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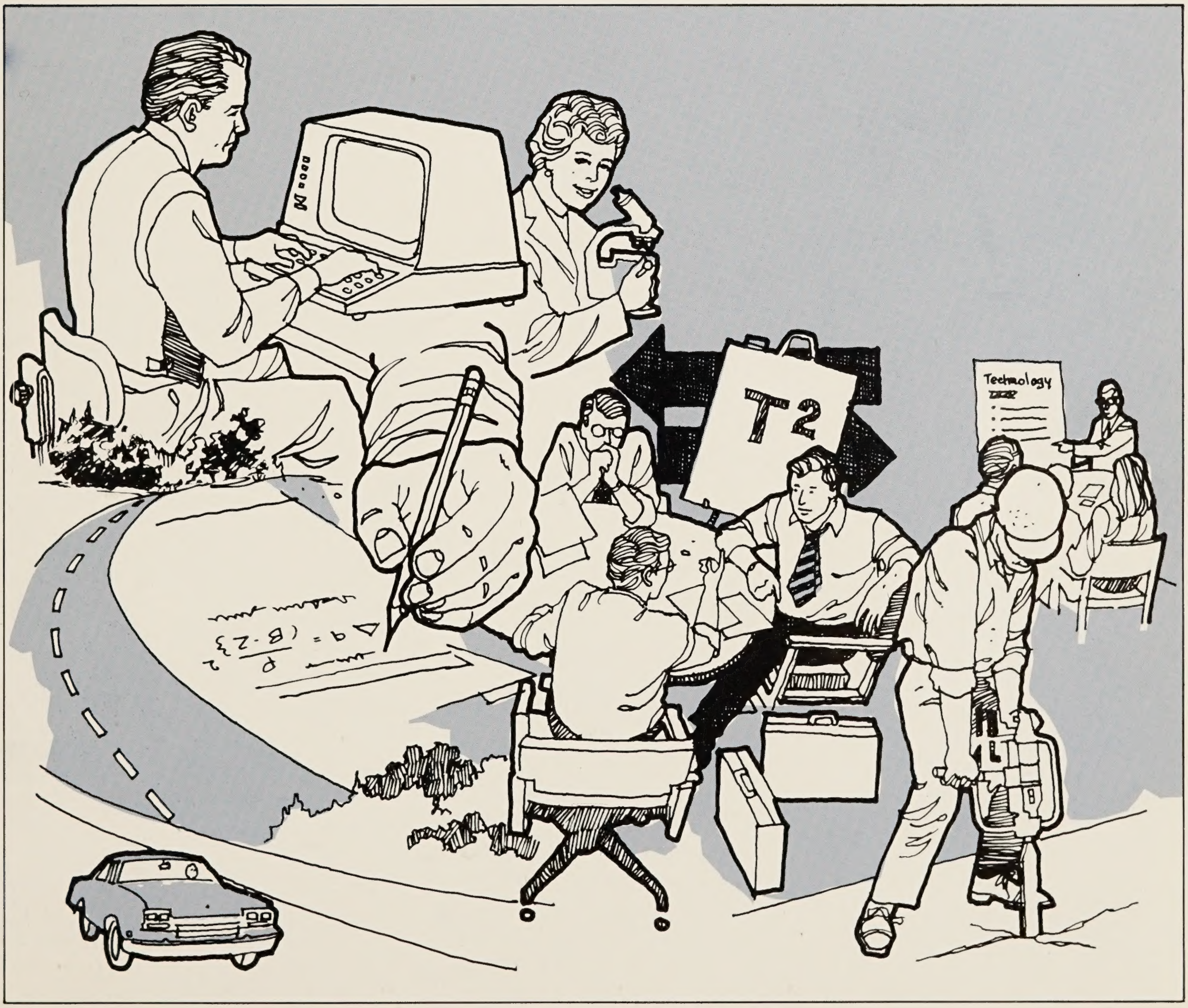
A Journal of Highway Research and Development



Public Roads

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U.S. Department of Transportation
Elizabeth Hanford Dole, *Secretary*

Federal Highway Administration
R.A. Barnhart, *Administrator*

U.S. Department of Transportation
Federal Highway Administration
Washington, DC 20590

COVER: Technology transfer is integrated into the everyday functioning of professionals within FHWA.

IN THIS ISSUE

Articles

Departments

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FHWA
TECHNOLOGY TRANSFER
TO BRIDGE THE GAP

Technology Transfer: Activities, Issues, and Opportunities

by
Robert J. Betsold

Introduction

There is "without doubt an unnecessary and undesirable time-lag between the conclusion of research work, resulting in findings that should be put into practice, and the actual widespread utilization of such information." (*1*)[1] This was a conclusion from a 1968 meeting of the Special Committee on Utilization of Research Findings for the American Association of State Highway Officials (AASHO). The Committee further stated that highway officials were aware of the problem but ineffective in correcting it for the following reasons:

- "Researchers do not present their findings in the form or language that can be immediately translated into the media of practice.
- Researchers do not fully understand the needs of practicing engineers and others whose problems are seldom communicated in terms of research need.
- Practicing engineers are frequently suspicious of the findings from research and are hesitant to take the lead in trying something new.
- Practicing engineers seldom have time to study the research work that led to conclusions that may be applicable.
- The research program frequently does not provide funds for the comprehensive test and evaluation at the field level necessary to generate confidence in the results." (*1*)

[1]Italic numbers in parentheses identify references on page 77.

The Committee concluded that an organized approach to the research/implementation process was needed and recommended that full-time professional generalists provide the missing link between research and operations.

Since that meeting, many organizations, programs, and activities have been created to address these problems and to fill the missing link. The general term technology transfer (T^2) has been applied to describe these efforts. The Federal Highway Administration (FHWA) has defined T^2 as the process by which existing research knowledge and new technology are transferred into useful processes, products, and programs. (*2*) Specific T^2 programs, with appropriate staff and dedicated funds, have been established in many Government agencies to facilitate the T^2 process.

T^2 Programs and Activities

Federal Government

U.S. Department of Transportation

The U.S. Department of Transportation (DOT) has a variety of mechanisms to make useful technical information available to State and local governments. The focal point for these efforts is the Technology Sharing Program of the Office of the Secretary of Transportation (OST). The program has three main goals:

- To ensure that State and local concerns and problem areas are reflected in DOT's research agendas.

- To make these research results available in a useful form to those who need it, particularly elected or appointed officials (for example, mayors, governors, State legislators, and their staffs).

- To make the results of innovative projects undertaken by individual State or local governments to solve a particular problem available to other jurisdictions with similar problems.

The OST Technology Sharing Program is designed to complement other ongoing efforts such as the Urban Mass Transportation Administration's Public Transportation Network; the Federal Highway Administration's Rural Technical Assistance Program (RTAP), including the university-based centers run for FHWA under the T^2 to Locals Program; and other technical assistance work by the various DOT elements.

Approximately 50 technical publications covering a wide range of topics are issued each year. Some of these are compilation documents issued under the OST Technology Sharing Program itself, some are issued jointly with other DOT elements, and some are "Technology Sharing Reprints" of State or local reports. The reprints are particularly popular because they deal with specific problems and have a pragmatic tone not found in many research reports. Also, the OST Technology Sharing Program retools training course materials developed by DOT's operating administrations to provide stand-alone technical references.

Each of these technical publications, announced separately using a widely distributed short abstract called the "white card" (fig. 1), can be obtained by sending a self-addressed mailing label to the appropriate DOT office.

In addition, an emphasis of the OST Technology Sharing Program is supplying presentations and summary publications for distribution at transportation conferences sponsored by State highway agencies.

Urban Mass Transportation Administration

Technical assistance and T^2 activities in DOT's Urban Mass Transportation Administration (UMTA) are managed by the Associate Administrator for Technical Assistance. (*3*) Technical assistance is provided in a broad range of disciplines and fields of knowledge that are essential to transit, including analyses, planning, demonstrations, management, vehicles, equipment, and facilities. New technology is disseminated through technical reports and other publications and by workshops and

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U.S. Department of Transportation
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HIGHWAYS

Improving Highway Information at Hazardous Locations - Seven Case Studies

March 1985

Description: This 77-page report describes the results of a demonstration which examined the operational and safety problems of several hazardous locations, and developed low-cost, short-range information system solutions to them. The seven projects dealt with a reverse curve/narrow bridge, a split between freeways, a "cut through" traffic circle, an interchange lane drop, an at-grade railroad-highway grade crossing, an urban intersection, and reverse curves on a rural two-lane road. Case studies are provided for each project, noting the problems and hazards at the sites, the signing and other changes implemented after conducting positive guidance planning, the results of these changes, and the costs that were involved. Five of the seven projects were considered to be successful. The document should be of particular interest to those involved with choices on highway traffic control or signing, and those interested in liability implications for state/local jurisdictions of such choices.

Availability: Single copies of this report are available to support state and local officials at no charge. Send a self-addressed mailing label to the Technology Sharing Program (I-30PG), Office of the Assistant Secretary for Governmental Affairs, U.S. Department of Transportation, Washington, D.C. 20590. Please note the report's title and document number, DOT-I-85-16, when ordering.

TECHNOLOGY SHARING
A Program of the U.S. Department of Transportation

Figure 1.—The "white card" announces technical publications available from the Department of Transportation.

training courses. In addition to initiating the development of new techniques and equipment, UMTA provides funding to transit operators to help evaluate and introduce new products developed by the private sector. UMTA also sponsors demonstrations, independent evaluations, peer reviews, seminars, and site inspections when necessary for effective transfer of new techniques.

UMTA's current T^2 program is based on needs and problems expressed by State and local agencies through conferences and workshops, industry liaison boards, special user advisory groups, and general solicitations. The UMTA regional offices support this communication process by providing a contact point for requesting technical assistance and by participating in project selection. These extensive communication efforts have enabled UMTA to direct its resources to programs that are readily usable by local agencies to improve their productivity.

Federal Highway Administration

Three offices within FHWA share primary responsibility for the promotion of innovative technology: The Office of Implementation, the National Highway Institute, and the Office of Highway Operations' Demonstration Projects Division.

• Office of Implementation—In this Office, research findings are verified and translated into a form readily understood by a practicing engineer or highway official. Following controlled tests by the researchers, new technology may require further testing to verify the performance under a wide variety of climatic and operating conditions. These field trials and evaluations are conducted in cooperation with the State highway agencies. If the technology proves useful in the field, user manuals, technical advisories, videotapes, and/or slide-tape presentations are developed to promote and facilitate the adoption of this technology by potential users. Other activities include sponsorship of workshops, seminars, and industry disclosure meetings to encourage face-to-face exchange of new technology.

• National Highway Institute (NHI)—This Office was established under section 321 of Title 23 USC to develop and present training in new highway technology to State and local highway personnel. NHI activities include presentation of courses in state-of-the-art technologies, techniques, and procedures relating to highway planning, environmental factors, acquisition of rights-of-way, engineering, construction, maintenance, contract administration, and inspection. In addition to the training courses, NHI conducts a college curriculum program, maintains a lending library of highway training materials, and publishes information exchange bulletins.

• Office of Highway Operations, Demonstration Projects Division—This Division administers two T^2 programs: The Demonstration Projects Program and the Experimental Projects Program.

The Demonstration Projects Program includes those successful research results and innovative technologies that can best be promoted through onsite demonstrations. Three promotional techniques used in this Program are hands-on demonstrations, workshop training seminars, and construction of pilot demonstration installations at appropriate locations.

The Experimental Projects Program determines whether previously researched, field tested, or documented materials, techniques, or equipment can be adopted for practical use in highway construction. Experimental features are incorporated in Federal-aid highway construction projects to determine the suitability of the features as regular construction items (fig. 2). Both proprietary and nonproprietary innovative features are included in this effort. It is under this Program that the private sector can introduce discoveries into the market. Performance of these experimental features is monitored and reported in the *National Experimental Projects Tabulation* published periodically by FHWA and accessible by computer terminals.

The Office of Planning within FHWA administers technology exchange and assistance in highway planning. Some of the planning technology, including computer software, is prepared in cooperation with UMTA.

The Office of Direct Federal Programs also evaluates and promotes innovative technology. Through three Direct Federal Divisions in the field, new technology is tested and/or demonstrated on Direct Federal construction projects and provided to other Federal agencies such as the National Park Service, Forest Service, and Bureau of Indian Affairs. Also, at the request of the U.S. Department of State, Direct Federal engineers can provide technology to developing countries for special problems.

Technology transfer also is an important function of the FHWA regional and division offices. In fiscal year 1983, T^2 was selected as an FHWA Program Emphasis Area. Specific T^2 responsibilities have been assigned in each FHWA field office, and some of the offices have T^2 committees that review available innovative technology and determine appropriate application and promotion. The field offices also arrange T^2 workshops and conferences in selected areas of new technology.

In addition to the T^2 efforts described above, which are principally directed toward State highway agencies,

Figure 2.—A thin-bonded concrete overlay containing polypropylene fibers is one of the features being evaluated under the Experimental Projects Program.

FHWA launched the T² to Locals Program aimed at reaching the thousands of local highway agencies through a new Federal-State-University concept. Although some States already provide technology assistance to local agencies, many States have neither the mandate nor the resources to do the job. Working with the States, FHWA selected 30 colleges and universities throughout the United States to serve as technology centers to promote and distribute technology to local highway agencies. In addition to being a contact point and maintaining a stock of new technology reports and other materials, the centers publish and distribute newsletters, give advice on technology available for specific local problems, and present short courses.

Other Federal Organizations

In addition to the T² activities within DOT, two other Federal organizations have broad responsibilities for Government-wide T² policies and coordination. These are the Center for the Utilization of Federal Technology (CUFT) of the National Technical Information Service and the Federal Laboratory Consortium for Technology Transfer (FLC). CUFT, a central clearinghouse for the collection and dissemination of Federal technology information and a licensor of Federally owned patents, provides information and services in response to requests from State and local governments and the private sector. FLC, a consortium of Federal research and development (R&D) institutions, is a nationwide network that uses a person-to-person approach to link its member institutions. Through FLC, the combined capabilities of the R&D institutions are used to respond to requests for technology or assistance, both within the Federal Government or with non-Federal users of technology. FLC also serves as an interagency forum on T² policy and practices.

State Highway Agencies

Responding to strong encouragement from FHWA and internally generated support, State highway agencies are increasing their participation in T^2 activities. Most States have appointed agency coordinators, and many have involved local highway agencies in the program.

A 1983 survey by the Washington State Department of Transportation indicated that 41 of the State highway agencies included T^2 activities in their research programs. (*4*) Reported activities included distribution of research reports, preparation and distribution of newsletters, personal contacts with potential research users, presentation of seminars and workshops, circulation of research lists and summaries, scheduling and notification of demonstration and experimental projects, and searches of the Transportation Research Information Service (TRIS) operated by the Transportation Research Board (TRB).

The States' programs range from a single individual assigned T^2 as a colateral duty to well-staffed units with adequate budgets and other resources (such as libraries, audiovisual production capabilities, and microcomputers). States that have a limited research program or a focus on materials testing have assigned T^2 coordinators to collect needed technology from FHWA, TRB, and other States.

Other major T^2 activities performed by the States are the field trial and evaluation of research findings from the governmental sector and evaluation of new products and materials from the private sector. Under Task Orders issued by FHWA, most States have been involved in the field trial and evaluation of findings from the FHWA research program. In addition, the FHWA Special Experimental Features Program encourages construction and evaluation of promising experimental features that have a limited performance record. The FHWA program finances the evaluation, and the findings are reported in the *National Experimental Projects Tabulation*.

Finally, the performance of a wide range of special highway products is tested through a joint effort of FHWA and the American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Materials. The latest edition of the *Special Product Evaluation List* contains over 6,500 evaluations conducted by 35 States and FHWA and provides information on who conducted the tests or accepted the material. (*5*)

Current T^2 Issues

In the past 15 years, substantial progress has been made in getting highway research into practice. A 1985 FHWA report to the Senate Committee on Appropriations describes 16 recent innovative technologies that have received varying degrees of acceptance by the State highway agencies. (*6*) Estimated construction and operational cost savings from these innovations total several hundred million dollars. However, despite these resounding successes, there are problems and constraints that should be recognized in the highway T^2 programs. These problems are related to the resources and the processes that are necessary for effective transfer of technology.

Resources

Personnel: As previously stated, the AASHO Committee report that initiated the highway T^2 programs recommended the assignment of full-time professional generalists to provide the missing link between research and operations. Particular attention must be given to the selection of these professional generalists because the characteristics and skills needed are often quite different from those of the typical scientist or engineer. "The transfer of technology requires a special type of talent not always present even in the best of scientists. . . . A successful transfer program must seek out the rare individual with the capacity for looking across disciplines and conventional scientific categories." (*7*) Locating people with the necessary skills can be difficult; keeping such people is even more difficult because good technology transfer professionals have high visibility and possess skills that are in high demand in any highway agency.

Finances: Adequate financial resources are essential for a T^2 program. In FHWA, support for the T^2 program has been excellent; approximately $15 million per year is provided for T^2 program activities. This amount includes 20 percent of the R&D funds allocated to the Implementation Program as well as other funding for the Demonstration and Experimental Projects, National Highway Institute, and Rural Technical Assistance Programs. At the State level, about 35 States use T^2 line items in the R&D portion of their annual Highway Planning and Research (HP&R) Program to finance a wide variety of T^2 activities. In future years the Federally assisted HP&R Program also will be an eligible source of support for the T^2 to Locals Centers established to provide technology to local highway agencies.

Commercial Incentives: Although Government-sponsored research may produce beneficial new products with commercial potential, it can be difficult to get highway-related industries to manufacture the products. Several factors must be considered, with questions about patent and proprietary rights heading the list. Lacking exclusive rights to commercialize a new technology, many companies have been reluctant to spend the substantial funds required to refine, manufacture, promote, and sell a new product. Recent Congressional legislation has been designed to solve many of the patent and proprietary rights problems that precluded commercial development in the past. Also, it must be recognized that the highway program presents a diverse and difficult marketplace. Most materials are acquired through competitive bids (with few provisions for life-cycle cost considerations), and the supplier faces a myriad of specifications and special requirements that vary with the 50 State highway agencies and the nearly 39,000 other governmental units that have some form of bridge or highway responsibility.

Processes

Head Start Activities: In many Government agencies and programs, the people involved in T^2 are introduced to the new technology after the research is completed. In some cases, and particularly for outputs from basic research projects, it can be difficult to identify potential users of the technology. These conditions seldom exist in highway research where the predominant activities involve applied research and the majority of the potential users are highway engineers and officials. In addition, most highway research programs have developed mechanisms to involve operational officials and policymakers in the initial selection of program activities, a prominent feature of the FHWA administrative contract research program and the National Cooperative Highway Research Program (NCHRP). In addition, the Washington State Department of Transportation survey showed that 43 of the 50 States use research committees to develop and/or monitor their highway research programs. (*4*) This early involvement in the research program significantly improves the later acceptance and implementation of the research findings.

Identifying Implementable Technology: Despite the applied nature of the highway research program, all studies do not result in implementable technology. Substantial screening is necessary to determine the appropriate use of the research findings and to identify implementable technology. In the FHWA R&D program, researchers assess the potential application of findings in each research study report, and T^2 program managers verify the assessment. If the reported findings have no implementation potential, few copies of the report are produced, and distribution is limited to researchers working in the topic area. A wider distribution is made for research reports with some implementation potential, and a broad distribution is made for reports with findings that are immediately implementable. The following questions should be asked in determining the implementation potential for research findings:

1. "Will the innovation cost more than can be justified?

