and similar activities that are somewhat unique to the local organization. Research in this area lends itself to separate studies by separate organizations. The integrated approach is likely to yield dividends in the development of new equipment; the evaluation of alternative rates of application of chemicals for given weather, traffic, and roadway conditions; and the evaluation of alternative application procedures (spread, windrow, spot, intermittent, liquid, solid) for given weather, traffic, and roadway conditions.

The second activity is the development of an alternative chemical; this requires an integrated approach. The development of CMA and the proposed studies of production and utilization do not permit piecemeal, independent studies without a large potential for duplication and omission. Currently this effort is being administered through FCP and pooled fund studies.

National Policy

Since World War II there has been an unwritten but generally accepted policy that the primary highway system will be kept open throughout all but the most severe winter storms. This policy has been responsible for a steadily increasing use of rock salt and limited use of calcium chloride as a supplemental material for low temperature applications. No change in this winter maintenance policy is likely to occur. The proposed research presumes that improved chemical control of snow and ice would be achieved without a reduction in levels of service on the highways.

Substantial policy changes have occurred as a result of national concerns about the environment (*4*). It is these policy changes that the proposed research will address. Although dilution and lower rates of application have reduced the effect of salt on roadsides and waterways, there is still a constant, nagging concern on the part of highway officials and environmentalists regarding the long-term effects of salt content increases in soils and water supplies. An alternative melting chemical such as CMA, if proven to be nonpolluting in the highway environment, could move the winter highway maintenance programs more closely into the line of compliance with national policies on pollution control.

Technological Change

In considering the impact of current or potential technological change on snow and ice control programs, several allied developments can be identified. Snow and ice control programs are pragmatic operations using labor, equipment, and materials to remove snow and ice from pavements and bridges as rapidly and economically as possible. Sensing devices and equipment changes have had and will continue to have an effect on winter maintenance programs. These include advances in such areas as

Detection. Temperature and moisture sensors placed on or near bridge decks can sense conditions that predict the presence of snow and ice. The sensors can be used to activate warning signs, send signals to monitoring stations, or trigger other responses to the measured environmental conditions.

Prevention. The technical capability exists for using electrical or hydraulic circuits in pavements or decks to maintain above-freezing temperatures. Technological changes that effectively harness low-cost energy and use highly durable materials in the unstable, hostile environments of decks and pavements may make such systems economical and practical in the future.

Removal. In addition to future technology providing new chemical removal options, technological changes in equipment such as material spreaders and snowplows can have an important effect on snow and ice control. Computer-controlled spreading equipment, teflon-coated snowplows, and similar developments will continue to provide incremental improvements.

Management. Continuing improvements in radio communications, electronic detection and identification of vehicles, and weather forecasting will enhance a managers ability to anticipate storms, analyze field conditions, instruct and control operations, and monitor performance.

In summary, there are no major technological changes in winter maintenance that are forcing a research response. However, a host of technological changes are occurring in other disciplines that can and should be serving this research area if an effective program of technology transfer is implemented.

Safety and Environment

Snow and ice control activities have as a basic objective the improvement of winter driving conditions to provide greater safety when roads become icy and during snowstorms. The proposed research, however, does not seek greater safety than is currently provided by conventional salting and plowing operations. Instead, the research would seek alternatives to rock salt that would continue that same level of safety but without the environmental and corrosive trade-offs that occur with the heavy use of rock salt. Consequently the proposed research is not likely to have a significant effect on safety. It will, however, have a less detrimental effect on the environment. Both rock salt and calcium chloride have been valuable tools in winter maintenance, and both chemicals have created significant environmental problems.

Salt, when applied to a pavement surface at the outset of a snowstorm, goes into solution as it comes into contact with the snowflakes, creating a brine-covered pavement surface to which snow and ice will not pack and bond. Salt, when applied at intervals throughout a snowstorm, causes snow on the pavement surface to become slushy and easy to remove with snowplows. Calcium chloride provides the same reactions with the added capability that it goes into solution under colder and dryer conditions because of its hygroscopic and exothermic properties.

On the other hand the excessive use of salt on pavement surfaces, in some instances, leads to contamination of adjacent streams and ponds due to runoff of the brines. Soils and subsurface water supplies also have been contaminated. In the early years of salt use on highways, casual storage of open stock piles of rock salt led to soil and water contamination caused by leaching during and following rain or snowstorms.

The level of chloride in the water supplies of cities showed a steady increase from the late 1940s through the early 1970s, paralleling the expanding use of salt on the nation's highways. Table 16, which originally appeared in *Transportation Research Record 506*, recorded a steady

TABLE 16 Chloride Levels in Municipal Water Supplies (5)

	Average Annual Chloride (ppm)					
City	1947	1952	1957	1962	1967	1971
Atlanta, Ga.						1.0
Buffalo, N.Y.				2.3	2.7	2.6
Chicago, Ill.	5.2	6.4	5.7	6.9	7.9	9.1
Cleveland, Ohio	20.0	20.1	20.6	24.0	27.2	23.5
Denver, Colo.	17.8	28.1	17.8	25.8	16.1	12.6
Detroit, Mich.	8	8	7	8	10	8
Hartford, Conn.	2.4	2.4	2.4	3.4	5.0	6.0
Houston, Tex.						
Indianapolis, Ind.	12	13	15	21	33	41
Los Angeles, Calif.	31	26	31	28	27	28
Milwaukee, Wis.	4.3	5.0	5.6	6.8	8.0	8.5
Minneapolis, Minn.	1.08	2.5	3.3	3.9	5.8	6.19
Montreal, Canada	14	20	22	24	25	28
New York, N.Y.						
Oklahoma City, Okla.				117	111	112
Philadelphia, Pa.				14.8	20.6	22.5
Phoenix, Ariz.				146	121	181
Pittsburgh, Pa.	25	23	25	23	21	19
Portland, Maine	1.5	1.5	2.5	2.5	4.3	3.5
Quebec, Canada	5	5	5	5	6	8
Rochester, N.Y.			18.6	19.1	19.1	20.4
San Francisco, Calif.	1.1		2.6	2.9	4.0	4.3
Seattle, Wash.	2.7	0.6	1.8	2.2	2.4	4.4
Springfield, Mass.	1.6	1.8	2.1	5.8	13.6	17.0
Toronto, Canada	17.9	20.1	22.3	24.0	25.5	29.2
Washington, D.C.	5.0	3.78	7.0	10.0	10.9	11.9
Worcester, Mass.						
Average	10.6	11.7	12.3	14.0	15.6	17.7

increase in water supply chloride levels in 16 out of 22 cities that are in areas where salt is used for highway deicing (*6*). Later statistics, if available, would probably show that this trend has leveled-off or reversed as new controls for chemical programs have been implemented.

The greatest problem in the use of chlorides, however, has been from the corrosive effects of brine. Vehicles using the highways have suffered from brine-induced rust, and metal structures on or adjacent to the highway have corroded. Of particular importance has been the corrosion of reinforcing steel in reinforced concrete bridge decks, piers, and abutments. Corrosion has been a major cause of bridge concrete deterioration that has become prevalent in all but a few southern states in the last two decades.

The environmental and structural damage caused by using chemicals to remove snow and ice has created a strong need for a new chemical program. Two avenues of research offer promise in addressing this problem. First, the storing, handling, applying, and controlling of chemicals and alternative winter maintenance programs offer many opportunities for improvement. Savings in chemicals and reductions in environmental and structural damage are important potential payoffs (*7*).

Second, new chemicals with the melting capabilities of sodium chloride or calcium chloride but without adverse environmental or corrosive effects could offer maintenance crews an acceptable alternative for winter maintenance. Obviously, an alternative chemical must compete with the relatively low cost of rock salt or establish a favorable cost-benefit relationship when environmental and corrosion savings are included in the evaluation.

Progress has been made in developing a pelletized form of calcium magnesium acetate (CMA) as an alternative melting agent. Continuing research is needed to try to develop the technology for producing CMA in quantities and at costs that make it acceptable for highway applications. Research is also needed to determine the environmental, technical, and economic ramifications of using CMA in winter maintenance programs.

PROJECT DEFINITION

The objective of this proposed research project is to improve chemical snow and ice control programs by

- Reducing the amount of chemicals used by limiting chemical applications and by optimum use of mechanical snow removal procedures.

- Eliminating or substantially reducing environmental pollution and corrosive effects of sodium chloride and calcium chloride by developing CMA or an alternative chemical in a usable, economically feasible form.

Reduction in Chemical Use

Attempts to control and reduce salt requirements have been made by applying a salt-saturated water solution to the road surface with a modified asphalt distributor. Brine is applied to the roadway under high pressure, which together with the melting action of the salt solution breaks the bond between the ice and road surface. However, the amount of salt used to deice a highway by applying brine has not proved to be appreciably different from the amount required when conventional application methods are used.

Also, there are some serious drawbacks to the use of brine for highway deicing. Water is added to the road surface; therefore, if the temperature drops below the freezing point of the brine solution and drainage is poor, icy road conditions may be exacerbated instead of alleviated. Moreover, additional capital expenditures by a highway department would be required for modification or acquisition of the special equipment needed to prepare and apply the brine.