2. Will a lower-cost product produce a lower level of service than can be justified?

3. Is performance too sensitive to workmanship for the innovation to be practical?

4. Will the frequency and cost of maintenance be greater than can be justified?" (*4*)

These kinds of questions should be asked in a forum that includes the researchers (to explain the technology), operating personnel who are potential users (to identify constraints and compare with current practice), and those who will be responsible for the T^2 activities (to determine what field trials will be necessary and how to package and present the material for effective transfer).

Selecting Appropriate Delivery Methods: When the research is completed and implementable outputs have been identified (and field tested, if necessary), the next step in the T^2 process involves selecting appropriate techniques for presenting the new technology to potential users. Many methods are available, and the T^2 plan should consider the following factors:

- Audience—Who are the potential users, and what is the typical level of their technical knowledge?
- Perceived need—Do the users recognize the problem and want a solution, or must they be convinced that change is needed?
- Difficulty—Is the technology simple or complicated? Does it require an adaptation of current practice, or learning a whole new subject area?
- Cost—Do the expected benefits from implementation of the technology justify more costly T^2 efforts?

Considering the answers to these questions, the T^2 managers can select from numerous methods for disseminating the technology, including the following:

- Written materials—Distribution of the research report or executive summaries of the report; compilation of research abstracts, reviews, summaries, and newsletters; preparation of synthesis reports, user manuals and guides, technology sharing documents, and implementation packages; distribution of typical plans, specifications, or standards (preferably with AASHTO endorsement); preparation of training manuals or guides; and publishing articles in commercial publications or professional journals.
- Audiovisual materials—Posterboard displays and photographs; slide presentations with script and/or taped narrative; videotapes; and 16-mm motion pictures.
- Meetings—Seminars, workshops, and conferences with formal sessions devoted to the technology and informal opportunities for discussion and exchange of experiences.
- Demonstrations—Person-to-person, hands-on opportunities to actually see the technology applied by knowledgeable persons in a controlled setting.
- Training courses—Short courses on selected topics (such as traffic signal controllers) or longer term training in technical areas that have substantial technological advances (such as pavement management or materials).

A recent report presents a Technique Selection Guide that rates each technique according to relative cost, immediacy, adaptability, rigor, and suitability for various audiences. (*8*) In addition, a study on dissemination strategies used by 17 program developers identified the following strategies, by order of usefulness:

- Demonstration and training centers.
- Long-term training.
- Short-term training.
- Word of mouth.
- Nonprint media.
- Commercial publications.
- Publication list.
- Conference presentations.
- Professional communications.
- In-house materials.
- Professional publications. (*9*)

As might be expected, the most costly T^2 techniques also are considered the most effective, or, stated simply, you get what you pay for.

Maintaining T^2 Linkages: The T^2 process is not a rigid structure; instead, it resembles a chain, with successive links from researchers to transfer agents to practitioners (fig. 3). For highway technology developed at the Federal level, the chain can be rather long and can break. Unfortunately, these breaks are not immediately evident and, considering the time required for new technology to be put into practice, may not be discovered for some time.

Another chain problem also occurs: One cannot push a chain. The most effective T^2 occurs when the chain is pulled from the field by users who need the technology.

Feedback and Evaluation: TRB estimates annual highway research expenditures in the United States to be $70 million to $75 million. (*10*) The obvious question asked by highway administrators and legislative appropriation committees is: What benefits result from these expenditures? A general answer is given in the report of the Strategic Transportation Research Study which states, "Every aspect of highway design, construction, maintenance and operation has benefited from the past stream of highway research." (*10*) The report also lists a variety of technologies developed through the highway research programs and incorporated into the highway system. In addition, TRB has collected and publicized brief case histories of research studies that have produced tangible payoffs for the sponsors and the public. (*11*)

Although lists of successful research products and selected case histories are useful, they do not provide the detailed information necessary to determine the bottom line success of the research program and the associated T^2 process. To get the necessary information, FHWA has initiated a multistage program evaluation. The desired result is a system that will improve feedback from the field offices on the value of the T^2 activities, the acceptance of new technology by the State highway agencies, actual use of the technology, and identification and measurement of benefits from the technology as determined by the users.

The FHWA program evaluation began in the spring of 1984 with a series of T^2 process site reviews in each FHWA regional office and in two FHWA divisions and State highway agencies in each region. The reviews, conducted by teams of senior program managers from the Office of Implementation, National Highway Institute, and Demonstration Projects Division, followed the advice that process evaluations should precede or accompany outcome evaluations. (*12*) This approach is necessary because processes can affect outcomes, and evaluators should not ignore issues of process even though program outcomes determine success. (*12*) During these site reviews, and in subsequent tri-regional T^2 meetings involving Federal, State, and T^2 to Locals Center officials, the FHWA program evaluation was discussed and several conclusions were reached:

- The trial and adoption of new technology for operational use may take several years.
- It is difficult to establish the impact of a single T^2 activity.
- Adoption of new technology results from a combination of T^2 program efforts rather than from a single activity.
- Program evaluators should focus on a topic area rather than a single T^2 activity.
- A topic area for which FHWA has promoted the technology for an extended period of time should be selected.
- Available FHWA technology transfer activities/packages in the selected topic area should be identified.
- The States' degree of acceptance and/or use of the technology should be determined.
- Readily available information on identifiable benefits or cost savings should be requested.
- The evaluation form should be kept simple.

The last point was emphasized by many participants because neither the FHWA divisions nor the State highway agencies had the personnel or resources to make extensive surveys or continually fill out voluminous forms.

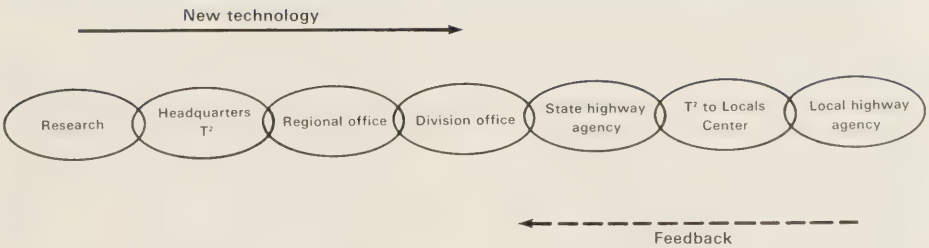

Figure 3. — Federal Highway Administration T^2 chain.

Using these guidelines, FHWA selected the following five topics for evaluation in 1985—one topic from each of the five program areas in the Federally Coordinated Program of Highway Research and Development:

- Safety through highway work zones.
- Time-based signal coordinators.
- Noise barrier cost reduction program.
- Hot-mix recycling of asphalt concrete pavement.
- Improved design practices for culverts.

Field responses still are being received and analyzed, but the early returns already have provided useful information. For example, weak links in the T^2 chain are apparent in some instances. Further investigation will be needed to determine whether the problems are caused by communication breakdowns, existence of gatekeepers at the division or State level, or other reasons. It also is obvious that the survey form for the topic of improved design practices for culverts was not specific enough to separate the desired technology (improved designs for culvert inlets) from other recent T^2 topics in the hydraulics area. Additional efforts to pretest future evaluation forms are necessary.

After the results of the survey have been analyzed, a summary report on State application of the technology and identified benefits will be prepared and returned to the field. FHWA also will use this information and experience to establish a feedback and evaluation system for future efforts.

Opportunities for Innovation

Current R&D programs are seeking better, longer lasting, and more efficient ways to construct, operate, and maintain our highway system. The proposed Strategic Highway Research Program (SHRP) is a sharply focused, concentrated effort to develop new technology to solve many of our most critical pavement and structural problems. Recognizing the current problems in T^2, new efforts and technology also are needed to deliver the results of the research program.

Recent advances in technology, particularly in the microcomputer, video, and telecommunications areas, offer new opportunities to overcome T^2 problems and improve the delivery systems. Following are some examples of new technology applications for T^2.

Microcomputers: Many highway agencies have purchased microcomputers, and more people are learning to use them. Many analysis programs that formerly were available only through mainframe computers have been converted for microcomputers. New programs have been written specifically for microcomputers, particularly in the areas of traffic operations, hydraulics, and pavement and structural design. Software centers, with user support services, have been established to make the new technology readily available to, and usable by, highway agency personnel.

Videotapes/laser disks: Videotapes frequently are used to transfer information about new highway technology or special applications of the technology. However, this media, and the more versatile laser disk, can be linked with a microcomputer to provide interesting, visually attractive, and easy-to-use programmed instruction training. Such training can be provided at the employee's office, as time permits, eliminating travel to a training site. This training approach may be particularly applicable in the highway maintenance area. New or improved maintenance procedures could be taught to the workers during inclement weather or other slack periods, and the maintenance supervisor would retain full control over the timing and duration of the training.

Teleconferencing: During the 1984 annual meeting of the TRB, a session on microcomputer applications in transportation was telecast live by satellite to about 20 States. The linkage included one-way video to all receivers and two-way audio communication with preselected sites. Less expensive options include use of audio only and enhanced audio conferencing. The enhanced audio method has several options including use of facsimile terminals to transmit graphic and textual information for the conferences, use of slow-scan video or freeze-frame video, and use of electronic blackboards. Helpful advice and cost information are presented in the pamphlet "Executive Guide to Teleconferencing" prepared by the U.S. General Services Administration.

Computer-based information systems: Most highway researchers are familiar with TRIS operated by TRB. A more recent resource is the Demonstration Projects Information System established in 1983 to provide online access to information about available demonstration projects as well as data from the *National Experimental Projects Tabulation.* This system is now being expanded to include the FHWA Implementation Catalog, NHI course offerings, and RTAP products. This FHWA T^2 information system will provide one-stop shopping for all T^2 material and resources developed by FHWA. When completed, this system will be linked with the new Highway Technology Information Management System (HTIMS) now being developed for the FHWA Offices of Research, Development, and Technology. Both the initial FHWA T^2 system and the HTIMS will be accessible to field users.

To determine efficient and appropriate uses of these emerging technologies in the T^2 program, FHWA has established a Technology Laboratory at the Turner-Fairbank Highway Research Center in McLean, Virginia. In addition to the necessary microcomputers and other electronic equipment, the laboratory has classrooms for presenting pilot training and conducting demonstration presentations under controlled conditions. Other features will include the capability for high-quality computer-generated graphics, videotaping facilities, and an extensive slide library. Future plans include providing video transmission capabilities for the auditorium adjacent to the laboratory.

Conclusion

As the Nation's highway research programs are accelerated to solve the most critical problems, it is essential that the T² systems be enhanced to efficiently and effectively deliver the products of that research.

Substantial progress has been made since the AASHO Committee report in 1968. Formal programs have been established at the Federal, State, and local levels. Reams of material have been written about the generic process of T², and the volume of highway-specific material is growing.

Congressional legislation has placed new T² requirements on Federal laboratories and, at the same time, made T² a legitimate function of the Federal Government. New T² coordinators or offices have been formed in most State highway agencies, and the T² to Locals Program has provided a new resource base for local highway agencies.

Despite these advances, there still are problems to be solved and opportunities for innovation. Current problems are being addressed at many governmental levels, and the entire highway community has focused on the need for innovative technology. With microcomputers in wide use and rapid advances in video- and telecommunications, the opportunities for improving the transfer of technology are limited only by the imagination of the decisionmakers and their ability to provide the resources to get the job done.

At this point, we have completed the circle. The 1968 report that started the highway T² effort focused on the personnel problems that prevented research from getting into practice. People still are the greatest challenge. "We have too many undertakers. They're the folks who do a job and do it so poorly that it dies under them. We generally have a surplus of caretakers—people who do the job neither adding nor subtracting anything from it. But innovators, the people who can unlock the doors leading to breakthroughs leading to the kind of quantum leaps that the public has come to expect in transportation, we don't have enough of these kinds of people." (*13*)

This leads to the crucial question in the efforts to get research into practice; a question that must be asked of those who develop the technology, those who transfer it, and those who are expected to use it. What role will *you* play—undertaker, caretaker, or innovator?

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Polymer Concrete Used in Redecking a Major Bridge[1]

by

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Introduction

Just as segmental bridge construction adds a new dimension in constructing economical, long-span structures, the techniques used in reconstructing the Woodrow Wilson Bridge (WWB) add a new dimension in the rehabilitation of old structures. The six-lane bridge, which spans the Potomac River and connects Maryland with Virginia, was kept open to traffic during rush hours. At night, one-half of the width was cut in sections, removed, and hauled away by barges. Replacement sections of precast, prestressed concrete, approximately 10 ft (3 m) long and 47 ft (14 m) wide, were lifted into place. About eight sections were placed per night, and 129 nights were needed to place the 1,026 sections. Intermittently, the sections were post-tensioned together in the longitudinal direction. The display art shows an overall view of the bridge with the new panels evident in the left foreground and the old bridge on the right.

This was neither the first time precast panels were used for redecking, nor was this the longest structure on which they were used. (*1-7*)[2] The uniqueness of this project comes from a combination of factors: The long length of the bridge, the six-lane width, the high traffic volume, the night construction while maintaining traffic flow, the opening of all lanes to traffic during rush hours, and the use of polymer concrete and other innovative construction techniques to speed construction.

[1]This article is a condensation of "Polymer Concrete Used in Redecking a Major Bridge," Report No. FHWA/RD-85/079, Federal Highway Administration, Washington, DC, June 1985. Available from the National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161 (Stock No. PB 85 249290).

[2]Italic numbers in parentheses identify references on page 89.

This article discusses the polymer concrete specially formulated for use on the WWB project. Numerous tests measured the properties of various polymer concrete mixtures, and this experience should be valuable to others contemplating the use of this relatively new material. Similarly, the experience gained in forming the supporting pedestals may be of interest in similar applications in placing (grouting) base plates or bearing assemblies.

Polymer concrete was used on the WWB project for three applications: Pedestals to support and level the precast sections, closure gaps between the sections when they were post-tensioned together and to set the expansion joints, and thin overlays near the expansion joints. This article is concerned only with the supporting pedestal construction.

Pedestals

Pedestals were placed every 3 ft (0.9 m) along the girders and stringers (on 6-ft [1.8-m] centers) to level and support the precast sections. The importance of these pedestals in the construction scheme was described as follows:

> "Perhaps the key to the entire system is the development of the bearing on the stringers and exterior girders. Each panel rests on three bearings at each of the five stringers it crosses, plus three or four bearings at the girder. The bearings are 8-in × 11-in (203-mm × 279-mm) plates. Studs welded to the plates help to ensure their bond to the methyl methacrylate polymer concrete poured between the plate and the bottom [surface] of the precast panels.
>
> The bearing plates are free to slide on the steel girders and stringers. This ability to move prevents the introduction of stresses caused by shrinkage, creep, and foreshortening during post-tensioning. Pairs of hold-down bolts at the pads on three stringers provide a positive tie between the precast panels and the structural steel." (*5*)

A drawing of the pedestal configuration is shown in figure 1. The polymer concrete used to construct these pedestals had to be placeable through the 2-in (50.8-mm) holes, be workable for at least 15 minutes, be able to attain a compressive strength of 4,000 psi (27.6 MPa) in 1 hour at temperatures from 20 to 100 °F (−7 to 38 °C), be dimensionally adequate to transfer the full loads, and have adequate durability and other properties equivalent to those of good quality portland cement concrete (PCC).

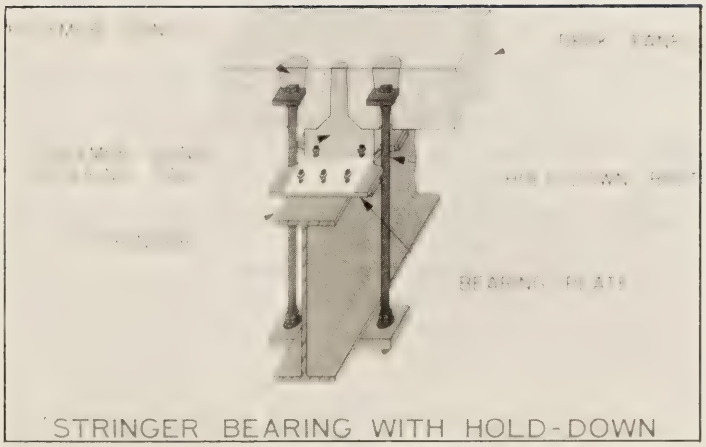

Figure 1.—Stringer bearing with holddown.

Basic Mixtures and Properties

Polymer concrete

The binder in the polymer concrete was methyl-methacrylate-monomer containing Dimethyl-p-toluidine as a promoter and powder aggregate containing Benzoyl-peroxide as an initiator. Products from three different sources were used (Faburcrete from Brookhaven, Crylcon from DuPont, and T-17 from Transpo) to make over 30 different mixtures of different proportions at various temperatures. Some variations were made in the amounts of monomer, initiator, and promoter to develop suitable mixtures for the extremes in temperature (20 to 100 °F [−7 to 38 °C]).

Monomer loading (by weight or volume) determines the most economical or workable mixture for a particular aggregate and gradation, because the monomer is expensive in comparison with the other ingredients. Unfortunately, because the proportions are not reduced to a unit volume, such as per cubic yard (cubic meter), the comparison of mixtures having different gradations of aggregates is almost impossible. To convert to a unit volume requires knowledge of the specific gravities (monomer specific gravity = 0.92) of the materials, the absorptions, and the amount of entrapped air, or alternatively, the theoretical unit volumes must be known and the yield must be measured. It should be kept in mind when comparing mixtures and properties that no attempt was made in this work to reduce the collected data to a unit volume.

A typical gradation of aggregate and powder (and other data) supplied by one of the producers is shown in table 1.

Preliminary testing

Using the aggregates described in table 1, six mixtures were made to find a workable product (table 2). It should be noted that 15 minutes is the minimally acceptable workability time.

Strength

Three 0.5-ft^3 (0.01-m^3) batches were made with the preliminary mixture proportions to evaluate the strength gain properties when mixed and cured at different temperatures. The ingredients were brought to the appropriate temperature—0, 20, or 73 °F (−18, −7, or 23 °C)—and then quickly mixed and cast at room temperature in about 20 minutes. Then, the specimens were returned to the appropriate temperature cabinet until being quickly tested at room temperature. Only one 3-in × 6-in (76.2-mm × 152.4-mm) cylinder was tested at each scheduled time. The results are shown in figure 2 for the 73 °F (23 °C) and the 20 °F (– 7 °C) testing. The 0 °F (– 18 °C) results were anomalous and deemed unreliable because of the difficulty in maintaining the specimens at this temperature during the testing at room temperature.

Table 3 shows the results of the strength tests for three different batches mixed and tested at different temperatures. The mixture cast at 20 °F (– 7 °C) was cured after the first day at room temperature because of a freezer malfunction. The shear strength values are shown for breaks within the base PCC, at the bond line (with and without primer in the 73 °F [23 °C] mixture), and within the polymer concrete overlay.

The results of the single shear tests must be interpreted in light of results obtained from mixtures of different proportions and manufacturers' products, particularly in regard to the effects of the primer. Another DuPont mixture had average values of 450, 595, and 905 psi (3.1, 4.1, and 6.2 MPa) for "no," "tacky," and "cured" primer preparations, respectively. A comparable mixture made with the Brookhaven product had values of 85, 470, and 290 psi (0.6, 3.2, and 2 MPa) for the "no," "tacky," and "cured"

Table 1. — Aggregate gradation and properties

Sieve size	Percent retained coarse (stone)[1]	Powder[2]
3/4 to 1/2	0	—
1/2 to 3/8	2.6	—
3/8 to 4	93.2	—
4 to 8	3.2	0.3
8 to 16	1.0	22.5
16 to 30	—	6.3
30 to 50	—	32.2
50 to 100	—	31.7
100 to 200	—	5.2
Passing 200	—	1.8
Total	100.0	100.0

[1]Specific gravity (Bulk SSD) 2.58 (approximately). Percent absorption (water) 1.34 (approximately).
[2]Specific gravity not determined.

Table 2. — Workability[1] of the preliminary mixtures

Mixture	Workability	Proportions by weight: Monomer	Powder	Coarse (stone)	Density
					lb/ft³
Concrete	Excellent	7.5	50	50	140
	Self-leveling	8.5	52.4	47.6	—
	Harsh	7.0	50	50	—
Mortar	Trowelable	10.0	100	—	—
	Flowable	12.5	100	—	128
	Pourable	14.0	100	—	—

[1]At room temperature, approximately 73 °F (23 °C).

1 lb/ft³ = 16 kg/m³

Table 3.--Strength test results[1]

Cast/Cure Conditions	Compress[2] PSI	Mod of Elast. 10^6 psi	Split[3] Tensile PSI	Flex.[4] PSI	Shear Bond[5] PSI: Bond line	Polymer	Portland
Mixture #1: Crylcon monomer:Powder:Stone = 7.5:50:50 parts by weight.							
Cast/Cure @73°F for 8 days	5920	-	990	1645	805 (Primed) (170) (Unprimed)	1405	1315
Cast @ 20°F for 1 day Cure @ 73°F for 5 days	7870	-	1155	1490	590	1100	1270
Cast/cure @ 0°F for 7 days	7190	-	1355	1720	705	1870	1135
Mixture #2: Crylcon monomer:Powder:Quartz #3 Sand = 9:60.5:30.5 parts by weight.							
Cast/Cure @73°F for 7 to 14 days	9333[6]	2.6[7]	1575	2395	415 (Primed) (335) (Unprimed)	-	-
Cast/Cure @30°F for 3 hrs. then 70°F for 2 days, then 4 days at:							
Test Temp= 0°F	10600	3.0					
" " = 70°F	9530	2.6					
" " = 140°F	4980	1.4	(Specimens deformed plastically)				
Mixture #3[9]: Crylcon monomer:Powder:Stone (Riverton 3/8-1/4)= 7.4:52.9:39.7 parts by weight.							
Cast/Cure @73°F for 5 days	7710[8]	-	1360[8]	2180[8]			
Mixture #4[9]: BrookhavenMonomer:Powder:Stone (Riverton 3/8-1/2)= 7.4:52.9:39.7 parts by weight.							
Cast/Cure @73°F for 5 days	11175[8]	-	-	-			

[1]Three tests per value, except as noted.
[2]AASHTO T-22, 3x6 cylinders
[3]AASHTO T-198, 3x6 cylinders
[4]AASHTO T-97, 3x4x16 in. (3rd pt)
[5]2-3/4" dia. cores tested in guillotine (Single shear) device
[6]7 tests
[7]10 tests with bonded electrical strain gauges
[8]2 tests
[9]Mixtures 3 and 4 are identical except for monomer source. The Crylcon mixture was more stiff.

°F=1.8°C+32
1 psi=7 kPa

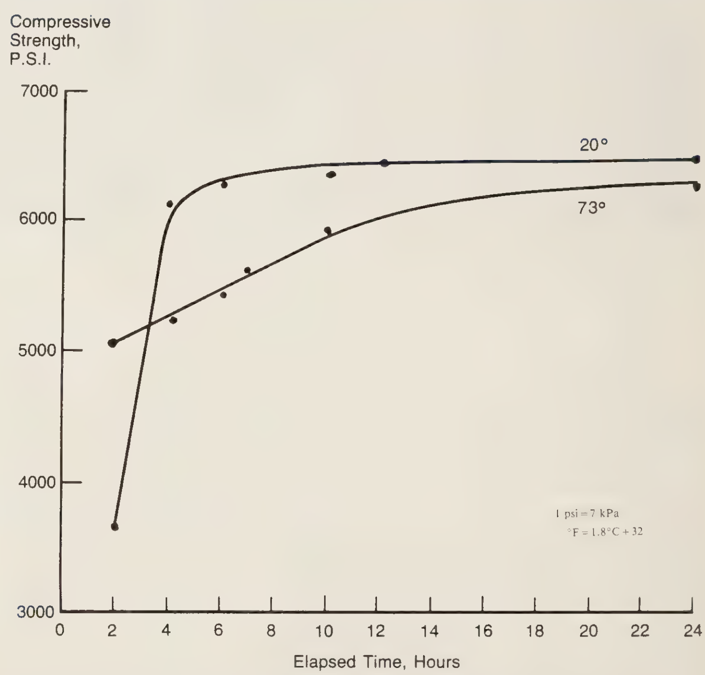

Figure 2. — Compressive strength versus time for different temperature mixtures.

primer preparations, respectively. Thus, a cured primer consistently increased the strength of the bond with the Crylcon system, but curing was almost of no benefit with the Brookhaven products. Apparently, the results are product-specific.

Shrinkage

The shrinkage also was measured at 70 °F (21 °C) by placing a light plastic disk with a fixed indicator marker on a freshly prepared cylinder specimen. The movement of this indicator mark was measured with a cathetometer. The total shrinkage after 3 hours was 1.3 percent, of which one-half of the shrinkage occurred within 10 minutes, two-thirds within 30 minutes, and very little shrinkage occurred after 60 minutes.

Bond to steel

The effects of a primer coating were further investigated in a series of direct tension tests in which the bond between the polymer concrete and clean steel was measured. Six steel caps were coated with a primer (in this case, Crylcon 3039), which was allowed to cure for 24 hours. Six other specimens had the steel primed immediately preceding the casting. The polymer concrete was placed in a mold in contact with the treated steel cap, and after curing, an aluminum cap was epoxied to the opposite end of the polymer concrete cylinder. Direct tension was applied through rods threaded into each end cap. The six specimens with the 24-hour cured primer broke at an average strength of 625 psi (4.3 MPa), and all but one specimen broke in the polymer concrete (a distance back from the bonded face). The other six specimens cast over the tacky primer failed at an average of 490 psi (3.4 MPa). Three broke in the polymer concrete, and three failed at the bonded interface. Similar tests were conducted on mortar mixtures (no coarse aggregate), and the average tensile strengths for three specimens of each were 670 psi (4.6 MPa) and 503 psi (3.5 MPa), respectively, for the 24-hour cure and the tacky condition. However, because none of the six specimens failed at the bonded interface, the difference is insignificant.

Thermal expansion

Three beams made from the polymer concrete with studs attached to each end were accurately measured in a length comparator. The thermal coefficients were determined on increasing and decreasing temperature cycles between 0 and 165 °F (– 18 and 74 °C) (table 4).

The coefficient is slightly higher with an increase in temperature than with a decrease because expansion is greater than contraction. Average net expansion from heating and cooling for 1 month between 0 and 170 °F (– 18 and 77 °C) is 0.05 percent. Overall, the coefficient is approximately 10 × 10^{-6}/°F (5.6 × 10^{-6}/°C) from 0 to 70 °F (– 18 to 21 °C) and 15 × 10^{-6}/°F (8.3 × 10^{-6}/°C) from 70 to 165 °F (21 to 74 °C).

Table 4.—Coefficients of thermal expansion of polymer concrete[1]

Temperature range °F	Thermal coefficient × 10^{-6}/°F
0–70	+ 12.0
70–0	– 10.7
32–70	+ 10.1
70–32	– 9.2
70–100	+ 14.1
100–70	– 12.0
70–165	+ 21.6
165–70	– 17.7
Comparable values of other materials:	
Steel	6.5
Portland cement paste	5 to 15
PCC with quartz aggregate	7.3
PCC with limestone aggregate	4.5

[1]Mixture No. 1 proportions, Crylcon product: Fine aggregate:stone = 7.5:50:50 parts by weight.

°F = 1.8°C + 32

Fatigue strength

Three polymer concrete beams (3 × 4 × 16 in [76.2 × 101.6 × 406.4 mm]) from each of the three batches, which were made at different temperatures, were tested for fatigue strength. Table 5 shows the maximum applied load as a percentage of the original flexural strength at a frequency of 5 Hz at room temperature. These data show that the number of cycles to failure increases with decreasing casting/curing temperature. In addition, the range of results is comparable to the literature value for PCC.

The lower section of table 5 shows data from compression-fatigue strengths on 3- × 6-in (76.2- × 152.4-mm)

Table 5.--Fatigue strength of polymer concrete

Polymer Concrete	Average Strength (PSI)	Specimen No.	Load %	No. of Cycles	Log Cycle
Flexure (3x4x16" 3rd pt. Loading on 4" face at 5 HZ)					
Mixture #1. Crylcon Mon.: Powder: Stone = 7.5:50:50 by weight					
Cast/Cured at room Temp. (73°F)	1645	1	70	450	
		2	70	539	
		3	70	1048	
		Average		680	2.8
Cast/Cured at 20°F for 1 day then at room temp.	1490	1	70	9985	
		2	70	46270	
		3	70	17298	
		Average		24520	4.4
Cast/Cured at 0°F for 7 days, then at room temp.	1720	1	70	59594	
		2	70	54870	
		3	70	124940	
		Average		79800	4.9
Mixture #2. Crylcon Mon: Powder: Qtz Sand No. 3 = 9:60.5:30.5					
Cast/Cured at Room Temp.	2395	1	60	38121	4.9
		2	70	56111	4.7
		3	80	8847	3.9
PCC (Literature Value) for reference				40000 to 158000	4.6 - 5.2
Compression (3x6" dia. at 14 HZ)					
Mixture # 2. Crylcon Mon: Powder: Qtz Sand No. 3 = 9:60.5:30.5					
Cast/Cured at 30° for 3 Hrs. then held for 4 days at 68°F and tested.	10,600	1	28.3	6.34×10^{6}+	6.8+ (No)
		2	28.3	5.44×10^{6}+	6.7+ (Failure)
		3	33.0	0.86×10^{6}	5.9
		4	33.0	1.51×10^{6}	6.2
		5	39.6	0.095×10^{6}	5.0 (Tested at 10 cps)
		6	39.6	0.035×10^{6}	4.5
		7	39.6	0.005×10^{6}	3.7
		8	39.6	0.124×10^{6}	5.1
		9	39.6	0.036×10^{6}	4.6

°F = 1.8°C + 32
1 in = 25.4 mm
1 psi = 7 kPa

cylinders cast at 30 °F (−1 °C) and cured/tested at 68 °F (20 °C). Eight of the nine specimens were tested at 14 Hz; No. 5 was tested at 10 Hz and was instrumented with an electrical-bonded strain guage.

The temperature of specimen No. 5 rose from 71 to 98 °F (22 to 37 °C) during the 2.8 hours it took to impose 95,005 cycles of load (200 to 4,200 psi [1.4 to 29 MPa]) at a rate of 10 Hz. This temperature rise was unexpected because control specimens of PCC tested at this rate of loading did *not* increase in temperature. Thus, an uncontrolled variable confounds the results. As shown on table 3, a testing temperature of 140 °F (60 °C) caused approximately a 40-percent decrease in the static compressive strength and changed the mode of failure from brittle to plastic. Because the temperatures were not recorded on the other specimens tested at 14 Hz, no corrections can be made. This phenomenon can occur and appropriate testing techniques should be selected, such as slower rates of loading or using specimen cooling techniques in fatigue testing of this material.

Durability

Twelve beams (3 × 4 × 16 in [76.2 × 101.6 × 406.4 mm]) of polymer concrete were tested for their resistance to rapid freeze-thaw cycling in accordance with ASTM C-666, procedure B (rapid freezing in air and thawing in water). Nine of the beams were from a Crylcon mixture proportioned as 7:46.5:46.5 for monomer, fines, and 1/4- to 3/8-in (6.4- to 9.5-mm) stone, respectively, by weight proportions. Three of the nine beams were mixed and cured at room temperature; three were mixed at 40 °F (4 °C) and cured at 35 °F (2 °C) for 1 day, followed by room temperature aging; and three were mixed at 20 °F (−7 °C) and cured for 7 days at 0 °F (−18 °C), followed by room temperature aging. The last three of the twelve beams were mixed in the proportions of 9:60.5:30.5 using Crylcon monomer, fines, and quartz sand No. 3. This was mixed at 70 °F (21 °C), cured 1 day at 35 °F (2 °C), and then stored at room temperature.

Three control specimens of PCC containing 25 percent fly ash also were tested. The concrete had a water-to-cement ratio of 0.53, a 4-in (101.6-mm) slump, 7 percent air, and a 90-day compressive strength of 4,500 psi (31 MPa). The controls were about 6 years old when tested and had durability factors of 95, 92, and 100 percent after 300 cycles, with a few minor popouts.

The polymer concrete weathered the cycling very well. At the end of 300 cycles, the lowest durability factors were 86, 89, 91, and 94; the remaining eight were in the range of 96 to 100 percent. No significant differences could be attributed to the different proportions or casting/curing procedures. Visual defects included small popouts, slight to severe scaling, and large popouts on four specimens. The beams with the visual defects did not have the lowest durability factors.

Structural Applications

Mockups of pedestals

Based on the preliminary tests, a mixture proportion by weight of 9 Crylcon, 60.5 powder, and 30.5 quartz sand No. 3 was selected for testing in the mockups. This mixture has a compressive strength of about 8,800 psi (60.8 MPa) for room temperature curing conditions.

Description

The prototype specimens consisted of a steel base plate with protruding studs and a section of simulated 8-in (203-mm) thick deck through which the polymer concrete was forced down an approximately 2.5-in (63.5-mm) hole to form a pedestal, either 2.5 or 6 in (63.5 or 152.4 mm) deep (fig. 1). Subsequent specimens had tapered holes and other modifications (belled bottom and shear lugs) to improve the load transfer properties. Some of these mockups also had pieces of No. 4 rebars projecting from the underside of the lightweight concrete to act as shear connectors to the pedestals, but the rebars subsequently were deleted because of the possible problems they posed for full-size plant castings.

In the first experiment eight pedestals were cast—four were 2.5 in (63.5 mm) high and four were 6 in (152.4 mm) high. The underside of the simulated deck slab was sandblasted, and the base plate was wire brushed. Simulated Nelson studs projected upward 1.25 in (31.8 mm) into the pedestal. The base plate and the underside of the slab were primed with monomer (Crylcon 3139) and allowed to cure for at least 24 hours. Wooden forms were built around the base plate, and the polymer concrete was poured through the 2-in (50.8-mm) hole and vibrated with a conventional concrete vibrator (1-in [25.4-mm] diameter). The vibration was stopped when the polymer concrete began overflowing at the underside of the slab at the top of the forms. No problems were encountered in filling the pedestal forms through the 2-in (50.8-mm) holes over a range of anticipated construction temperatures. All edges of the pedestals appeared to be in tight contact with the undersides of the slabs.

Compressive load resistance

One each of the 2.5-in (63.5-mm) and the 6-in (152.4-mm) pedestal mockups were tested in compression at a rate of 200,000 lb/min (890 kN) in a 12M lb (53.4 MN) capacity universal test machine. They failed at loads of 662,500 and 694,000 lb (2.9 and 3.1 MN) by crushing the lightweight PCC—an average unit load of 6,300 psi (43.4 MPa).

Examination of the crushed specimens indicated a lack of bonding of the 2-in (50.8-mm) diameter concrete plug and no bond between the polymer concrete and the steel base plate after the simulated Nelson studs were unbolted.

Shear load resistance

A double-shear specimen was made to test the pedestals by applying load to the two steel plates that were welded together. Two 2-ft × 2-ft × 8-in (0.6-m × 0.6-m × 203-mm) thick concrete slabs made of lightweight aggregate and two 9- × 14- × 0.5-in (228.6- × 356- × 12.7-mm) thick steel plates with eight Nelson studs were used to make the specimens.

In addition to welding the two steel plates together, three 0.5-in (12.7-mm) diameter, 2-in (50.5-mm) bolts with nuts added strength to the plates during loading. The undersides of both of the concrete slabs were sandblasted and cleaned, and each had four 1.25-in (31.8-mm) long No. 4 rebars projecting outward. Both the exposed surfaces of steel plates and the sandblasted undersides of the slabs were primed with 3039 Crylcon primer and cured for 24 hours. Polymer concrete was poured through the tapered hole in the one slab into the wooden forms built around the welded steel plate to cast a 2.5-in (63.5-mm) thick polymer concrete pedestal. This slab with the polymer concrete pedestal (after cure) then was flipped and a second 2.5-in (63.5-mm) thick polymer concrete pedestal was cast. After the wooden forms were removed, a slight honeycombing was noticed, but there was no visible gap at the interface between the slabs and pedestals.

This double specimen was tested at a loading rate of 20,000 lb/min (89 kN) and failed at a total load of 89,000 lb (395.9 kN), for a unit shear strength of 353 psi (2.4 MPa). Voids existed between the slab and the pedestal in a completely debonded interface.

The gap problem

To further investigate the voids that formed at the underside of the slab on top of the polymer concrete pedestal, a second series of mockups was made. The filling procedures, forming methods, and venting systems were varied. The specimens were cast without the steel-bearing plates to make it easier to cut the specimens apart to view the cross sections. The mockups made in plexiglass simulations to observe the flow characteristics are described below.

1. A polymer concrete pedestal (12 × 9 × 2.5 in [304.8 × 228.6 × 63.5 mm]) was cast under a clear 3/16-in (4.8-mm) thick plexiglass sheet. A 6-in (152.4-mm) long × 2-in (50.8-mm) diameter tube was cemented to the drilled plexiglass sheet to simulate the filler hole for the placement of polymer concrete into the wooden form. A slight gap was left between the plexiglass surface and the wooden form to allow the air to vent during compaction and vibration. The material flowed evenly as it vibrated through the plexiglass tube until it started flowing at the interface with the underside of the plexiglass. The top of the pedestal was a smooth surface finish with no visibly trapped air. About 15 minutes after the placement, some air voids were seen forming under the plexiglass, and they spread and became larger with time. After the polymer concrete had cured, there was a cracking pattern over the top of the plexiglass sheet caused by the strains created by the shrinkage of the bonded polymer concrete as it cured. Also, a crack was noticed on the top of the polymer concrete in the plexiglass tube (fig. 3).

2. As a comparison, the same procedure (but without the filler tube) was repeated with a portland cement-sand aggregate mixture. Precautions were taken to compact and vibrate the mixture sufficiently to allow the grout to run out at the interface of plexiglass and the forms, as had been done with the polymer concrete specimen. There was no bowing or cracking of the plexiglass.