Another area of research has been based on the use of ice inhibitors built into the road surface (*8*). A Swiss patented process called Verglimit imbeds calcium chloride particles treated with linseed oil into asphalt pavements. The movement of traffic (no less than 5,000 cars per day are required) releases ice melting particles that break the bond between the ice and pavement. Drawbacks to Verglimit are the continual release of chlorides into the environment in all seasons of the year, together with a 40 percent increase in pavement costs and a 50 percent reduction in service life.

Solar and electrical energy and heat pumps using subsurface soil temperatures have been used to heat pavements and bridge decks to keep them free from ice (*9*). High costs and unreliability have limited the use of these technologies to date.

Additional research has been conducted to establish optimum distribution rates for the application of salt under various sets of temperature, humidity, and traffic conditions. The recent development of reliably calibrated salt spreaders that correlate flow of material with speed of the vehicle has made it possible to exercise greater control over the amount of salt dispensed than was possible previously.

Some improvements have been developed for snowplows. These include various hydraulic or mechanical controls, operated from the truck cab, to position plows for left or right hand casts and for pushing snow across intersections and driveway areas. Some improvement in performance has been achieved through coatings or treatments for plow faces that allow the snow to slide more easily across the face and be cast in windrows at the roadside. The cutting edge or blade along the bottom of the plow has been the subject of research also. High-strength steel blades are used for extended wear, and heavy duty rubber blades are used for squeegeeing slush and moisture from pavement surfaces. In general, however, no major unified research effort has been directed toward the improvement of snow removal equipment, and the basic characteristics of spreader trucks and snowplows have remained the same for 30 years.

Several research areas, then, require continued effort to reduce the amount of chemicals used on highways (*10*). The control and improvement of storage, handling, application strategies, and procedures should be studied by state organizations under a nationally coordinated effort funded through the HP&R program. Under FCP it is recommended that contract research projects be established to (a) develop improved snowplowing and spreading equipment and (b) develop pavement heating systems for bridge decks and other selected pavement areas. Five-year funding for this effort is recommended at $5.5 million.

Development of Alternative Chemicals

Research has produced an understanding of the deleterious effects caused by the use of salt to deice the highways and the skills and caution necessary to ameliorate those effects. Major advances have been made in controlling and mitigating the adverse effects of salt use, but further advances in highway deicing may be achieved through the development of alternate chemicals.

An acceptable and affordable salt substitute for highway deicing would be a major breakthough. To be considered a viable alternative, the salt substitute must have the same effective melting range as salt, lack detrimental effects, and not be excessively expensive. Research has identified salt substitutes that have, to a limited degree, proved to be effective but have not demonstrated sufficient success to warrant their application on other than an experimental scale (*11*). Included in this group are

- Formamide,
- UREA,
- UREA-Formamide mixture,
- Tetrapotassium pyrophosphate (TKPP),

- Ethylene glycol, and
- Ammonium acetate.

The substitutes for salt that have been examined have disadvantages that may be grouped into six types (*11*): (a) cost , (b) corrosion, (c) toxicity, (d) solubility, (e) flammability, and (f) application (liquids). Other alternative deicing chemicals that were examined have undesirable characteristics equal to, or exceeding, those of salt. These included

- Ammonium acetate,
- Ammonium nitrate,
- Ammonium sulfate,
- Alcohols,
- Glycols,
- Sodium formate,
- Calcium formate, and
- Ammonium carbonate.

At this time the most promising chemical alternative to salt for highway deicing appears to be CMA. CMA is made from dolomitic limestone that has been treated with acetic acid. A major stumbling block to the production of CMA in commercial quantities is the unavailability of acetic acid (vinegar) in sufficient quantities.

During the past years a process using a bacterium to ferment biomass into acetic acid has been developed at the Stanford Research Institute under a FHWA contract. This process has produced in the laboratory an exceptionally high yield of acetic acid—as much as 83 percent of theoretical yield—that is at the same time uncontaminated. Further research and development is required, however, before the bacterium fermentation process will be ready to produce commercial levels of acetic acid.

In fiscal year 1983, the FHWA obligated $653,000 for research and development of CMA; much of this was devoted to developing an economical and efficient method of producing acetic acid. The NCHRP recommendations for fiscal year 1985 include a $400,000 project of field environmental monitoring of CMA over a 4-year period. FHWA has obligated $200,000 in fiscal year 1984 for CMA research and development. If the bacterium fermentation process for acetic acid is developed sufficiently FHWA expects to obligate $300,000 in fiscal year 1985 for CMA production and $1.8 million in fiscal year 1986 for production and testing.

Planned work would include further testing of CMA to determine its specific deicing properties, at what temperature range and in what amounts

CMA is effective, and when it ceases to be effective. Further evaluation of CMA's environmental acceptability and examination of whether it is at all corrosive or detrimental to highway structures and motor vehicles is also intended.

Four states have experimented with methods for producing CMA. South Dakota studied a process reacting cellulose with alkali and alkaline earth hydroxides to produce CMA. This work was performed by the South Dakota School of Mines and Technology in conjunction with the South Dakota Department of Transportation. Maine experimented with producing commercial quantities of acetic acid from the fermentation of apples. Maine also prepared large quantities of CMA by reacting acetic acid with dolomitic limestone.

Iowa studied the use of sand treated with CMA. Alaska is preparing acetic acid from catalyst-aided oxidation of natural gas and then reacting it with native Alaskan limestone to produce a product that is more than 90 percent pure calcium acetate. Magnesium is almost eliminated from the final product in this process, and the properties of the final product have not yet been determined. Work on this project is being done by the Petroleum Engineering Department at the University of Alaska, Fairbanks, and the Alaska DOT.

Continuing research to develop production capabilities for CMA and to evaluate the environmental impact and corrosive effects of its use on highways and structures is warranted. The funding levels currently provided by FHWA are at the minimum level required to advance this technology. It is recommended that $2.5 million be budgeted over a 5-year research program period for the continuation of this effort under the FCP.

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10
Alternative Institutional Arrangements

The strategic transportation research program presented in this report calls for a unique, special-purpose organization. It is an exceptionally large program, but the research would be concentrated in a few specific areas. The Federally Coordinated Program of Highway Research and Development (FCP), including Highway Planning and Research (HP&R), National Cooperative Highway Research Program (NCHRP), and Federal Highway Administration (FHWA), currently has more than 1,400 active studies in 64 project areas under 9 major categories. These ongoing demand-responsive research programs serve a continuing and changing need for research in a dynamic technology.

The Strategic Transportation Research Study (STRS), on the other hand, does not cover such a broad array of many possible research areas; instead it selects six topics to be investigated in depth. These six are research topics that appear to have exceptionally large payoffs yet represent areas that existing research programs have not been able to address fully.

ORGANIZATIONAL REQUIREMENTS

These differences relative to current programs, then, suggest several special requirements for the organization and administration of the STRS program. These requirements are discussed in the following paragraphs.

As will become apparent, these requirements represent an ideal nonexistent organization, and various practical compromises may be necessary. Nonetheless, it is helpful to begin by considering the organizational characteristics that would best serve this major new research program.

Independence

The organization should be independent of other allegiances and responsibilities if it is to administer $150 million efficiently and with early results. Independence from established cumbersome policies and procedures will facilitate action and accomplishment. For example, when the Department of Defense assigns a mission-oriented R&D project, it goes to an independent task force created to get the job done and licensed to exist only for that purpose and only for that time.

The turf wars and budget battles that accompany permanent organizational changes are avoided. Archaic processes for action and decisions do not exist, and there is no need for extensive regulations, procedural manuals, and policies. Funding commitments and staff assignments are made without fear of establishing precedents for future years (because the organization is temporary); and the staff, without a preoccupation with administrative tasks, is free to concentrate its attention on the research program and the goals to be achieved.

Insulation from Outside Influences

Along with independence there must be insulation from special interest groups; parochial or regional biases; political, social, or environmental advocates; and others who would seek to influence the research or the interpretation of the results. However, researchers and staff must remain aware of and responsive to the real-world concerns and conditions under which the results will ultimately be tested and accepted or rejected.

Continuing Organizational and Financial Commitments

The organization must have continuity of staff, management, and operations for the proposed 5-year term of the program. This period exceeds the political and budget terms in most existing governmental organizations. Appointments must not be tied to political administrations or conventional budget cycles. Staff expertise must be permitted to grow throughout the project and to become a valuable asset. Understanding of the program objectives, risks, and alternatives by management needs to be developed and retained throughout the program.

None of the other desired characteristics of the program can be realized unless there is a reliable, known, continuing commitment of funds adequate to carry it to a successful conclusion. Financial commitments are critical at two levels. First, an adequate source of funds must be established for the program so that it can proceed without interim financial decisions. Such a commitment will require federal legislation and/or a contractual agreement among the states. One alternative would be federal legislation (with state support) for setting aside an additional 0.25 percent of federal-aid funds. Current HP&R funds set aside by FHWA from each state's federal-aid apportionment can be used by the state for planning and research activities in proportions determined by the state. An additional 0.5 percent can be set aside at the option of the state. If the criteria for a financial commitment are to be met, funds should be automatically set aside for the strategic research program.

At the second level, the research organization itself must make a financial commitment to the specific projects that are included in the program. At the same time it must monitor progress and reallocate resources among the projects as costs and payoffs are reassessed.

Constituent Involvement

Highway administrators and engineers, contractors, suppliers and manufacturers, universities, research agencies, consultants, and other implementers of new technology must be kept closely involved in the STRS program. State and local public agencies, responsible for constructing and maintaining the majority of roads and streets, and private sector representatives should be an important part of the program.

Because of their experience and technical expertise, constituents must have an opportunity to (a) review and guide the research, (b) participate in field testing, and (c) make suggestions on applications and real world constraints. Involving constituents in the planning and implementation of the research effort also should win the support of those agencies for the research effort, provide an early opportunity to understand and use the research findings, and generate a willingness to serve as advocates for technology transfer and implementation in other agencies. At the same time, the organization needs to be structured so that research management is supported and guided but not hampered by groups or committees.

Central Management With A Clear Mission

An effective central management must be assured under the guidance of appropriate boards and operating committees. The program director should be responsible for achieving designated goals and objectives within his budget. He should have maximum flexibility of operation within reasonable and clearly established guidelines. A small body of representatives from the principal agencies (e.g., AASHTO, FHWA, and TRB) should be established. This body should set general operating guidelines and direction for the research program.

Finally, the organization should be given a clear mission.

Competence

An obvious but easily understated requirement of the STRS organization is the need for special competence and experience in the technical and managerial tasks to be performed. Part of the challenge lies in rebuilding technical expertise in areas where research has been neglected.

The program requires unique managerial skills in administering a complex technical program and in understanding and implementing research strategies. Managers will have to be particularly sensitive to the role and process of innovation in the economic, political, and social structures affecting highway transportation.

A competent, experienced team is needed to ensure useful results from the massive, short-term research effort envisioned for STRS and to win the necessary support and cooperation of highway agencies and industries.

ORGANIZATIONAL OPTIONS

Several alternative institutional arrangements need to be considered. Because of the special characteristics of the program, no existing organization appears to be an obvious candidate to undertake it in addition to ongoing activities. There are, however, organizations that have had substantial experience with somewhat similar programs that might administer it effectively. The FCP is an obvious candidate; also new organizations such as an AASHTO Commission or a federally chartered nonprofit research agency might be considered. The TRB might play a role in supporting such an agency. In any event, a substantial part of the research effort would be performed by contract or subcontract to universities and other research agencies to take full advantage of the resources available in the national research community.

If a new organization is considered, the general requirements and the alternative institutional arrangements need to be studied with a realistic assessment of the political, legal, and economic factors that would influence the chances for successfully creating such an organization. What action is necessary for the organization to be created promptly and effectively? What are the legal constraints? Legislative requirements? Interagency agreements? How would staffing and management be supplied? What physical facilities and equipment would need to be acquired? Would these needs (people and things) be available when funding is in place?

A major undertaking such as the strategic research program cannot be launched without a substantial effort to create, house, equip, and operate the required organization. The task should also be approached with a candid recognition of those options that are more likely to be achieved without major complications. In the following sections, several institutional arrangements are discussed and evaluated.

An AASHTO Task Force

An option that would permit prompt action, probably without legislation, would be for AASHTO to create a special task force to manage and partially perform the strategic highway research program. The task force staff could be augmented by loaned staff from member state DOTs for the program term on a cost-reimbursement basis. The management of the task force could be assigned to a special AASHTO committee in a structure such as shown in Figure 8. The AASHTO Select Committee on Research could have a role in such an organization although it would not have the broad responsibilities for project selection that it holds in other programs.

Parts of the program, such as the long-range pavement performance study, could be handled by the task force staff research teams if the longevity of the staff beyond the initial 5-year period were assured. Other parts could be assigned by contract to outside research organizations.

This option offers the advantage of being relatively simple to create. Also, the assigned staff would bring experience and knowledge of operating agency problems and needs, thus assuring constituent involvement in the research program.

Disadvantages in the task force concept also must be considered. The loyalties of the loaned staff could be divided between the research program and their state agency. Although the organization could be created administratively, legislation would still be needed for the research pro-

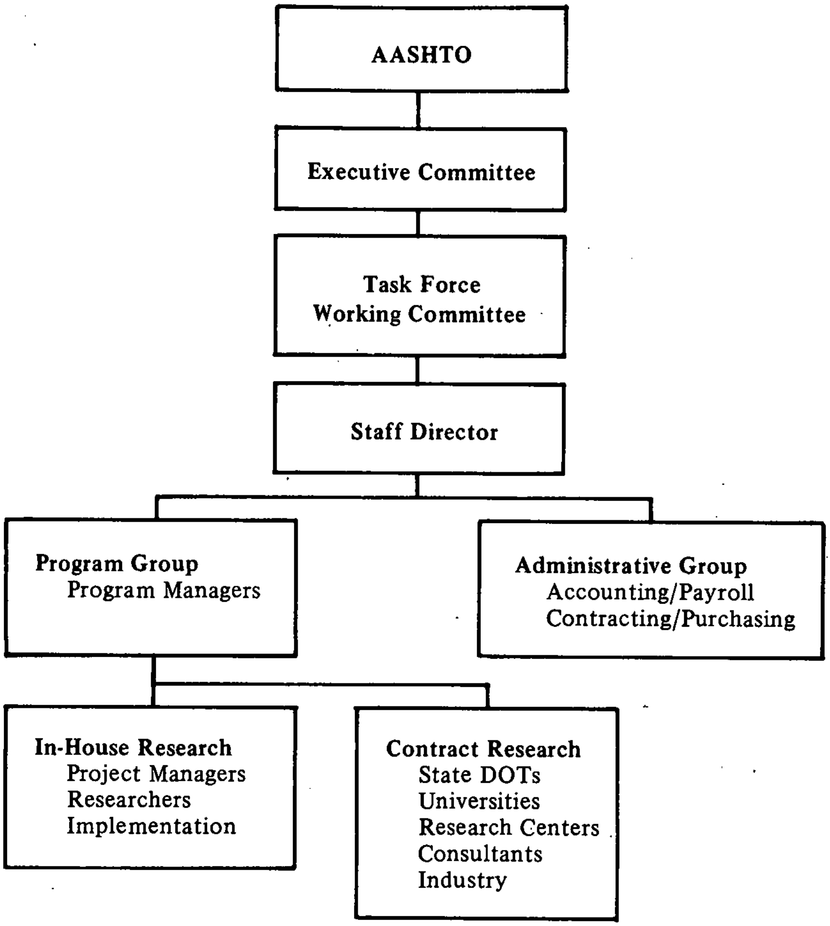

FIGURE 8 A proposed AASHTO task force.

gram funding. Also a task force, unless chartered or incorporated, would not be a legal entity with the power to enter into contracts. Another organization, such as a state DOT, FHWA, TRB, or AASHTO, would have to perform such functions. Thus, The AASHTO task force concept presents some difficulties, but they do not appear to be insurmountable.

AASHO Road Test Organizational Model

The successful role model provided by the AASHO Road Test could be considered in selecting an institutional alternative. The federal and state governments and the highway industry (truckers and materials suppliers) funded or provided valuable services to the to the program. Universities, foreign governments, trade associations, and others loaned personnel to the TRB staff, to committees, and to research review groups. The basic management team for the AASHO Road Test was supplied by TRB, and drivers for the vehicles were supplied by the Department of Defense.

The advisory committee for the AASHO Road Test included representation from all interested parties and provided a broad spectrum of expertise related to pavement research. This committee advised the staff in matters related to the administration of the project. To repeat the success of this model would require careful selection of the principal members of both the staff and the advisory committee to ensure mutual respect and a real interest in doing the job well.

The National Research Council (NRC) is able to accept, hold, commingle, and administer funds from government and private agencies. It also may perform work in-house or contract it out to government or private agencies; this flexibility is important.

TRB and the other units of the National Research Council have existing relationships (through their committees and contract research programs) with several thousand scientists, educators, engineers, and researchers. This talent pool is available to support NRC projects.

Federally Chartered Research Agency or Special Study Commission

An option that offers a clear-cut separation of the strategic research program from ongoing research programs and agencies is the creation of a special, federally chartered nonprofit research agency or special study commission. Such an agency could be created by the U.S. Congress, perhaps as a part of the federal-aid highway bill that would also set aside funding for the program.

Precedents have been set by the U.S. Congress for creating special commissions or councils with a fixed mission and life span. In the Federal Water Pollution Control Act of 1972 (Public Law 92-500), Section 315 established a National Study Commission to study the technological aspects of achieving effluent limitations and goals. The commission was directed to submit a report on its study not later than 3 years after its creation. The Act authorized $15 million for the commission to use in carrying out its task.

The Clean Air Act of 1977 (Public Law 95-95) also created a National Commission on Air Quality. Section 323 called for the commission to study and report on a series of air quality issues by no later than 3 years after enactment of the legislation, after which the commission ceased to exist. The commission was authorized to contract with nongovernmental agencies competent to perform research, and $10 million was authorized for appropriations to the commission.

In a current bill being drafted for the 1984 session of the Congress, cited as the Federal Capital Investment Program Information Act, Section 107 proposes the establishment of a National Commission on Capital Investment to assess the condition of national infrastructure. The proposed commission is directed to develop a National Public Improvements Plan. The plan will list in priority order needed construction, rehabilitation, or repair of national public improvements (defined as the nation's system of highways, roads, bridges, mass transit, main water supply and distribution systems, and sewer systems) on a regional and state basis for a 5- and 10-year period. The commission will have 2 years to complete its work and a budget authorization of $5 million plus a staff of up to 30 federal employees detailed from other agencies.