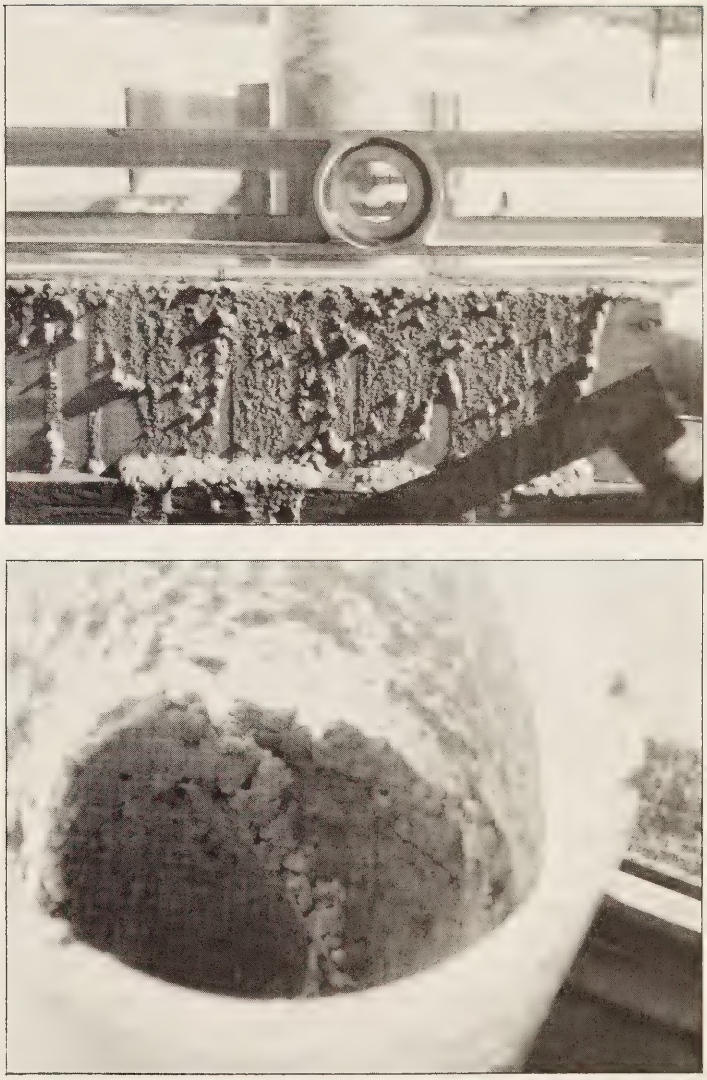

Figure 3.—Shrinkage of the polymer concrete after polymerization. a) Bowing of plexiglass sheet. b) Crack in polymer concrete at the top of plexiglass tube.

3. A pedestal (12 × 9 × 2.5 in [304.8 × 228.6 × 63.5 mm]) was cast under a concrete slab (by using a 2-in [50.8-mm] hole) into plexiglass forms. A 1/16-in (1.6-mm) spacer was used at the interface to allow the polymer concrete to overflow and leak out of the filled form and to vent any entrapped air. The material flowed smoothly under the vibrations and seemed well compacted. By all estimates the pedestal should have been completely filled and bonded to the underside of the PCC slab. Unfortunately, subsequent sawing and dismantling of the mockup revealed a 1/16- to 1/8-in (1.6- to 3.2-mm) gap at the underside.

4. Two vented pedestals (12 × 9 × 2.5 in [304.8 × 228.6 × 63.5 mm]) were cast—one in sideforms of wood and the other in sideforms of plexiglass. The sideforms were caulked at the bottom and top. Four drilled 0.5-in (12.7-mm) diameter holes 2 in (50.8 mm) from the central filler hole served as vents through the PCC. The polymer concrete was carefully placed and vibrated. No flow problems were seen through the specimen with plexiglass sideforms. As the forms were filled, the polymer concrete rose in the drilled vent holes. Again, by all estimates the polymer concrete was in intimate contact with the underside of the slabs. Subsequent dissection of the specimens revealed a 1/8- to 1/6-in (3.2- to 4.2-mm) gap at the underside of the concrete slabs.

Pressure compensation for shrinkage/settlement flow

Two pedestals were cast with polymer concrete, and the material was counterweighted to create a plastic flow to simultaneously fill the gap being created by the shrinkage/settlement.

In the one mockup, the simulated deck concrete slab was 15 × 12 × 3 in (381 × 304.8 × 76.2 mm) with a 2-in (50.8-mm) core hole for filling. The pedestal was formed to be 14 × 10 × 3 in (355.6 × 254 × 76.2 mm). Polymer concrete was poured through the cored hole and was vibrated until it flowed at the interface of the slab and forms. After 15 minutes, about a 1-in (25.4-mm) long by 1.75-in (44.5-mm) diameter hardened concrete plug was placed on the top of the plastic polymer concrete in the drilled core hole. This concrete plug was pushed into the plastic polymer concrete until leakage occurred at the interface of the slab and the forms. Additional polymer concrete then was placed, and another concrete plug, about the same diameter as the hole, was placed on top of the freshly placed polymer concrete. This concrete plug was long enough to project at least 2 in (50.8 mm) above the top of the slab. Fifty-five lb (24.9 kg) of steel weights were placed on top of the projecting plug. The specimen was allowed to cure with the constant load acting on the top of the concrete plug, which was bearing on the partially polymerized polymer concrete. After a 24-hour cure, the specimen was sawcut in the longitudinal direction at the center. No gap was found at the interface of the slab and pedestal.

The second polymer concrete pedestal was cast under a 24- × 24- × 8-in (609.6- × 609.6- × 203-mm) thick concrete slab. The polymer concrete was poured through a tapered hole into a 10- × 14- × 3-in (254- × 355.6- × 76.2-mm) wood mold placed under the concrete slab. The 2-in (50.8-mm) diameter concrete plug was pushed into the hole after the polymer concrete was partially polymerized (15 minutes). Seventy-five lb (34 kg) of steel weights were placed and left on the concrete plug over the polymer concrete during curing.

This specimen was cut into quarters, and the interface of the slab and pedestal was examined. All of the sections were well bonded, and no gap existed at the interface of the slab and pedestal.

It appeared from the two specimens that the vertical shrinkage/settlement of the polymer concrete can be overcome by applying a 16- to 32-psi (110- to 221-kPa) load on a plug. The method depends on the rate of polymerization and placing the load on the concrete plug at the right moment.

Geometrical configurations to counter the shrinkage/settlement effects

Other configurations were tested to compensate for the gap that formed at the top of the pedestal and at the underside of the slab. In one case, the forms were built around the perimeter of the base plate, to allow the base plate to move upward as the material shrinks (unrestrained vertical movement).

In the second case, the forms were placed between the base plate and the slab to prevent upward movement of the base plate (restrained vertical movement). A third case involved "belling" the bottom of the fill hole in the lower section of the simulated deck slab to provide a wider cone of polymer concrete at the interface.

A fourth case involved the creation of a "doughnut" of polymer concrete to protrude downward from the bottom of the slab and create a lug. All of the pedestals were cast with either the Crylcon mixture 3 or the Brookhaven mixture 4, as described in table 3.

Restrained versus unrestrained forms

The bottom surfaces of the five 24- × 24- × 8-in (609.6- × 609.6- × 203-mm) slabs were sandblasted and primer was applied. The surfaces were allowed to cure for 24 hours before the pedestal was fabricated. Three specimens were made with wooden molds built around the steel plate and were supported above the ground to measure any upward movement of the steel plate caused by the shrinkage of polymer concrete during polymerization (unrestrained shrinkage). The other two specimens were made with wooden forms built on the surface of the steel plate (restrained shrinkage). These specimens were used to also evaluate the "belling" and "doughnut" configurations for increasing shear resistance. Neither the restrained shrinkage nor the unrestrained shrinkage forms appeared to affect the formation of gaps at the interface.

Mockups with 6-in (152.4-mm) conical hole in the PCC slab

Using a rotary hammer, concrete was chipped from around the centered tapered core hole of two 24- × 24- × 8-in (609.6- × 609.6- × 203-mm) thick PCC slabs. The diameter of the hole at the bottom of the slab was widened to about 6 in (152.4 mm) and extended upward about 3 in (76.2 mm) into the slab at a 45° angle. The upper 5 in (127 mm) of the core hole were not altered. The modification produced an "inverted funnel" hole through which the polymer concrete was to be placed.

Mockup No. 1—The Crylcon mixture 3 was used to cast the pedestal with wooden forms built on the steel plate (restrained shrinkage). After hardening, the specimen was sawcut in the longitudinal direction at the center. A 1/16- to 1/8-in (1.6- to 3.2-mm) gap formed around the modified conical surface as well as the interface of the pedestal and slab surface.

Mockup No. 2—The Brookhaven mixture 4 was used to cast the pedestal in wooden forms that were fitted around the steel plate (unrestrained shrinkage). The steel plate and the forms were supported above the ground to observe any upward movement of the steel plate from the shrinkage of polymer. No upward movement of the steel plate was detected relative to the forms after the polymer concrete had polymerized. No gaps were observed between the cured polymer concrete and PCC at the modified conical surface, but there was a 1/16- to 1/8-in (1.6- to 3.2-mm) gap at the interface of the pedestal and the slab bottom surface, away from the fill hole (fig. 4).

Mockups with 8-in (203-mm) doughnut

A doughnut-shaped casting was made on the underside of two 24- × 24- × 8-in (609.6- × 609.6- × 203-mm) thick concrete slabs. Rubber tubing 1 in (25.4 mm) in diameter was tied to the projecting steel rebars and formed the outer limits of the doughnut. The inside limit was the 2.5-in (63.5-mm) fill hole that was blocked with a plastic bottle. An epoxy-sand mixture was poured into the tubular forms, leveled, and cured for 24 hours.

Mockup No. 3—The Crylcon mixture 3 was used to cast the pedestal under the bonded, hardened doughnut. In this specimen, the wooden forms were fitted around the steel plate (unrestrained shrinkage). As before, no upward movement of the steel plate was detected relative to the wooden forms after the material had polymerized. The specimen was cut in the longitudinal direction at the center. No visible gap existed at the interface of the cast doughnut and the polymer concrete pedestal, but there was a 1/8-in (3.2-mm) gap between the slab and the pedestal, away from the doughnut.

Mockup No. 4—The Brookhaven mixture 4 was used to cast this pedestal in wooden forms that were built on the steel plate (restrained shrinkage). The sawcut section at the longitudinal center of this specimen showed no gap between the doughnut and polymer concrete pedestal. A 1/8-in (3.2-mm) gap was visible at the interface of the PCC slab and pedestal surface, away from the doughnut, similar to mockup No. 3.

In summary, no visible gap existed between the modified bottom surface of the slab and the cast polymer concrete pedestal within the radius of the modified core holes (inverted funnel and doughnut). The interface gap was observed only at the extreme ends of the unaltered surface. Overall, the Brookhaven mixture was more fluid and workable than the Crylcon at the same monomer content level, probably because of the differences in gradation (surface area) of the aggregates.

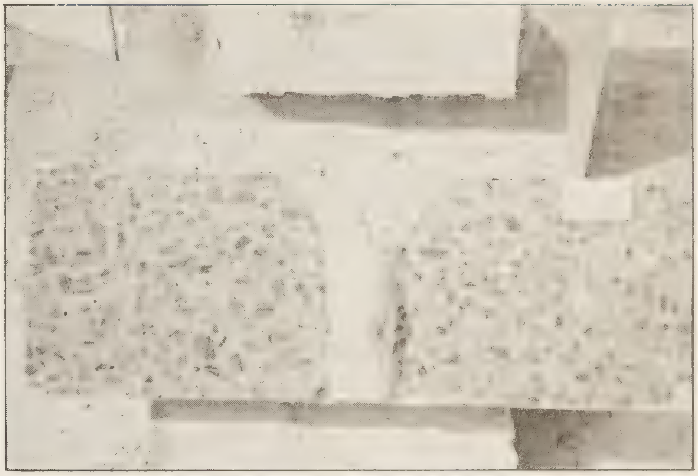

Figure 4.—The specimen with the conical hole in the PCC slab (Brookhaven material).

Acceptance Testing

The Federal Highway Administration (FHWA) tested the materials used on the WWB project for acceptance and to qualify the contractor's procedures in the use of the products. The gradation of the aggregates supplied is shown in table 6.

Mixture proportions and properties

The polymer concrete for the pedestals and for panel joints at prestressing locations was proportioned to be (in parts by weight): Liquid monomer 8.5, powder 66, and small-size stone 66.

The results of the strength tests on the polymer concrete and the specification are shown in table 7. The ambient temperature was 60 °F (16 °C) for the pedestal concrete. For low-temperature tests the promoter concentration in the monomer was increased from 1 to 5 percent as a "cold additive." The cold temperature curing of the polymer was done at 20 °F (−7 °C) in the laboratory freezer after casting the specimens. All of the ingredient materials for the three mixture designs were preweighed and stored overnight in the freezer and maintained at 5 °F (−15 °C).

Table 6.—Gradation of stone supplied by Transpo

Sieve size	Smaller size stone	Larger size stone
	Percent retained	*Percent retained*
1 to ¾	0	4.1
¾ to ½	8.5	38.6
½ to ⅜	33.1	28.2
⅜ to No. 4	56.9	26.0
Passed No. 4	1.5	3.1
Total	100.0	100.0

1 in = 25.4 mm

Table 7.—Physical testing of polymer concrete [1]

Property	Pedestals 1-hr ambient cure	Pedestals 24-hr room cure	Pedestals 1-hr 20 °F cure
Compression, psi (AASHTO T22)	8,960[2]	10,680[3]	6,590[4]
Tensile split, psi (AASHTO T198)	—	1,490[5]	—
Flexural, psi (AASHTO T97– ⅓ pt 3x4x16 in beams)	—	2,190[6]	—

[1] Each value is the average of three specimens. The compression and tensile tests were on 3-in x 6-in cylinders.

Specification as a special provision for the contract:
[2] >4,000; [3] >8,000; [4] >4,000; [5] >1,000; [6] >2,000

°F = 1.8°C + 32
1 in = 25.4 mm
1 psi = 7 kPa

The ingredient materials of the particular mixtures were mixed in the laboratory at 70 °F (21 °C). The temperature of each mixture was monitored during mixing/casting of the cylinder specimens for the compressive strength tests. The cast cylinders attained 20 °F (−7 °C) in less than 10 minutes and were immediately stored in a freezer maintained at 20 °F (−7 °C). The first cylinder was removed from the freezer after exactly a 1-hour cure at 20 °F (−7 °C) for a compressive strength test. It took approximately 7 minutes to test each cylinder; hence, the last cylinder was cured for 75 minutes before it was tested. Shrinkage test results are shown in table 8.

The materials did not meet the specification for shrinkage, although previous tests had yielded values of 0.10 and 0.11 percent for a 2-in (50.8-mm) thick slab at 73 °F (23 °C). Therefore, it was believed that the specification could be met with a better proportioned mixture so subsequent mixtures were reproportioned to reduce the amount of monomer.

Table 8.—Linear shrinkage of polymer concrete (Transpo)

System	Thickness	Temperature	Compressive strength	Shrinkage (percent) 2-hr	Shrinkage (percent) 4-hr	Shrinkage (percent) Specified (max)
	Inches	*°F*	*Psi*			
Pedestal	2	20	5,185	0.26	0.28	0.10
Pedestal	2	73	—	0.17	0.19	0.10

°F = 1.8°C + 32
1 in = 25.4 mm
1 psi = 7 kPa

Pedestal casting procedures

The contractor made 12 pedestal castings to demonstrate the procedures for filling the forms and attaining the specified strength at temperatures from 20 to 105 °F (-7 to 41 °C). As can be seen in table 9, the first five specimens either did not meet the strength or did not fill the forms. Specimens 6 and 7 were marginal in strength; specimens 8 to 11 indicate an adequate procedure was used. Specimen 12, again, had a setup problem (too soft) at 1 hour; the strength was 6,250 psi (43.1 MPa) at 1 1/2 hours.

Final proportions and properties/performance

As a result of the problems experienced by the contractor with the materials and procedures, the proportions were again changed (table 10).

The data indicate that the shrinkage of the polymer concrete with the 5/8-in (15.9-mm) stone and that with the combination of 5/8- and 1.25-in (15.9- and 31.8-mm) stone are above the specified limits at 20 and 100 °F (– 7 and 38 °C). The mortar shrinkage tests were run at a 0.5-in (12.7-mm) thickness, and as the thickness is increased, the shrinkage also increases.

Table 9.--Prototype castings

Specimen Number	Mixture/Cure Temperature F.	Mixture Proportions Parts by Wt.**	Compressive Strength PSI at 1 Hr.*	Remarks, Visual Observations
1	20/20	6.44:0.32:50/50	Soft; could not be tested after 1 Hr.	Wrong mixture design; contractor forgot to add cold additive. Compressive strength was 9122 psi after 1-hour cure at 20 F. plus 1 hour at 70 F. Saw-cut sections have no gaps between the pedestal and the concrete slab. Gap visible around the outer edges of pedestal and the slab. The mold was vented at the top.
2	105/105	6.44:0:50/50	3510	The powder and aggregate at elevated temperature, around 110 F, for 2 days before the polymer concrete was mixed. The pedestal saw-cut section and periphery is about the same as Pedestal No. 1. The mold was vented at the top.
3	40/40	6.44:0.32:50/50	8330	1/2 to 1 in. gap around the outer edges of pedestal and the slab. Saw-cut sections showed big wide gap. The mold was sealed against the concrete slab and had no vents.
4	100/100	6.44:0:50/50	4770	Same as Specimen No. 3. The mold was sealed against the concrete slab and had no vents.
5	25/16	6.44:0.32:50/50	Soft; could not be tested after 1 Hr; 4720 after 1 Hr. at 16 F. and 15 min@70 F; 5880 after 1 Hr. at 16 F. and 25 min. at 70 F.	1/16 to 1/8-in. gap in the saw-cut sections and around the cone.
6	29/20	6.44:0.32:50/50	4100	During saw-cut, one-half of the polymer pedestal with cone fell off and had no bond with the concrete slab.
7	95/105	6.44:0:50/50	4040	The pedestal appears in good condition. No gaps in the saw-cut section or around the outer edges of pedestal.
8	40/35	5.00:0.26:50/50	6210	" " " " " " "
9	25/18	5.00:0.26:50/50	6090	" " " " " " "
10	28/20	5.00:0.26:50/50	5770	--
11	86/110	5.26:0:50/50	5100	--
12	35/40	5.00:0.26:50/50	Soft; could not be tested after 1 Hr: 6240 after 1-1/2 Hr.	--

*Three specimens tested per mixture/cure condition; 3x6", AASHTO T-22.
**Proportions are Monomer:Cold Additive:Powder/Small Stone.

°F=1.8°C
1 in=25.4
1 psi=7 kPa

Table 10.—Proportions, strength, and shrinkage of polymer concrete[1]

Proportions						Properties							
Use	Powder	Monomer	Low-temp. additive	Stone 5/8"	Stone 1-1/4"	Temp. mat.[2] & Test	Compress 1 hr.	Str.[3] 24 hr.	Tensile[4] Split Str. 24 hr.	Flex.[5] Str. 24 hr.	Thickness of shrink. Specimen	Shrinkage[6] 2 hr.	Shrinkage[6] 4 hr.
						°F	psi	psi	psi	psi	in.	%	%
Pedestals	50	4.96	0.26	50	---	20	7109	9895	1234	2361	2	0.20	0.21
Pedestals	50	5.22	---	50	---	100	6328	11127	1215	2324	2	0.25	0.26

[1]Materials supplied by Transpo Industries, Inc.

[2]All material stabilized at test temperature for minimum of 18 hrs. prior to mixing/making specimens.