These examples illustrate that the new agency could be established for a specific time and purpose. A new agency would bring independence to the task and would be challenged to achieve its specific mission. The charter or legislation could be drawn to ensure strong central control with participation by constituent agencies. The organization would require a small staff that would function in a structure similar to that shown in Figure 9.

The chief disadvantage of establishing a chartered research agency or study commission for the strategic research program is the cost and time expended to get started. It could take an extended period of time to get the legislation through Congress; and housing, staffing, and organizing the agency would occupy the early efforts of the team. Also, as an agency of the federal government, it would probably be required to meet federal procurement and hiring rules.

Recruiting high level professionals for an organization with a limited life and an unknown identity could be difficult. Other similar short-term commissions or councils, however, have been successful in staff recruitment. The high visibility of the assignment and the opportunity to advance the frontier of technology may provide incentives sufficient to offset the short term.

The pattern of bringing together a high-level staff for a major fixed-term effort is generally successful in the consulting engineering industry, major construction industry, defense industry, and others. It should not be an overriding factor in this program.

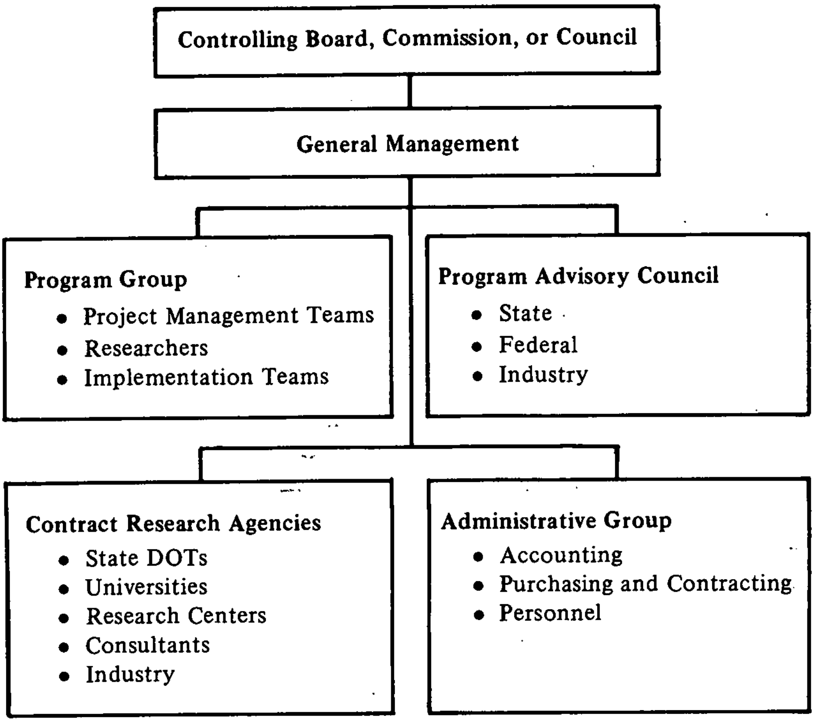

FIGURE 9 Proposed organizational structure for a chartered research agency or study commission.

National Cooperative Highway Research Program (NCHRP)

As an ongoing research program with strong support by its constituency, NCHRP might be modified to incorporate, under a separate wing of the program, the strategic research program. This option would require that NCHRP set up an organizational structure with a staff and constituent representation independent of the existing NCHRP program. Existing funding channels and controls could accommodate the addition of the strategic highway research program without change. A concept for the organizational structure is shown in Figure 10.

Unlike ongoing NCHRP activities, its role for STRS would be to monitor and advise rather than to select research projects. The STRS committee would participate in defining the research program and developing the research plan, in monitoring the ongoing program, and advising the STRS administration as the program progresses.

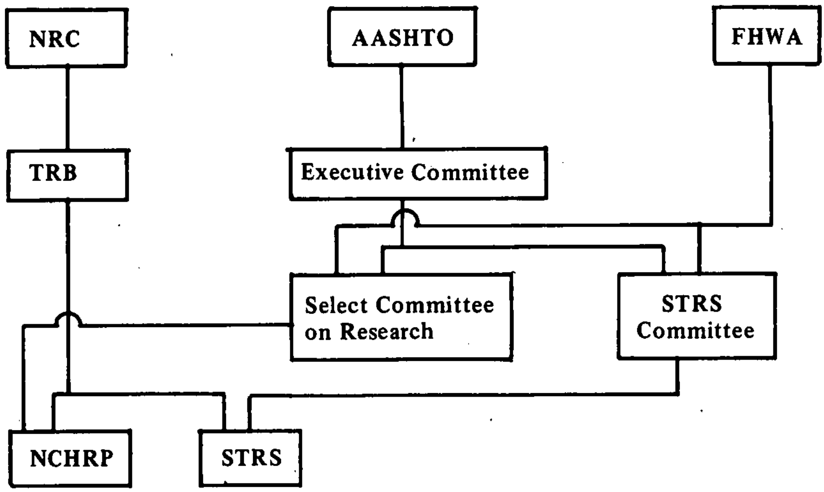

FIGURE 10 Concept for modifying NCHRP.

Several aspects of the NCHRP process would have to be modified to accommodate STRS. The STRS contracting process could proceed through staff for final approval by the STRS Committee. The obvious advantage of using NCHRP to implement STRS is that NCHRP is already staffed, housed, and operating. Although additional staffing would be required, the existing staff is familiar with most aspects of the proposed strategic research areas and with the research community that would carry out the new program. Operating processes are established for transferring funds into the research program, and it has a proven capability for administering an ongoing contract research program.

Another advantage that NCHRP offers is continuity of staff and programs—a key element in STRS and of critical importance in the long-range pavement performance studies that will continue long after the 5-year program is completed. Certain hazards also must be recognized in considering NCHRP for the STRS program. The concerted focus of the STRS program, with its requirements for strong central control, may not be compatible with the project-by-project processes of NCHRP. Because of the magnitude of the program, the National Research Council or the Academies may not wish to have TRB assume this role (although the AASHO Road Test set a precedent for such a major short-term task). Also, the demands of the STRS effort could be seen as a diversion of TRB from its primary responsibilities in the research community.

Federally Coordinated Program of Highway Research and Development (FCP)

Another ongoing research agency that might manage STRS would be the Office of Research Development and Technology of the FHWA. A separate program category or categories might be organized within FCP for STRS. A new Office of Strategic Highway Research could be established under the Associate Administrator to manage the program. Figure 11 suggests an organization that could be established in FHWA.

Like NCHRP, FCP brings the advantage of an established organization, knowledgeable in the program areas and research community. FCP also operates a major new research laboratory in which some important parts of the strategic research program might be undertaken.

Although the FCP could undertake a major new program of the magnitude of STRS, it would require substantial additional staff. The FCP contracting processes, fixed by Department of Transportation regulations, might require modification to accommodate the needs of STRS. The FCP processes for involving AASHTO and its members and industry in the research program would need to be expanded and formalized.

National Bureau of Standards

Another option for managing the STRS program is the National Bureau of Standards (NBS). Since 1965 AASHTO has participated in the NBS Research Associate Program whereby NBS operates the AASHTO Materials Reference Laboratory. The primary responsiblity of the Laboratory has been to promote uniformity in the testing of construction materials by inspecting state DOT and other laboratories and by distributing proficiency test samples and statistical analysis of test results. This existing working relationship between AASHTO and the NBS could provide the basis for a similar contractual arrangement for managing STRS.

Through the Research Associate Program, NBS is currently hosting over 100 scientists and engineers from various other (public and private) organizations who are working on research projects of mutual interest. Research associates remain on the payrolls of their sponsoring employers while benefiting from the use of NBS facilities and the opportunity to do cooperative research with the diverse NBS professional staff. In addition to the research results, the sponsors benefit by the increased expertise of the returning employees who are able to apply the new

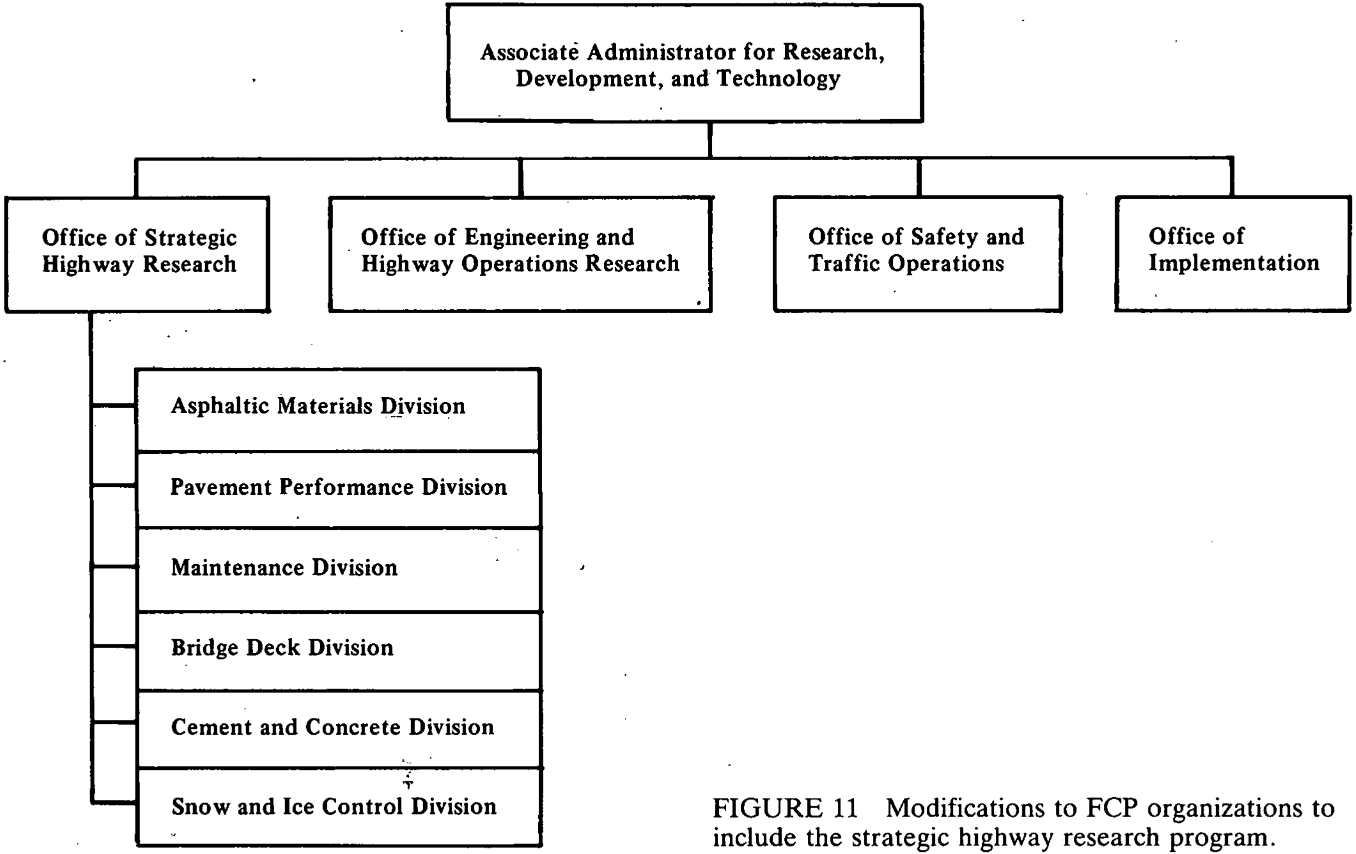

FIGURE 11 Modifications to FCP organizations to include the strategic highway research program.

technology. Approximately 60 percent of the research associates at NBS have been sponsored by private industrial companies.

If STRS were established and performed under the NBS Research Associate Program, a significant part of the research could be performed at NBS. Because of the magnitude of the program, some special organizational accommodations would be required within NBS. At a minimum, an office would need to be established to coordinate the program and to integrate it effectively with the ongoing research programs at NBS (estimated at $151.5 million for fiscal year 1984). A research team, or teams, would have to be assembled from AASHTO member agencies and others. Sponsoring employers could be reimbursed for research team salaries or credited in HP&R apportionments.

Industry participation in STRS could be achieved readily under the NBS organization and such a plan should include an opportunity for industry to be represented. Industries might contribute research associates to the effort without reimbursement and thus make a financial contribution to the program. The interaction of private industry and public employees on the research team should yield additional benefits through a greater understanding by both parties of the challenges and opportunities for private and public sectors of the highway industry.

NBS could administer a contract research program as a part of STRS to handle that part of the research not done within the agency. There is a substantial contract research capability within the research community that could be used effectively under the NBS plan.

A Research Center

Several major public or private nonprofit research centers in the United States could manage STRS. In most instances such research centers would be able to undertake a portion of the work in-house but would find it necessary to contract with other research agencies to handle large parts of the program. Such an arrangement would effectively be engaging a research center to serve as the research program management agency with authority to subcontract portions of the work and to perform portions of the work. This organizational plan has been employed by many public agencies to achieve a major program effort over a relatively short time without disruptive short-term staffing, reorganization, or other actions.

If an independent research center undertook the STRS management role, careful planning and arrangements would be required to keep AASHTO and FHWA properly involved in the program without usurping or relieving the research center of its responsibilities. The concentration of research funds in a single research center could create problems within the research community, however, and might not meet AASHTO requirements for involvement and control.

SUMMARY

Special organizational requirements must be considered for the strategic highway research program. These include independence, freedom from outside influence, continuity, financial and organizational commitment, constituent involvement, strong central control, competence, and a clear mission. Although real-world compromises will have to be made in selecting or creating an organization for the program, several alternative institutional arrangements can be considered including an AASHTO task force, the TRB/AASHO Road Test organizational model, a federally chartered agency or special study commission, a modification of NCHRP, an expansion of FCP, the National Bureau of Standards, or an independent research center. Regardless of which organizational arrangement is selected, the key factors in its success will be the caliber of the staff it assembles and the support and confidence it wins from its sponsors and constituents.

11

Conclusions and Recommendations

what ?- Who's Neglect

The nation's highway system is deteriorating at an accelerating rate. After years of neglect national attention is being directed to the need to maintain, repair, and preserve this system. Congress recognized the need for a revitalized highway program by enacting legislation in 1982 that provides $58 billion in federal aid for highways over the next 4 years.

If we are to meet the challenges of this new building program without the problems of the past, now is the time to develop the needed technology. If current technological needs are to be met through a research program, this is the time to put that program into place. The Strategic Transportation Research Study (STRS) focuses exclusively on the six high-payoff research areas set out in Table 17. These major gaps in our technological progress require an immediate large-scale research effort that cannot be met within existing institutions and resources. Such an effort requires a new research program because a clear mission must be maintained to ensure that the resources necessary to make significant breakthroughs are available.

At the same time, the commitment within STRS to these efforts must not distract from the necessary and continuous progress being made under other programs in other areas such as planning, finance, and human factors. Ongoing national research programs, including Federally Coordinated Program for Highway Research and Development and Na-

TABLE 17. Overview of Proposed Strategic Highway Research Study

Research Area	Objective	Projected 5-Year Costs ($ million)	Potential Results
Asphaltic materials	Define Chemical and physical characteristics of asphalt and their relationship to performance in pavement systems.	50	Better quality control and better materials; and improved design capability and performance predictions. Potential saving of $100 million per year.
Pavement performance	Assess long-term performance of various pavements under various loading and environmental conditions. (Studies would continue for three additional 5-year terms of data collection and analysis.)	50	New capability to assess and select alternative pavement maintenance and rehabilitation strategies; and improved design and construction techniques. Potential saving of $10 billion.
Maintenance cost-effectiveness	Develop improved procedures for administering and controlling maintenance programs; develop new processes, equipment, and materials; and improve productivity of maintenance program.	20	New management systems and increased maintenance productivity. Potential saving of $150 million per year.
Concrete bridge component protection systems	Develop new methods to stop further deterioration of existing chloride-contaminated bridge decks and other components.	10	More effective techniques for removing chloride from concrete or protecting concrete from chloride contamination? Potential saving of $400 million per year.
Cement and concrete	Understand chemical and physical phenomenon of hydration; evaluate new options such as recycled concrete and energy saving components; and develop nondestructive testing methods.	12	Ability to produce a better quality and more durable concrete. Potential saving of $50 million per year.
Chemical control of snow and ice	Reduce the use of salt through management techniques and optimum use of mechanical or thermal removal plus alternative chemicals.	8	Reduction in corrosion and environmental problems without a reduction in the level of service of snow and ice control programs. For example, potential savings from a decrease in automobile corrosion could be $45 million per year.

tional Cooperative Highway Research Program, have made and must continue to make vital contributions to highway technology. A new special research program will have to be structured in careful coordination with and protection for the continuity and health of existing national research programs.

The strategic highway research program discussed in this report is a unique, highly focused program concentrating major efforts and funds on six specific areas of highway technology. The areas are inherently interrelated with many opportunities for synergism if the problems are approached as part of a common program. The program includes areas of national importance that have not received a concentrated effort under previous research programs. A concentrated research effort in these areas promises significant returns in cost savings and system improvements.

Funding in the range of $30 million per year is required; and a long-term commitment of these funds to assure the continuity and completion of the program is essential. This major funding requirement can be met by permitting about 0.25 percent of federal-aid highway funds to be used for this purpose. Under the authorizations contained in the Surface Transportation Assistance Act of 1982, the 0.25 percent set aside would be about $35 million per year. This amount closely matches the funding requirements for STRS and administrative costs.

The 5-year strategic highway research program summarized in Table 17 outlines a pragmatic approach to tangible problems that are related to materials and processes used to build, maintain, and manage the physical structures of the highway system. Research in two critical areas, asphaltic materials and pavement performance, will address the need to understand, improve, and control the quality of the most commonly used materials in highway pavements and the relationships of the measurable characteristics of these materials to pavement performance.

The pavement performance study differs from the others proposed in the program in that it will entail continuous data collection and analysis beyond the 5-year term of the program because very little happens to a pavement in the first few years of its life. Additional funds and an additional 15 years will be required for the long-range pavement performance study. Four study areas, maintenance, concrete bridge components, cement and concrete, and ice-melting chemicals, also represent major challenges for research and provide opportunities for payoffs.