[3]Compression strength per AASHTO T22 (3 by 6 in. long cylinders). Specimens were kept at test temperature for 24 hrs. prior to testing. Each value is an average of three tests.

[4]Tensile splitting strength per AASHTO T198 (3 by 6 in. long cylinders). Specimens were kept at test temperature for 24 hrs. prior to testing. Each value is an average of three tests.

[5]Flexural strength per AASHTO T96, Third Point Loading (3 by 4 by 16 in.). Specimens were kept at test temperature for 24 hrs. prior to testing. Each value given is an average of three tests.

[6]Shrinkage testing device was designed by DuPont and manufactured at Brookhaven National Laboratory. It measures the shrinkage over a nominal 10 in. gage length and

$$\text{Shrinkage Percent} = \frac{\text{Shrinkage in inches}}{\text{Gage Length in inches}} \times 100 .$$

°F=1.8°C+32
1 in=25.4 mm
1 psi=7 kPa

The work time of the material at 100 °F (38 °C) appears to be only 4 to 5 minutes; this would require extremely expeditious handling in placing the material.

The 1- and 24-hour compressive strengths and the 24-hour tensile splitting and flexure strengths are all higher than the minimums called for in the specifications.

In all cases the materials (powder, liquid, and stone) were kept in environmental chambers at the test temperature for 18 hours before mixing to stabilize the material at the desired temperature. Once the samples were made, they were kept at their respective temperatures until they were tested.

A further requirement of the contract was that the strength of the polymer concrete be monitored throughout construction. At one point in the construction sequence, the strength was not met and the problem was traced to the use of an unwashed aggregate that was contaminated with excessive fines.

Conclusions

Based on the experimental work discussed in this article, the following conclusions are drawn:

- Polymer concrete (methylmethacrylate-based) has compressive strength and freeze-thaw durability properties very similar to a good quality PCC (about 10,000 psi [68.9 MPa]), although the modulus of elasticity is less (2.6 × 10^6 psi [17.9 GPa]).

- A polymer concrete with a 15-minute workability period easily met the 4,000 psi (2.8 MPa) compressive strength at an age of 1 hour over a temperature range of 0 to 100 °F (−18 to 38 °C).

- Testing temperatures of 140 °F (60 °C) had a deleterious effect on strength because of softening and plastic flow.

- Relatively high compressive loads and high rates of loading (10 Hz) during fatigue testing caused internal heating of the polymer concrete specimens and, possibly, plastic flow.

- Polymer concrete has a much higher shrinkage than PCC, and its magnitude is dependent on the amount of monomer in the mixture.

- Polymer concrete properties are dependent on the aggregate amounts, gradations, and manufacturer of the binder, even though the binder is of the same generic material.

- The bonding of polymer concrete to hardened PCC surfaces or clean steel can be good or poor, depending on the use of either a fresh or cured primer and the manufacturer.

- Pedestals or bearing areas for precast slabs of 2.5-in (63.5-mm) thicknesses or more cast from polymer concrete are subject to significant shrinkage/settlement effects, which can cause gaps or voids between the slab and the pedestal. Vent holes will not eliminate the problem nor will unrestrained vertical forming techniques, but applying pressure during hardening can activate plastic flow to offset the shrinkage/settlement.

- Pedestals or bearing areas cast of polymer concrete under the slabs should be properly designed for any shear loads because bond between the underside of the slab and the top of the pedestal is not assured. Metal (studs) or concrete (lugs or doughnuts) projections from the underside of the slab appear to be effective. Alternatively, the underside of the slab can be belled to form a cone-shaped plug of polymer concrete to mechanically compensate for the large shrinkage.

- A polymer concrete mixture proportioned for use at higher temperatures (100 °F [38 °C]) was made effective (workability, time, strength) at low temperatures (20 °F [−7 °C]) by increasing the promoter concentration in the monomer from 1 to 5 percent.

Recommendations

Because of the success of the redecking of the Woodrow Wilson Bridge, it is recommended that the procedures be considered for use in other rehabilitation projects. Polymer concrete should be considered as an alternative to the use of rapid-setting inorganic products because of its potential to attain high early strengths even at extremely low temperatures.

Designers are cautioned to test the proposed specific formulations in mockups of the actual construction so that nothing is taken for granted and unforeseen problems can be discovered and eliminated or avoided.

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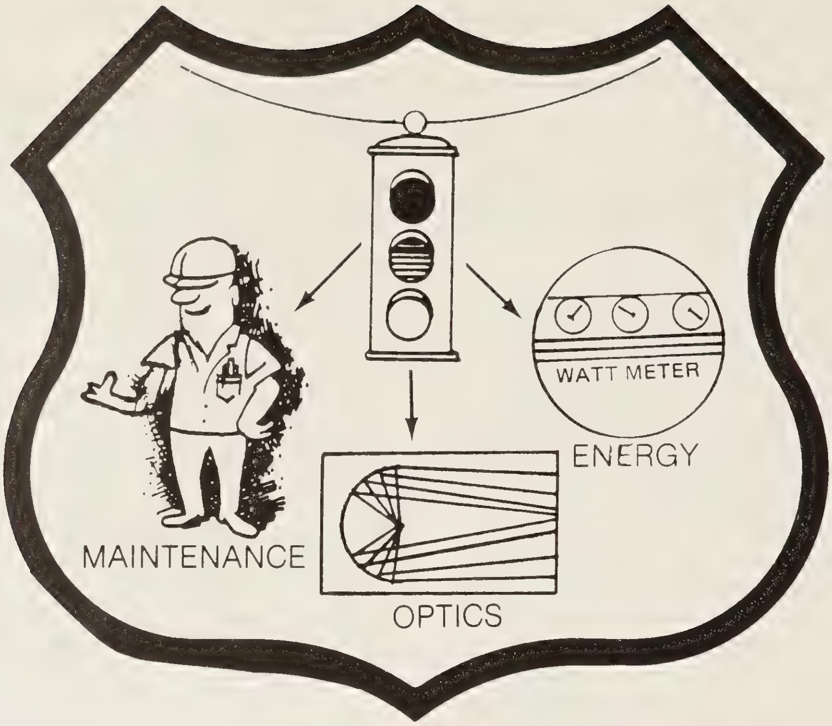

The Optical and Energy Efficiency of Traffic Signals[1]

by
Ian Lewin and Richard G. Reynolds

This article discusses methods of improving the optical efficiency of traffic signals to reduce power usage while maintaining high safety standards. Indepth investigations found that quartz-halogen and low-voltage lamps, redesigned lenses, and nighttime dimming all decreased power usage, although in some cases, the increased initial cost did not justify their application. Large efficiency gains were obtained using redesigned lenses.

Introduction

Traffic control devices at highway intersections improve highway safety and reduce certain kinds of congestion by providing for the orderly and predictable movement of traffic through the intersection. Electrically powered traffic signals visually warn and direct intersection users.

Improving the existing traffic signal has been investigated, particularly ways to improve its optical and energy efficiency without sacrificing visibility and conspicuity or increasing maintenance requirements. A recent study sponsored by the Federal Highway Administration (FHWA) investigated the potential and feasibility of alternative ways to improve the operating efficiency of the traffic signal light through the use of alternative lamp designs and structures, alternative filaments and operating voltages, and improved reflectors and lenses. This 1-year study also considered time-of-day alternatives for efficiency improvements, such as nighttime dimming of signals. Estimated costs and projected benefits of the alternatives were analyzed as a basis for possible future changes to the traffic signal light.

Each of the approximately 240,000 signalized intersections in the United States typically has two or more signal faces controlling traffic

[1]This article is based on report FHWA/RD-85/089, "Alternative Incandescent Traffic Signal Lamps and Systems for Improved Optical and Energy Efficiency," Federal Highway Administration, Washington, DC. Not yet published.

movements in each approach direction, and each signal face has at least one signal indication illuminated at all times. An urban intersection may contain as many as 60 traffic signal light units, with 20 or more of these units illuminated at any one time. Electrical power for active traffic control devices is overwhelmingly the single largest operating cost associated with signalization of an intersection, and it is a continual cost throughout the operating life of the signal.

The cost of electrical power to operate signalized intersections is becoming a major portion of the operating budgets of many highway departments, and in recent years utility costs have increased at a rate greater than the overall inflation. Further, the basic need to reduce energy consumption and encourage conservation suggests there may be potential for both cost savings and energy conservation through improvements to the traffic signal system.

Background

Electrically illuminated traffic signal lights, the basic active highway intersection warning and control device, have been in operation since 1921. Although there have been many changes made to the signal system since the 1920's, the signal itself has remained essentially the same.

The main optical components of the traffic signal are the lamp, reflector, and lens and their associated hardware. The lens, made of glass or polycarbonate (plastic), has either an 8-in (203-mm) or 12-in (305-mm) diameter. The lens provides the signal light with its dispersion and intensity characteristics and color. The lamp, located behind the lens and in front of a reflector, ranges from 67 W to 150 W, all operating on 120 Vac. The lamp socket, centered in the round mirrored reflector, positions the lamp so as to direct available light off of the reflector and out of the housing through the lens.

The existing traffic signal has very poor energy efficiency because of the component parts of the light unit. The 120-V, C-9 filament of the incandescent lamp provides a large distributed light source that does not provide precise or efficient optical control. The large, high-voltage filament also exhibits poor luminous efficiency in converting the electrical energy into visible light. The reflector usually is not a precision, quality optical device, although generally it collects light from the lamp and directs it through the lens. A typical reflector exhibits several discontinuities and areas of non-uniformity, which could result in a flawed signal if the unit were required to operate efficiently from a point source of light. The lens has very low transmissibility not only because of the color filtration required but also because of the diffusing prisms used on the inner surface. These prisms scatter the light, therefore wasting energy.

In addition, nighttime operation of traffic signals at daytime intensity levels is not energy efficient, and savings from nighttime dimming must be considered. (*1*)[2]

Methodology

A general scope of work was developed to identify potential approaches to increasing the optical and energy efficiency of traffic signals, including the study of any impact on the operational effectiveness of the signal, service life, and maintenance. The initial task consisted of a broad-based review of many possible alternatives. Any new technology appearing to have promise was investigated, including enhanced reflector materials, unique reflector designs and lamp orientations, reflectorized lamps, double-ended lamps, redesigned lenses, dual filament lamps, low-voltage and quartz-halogen lamps, and signal dimming during nighttime operation. Each alternative was investigated from the following standpoints:

- Intensity and dispersion of the light beam.
- Light spectral composition (chromaticity).
- Energy efficiency.
- Lamp voltage, wattage, life, and color temperature.
- Lamp placement and placement accuracy requirements.
- Reflector shape and uniformity.
- Susceptibility to "sun phantom."
- Auxiliary hardware and control requirements.
- Maintenance requirements.

In reviewing the candidate alternatives, the four most promising alternatives—quartz-halogen lamps, low-voltage lamps, redesigned lenses (with reflector modifications also considered), and nighttime dimming—were selected for detailed study because of technical features particularly attractive in traffic signal applications.

The detailed study of the four alternatives began with an analysis of the technical and cost characteristics of presently used signals as a basis of comparison for the anticipated design improvements. In performing this work, certain typical signal configurations for four-way intersections were identified, and initial and operating cost data for these configurations were collected.

Evaluation techniques were developed to provide computer simulations of the performance of traffic signals incorporating the potential improvements. Using computer-aided design (CAD) software, the effects of the smaller filaments of quartz-halogen and low-voltage lamps were investigated. Using a computer simulation process for lenses, many different forms of redesigned lenses were investigated, and a method was developed whereby prism details could be optimized for a particular lamp type.

The manufacturing and installation tolerance effects on optical components such as lamps, reflectors, and lenses were investigated. Information was developed relating positional accuracy of the lamp and reflector surface finish to the efficiency and light intensity distribution of the signals.

[2]Italic numbers in parentheses identify references on page 94.

The cost data also were handled by computer, using a program capable of generating life-cycle cost data and payback periods for any given set of cost conditions. A wide range of cost situations was studied along with the technical implications of proposed signal modifications.

The Selected Alternatives

Quartz-halogen lamps are miniature incandescent lamps that use a quartz glass bulb to withstand very high temperatures. By introducing a halogen vapor into the bulb, a "halogen cycle" is created. Here a chemical reaction occurs between the tungsten atoms evaporating from the filament and the halogen atoms, producing tungsten iodide or bromide. These molecules circulate within the bulb and, on contact with high-temperature filament, break into halogen atoms and tungsten, thereby redepositing tungsten back onto the filament. The net effect is the ability to burn the filament hotter for a given life, which is highly desirable because a hotter filament produces more lumens per watt. In addition, because a higher current can be used, the filament resistance can be lowered, resulting in a shorter and more compact filament.

The smaller filament produces considerable advantages in optical control. A small light-producing volume creates less scattered light within the optical system, giving more exact control and the ability to effectively direct the light in the required directions.

Low-voltage lamps similarly provide the benefits of a compact filament. If the design operating voltage is stepped down, a given wattage lamp will operate at a higher current. Because the heating effect and the light output basically depend on the current, light output increases with no increase in power. Obvious disadvantages are the cost of a transformer, the transformer power losses, and the possible increase in maintenance.

Improving lenses by optical means is based upon increasing the luminous intensities over the range of directions specified by the Institute of Transportation Engineers (ITE) (*2*), while reducing intensity in unwanted directions. By using a lower wattage lamp, power can be saved while maintaining equal performance to currently produced lenses over the ITE angular range. The basis of the optical improvement is the design of specially shaped prisms that collect and redistribute the light in a scientifically designed fashion, unlike the general scattering created by lenses currently used in signals. For example, present signals produce intensities above the horizontal more or less equal to those below the horizontal, which clearly is wasteful in most applications.

During the study, many prism shapes were investigated before deciding on an ideal prism design for distributing light over the ITE range. The ideal prism is different for different lamp and signal types.

Nighttime dimming can be achieved by a variety of means, such as a transformer, half and full-wave rectification, and a phase-control thyristor. The thyristor appears to offer the greatest benefits, although care must be taken to control possible conflict monitor problems.

After considering a 12-month period and different locations across the United States, the average period of dimming has been estimated at 12 hours per day. (*1*) A power reduction of 42 percent (or 21 percent over a 24-hour average period) can be achieved by reducing lamp voltage from 120 Vac to approximately 85 Vac. The substantial power savings must be weighed against the increased component costs and possible increases in maintenance. The luminance levels required for safe operation of traffic signals under dimmed conditions has been investigated. (*1*) ITE is developing standards for when dimming should be permitted.

Research Findings

During the study of the signals in current use, at least for the limited number of signals evaluated, the performance did not meet the specifications of the ITE. Therefore, additional work was performed to evaluate the newly proposed designs in two different ways: First to use lamps of a wattage sufficient to meet the performance of presently used signals, and second to meet ITE specifications.

Substantial improvements in signal efficiency were obtained with both low-voltage lamps and quartz-halogen lamps because of the smaller filament and the more accurate focusing. However, such a change in optical characteristics requires a redesigned lens to use this benefit fully. Otherwise, certain angular ranges of light output would have inadequate intensity while other areas would have excess intensity.

The cost of using either of these forms of lamp both in new and retrofit situations was found to be high because of the higher cost of the lamps, plus the need for an auxiliary transformer.

The use of improved lens designs with existing kinds of signal lamps proves very effective in increasing the optical efficiency of the signals. With the use of prisms specially shaped to distribute light at the specified angles without waste at unwanted angles (such as in uplight directions), signal efficiencies could be improved more than 50 percent. Substituting new lenses in existing signals would improve signal performance sufficiently to meet ITE specifications. Alternatively, if present signal performance is regarded as satisfactory, such lenses will reduce signal power about 20 percent for 8-in (203-mm) diameter signals and 33 percent for 12-in (305-mm) diameter signals.

The analysis of signal dimming indicates savings would depend upon latitude and time of year, but on the average throughout the United States, a 24-hour mean power reduction of approximately 20 percent could be achieved. However, cost studies indicate generally poor payback periods because of the initial and installation costs of the required dimming hardware.

Acceptability of Proposed Alternatives

After analysis of all technical characteristics, the findings were submitted to nine traffic engineers (including manufacturers and users) to evaluate the relative implementability of each of the four proposed alternatives.

Detailed operating and cost information was supplied to each engineer for each system in two configurations—two 8-in (203-mm) signals per approach and two 12-in (305-mm) signals per approach. In addition, except for signal dimming, data for two performance levels were provided—the first meeting ITE's requirements for the luminous output of signals, and the other at a lower luminous output level equal to signal equipment commonly in use in the United States. The data for all alternatives under each design configuration and performance level were provided in tabular form.

The traffic engineers evaluated each alternative using a 5-point scale (from very poor to very good) in terms of the following 10 attributes:

- Potential to improve safety.
- Potential to reduce energy costs in respondent's jurisdiction.
- Initial cost of hardware components.
- Ease of installing hardware.
- Cost of installing hardware.
- Ease of maintaining hardware.
- Cost of maintaining hardware.
- Cost of operating system.
- Durability of hardware.
- Compatibility with existing hardware.

Before evaluating any of the alternatives, however, each traffic engineer indicated the relative importance of each attribute by ranking them (table 1). This rank provided insight into the aspects of signal systems of greater importance to signal engineers. It also facilitated application of a weighting scheme to combine the inputs of all of the traffic engineers into a single score for each alternative. The weighted score was used to determine the relative desirability of each alternative signal system. It can be seen that the potential to increase safety is clearly ranked first.

Table 2 shows a combined weighted score and rank for each alternative, as analyzed for both 8- and 12-in (203- and 305-mm) signals and for meeting present performance or meeting ITE specifications.

Table 1.—Ranking of each attribute with average score

Rank	Attribute	Average score[1]
1	Potential to improve safety	1.57
2	Durability of hardware	3.79
3	Cost of maintaining hardware	5.36
4	Ease of maintaining hardware	5.43
5	Compatibility with existing hardware	5.43
6	Potential to reduce energy costs in respondent's jurisdiction	5.93
7	Initial cost of hardware components	6.07
8	Cost of operating system	6.29
9	Cost of installing hardware	7.14
10	Ease of installing hardware	8.07

[1]The lower the rank, the more important the attribute.

Table 2.—Combined weighted scores for each signal improvement alternative

Signal design alternative	Combined weighted score	Rank[1]
Two 8-in (203-mm) signals per approach		
—Meets ITE performance specifications		
#1 Low-voltage lamp—new	38.2	11
#2 Low-voltage lamp—retrofit	40.9	9
#3 Quartz-halogen lamp—new	47.5	5
#4 Quartz-halogen lamp—retrofit	47.1	6[2]
—Meets present performance level only		
#5 Low-voltage lamp—new	43.0	8
#6 Low-voltage lamp—retrofit	47.1	6[2]
#7 Quartz-halogen lamp—new	47.6	4
#8 Quartz-halogen lamp—retrofit	51.5	3
#9 New lens design—new	66.1	2
#10 New lens design—retrofit	68.8	1
#11 Signal dimming—retrofit	38.9	10
Two 12-in (305-mm) signals per approach		
—Meets ITE performance specifications		
#1 Low-voltage lamp—new	46.6	7
#2 Low-voltage lamp—retrofit	40.2	11
#3 Quartz-halogen lamp—new	46.0	8
#4 Quartz-halogen lamp—retrofit	48.4	5
—Meets present performance level only		
#5 Low-voltage lamp—new	43.6	9
#6 Low-voltage lamp—retrofit	47.0	6
#7 Quartz-halogen lamp—new	52.4	4
#8 Quartz-halogen lamp—retrofit	54.5	3
#9 New lens design—new	67.1	1
#10 New lens design—retrofit	65.2	2
#11 Signal dimming—retrofit	43.0	10

[1] The lower the rank, the more desirable the alternative.
[2] Tied for sixth rank.