A special institutional arrangement is required to carry out this strategic research effort. That organization, whether it is carved out of an existing institution or created separately, must have independence to concentrate on the new mission, insulation from special interests, continuity throughout the program term, an adequate full-term financial commitment, constituent involvement, effective central control, competent management, and adherence to the clear mission that has been established.

Using conservative projections and eliminating those areas where double counting might occur, the potential payoffs from this program could exceed $600 million per year. Further, most of the saving to taxpayers will continue to accrue each year—long after the 5-year research program has been completed.

Appendix
Steering Committee Biographical Information

THOMAS D. LARSON, *Chairman*, is a state transportation administrator. He is Secretary, Pennsylvania Department of Transportation and President, Northeastern Association of State Highway and Transportation Officials. A graduate of Pennsylvania State University with a B.S. in civil engineering, Dr. Larson served as a project engineer for highway construction after receiving his M.S. and Ph.D degrees from Pennsylvania State University. He taught civil engineering courses in materials, transportation engineering, and planning at Pennsylvania State University, beginning as an instructor in 1957 and becoming a full professor in 1968. In 1967 he headed the committee that organized the Pennsylvania Transportation Institute; he was appointed director of the institute in 1968. Dr. Larson has served on a number of TRB committees and panels, including a term as Chairman of the TRB Executive Committee.

DUANE BERENTSON is a state transportation administrator. He is Secretary of the Washington State Department of Transportation and Chairman of the Standing Committee on Public Transportation of the American Association of State Highway and Transportation Officials. He was graduated from Pacific Lutheran University and attended the graduate schools of the University of Washington and Western Washington University. Mr. Berentson was a member of the Washington State House of Representatives from 1963 to 1980, serving in leadership positions such as Co-Speaker of the House, Minority Leader, Transportation Committee Chairman and Secretary, and was the Washington State representative to the Western Conference of State Governments for Transportation.

DONALD COLLIER, a corporate research executive, is Senior Vice-President of Corporate Strategy at Borg-Warner Corporation where he was also Vice-President for Research and Vice-President for Technology. Dr. Collier received a M.S. in Chemical Engineering and a Ph.D in Physical Chemistry from Princeton University. He was President of Thomas A. Edison Research Laboratory, McCraw-Edison Company, New Jersey. He is a member of American Association for the Advancement of Science, American Chemical Society, Research Directors Association of Chicago, Association of Research Directors of New York, and Chairman, Corporate Planning Committees' Development Council (an advisory group on business strategies). In addition, he has chaired other distinguished committees including Directors of Industrial Research, and the Advisory Council of the Polymer Materials Program, Princeton University; was president of Industrial Research Institute, Inc.; and was a member of the Technical Advisory Board, U.S. Department of Commerce.

FRANCIS B. FRANCOIS is a coordinator of highway programs and plans. He has been the Executive Director of the American Association of State Highway and Transportation Officials since 1980. He received a B.S. in Engineering from Iowa State University and a LL.B from George Washington University. From 1962 to 1980 Mr. Francois was prominent in Prince George's County, Maryland; he served on the Board of County Commissioners for 8 years and was chairman of the County Council for 4 years. In addition, he was President, National Association of Regional Counties in 1972; Chairman, Water Resources Planning Board from 1975 to 1977; member, Board of Directors, Washington Metropolitan Area Transit Authority from 1978 to 1980; Chairman, Washington Suburban Transit Commission; and President, National Association of Counties, 1979 to 1980; and is an ex officio member of the TRB Executive Committee.

ROBERT N. HUNTER is a state transportation administrator. He is Chief Engineer of the Missouri Highway and Transportation Department. Mr. Hunter began his career with the state of Missouri soon after receiving a B.S. in Civil Engineering from the University of Missouri at Columbia in 1950. He has also been a District Engineer, Engineer of Surveys and

Plans, and Assistant to Chief Engineer for Planning and Design for the Missouri Transportation Department. His participation in professional organizations has included President of the American Association of State Highway and Transportation Officials Executive Committee, National Director of National Society of Professional Engineers, and Chairman of the TRB Executive Committee. He received the George S. Bartlett Award for outstanding contribution to transportation progress in 1980.

HAROLD L. MICHAEL is a university research administrator. He is Head of the Civil Engineering Department of Purdue University. After receiving an M.S. from Purdue he became a faculty member, Director of the Joint Highway Research Project, and Head of Transportation and Urban Engineering. Mr. Michael has been closely associated with TRB and transportation-related activities for more than 30 years. He was the first Chairman of Group 3 Council, Chairman of Division A Council, and Chairman of the TRB Executive Committee, and received the Roy W. Crum Distinguished Service Award in 1978. A few of his current professional affiliations are member of the National Academy of Engineering and the National Commission on Uniform Traffic Laws and Ordinances; Vice-Chairman, American Road and Transportation Builders Association; and National Director of the National Society of Professional Engineers. His primary interests are traffic operations, transportation planning, highway safety, and transportation finance and administration.

THOMAS D. MORELAND is a state transportation administrator. He has been Commissioner and State Highway Engineer for the Georgia Department of Transportation since 1975. He is a member of the Georgia Department of Transportation Engineers Association and Board of Directors, Metropolitan Atlanta Rapid Transit Authority. A graduate of Georgia Institute of Technology with a B.S. and M.S. in Civil Engineering, Mr. Moreland has worked for the state of Georgia since 1957, beginning as a Resident Engineer on Construction followed by Soils Engineer, State Highway Materials Engineer, and State Highway Engineer. He was Vice-Chairman of the TRB Executive Committee in 1977, President of American Association of State Highway and Transportation Officials in 1978-1979, and President of the Southeastern Association of State Highway and Transportation Officials in 1980-1981. He has received numerous awards in the transportation field.

DANIEL T. MURPHY is a County Executive for Oakland County, Michigan. He is a member of the TRB Executive Committee, Chairman of the Transportation Steering Committee, and a member of the Board of Directors for the National Association of Counties. Mr. Murphy was graduated from Wayne State University. He began his career for Oakland County in 1956 as County Clerk-Register and was Chairman of the Board of Auditors for 10 years before becoming County Executive in 1975. He is a member of the following professional organizations: Oakland University Foundation, Walsh College Academic Advisory Council, National Association of Elected Finance Officers Association, American Society for Public Administrators, Michigan Association of Counties, and American Association of Airport Executives.

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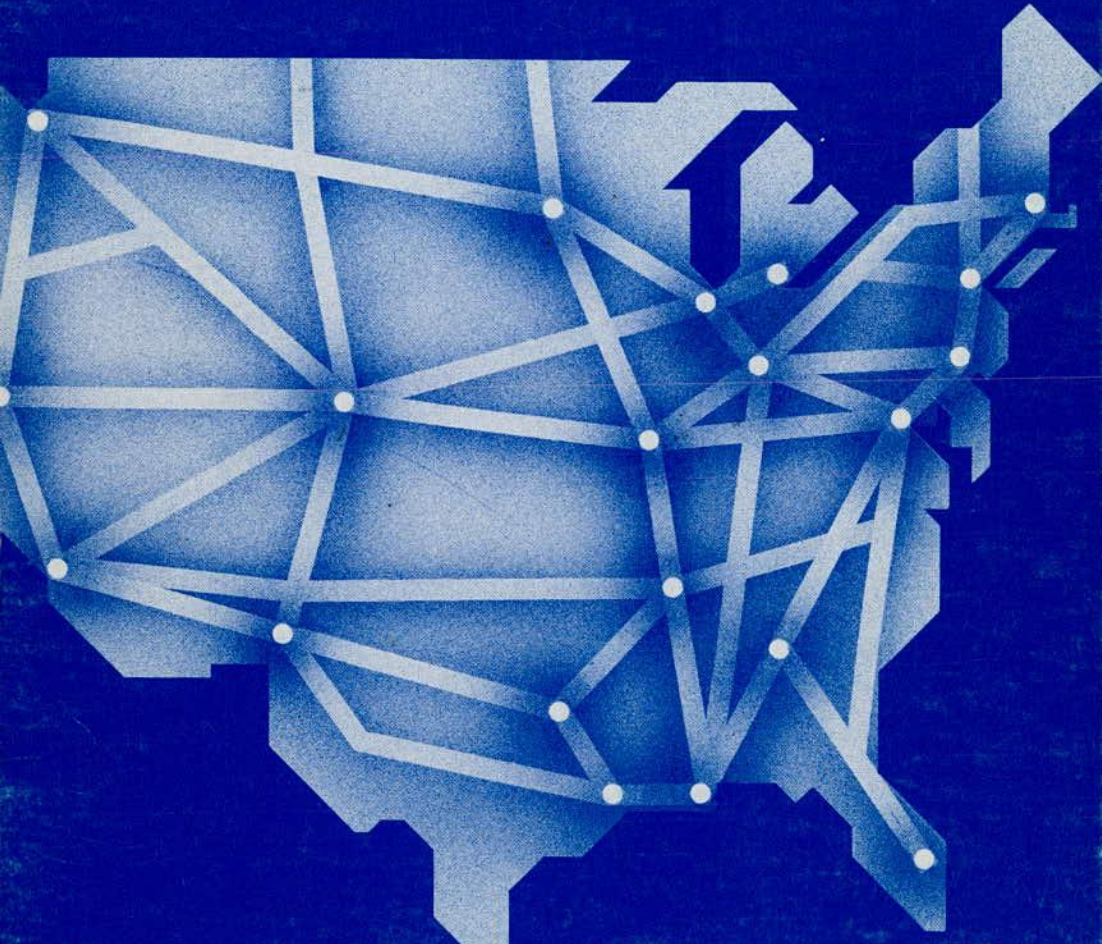

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Strategic Transportation Research Study: Highways

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

Washington, D.C. 1984

The complete report of *America's Highways: Accelerating the Search for Innovation* (price $18.60) is available from the Transportation Research Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

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Executive Summary

INTRODUCTION

At present state transportation agencies have a unique opportunity to make major improvements in the ways they build, maintain, and operate highways. Because of the infrastructure crisis, the public has awakened to its stake in the highway network. Over the years Americans have invested an astronomical $1 trillion in their highway system and are just beginning to realize that without a massive infusion of funds for rehabilitation and maintenance, the system will deteriorate rapidly. But merely replacing failing facilities will not solve the problem in the long run; better products and processes are also needed, and the research to create them is long overdue.