Study Conclusions

A new lens system designed to meet existing performance levels as either a new system or as a retrofit application was judged superior by all participating traffic engineers because of its low initial cost as well as ease and low cost of installation and maintenance. Signal dimming was deemed least attractive by the traffic engineers because of its high initial cost, complexity, and anticipated high installation, maintenance, and operating costs.

Although energy costs are significantly higher than they were a decade ago, reducing the cost of energy for traffic signal illumination is not nearly as important to traffic engineers as ensuring safety, high reliability, and low maintenance costs.

The most important findings of the study are as follows:

- Presently used traffic signals are simple in their operation and basic in their design. Numerous improvements are possible to increase the electrical and optical efficiency of the signals.

- Of the various alternatives considered, the most promising are the application of newly designed high-efficiency lenses, the use of low-voltage lamps, and the use of quartz-halogen lamps.

- Although many improvements are possible, many factors must be considered, the most important of which are initial cost, operating cost, implementability, reliability, and maintenance. The various alternatives differ greatly in these areas, rendering some unsuitable and suggesting others may be acceptable.

- The calculated payback periods for the various alternatives studied are influenced very heavily by power costs. An alternative having little benefit in a location with low power costs may be highly desirable in a location with high power costs. Alternatives rejected during this study either by the researchers or by the traffic engineering community may prove to be desirable in the future with ongoing escalations in power costs.

- Investigations suggest many traffic signals presently in use do not meet ITE luminous intensity specifications. This does not appear to be a marginal failure, but represents departures from the ITE specifications at many of the ITE test angles.

- Several of the alternatives studied, mainly the use of quartz-halogen or low-voltage lamps and the use of improved efficiency lenses, can increase the traffic signal efficiency sufficiently to meet ITE signal performance specifications.

- Many of the alternatives studied have no payback, possibly because there is no improvement in operating costs to offset the increased initial or retrofit cost of the improvement or because the operating cost savings are so low that a payback does not occur during the life of the signal. In any case, a payback period of at least 3 years appears necessary for an alternative to be worthwhile from a cost standpoint.

- The acceptability of quartz-halogen or low-voltage lamps is heavily influenced by lamp cost. The cost of these lamps is higher than that for present signal lamps, and in some instances, may be extremely high. Because lamps must be replaced frequently, this is a strong negative factor with higher cost lamps.

- The use of a complex form of prism with carefully controlled curvatures both in vertical and horizontal planes will be necessary to optimize signal performance. Such a prism can be designed and manufactured specifically for a given lamp type and signal head geometry to substantially increase optical efficiency. This is likely to decrease power costs 20 percent for 8-in (203-mm) signals and 33 percent for 12-in (305-mm) signals if lower wattage lamps are used to provide signal intensities comparable to presently used signals.

- Some deterioration in signal performance will be caused by manufacturing tolerances, assembly tolerances, and tolerances in the location of the lamp filament because of the insertion of the lamp in its socket. Some overdesign of the signal is desirable to overcome the effect of these tolerances. Analysis has shown that the use of newly designed lenses in existing signal lamps will not have high sensitivity to tolerances.

- While the effects of nationwide adoption of the improved lensing is difficult to assess, it is estimated an annual power savings equivalent to $59 million could be expected if lower wattage lamps were used to provide signal intensities comparable to those produced today. If improved lensing was adopted but present lamp sizes retained, no power savings would be realized, but an improvement in signal efficiency should provide increased safety on the Nation's highways.

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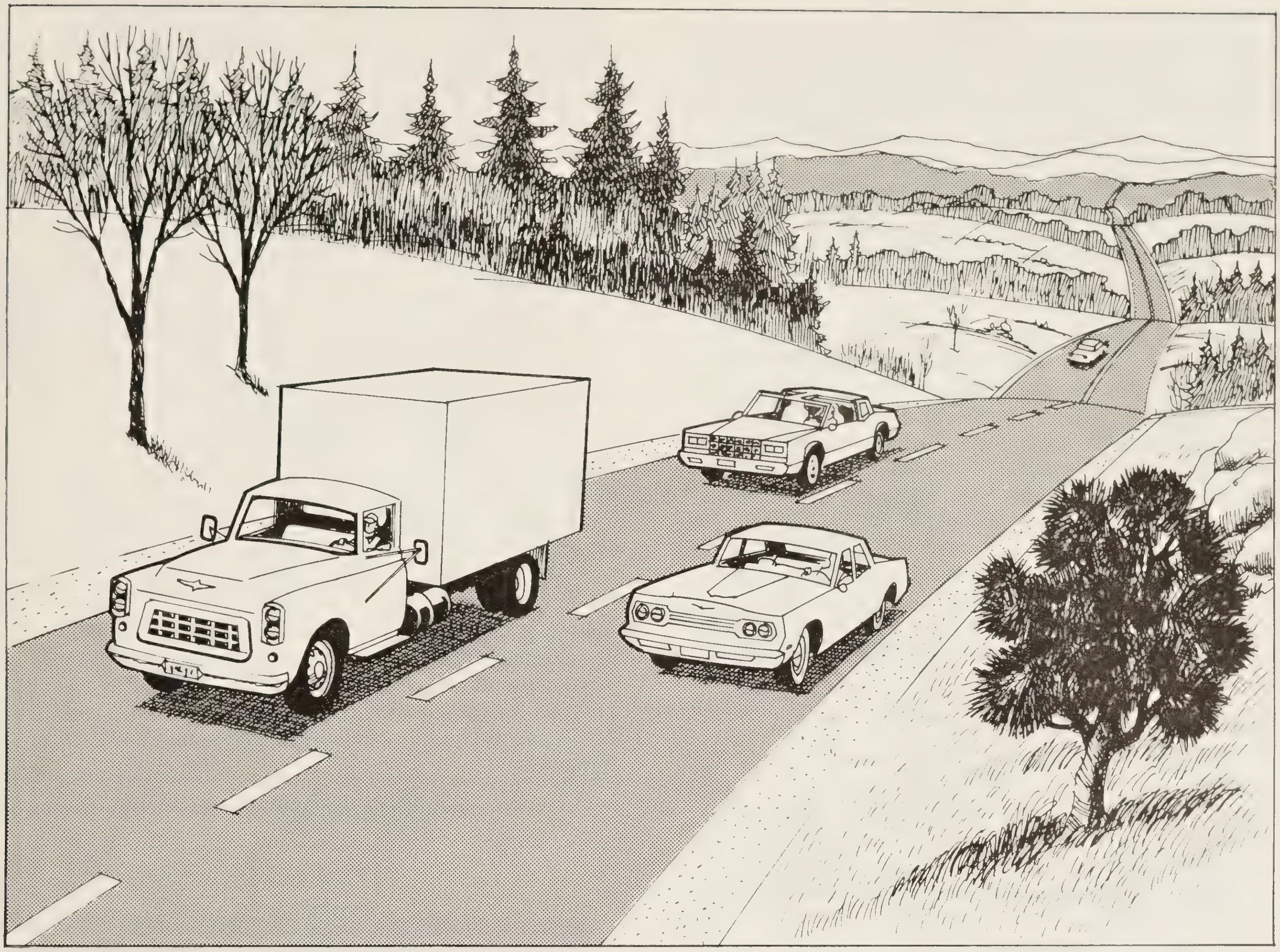


Two-Lane Traffic Simulation— A Field Evaluation of Roadsim

by
Juan M. Morales and Jeffrey F. Paniati

Introduction

Traffic simulation, a tool used by traffic engineers in the analysis of roadway capital investment and traffic control management, provides valuable information to decision-makers by predicting the likely effects of traffic or geometric changes in a roadway before the changes actually occur. Using simulation results, decisions can be made to proceed with the change, modify it, or abandon it. Simulation can determine the most effective way to spend available funds.

Initially, traffic simulation was directed to the urban scene. Because urban intersection traffic essentially behaves as a multi-lane queueing system, traffic can be simulated using simulation techniques developed for operations research. Simulation of freeway ramp traffic required modeling of traffic behavior using queueing analogies. Freeway simulation studies were the pioneers of traffic simulation as a research tool.

Simulation of rural traffic on two-lane roads developed at a slower pace because the two-lane flow is complicated by platooning and passing decisions and therefore not easily modeled. Also, the low volumes on rural two-lane roads usually do not make simulation cost-effective. In addition, two-lane traffic simulation requires numerous computations, which require considerable computer time and memory, particularly for microscopic models. To date, most of the two-lane simulation models are microscopic. Microscopic models simulate and trace individual vehicles and are more accurate and realistic than macroscopic models, which simulate traffic using aggregate variables such as traffic volume and average speed.

Simulation models for two-lane roads have evolved over the past two decades. Most of the early attempts contributed little to the study of two-lane flow at a practical level. However, those attempts were stepping stones for other sophisticated simulation models currently available.

This article evaluates the ability of Roadsim, a traffic simulation model for two-lane rural roads that was developed in 1980 for the Federal Highway Administration (FHWA), to replicate traffic operations observed on an existing two-lane rural road. Field data were collected on a two-lane rural road in Loudoun County, Virginia. Statistical analyses performed to compare the measures of effectiveness (MOE's) observed in the field to those obtained from the simulation showed Roadsim's simulation results compared favorably with those observed in the field. Results support its potential usefulness to the transportation engineering community after the model is further validated under a range of traffic and geometric conditions.

Evolution of Roadsim

Roadsim, the latest product of the evolutionary process of two-lane simulation model development, is not a new model with new methodology and logic but rather a reprogrammed version of an earlier model (called TWOWAF) with modified routines and adaptations from other models. (*1*)[1]

TWOWAF, a microscopic traffic simulation model, was developed in 1978 as part of the National Cooperative Highway Research Program (NCHRP) Project 3-19. (*2*) The model can "move" individual vehicles in accordance with several parameters specified by the user. The vehicles are "advanced" through successive 1-second intervals taking into account the roadway geometry, traffic control, driver preferences, vehicle type and performance characteristics, and passing opportunities based on the oncoming traffic. Spot data, space data, vehicle interaction data, and the overall travel data are accumulated and processed. Several statistical summaries are reported.

TWOWAF logic was modified to include logic elements from two other simulation models—INTRAS and SOVT. (*3*) INTRAS, a microscopic freeway simulation model developed in 1976 for FHWA, provided the basic car-following logic to TWOWAF. This logic is based on the premise that a vehicle that is following another will always maintain a space headway relative to its lead vehicle which is linearly proportional to its speed. This premise was much simpler than the one used in TWOWAF and thus easier to calibrate. SOVT, a microscopic two-lane simulation model developed in 1980 at North Carolina State University, provided its vehicle generation logic to TWOWAF. This logic emits vehicles onto the simulated roadway at each end. For low volumes, the Schuhl distribution used in SOVT provides a realistic approximation of vehicles generated. However, for high volumes where traffic density approaches queueing, a shifted exponential headway distribution is used.

The new TWOWAF model was reprogrammed according to FHWA specifications, modified with new input and output subroutines, and renamed Roadsim. Detailed documentation was made available as part of TRAF, an integrated system of simulation models. (*1*) This evolutionary process is illustrated in figure 1.

MOE's Generated by Roadsim

Roadsim is structured in a link-node format, which requires the simulated roadway to be divided into segments called links. Links are interconnected at points called nodes. It is through the links that the roadway geometrics are specified to the model.

In addition to "overall" statistics, some of the MOE's generated by Roadsim are reported as "link-specific" or "link- and direction-specific." Link-specific MOE's are specified for each direction of travel. Table 1 lists the MOE's and their units reported in the cumulative output of Roadsim.

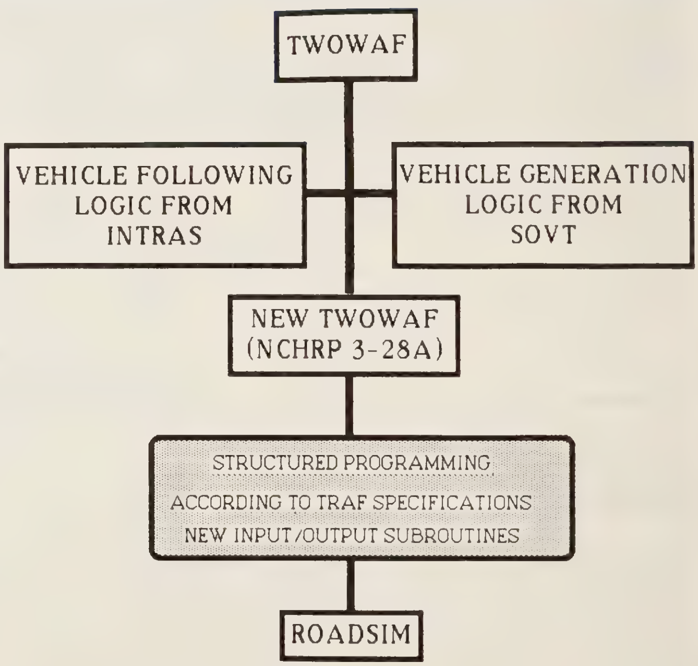


Figure 1.—Evolution of Roadsim.

[1] Italic numbers in parentheses identify references on page 104.

Table 1.—Measures of effectiveness generated by Roadsim

Measure	Units
Link-specific and direction-specific by vehicle category (automobiles, recreational vehicles, trucks):	
Travel	Vehicle-miles Vehicle-trips
Travel time (ideal, zero traffic, and actual)	Seconds/vehicle
Standard deviation of travel time	Seconds
Delay (geometric, traffic, and total)	Seconds/vehicle
Standard deviation of delay	Seconds
Mean speed, standard deviation of speed, speed extremes	Miles/hour
Passes attempted, completed, and aborted	Number, per mile per hour
Link-specific:	
Distribution of headways	Number in each range, percent of total, cumulative percent
Distribution of speeds	Number in each range, percent of total, cumulative percent
Distribution of platoon sizes	Number in each range, percent of total, cumulative percent

1 mile = 1.6 km

Data Collection and Methodology

Site

A 4.6-mi (7.4-km) section of U.S. Route 15 in Loudoun County near Leesburg, Virginia, was chosen as the site for the data collection based on the following geometric and operational factors:

- Significant truck volume.
- Rolling terrain.
- Minimal roadside activities.
- No major intersections.
- Standard roadway features (for example, signing, shoulder width, sight distance).
- Adequate two-way volume to cause significant platooning and passing opportunities.
- Attainable free-flow speed of 55 mi/h (89 km/h) or higher.

Road geometry data, obtained from construction plans supplied by the Virginia Department of Highways and Transportation (VDHT), included horizontal and vertical alignment (fig. 2). Passing zones and link lengths were measured in the field using a calibrated fifth-wheel. Information on sight distance was computed manually using the following fomula:

Maximum passing sight distance = Length of passing zone + 1500 ft (457 m)[2]

[2] 1,500 ft (457 m) is the minimum passing sight distance recommended by VDHT.

Volume and other traffic characteristics were measured in the field. Route 15 carries a significant truck volume because its weight limits are higher than those of adjacent roadways. Observed traffic volume during most of the daylight hours was between 300 and 400 vehicles per hour (both directions) with 25 percent trucks. These characteristics were desirable for the study because low volumes would create frequent passing opportunities and the high percentage of trucks would create platoons.

Procedure

Two-way traffic was observed on the selected roadway section, which was divided into four links based on the geometric similarities of the roadway within each link. Data were collected at each node (called stations) using color video recording equipment. The recording procedure was chosen because of the following:

- Data reliability is high.
- Staff requirements are low (1 person per node).
- Manual data logging in the field is not required.
- Vehicles can be tracked without recording license plate numbers.
- Data can be easily verified and corrected.
- A "permanent" record of the data is available for future studies.
- Equipment cost is low.

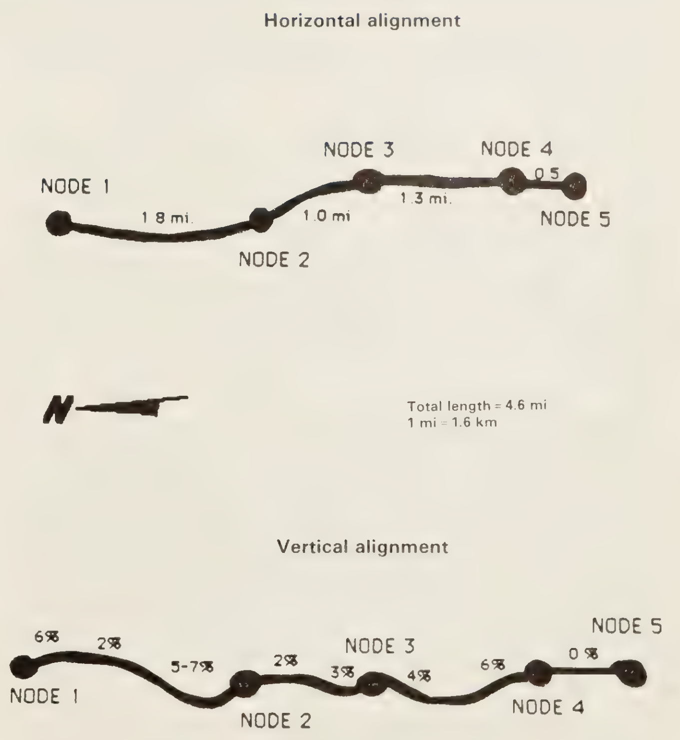


Figure 2.—Geometric characteristics.

Each node required a color video recorder, a camera, a power supply, a digital stopwatch, and a tripod. The average setup rental was $100 per day.

Both equipment and attendants were stationed in an unobtrusive location off the roadway. All cameras were positioned at the same angle to obtain similar views of each vehicle and facilitate vehicle tracking from node to node.

Data were collected for three 2-hour periods over 2 days. The video recorders were run in real time for the duration of each period. Digital watches were used to synchronize the cameras. Each camera attendant audibly recorded the time on the recorder every 15 minutes to provide a time reference during data reduction.

Data reduction

The videotaped traffic data were manually coded onto data forms. This task required approximately 48 person-hours to reduce each of the three 2-hour data collection periods for all five nodes.

The data obtained from the videotapes were: Arrival time (to the nearest second); vehicle type (automobile, recreational vehicle, single-unit truck, or combination truck); and vehicle description for tracking purposes (for example, color, make, model).

Although the selected roadway section contained no major intersections, there were several residential driveways and two minor intersections. Eight percent of the observed vehicles did not travel the entire roadway (entry at Node 1 and exit at Node 5) so were not included in the data analysis. Data, entered into an electronic spreadsheet for compilation, could be corrected and updated. After the data were input, they were checked for errors against the videotapes.

Vehicle data were stored separately for each direction of travel. Vehicles were numbered sequentially based on their arrival order at the entry node. The difference between a vehicle's arrival times at the individual nodes determined its travel time for each link. Speeds were obtained by dividing the length of each link by the travel times. The difference between the arrival time of a vehicle and the arrival time of the next vehicle was defined as the headway.

To complement the spreadsheet, programs were developed to compute platoon sizes and the number of completed passes. Platoon sizes were computed after determining whether a vehicle was a leader or a follower. By definition, a vehicle was said to be following another if its bumper-to-bumper headway was 6 seconds or less. This is the same headway used by Roadsim for this purpose. Each platoon consisted of a leader and its followers, if any.

The number of completed passes was determined by comparing the arrival sequence at individual nodes to the sequence at the previous node. Separate data were obtained from the spreadsheet for the four vehicle types for comparison with Roadsim. The data included mean speeds, headways, travel time, and number of completed passes. Some data had to be discarded after careful examination; for instance, artificial delays were created because of extremely slow vehicles (tractors) in the traffic stream, and the simulation is unable to represent this. Of the 6 hours of traffic data collected, two segments (one 30-minute and one 60-minute) were used in the comparative analysis.

Comparison of the two selected periods showed their traffic flow characteristics to be different. Therefore, they were compared separately with the simulation results. The factors considered were variations in traffic volume, vehicle mix, directional split, and platooning because these data have to be input into the model.

The reduced data included statistics for the overall roadway length as well as for individual links and vehicle types.[3]

The Simulation Procedure

Once the field data were reduced, Roadsim was coded and executed to obtain data for comparison.

Coding Roadsim

To replicate field conditions and simplify coding the model, the following assumptions were made:

- All vehicles fell into one of four possible vehicle types: Type 1—automobiles, vans, pickup trucks; type 2—recreational vehicles, horse trailers, tow trucks; type 3—single-unit trucks, schoolbuses, sanitation trucks; or type 4—combination trucks.
- Field maximum passing sight distance, required in the input stream, was determined by adding the length of the passing zones to 1,500 ft (457 m) (VDHT standard minimum), as previously explained.

Several default values contained in the model that were judged adequate and compatible with the field data were used to simplify coding. Table 2 lists the data required to run the model and the default values used in this study.

Coding the required input was tedious because interactive data input procedures were not available. The model is coded by entering data into specific fields of 80-column cards from a mainframe computer terminal. This required constant reference to the Users Guide (*1*) and several runs to correct misplaced data entries. The Users Guide, however, contains a complete error message section that proved to be very useful in completing this task.

Adjusting Roadsim

To simulate the observed field conditions, the model's control input initially had to be adjusted. These adjustments are not to be confused with model calibration, which refers to the fine tuning of empirical coefficients in

[3]These data, along with the spreadsheet templates (LOTUS 1-2-3, IBM compatible) and other programs (IBM BASIC) generated for this study, are available to other researchers through the authors.

Table 2. — Required data and values used

Variable	Comment/value
Free-flow speed	Variable (see text)
Standard deviation	9% of free-flow speed
Forward sight distance	1,500 ft
No passing regions	Variable (3/link max.)
Link length	Variable (9,999 ft max.)
Passing sight distance	Variable (3 regions/link max.)
Horizontal curve data	Variable (1 curve/link max.)
— length	
— radius	
— superelevation	
Vertical curve data	Variable (2 curves/link max.)
— length	
— grade	
Vehicle type data	Variable (16 types max.)
— automobiles:	
length	17 ft[1]
max. acceleration	5.5 mi/h/sec[1]
max. speed	75 mi/h[1]
max. entry speed	75 mi/h[1]
volume	Variable (vph/direction)
— recreational vehicles:	
length	25 ft[1]
max. acceleration	5.9 mi/h/sec[1]
max. speed	65 mi/h[1]
max. entry speed	65 mi/h[1]
volume	Variable (vph/direction)
— single-unit trucks:	
length	30 ft
weight/horsepower (power factor)	72 lb/horsepower
weight/frontal area (mass to frontal area factor)	158 lb/ft^2
elevation factor	1.0
drag factor	0.96
max. entry speed	65 mi/h
volume	Variable (vph/direction)
— combination trucks:	
length	65 ft
weight/horsepower (power factor)	266 lb/horsepower
weight/frontal area (mass to frontal area factor)	620 lb/ft^2
elevation factor	1.0
drag factor	0.96
max. entry speed	65 mi/h
— max. acceleration using partial horsepower	81 percent
— max. 0-grade speed using partial horsepower	90 percent[1]
— pass suppressing influence upstream of curve to right	10 sec[1]
— bias to add to trucks' desired speeds	−1.5 ft/s[1]
— bias to add to recreational vehicles' desired speeds	−2.2 ft/s[1]

[1] Indicates a default value applied by the model.

1 ft = 0.305 m 1 lb/horsepower = 0.608 kg/kw 1 mi/h/sec = 1.01 km/h/sec
1 mi/h = 1.6 km/h 1 lb/ft^2 = 4.88 kg/m^2

the actual computer code. The adjustments were made to the control data and not to the Roadsim code. Because of the random nature of traffic behavior, these adjustments were necessary to assure that the collected field data could be directly compared with the simulation data. Other adjustments made because of the input and output formats of the model include the following:

- Model links versus field links — Because the Roadsim input format allows the user to specify only one horizontal curve, two vertical curves, and three no-passing zones per link, it was necessary to divide the four field links into seven smaller model links.

- Buffer (dummy) links — The Roadsim output does not generate speed, headway, or platoon distribution data for exit links because of the "breakdown" of the car-following logic when vehicles are leaving the simulated road. To obtain the distribution data for these links (for each direction of travel), a buffer link was added to both ends of the simulated roadway section. Each link was 750 ft (229 m) long, had no horizontal or vertical curvature, and no passing was allowed. This was the shortest possible length that would not affect upstream conditions.

- Free-flow speed — Free-flow speed is the mean speed at which unimpeded passenger cars (platoon leaders) travel. Roadsim requires a free-flow speed to be specified for the entire roadway or by individual link. An overall free-flow speed was obtained from the field data by averaging the speed of all the platoon leaders. Using this speed in the model's input resulted in mean speeds that were significantly lower than those observed in the field. It was decided to adjust the free-flow speed inputs of individual links to "force" the model mean speeds to be comparable with the observed mean speeds. Therefore, mean speed was a controlled variable. The 30-minute data were used to determine this adjustment. The same adjustment then was used in the 60-minute data. The average bias per link ranged between 2 and 8 mi/h (3.2 and 12.9 km/h). An increase of 5 mi/h (8 km/h) in the overall free-flow speed appeared to give similar Roadsim and field results for the mean speed of the overall roadway section.

• Traffic volume—To compare the selected MOE's, a similar number of field vehicle trips and simulation vehicle trips was necessary. Directional hourly volumes for each of the four vehicle types are required input for the model. These volumes are used by Roadsim as an approximation to generate vehicle trips. The actual number of vehicle trips might differ from the input volumes because vehicles that had not traveled the entire roadway when simulation stopped are excluded from the vehicle trip tally and because of the randomness of the vehicle generation logic. To compensate for these, the input volumes were adjusted by trial-and-error on several Roadsim runs until the number of vehicle trips was similar to the number of trips observed in the field. Therefore, traffic volume was the second controlled variable.

Having the same mean speeds and the same traffic volumes constrains the modeled speed distributions to approximate those observed in the field.

Roadsim execution

Although the simulation runs would have the same volumes and mean speeds, certain variations were expected because of the randomness of the model's logic. These variations can be observed by changing the "random number seeds" of each run for the initial selection of various parameters, such as headway distributions and driver aggressiveness.

To account for these variations, 10 runs were executed using different random number seeds. An analysis of variance indicated that 10 mean speeds were not statistically different. Therefore, the results of the 10 runs were aggregated into a single data set for comparison with the field data.

Data reduction

In most instances, the output generated by Roadsim was in a format that was not directly compatible with the field data. Data manipulation was necessary to convert the simulation data to a comparable format. This inconvenience was a direct result of having to break down the field links into smaller model links and Roadsim's inability to aggregate individual link data into longer links. Enhancing the model to overcome these limiting factors is desirable because restricting the number of horizontal and vertical curves per link results in short links. The user typically is interested in MOE's over long sections of roadway, which might require a large number of links.

Data were manually taken from the Roadsim outputs and manipulated using the spreadsheet. After all the simulation data had been reduced to the same format as the field data, a statistical comparison was possible.

Statistical Comparison

Having reduced the field data and the simulation data to similar formats, the MOE's of interest could be compared and analyzed statistically. Because the simulation volume and the mean speed were controlled by varying the input volumes and the free-flow speed entry, an inferential statistical analysis was not appropriate. Instead, the primary MOE's of interest were percent trucks, percent of vehicles following, cumulative platoon distributions, average platoon size, and the number of completed passes. Tables 3 and 4 summarize the collected field data and the simulation data.

Traffic volume

Once traffic volumes were adjusted to obtain a similar number of vehicle trips, no difference was apparent.

Mean speed

The mean speed of all vehicles was an adjusted variable. To verify that the model was reasonably adjusted, a t-test at a 95-percent confidence interval was performed. As expected, no statistical difference between the field and Roadsim overall mean speeds was found.

Percent trucks

To verify the accuracy of the vehicle generation logic, the percentage of trucks observed in the field was compared with the Roadsim percentage of trucks. No difference was apparent.

Cumulative platoon distributions

The cumulative platoon distributions, a good indicator of the level of service of a given roadway, were considered the most important MOE. On two-lane roads, platooning has been proposed as a better method of quantifying level of service than the operating speed method currently used in the Highway Capacity Manual. (*4, 5*) Platooning characteristics can account for the effect of road geometry and traffic conditions on traffic performance.

The platoon distributions were statistically analyzed using the Kolmogorov-Smirnov test, which is useful in comparing cumulative distributions that may not be normally distributed. The overall comparison of the field and simulation distributions was found to have no significant difference at a 95-percent confidence interval. These cumulative distributions are presented graphically in figures 3-6.

Table 3.—Summary of the 30-minute data

MOE's	Field data Northbound	Field data Southbound	Roadsim data Northbound	Roadsim data Southbound
Volume (vehicles/hour)	150	152	143[1]	138[1]
Mean speed (mi/h)	54.8	55.4	54.5[1]	55.6[1]
Percent trucks	24	24	22	25
Percent following	44.5	38.5	44.5	38.7
Average platoon size	1.80	1.62	1.83	1.75
Completed passes	2	13	5	12

[1] After adjustment.

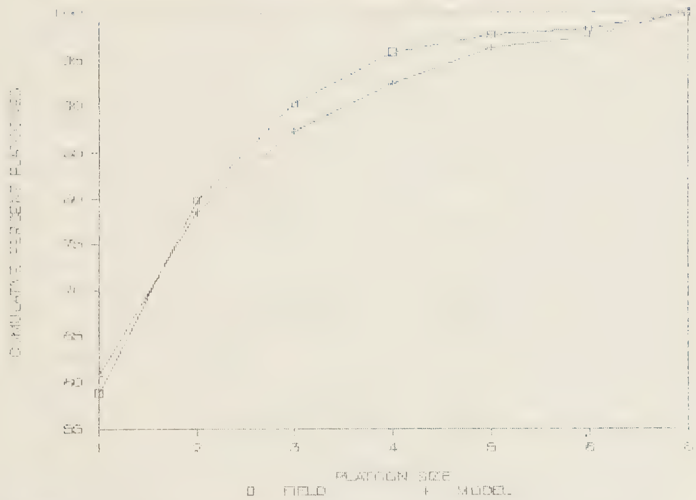


Figure 3.—Platoon distribution, northbound overall—30-minute data.

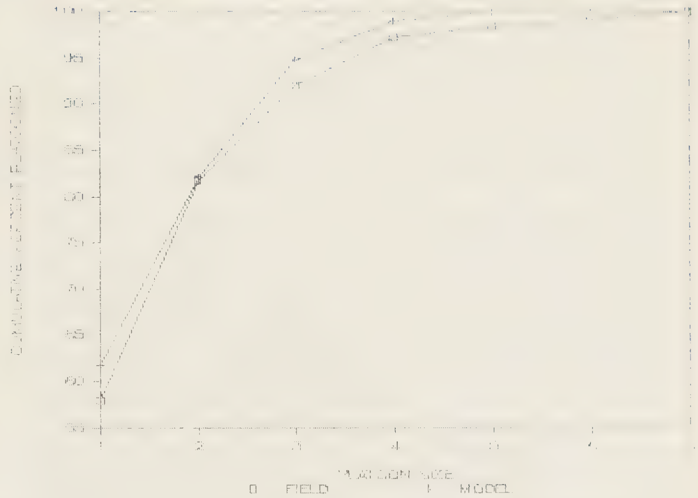


Figure 4.—Platoon distribution, southbound overall—30-minute data.

Table 4.—Summary of the 60-minute data

MOE's	Field data Northbound	Field data Southbound	Roadsim data Northbound	Roadsim data Southbound
Volume (vehicles/hour)	138	130	143[1]	136[1]
Mean speed (mi/h)	54.2	54.6	54.7[1]	54.8[1]
Percent trucks	23	25	21	26
Percent following	42.5	41.7	42.0	41.2
Average platoon size	1.74	1.72	1.74	1.71
Completed passes	10	19	10	26

[1] After adjustment.

Percent of vehicles following

The percent of vehicles following (vehicles impeded by the vehicle immediately in front) is another MOE that can be derived from the platoon distributions. The results obtained from this MOE for the overall section compared favorably.

Average platoon size

This comparison provided another measure of Roadsim's ability to replicate the vehicle "grouping" that occurred in the field. Comparison of the overall section results indicated a negligible difference between field observations and those obtained through simulation.

Completed passes

The comparison of the number of completed passes between the field data and the simulation data should be studied carefully. Passing is a traffic measure that reflects the degree of constraint on drivers. Passing opportunities are a function of the opposing traffic and the available sight distance. The lack of passing opportunities translates into an increase in traffic platooning and a decrease in operating speeds and, therefore, a reduced level of service.

When comparing the number of completed passes, it should be remembered that there are several factors that influence the decision of attempting to pass (for example,

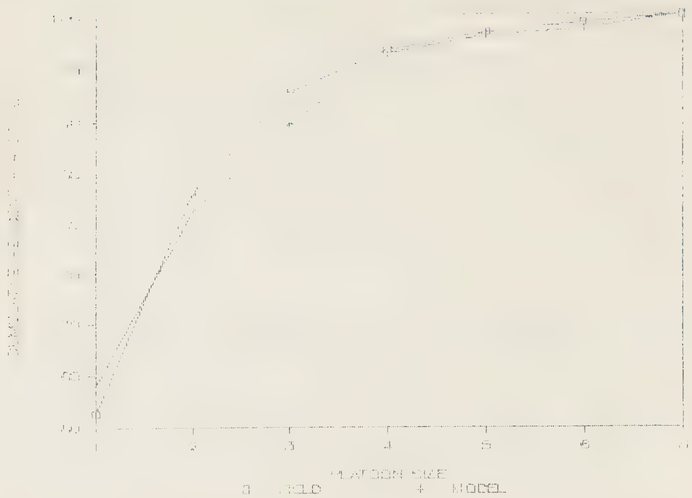


Figure 5.—Platoon distribution, northbound overall—60-minute data.

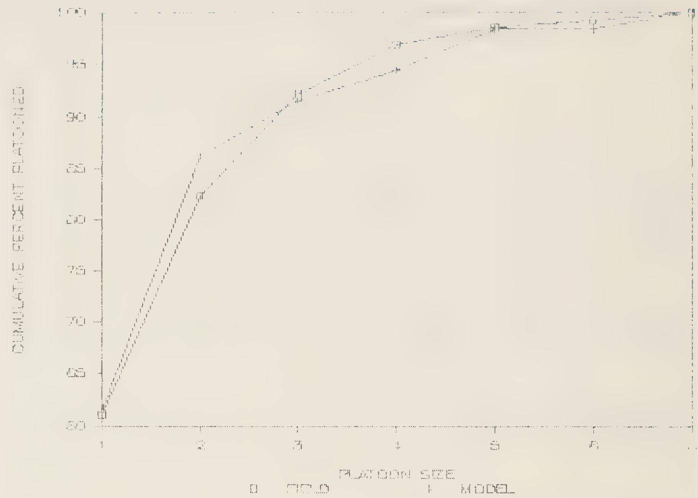


Figure 6.—Platoon distribution, southbound overall—60-minute data.

driver's aggressiveness and gap acceptance). These factors, although considered in the simulation, cannot be replicated without collecting data for long periods of time. The short data periods being compared in this study were judged insufficient to reach a definite conclusion on the validity of Roadsim's passing logic. Ideally, passes should be compared per unit of time (such as passes per hour) for which longer data periods are desirable. However, the number of completed passes simulated by Roadsim for the available data periods seemed to compare adequately to the field data for the overall roadway section.

Sensitivity Analysis

In addition to testing the ability of the Roadsim model to simulate field conditions, the sensitivity of the model was examined by varying several input parameters to study what effect the parameters have on the mean vehicle speed. The effect on other MOE's was not examined. The parameters studied were the horizontal alignment, the vertical alignment, and a combination of the two. This sensitivity analysis indicated which "ranges" of the studied parameters significantly affect the mean vehicle speed in Roadsim.

Horizontal and vertical alignments were selected because they are the limiting factors when dividing a roadway section into smaller simulation links. Excluding insignificant geometric features makes possible the use of longer links and simplifies coding the model.

A simple scenario, independent of the field data collection site, was chosen to test these parameters. The following analysis has not been compared with any field data and was undertaken to study the sensitivity within the model.

Horizontal alignment

Ten simulation runs were executed varying the radius of a curve joining two tangents. The following parameters were held constant during these runs:

- Length of tangents (3,400 ft [1 036 m] each).
- Delta of the curve (40 degrees).
- No vertical curvature (0-percent grade).
- Passing allowed on tangents; no passing on curve.
- Free-flow speed (60 mi/h [97 km/h]).
- Volume (300 vph, 50/50 directional split).
- Vehicle mix (20 percent trucks, 0 percent recreational vehicles).

The radius of curvature was varied from 500 ft (152 m) to 3,000 ft (914 m) in increments of 500 ft (152 m). The length of curve was computed and the superelevation rates were obtained from the American Association of State Highway and Transportation Officials (AASHTO) "Green Book." (*6*)

Roadsim's results indicated that the effect of curves with a radius greater than 1,500 ft (457 m) was negligible for both automobiles and trucks. This suggests that horizontal curves with radii larger than 1,500 ft (457 m) will not affect the mean vehicle speeds in Roadsim (figs. 7 and 8).

Vertical alignment

Vertical alignment was studied to examine the effect of both the length and magnitude of positive grades. Forty runs were made to study the various combinations. The same parameters listed above remained constant with the addition of the horizontal curvature (tangent).

The typical truck used had a 266 lb per net horsepower ratio (162 kg/kw) power factor and 620 lb/ft^2 (3.03 Mg/m^2) mass to frontal area factor.

Results suggested that mean speeds are not significantly affected by grades of 2 percent or less in Roadsim for

Figure 7.—Sensitivity analysis, horizontal alignment—right.