Research for improved highways has been seriously neglected by all measures. Relative to the size of the nation's highway expenditures, spending on highway research has fallen from 0.25 percent in 1965 to 0.15 percent in 1982. This 0.15 percent is far smaller than the research commitment of virtually all other industries: high-technology industries, such as semi-conductors or aerospace, spend 40 times as much on research; medium-technology industries such as the automobile manufacturing or chemical industries spend more than 20 times as much per dollar of sales. Even low-technology industries such as rubber, paper, and steel outspend highways by a factor of eight. Since 1973 state and federal governments have cut their highway research spending in half.

Why has not a system so crucial to everyday life, so large (4 million miles), and so expensive ($1 trillion) been supported all along by large-scale, long-term research? Chiefly because of the extreme fragmentation of the transportation industry. The U.S. highway system's operation is divided among thousands of federal, state, county, city, and private organizations.

In addition, these public agencies maintain complex contract arrangements with the private organizations that usually build or rehabilitate roads. Even routine maintenance is sometimes contracted out to private firms. Highway construction firms buy many materials locally. Both political pressure to favor local suppliers and the high cost of transporting bulky, low-value, construction materials dictate this practice. Thus an army of small, local suppliers supports many equally small, local construction firms.

This structure impedes innovation because it produces a situation in which no one organization has the resources or the incentive to undertake major research to increase facility life, reduce costs, or improve performance. Highway agencies face budgetary pressures and electoral priorities that favor short-term, highly visible projects. Further, high turnover in top management positions forces top officials to focus on visible current issues rather than on long-term functions such as research.

Despite this neglect thousands of improvements in the durability and safety of highway products have been made. For example, highway safety has been enhanced by breakaway sign posts, impact attenuators, and Jersey barriers. Increasing the life of bridge decks by the use of epoxy-coated reinforcing bars, and thousands of other product innovations make today's highways dramatically different from those of 50 years ago. Nevertheless, much more progress could be made in improving the nation's highways by devoting sufficient attention—both financial and managerial—to needed research.

A STRATEGY FOR SETTING PRIORITIES

The limited research in the highway area is largely directed at developing incremental solutions to current local problems. This is logical in view of the diversity of climate, soils, topographies, local paving materials, and traffic loadings throughout different states and counties. It is also top priority for the limited research funding available. The downward trend in research funding has caused the highway industry to overlook or neglect several of the big problems facing the industry as a whole. Research designed to fill these technological gaps must meet many stringent tests. This study outlines a strategy for screening potential research areas to identify the most promising for a national program. Specifically, this strategy involves answering the nine following questions:

1. *Will the research yield big payoffs if successful?*

Many areas of feasible highway research will potentially deliver payoffs far in excess of the necessary original investments. For example, even if research on better asphalt paving materials yielded only a 1 percent reduction in the cost of pavements, this reduction would save $100 million a year—far in excess of the total of $70 million or so now spent on research for highways. Much greater savings would probably result in view of the frequency of premature pavement failures and the ever greater demands that increased traffic and weights of vehicles make on pavements.

2. *Is the research area currently neglected?*

When measured against potential payoffs, virtually all highway research is neglected. However, some categories are funded much more inadequately than others. Research on asphaltic materials, for example, represents only a minuscule fraction of highway research, even though more than 93 percent of all paved roads and streets are surfaced with paving mixtures or surface treatments containing asphalt.

3. *Will the project deal with important research previously hampered by institutional or organizational barriers?*

Improvements in highway products and processes lag when procurement procedures (specifications and low bids) do not encourage the purchase of better products and processes. The profitability of proprietary products, the emphasis on life-cycle costs within procurement processes, and the pressure to buy local materials and services must be considered in choosing realistic research objectives.

4. *Can the research findings be used?*

Research often fails to change practice because of limited understanding, organizational inertia, inflexible standards, preoccupation with first costs, mistrust of change, or a desire to perpetuate jobs. A research program designed without taking into account such obstacles will fail. Nevertheless, determining what is achievable is probably the most difficult, albeit the most crucial, judgment in the entire research process.

Training requirements, organizational changes, investment in equipment, cash flow requirements, personnel implications, and legal liabilities of new approaches can make or break the acceptance of research findings.

Technical research personnel are not necessarily in a position to make these judgments, and, similarly, administrators and political leaders may not be fully aware of the technological options that might be developed. Both viewpoints are needed to identify promising research topics.

5. *Does the research require a large-scale effort?*

Most of the $70 to $75 million now spent on highway research is parceled out in problem-specific contracts of $30,000 to $300,000. Such small-scale efforts can be effective in addressing clear, well-defined problems. However, highway research funds are so broadly distributed that no single organization can attack the major problems that plague the industry.

Pavement performance, in particular, requires long-term research because of the long design life of pavements. The careful evaluation of paving materials and techniques under long-term field conditions could substantially reduce the life-cycle costs of maintenance and construction. Increasing fundamental knowledge of how pavements perform under diverse circumstances and using this knowledge to improve those pavements will require a substantial commitment of time, funds, and research direction.

6. *Does the research require an integrated or national approach?*

Existing highway research procedures are likely to overlook processes such as highway construction that include a sequence of distinctly autonomous steps, each managed by a different organization or unit. Because more than one organization is involved at each stage, none is able to evaluate and control the other stages. A prime example is the construction of an asphaltic pavement, which involves many major steps from mining crude oil to constructing the pavement and opening the road to traffic. The various links in the construction chain are managed by oil companies, refineries, batching plants, aggregate producers, construction companies, and federal, state, and local highway departments. Each depends on the work of the others, but none is able to control the others. However, research on improved binding materials could lead to products and specifications that stimulate more efficient use of resources by all of the organizations involved.

7. *Does the research respond to new and potential changes in national policy?*

Because of the immense variety in local materials, building conditions, and topographic features, the strong problem-solving research capability of state agencies is essential. At the same time this decentralized research structure can lead to duplication, particularly if shifts in national policy create new operational issues simultaneously in all states and counties (e.g. the 55-mph national speed limit or increases in truck size and weight limits). The most efficient and timely response to such changes is to create a coordinated research effort that can immediately address the operational implications of the policy change in all of the states.

8. *Does the research use or respond to other technological changes?*

Technological changes in highway vehicles, communications, materials, and other sciences bring new opportunities and new challenges to all states and counties. If research to tap this potential is too fragmented, it may be incremental and duplicative. Also, not all organizations have the resources or skills to monitor properly new developments in technology. Even more stable technologies, such as asphalt, are subject to far-reaching changes when shifts in petroleum distribution and refining processes occur. Various new technologies, such as miniaturized electronics generated in the space program, may have many more highway applications than are currently being explored.

9. *Will the research affect safety or the environment significantly?*

In addition to major cost savings, research also can help to save some of the 46,000 lives lost each year on the roads and to prevent the suffering of many of the more than 3 million persons injured. For example, research to prevent deterioration of bridge decks could reduce the hazard now posed by potholes and pavement irregularities on bridges and other places where there are no obstruction-free maneuvering zones.

A STRATEGIC RESEARCH PROGRAM

On the basis of the selection strategy discussed in the foregoing sections, six priority areas have emerged where it is believed that a concerted research effort can produce major innovations that will increase the productivity and safety of the nation's highway system. A program focused on these research areas could substantially alleviate the biggest, most pervasive problems now faced by the highway industry. Such a research program could be supported if states would allocate one-quarter of 1 percent of their federal-aid highway funds. The six components of this program are sketched below and organizational and financial implications are addressed in the closing section.

Asphalt

Asphalt use dominates the nation's highway industry. Highway agencies spend $10 billion a year on asphalt pavements—10 times as much as the nation spends on AMTRAK and 6 times as much as is spent on the entire intercity bus industry. Despite the huge sums it spends on asphalt, the highway industry has done very little research to improve this basic material or control its quality. As a result, the highway industry still suffers from premature, costly, and embarrassing pavement failures. Variations in asphalt cements caused by post-embargo shifts in sources of crude oil and new refining processes may have added to this problem. Pavement failures are also caused by substandard construction, faulty mixing, poor quality aggregates, inadequate pavement design, and other factors.

Stable, predictable, clearly specified asphalt cements could greatly reduce pavement failures. Even poorly constructed pavements could last longer if asphalt performance were better understood and if the specifications for this material were developed to compensate for possible failings at other steps of the paving process. Developing improved asphaltic products and specifications will require a closely coordinated research program to

1. Define properties of different asphalts,
2. Improve testing and measuring systems,
3. Determine relationships between asphalt cement and pavement performance,
4. Develop improved asphalt binders, and
5. Validate performance in the field.

The highway industry's use of asphalt is huge and growing. Research on this key product could result in substantial cost savings. But even very modest gains—such as a 1 percent saving in the cost of asphalt paving—would save the industry $100 million per year and more than pay for the research effort in less than 1 year. The five research tasks listed above would cost about $10 million per year for 5 years.

Long-Term Pavement Performance

The nation will spend about $400 billion replacing and rehabilitating pavements before the end of the century. Not only will the Interstate and primary systems need repair but also state, county, and local highways and city streets will require massive investments in pavement. Despite these immense expenditures, no comprehensive research on long-term pavement performance has been conducted since the AASHO Road Test—a large-scale field test completed in 1960. This was an accelerated test done under one set of climate and soil conditions. Fundamental questions concerning climatic effects, maintenance practices, long-term load effects, materials variations, and construction practices remain unanswered.

Answers cannot be found without intensive study of pavements under a large number of actual field conditions over many years. Such a large-scale research program (roughly $10 million per year) over such a long period (approximately 20 years) cannot be undertaken by any existing organization. It requires an unprecedented, long-term commitment that is largely incompatible with the short-run terms of public office and intense budgetary pressures. Nevertheless, the costs represent only about one one-thousandth of what the nation will spend on pavements during the 20 years that the field test would be conducted, and many early results could be obtained in time to reshape future pavement designs and expenditures. In additon, the pavement performance study could help cut the costs that motorists incur from driving on deteriorated highways. It could also help public officials make more informed decisions on axle load limits, cost allocations among various classes of highway vehicles, and restrictions on truck dimensions and configurations.

Maintenance Cost-Effectiveness

Maintaining the nation's 4-million-mile state and local road network currently requires more than one-third of the total highway budget, and the share of highway resources going to maintenance is growing. Despite this spending, continued deterioration of the nation's road systems indicates the need for more efficient and more effective maintenance. Methods, equipment, and materials have not changed significantly in recent years, although both the mileage and traffic volume of the highway system have increased significantly. The opportunity for major improvements through maintenance research is substantial: further mechanization, better repair materials, off-site prefabrication, and more efficient staffing and scheduling could all yield substantial savings.

Protection of Concrete Bridge Components

An epidemic of bridge deterioration has developed throughout the United States. Currently more than 132,000 bridges are classified as structurally deficient, and 3,500 more become deficient each year. About one-third of the structurally deficient bridges are so classified because of deck deterioration. Bridge deterioration will continue unless technology is developed to arrest the corrosion process in existing salt-contaminated bridge decks and other reinforced concrete structural members and to protect new and replacement concrete now being constructed from contamination or corrosion.

The procedures that appear to be the most promising for extending the life of bridge concrete are as follows:

1. Prevent deterioration of chloride-contaminated concrete through electrochemical removal of chlorides, impregnation of the concrete and upper steel, or cathodic protection; and
2. Prevent deterioration of new and uncontaminated concrete by using newly developed coatings for the reinforcing steel and external or internal sealants for the concrete surface.

In addition to the research on the protection of concrete from chlorides, research on alternatives to the use of chlorides for snow and ice control is proposed in another of the six program areas.

Cement and Concrete in Highway Pavements and Structures

The highway industry consumes more than $400 million of portland cement annually; this is about 13 percent of all portland cement made in the United States. Concrete is used for 85,000 miles of roads, thousands of miles of median strips, curbs, and virtually all sidewalks. Also most bridge decks, short-span bridges, and the supporting structures for thousands of bridges are made of concrete. Yet, cement and concrete research is diminishing just at the time when the quality, reliability, and utility of this basic building material are of the most importance.

A major cause for failure in concrete structures is deterioration of the concrete; therefore, research is needed to find ways to increase durability, particularly for structural uses.

Chemical Control of Snow and Ice on Highways

All but 7 of the 50 states can count on snow covering parts of their highway systems every winter. Salt was first used on intercity highways for snow and ice control about 50 years ago; by 1982 salt use had grown to 12 million tons a year. This heavy use of salt for snow and ice control exacts a price in vehicle corrosion, bridge deck and concrete pavement deterioration, and contamination of soils and waters. Two avenues of research could help to reduce the adverse effects of chlorides while maintaining the safe levels of service required on highways during winter storm periods.

First, the storing, handling, applying, and controlling of salt offer many opportunities for improvement, and research should be directed at better chemical management techniques. In addition, research should explore improvements in mechanical and thermal means of snow removal. Second, new chemicals with acceptable melting qualities and without adverse environmental effects should be developed for use in winter maintenance programs, and further assessment should be made of calcium magnesium acetate (CMA) as an alternative to salt.

CONCLUSIONS AND RECOMMENDATIONS

Each of these six proposed research areas represents an outstanding opportunity to fill in the gaps in highway research and make dramatic advances in transportation technology. An assessment of these high priority research areas in terms of the nine strategic criteria previously discussed is given in Table 1.

Together the six research components comprise a program of about $30 million per year for 5 years. This major funding requirement can be met by allocating one-quarter of 1 percent of federal-aid highway funds to research. This procedure would require no new money. Rather, a small fraction of today's program funds would be devoted to reducing tomorrow's program needs by developing better materials and techniques. The data in Table 2 indicate how these funds would be distributed. Cost savings of about $600 million per year could result from implementing new technology developed by this research effort. Although the savings would only be realized after the research results were put into practice, they would continue to accrue long after the research program is completed.

The strategic research plan described in this study is a practical approach to solving real-world problems and is carefully related to the materials and processes used to build and maintain the physical struc-

TABLE 1 Assessment of High-Priority Highway Research Areas

	Asphalt	Long-Term Pavement Performance	Maintenance Cost-Effectiveness	Protection of Concrete Bridge Components	Cement and Concrete in Pavements and Structures	Chemical Control of Snow and Ice
Probability of a big payoff	High	High	High	High	Medium	High
Has research on this topic been neglected in recent years?	Yes	Yes	Yes	No	Yes	Possibly
Degree to which organizational barriers now impede research	High	High	Medium	Low	High	Low
Likelihood that research findings will be usable	High	High	High	High	High	Medium
Scale of effort required for successful project	Large	Large	Small	Large	Medium	Medium
Does the research require greater unity of effort, now splintered?	Yes	Yes	Probably	Probably	Yes	Probably
Do changes in national policy create a common, multistate research need?	Possibly	Yes	Possibly	No	No	Yes
Do major technological changes require research here?	Yes	No	Possibly	Possibly	Possibly	Possibly
Likely magnitude of impact on safety and environment	Medium	High	High	High	Medium	Medium

TABLE 2 A 5-Year Strategic Transportation Research Program

Problem Area	Annual Expenditure ($ Million)	Total Expenditure ($ Million)
Asphalt	10.0	50
Long-term pavement performance[a]	10.0	50
Maintenance cost-effectiveness	4.0	20
Protection of concrete bridge components	2.0	10
Cement and concrete in highway pavements and structures	2.4	12
Chemical control of snow and ice on highways	1.6	8
Totals	30.0	150

[a]Continuation required for an additional 15 years at approximately $10.0 million per year.

tures of the highway system. It is tailored to focus on observed gaps in current research and the organizational structure and resources required to close these gaps. It advocates innovative approaches to down-to-earth problems. The plan can be characterized as follows:

- It is more sharply focused than current highway research efforts.
- It concentrates on a few specific, goal-oriented areas. It would exist for only 5 years (with the exception of the pavement field test, which would necessarily have to be longer).
- It represents a crash effort, a high concentration of time and money and technical expertise on crucially important and achievable targets.
- The staff should be independent of old allegiances thereby ameliorating some organizational barriers.
- It should include involvement by constituent highway operating agencies but insulate research efforts from special interests.
- It should have continuity both of staff and funding throughout its 5-year term and a strong central control.

Because of these special characteristics, no existing organization can simply absorb this strategic program. Various existing organizations could be modified to assume responsibility for this program, including the following:

- An American Association of State Highway and Transportation Officials (AASHTO) task force;
- A special-purpose unit of AASHTO, such as was created to oversee the AASHO Road Test;
- A new component of the National Cooperative Highway Research Program of Highway Research and Development (NCHRP);

- A new special project under the Federally Coordinated Program of Highway Research and Development (FCP);
- A modified Research Associate Program under the auspices of the National Bureau of Standards;
- A university research center or research institute; or
- A major private research organization.

Alternatively, a new organization, such as a special-purpose, chartered, nonprofit research agency, could be considered.

The current infrastructure crisis has reawakened the nation to the economic importance and the physical problems of its highway system. The appropriation by Congress in 1982 of $58 billion in federal aid for highways over 4 years must be matched by a serious, concerted research effort to find better ways to build, maintain, and operate the highway system of the future. Merely increasing support for current research activities will not focus the resources that are crucial to achieving that goal. The strategic research program proposed here is an efficient and productive way to initiate and monitor a concentrated research effort and it is well within the industry's financial ability. With the appropriate funding and institutional commitments, the strategic research program outlined here promises to make a monumental contribution toward improving highway technology.

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