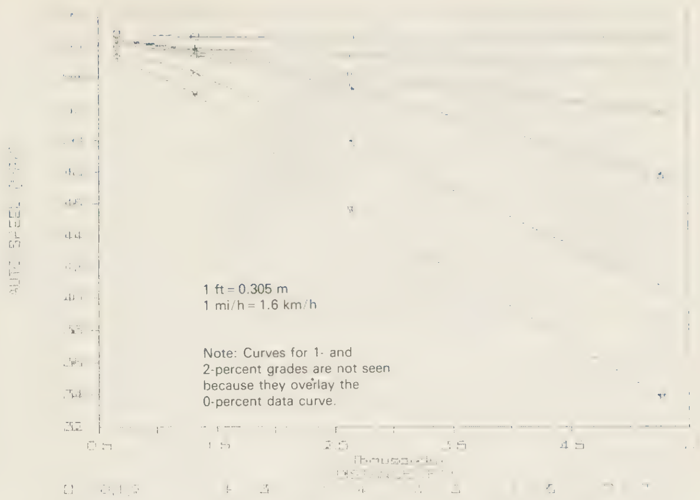


Figure 9.—Sensitivity analysis, vertical alignment—automobiles.

both automobiles and trucks. At grades of 3 percent and above, the reduction in speeds is significant primarily because of the substantial reduction in truck speeds on uphill grades. The relatively high percentage (20 percent) of trucks used had a major effect on the overall speeds (figs. 9-11).

Combined horizontal and vertical alignment

Next, the combined effect of horizontal and vertical alignment was studied. Having found that grades over 3 percent and curves with a radius of less than 1,500 ft (457 m) substantially reduced speeds, it was decided not to consider values beyond these thresholds. The "worst case" of the remaining combinations was selected—a horizontal curve with a 1,500-ft (457-m) radius combined with an uphill grade of 2 percent. Results showed no apparent difference between the mean speeds on a level, tangent section and the worst case section.

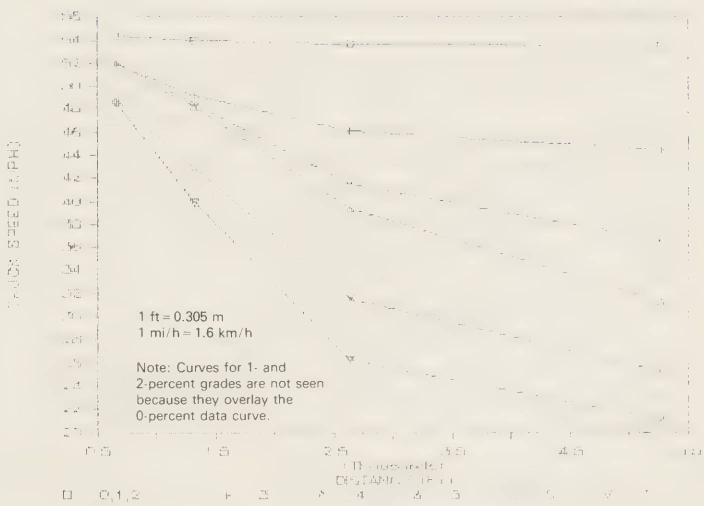


Figure 10.—Sensitivity analysis, vertical alignment—trucks.

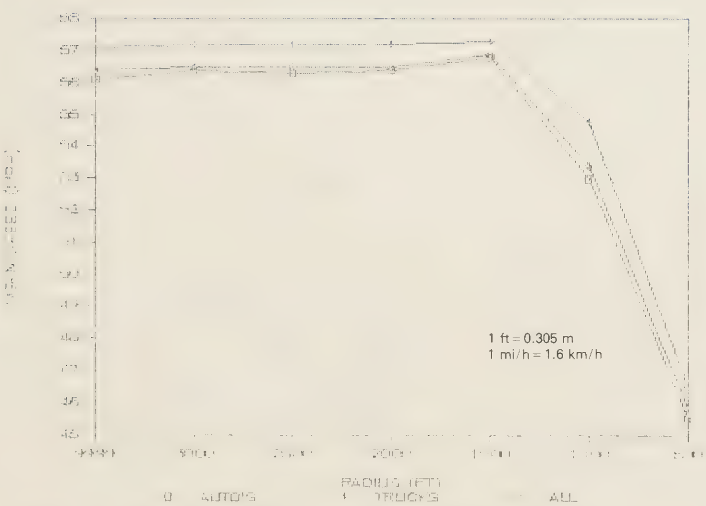


Figure 8.—Sensitivity analysis, horizontal alignment—left.

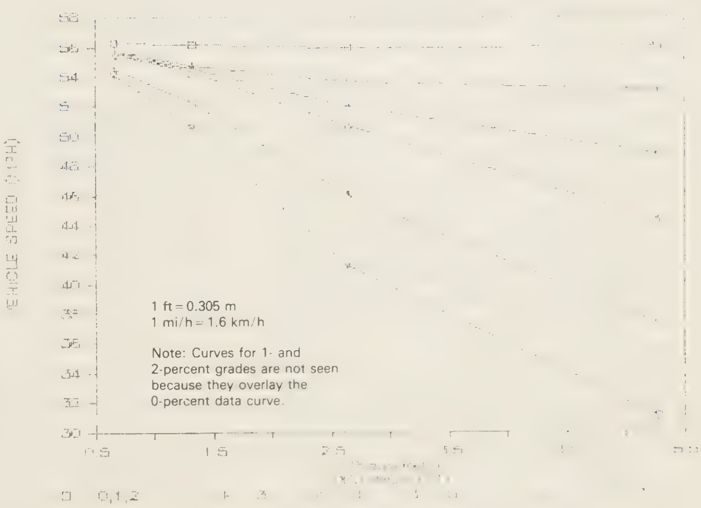


Figure 11.—Sensitivity analysis, vertical alignment—automobiles and trucks.

Conclusions

Based on this comparative evaluation of Roadsim under specific geometric and traffic conditions and the performed sensitivity analysis presented in this article, the following conclusions can be drawn:

- Roadsim appears to work satisfactorily under the geometric and traffic conditions studied.
- The free-flow speed input appears to be biased. After adjusting this input upward, most MOE's compared well with the collected field data for the overall section of road. This bias should be further studied and calibrated.
- Horizontal curves with radii greater than 1,500 ft (457 m) do not appear to significantly affect the overall mean speed of the traffic stream.
- Vertical curves with positive grades of 2 percent or less do not appear to significantly affect the overall mean speed of the traffic stream.
- In its present form, Roadsim can evaluate changes in passing zones, changes in alignment, the effect of volume increases, and the effect of variations in traffic composition.

Future Evaluations and Enhancements

The study described in this article portrays an optimistic future for Roadsim; however, its full acceptance as a totally valid model is premature. Additional similar studies are necessary to verify the model's performance under a range of traffic and geometric conditions. For example, the performance of Roadsim must be examined in comparison with different real-world traffic bi-directional volumes such as 500, 750, 1,000, and 1,500 vehicles per hour for various terrains (flat, rolling, and mountainous). Further examinations of the free-flow speed input also are needed.

If Roadsim consistently yields results similar to those obtained in the field, the model could be made available for widespread use. However, if it is found that changes and improvements not mentioned in this article are needed, they could be made when programming upgrades for passing lanes, climbing lanes, and rural intersections are added.

To further assess the functional ability of Roadsim, FHWA would like to receive research reports, results, and recommendations from other users. All comments should be directed to:

Mr. Juan Morales
Federal Highway Administration, HSR-30
6300 Georgetown Pike
McLean, Virginia 22101-2296

REFERENCES

(*1*) "TRAF Users Guide," Report No. FHWA-IP-82-18, *Federal Highway Administration,* Washington, DC, June 1983.

(*2*) A.D. St. John and D.R. Kobett, "Grade Effects on Traffic Flow Stability and Capacity," NCHRP Report No. 185, *National Cooperative Highway Research Program,* Washington, DC, 1978.

(*3*) "Final Report, Project 3-28," *National Cooperative Highway Research Program,* Washington, DC, 1983.

(*4*) C.J. Hoban, "Toward a Review of the Concept of Level of Service for Two-Lane Rural Roads," Technical Note No. 1, *Australian Road Research,* September 1983.

(*5*) "Highway Capacity Manual," Special Report No. 87, *Highway Research Board,* Washington, DC, 1965.

(*6*) "A Policy on Geometric Design of Highways and Streets," *American Association of State Highway and Transportation Officials,* Washington, DC, 1984.

Juan M. Morales is a highway research engineer in the Traffic Safety Research Division, Office of Safety and Traffic Operations R&D, Federal Highway Administration. Since 1983 he has been working in FCP Project IM, "Rural Two-Lane Highways," and FCP Project 1A, "Traffic and Safety Control Devices."

Jeffrey F. Paniati is a highway research engineer in the Traffic Safety Research Division, Office of Safety and Traffic Operations R&D, FHWA. He assisted in the research study described in this article as a special assignment as part of the FHWA Highway Engineering Training Program from which he graduated in 1985. Mr. Paniati currently is working in FCP Project 1P, "Night Visibility."

Recent Research Reports You Should Know About

The following are brief descriptions of selected reports recently published by the Federal Highway Administration, Offices of Research, Development, and Technology (RD&T). The Office of Engineering and Highway Operations Research and Development (R&D) includes the Structures Division, Pavements Division, and Materials Division. The Office of Safety and Traffic Operations R&D includes the Traffic Systems Division, Safety Design Division, and Traffic Safety Research Division. The reports are available from the source noted at the end of each description.

Requests for items available from the RD&T Report Center should be addressed to:

Federal Highway Administration
RD&T Report Center, HRD-11
6300 Georgetown Pike
McLean, VA 22101-2296
Telephone: 703-285-2144

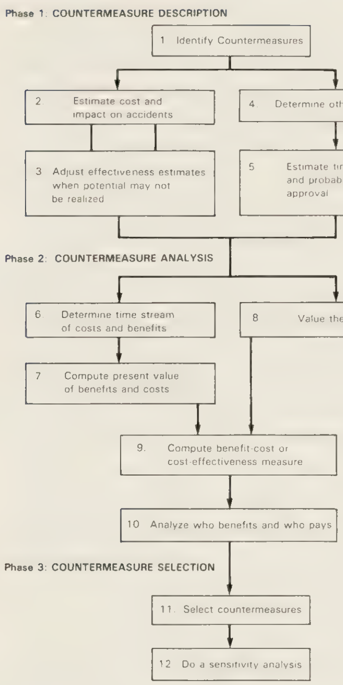
When ordering from the National Technical Information Service (NTIS), use PB number and/or the report number with the report title and address requests to:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Development of a Value Criteria Methodology for Assessing Highway Systems Cost-Effectiveness, Report No. FHWA/RD-85/086

by Traffic Safety Research Division

A resource allocation procedure was developed for selecting the most cost-effective set of countermeasures to address any given highway safety problem. In phase 1 of the procedure the possible countermeasures are



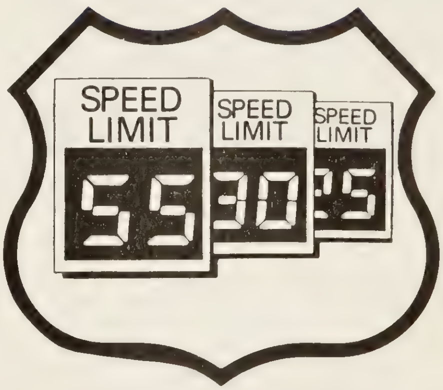
identified; their cost and potential impact on accidents are estimated; the effectiveness estimates are adjusted to reflect the loss in impact that is likely from the failure to properly install, use, and maintain each countermeasure; other nonsafety impacts of each countermeasure are identified; and the timing, cost, and probability of gaining approval for each countermeasure are estimated.

In phase 2 the present value of the benefits and costs for each countermeasure is determined, values are placed on the nonmonetary benefits, a benefit/cost or cost-effectiveness measure is computed for each countermeasure, and any groups that disproportionately benefit from or pay for each countermeasure are identified.

In phase 3 a methodology is applied for selecting the most cost-effective set of countermeasures to implement and for analyzing how sensitive the set is to variation in parameters like discount rates and accident costs that were used in the value procedure.

The report may be purchased from NTIS (PB No. 85 219236).

Methods for Reducing Large Speed Differences in Traffic Streams, Vol. I, Inventory of Methods, Report No. FHWA/RD-85/103, and Vol. II, Final Report, Report No. FHWA/RD-85/104



by Traffic Safety Research Division

Methods for reducing large speed differences could significantly improve safety on high-speed highways. Volume I provides an inventory of methods that may reduce conflicts created by large differences in travel speeds and increase voluntary compliance with posted speed limits. The inventory describes highway and traffic engineering methods that have been used in the past such as pavement delineation, minimum and maximum speed limits, dynamic signs warning of excessive speed, and variable speed signing based on traffic and/or environmental conditions. Vehicular control methods included increased accelerator pedal resistance at higher speeds (deaccelerator) and vehicle headway warning devices (proximity radar). Other methods, such as police enforcement and driver training, are included. Background, application, and effectiveness information for each method is presented.

Volume II discusses the feasibility of the methods having potential. Estimates indicate that posting realistic maximum and minimum speed limits, based on the speed the majority of motorists consider safe and reasonable for existing conditions, could reduce rural Interstate system accidents 5 percent and injuries 11 percent. This can be implemented at low cost. A variable speed limit system, which assigns speed limits based on real-time traffic and environmental conditions, is suggested for further research and evaluation. Two vehicle control systems, the deaccelerator and proximity/radar, were found to have potential for reducing speed differences and increasing speed limit compliance. Further research and development is suggested.

The reports may be purchased from NTIS (PB Nos. 85 249761 and 85 249779).

Effects of Shoulder Textured Treatments on Safety, Report No. FHWA/RD-85/027

by Traffic Safety Research Division

A study on the use of textured shoulders as a run-off-the-road accident countermeasure reported that shoulder textured treatments can have a benefit/cost ratio of 50/1. Twenty-four textured shoulder sites in 11 States were analyzed along with their corresponding control sections. The least squares regression analysis of accident rates before texturing compared with accident rates after texturing at the test sites showed a significant 9 percent reduction. Also, an analysis of variance of the sound and vibration data indicated a significant difference among treatment types and a significant increase in both sound and vibration levels because of the textured treatments. The continuous bituminous indented strip and the bituminous surface treatment gave the most effective stimuli to alert drivers crossing the shoulder.

Limited copies of the report are available from the RD&T Report Center.

Cost-Effectiveness Techniques for Highway Safety: Resource Allocation, Executive Summary, Report No. FHWA/RD-84/010, and Final Report, Report No. FHWA/RD-84/011

by Traffic Safety Research Division

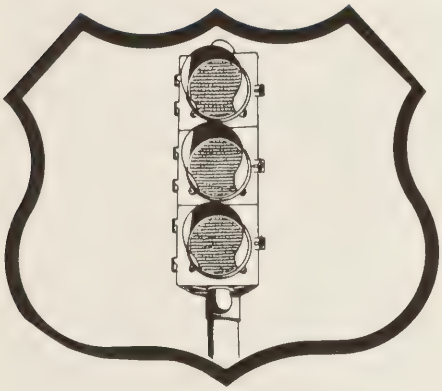
Budget constraints, political input, public concern, and agency emphasis areas are among the factors that serve as a basic framework for the resource allocation process when prioritizing a group of highway safety projects. With dwindling resources, it is particularly important to select the right projects to maximize safety benefits.

Three cost-effectiveness techniques—dynamic programming, integer programming, and incremental benefit/cost—were tested using data from five States. As a key input, accident cost estimates for each State were examined and updated using traffic accident and roadway data. Computer programs for the three techniques were documented, and a self-instructional text was written on how to apply the evaluation techniques.

These reports document the testing of the three cost-effectiveness techniques and compare them with the simple benefit/cost procedures. Each resulting prioritized listing of highway safety projects provided over 35 percent more benefits for the same cost than those obtained using simple benefit/cost ranking.

The reports may be purchased from NTIS (PB Nos. 85 219186 and 85 219194).

Catalog of Functions for Computer-Based Traffic Signal Systems, Report No. FHWA/RD-85/078



by Traffic Systems Division

This report catalogs functions available in computer-controlled traffic signal systems. The functions include a complete selection of both hardware and software features. Each function is described and its advantages and disadvantages are summarized. Capital cost, maintenance, and traffic performance are considered. The report is organized around a "basic" signal system with options that can be added according to specific situations and budgets.

Limited copies of the report are available from the RD&T Report Center.

SPEL: Special Product Evaluation List, Report No. FHWA/RD-85/082

by Materials Division

This report lists special products evaluated by State highway and transportation departments to provide information on who tested the products or materials. Results are presented on approximately 6,500 evaluations contributed by 35 States and FHWA.

AASHTO-FHWA

SPEL

Special Product Evaluation List

The SPEL is a continuing joint effort of FHWA and the AASHTO Subcommittee on Materials. The initial report was published in 1974, with updates in 1975, 1977, 1979, and 1983. Plans are being implemented to put the file online to allow States to extract information directly.

The report may be purchased from NTIS.

Criteria for Designing Lightweight Concrete Bridges, Report No. FHWA/RD-85/045

by Structures Division

This report presents the state-of-the-art in the use of lightweight concrete in the design, construction, and maintenance of bridges. Included is a review of the history of the development of lightweight concrete, its properties and limitations, and its production. Twelve case studies are evaluated from visits and inspections, and policies and practices on the use of lightweight concrete are reported. Results are presented from analytical studies conducted to develop data on material economics for lightweight and normal-weight concretes.

Conclusions, recommendations for future actions, references, and a bibliography are included. Guide specifications and field control procedures also are provided.

Limited copies of the report are available from the RD&T Report Center.

Implementation/User Items "how-to-do-it"

The following are brief descriptions of selected items that have been completed recently by State and Federal highway units in cooperation with the Office of Implementation, Offices of Research, Development, and Technology (RD&T), Federal Highway Administration. Some items by others are included when the items are of special interest to highway agencies.

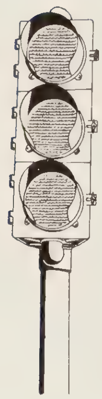
Requests for items available from the RD&T Report Center should be addressed to:

Federal Highway Administration
RD&T Report Center, HRD-11
6300 Georgetown Pike
McLean, VA 22101-2296
Telephone: 703-285-2144

Traffic Signal Brightness: An Examination of Nighttime Dimming, Report No. FHWA-TS-85-213

by Office of Implementation

This report summarizes the findings of a study to determine the traffic operations, safety, and economic impacts of dimming traffic signals at night. Laboratory and controlled field experiments measured how quickly and accurately drivers (including color vision-weak and elderly) responded to 8-in (203-mm) and 12-in (305-mm) red, yellow, and green traffic signals dimmed to as low as 10 percent of Institute of Transportation Engineers (ITE) recommended intensity levels. Observational field studies at six in-service intersections confirmed that drivers behaved safely and efficiently when signals were dimmed to as low as 30 percent of ITE recommendations. Economic analysis showed that dimming can save about 10 percent in energy and repay the initial investment within 3 years. Guidelines for when and where to dim signals were developed.

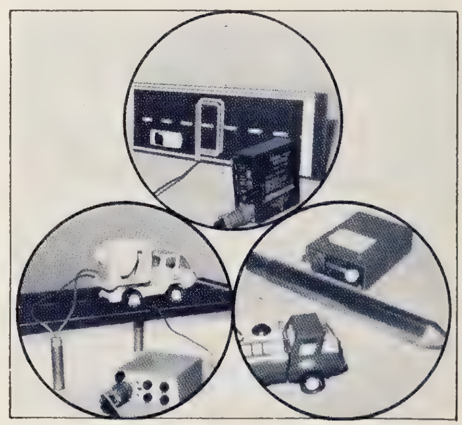


Limited copies of the report are available from the RD&T Report Center.

Traffic Detector Handbook, Report No. FHWA-IP-85-1, Handbook; Report No. FHWA-IP-85-2, Field Manual; and Report No. FHWA-IP-85-3, Technical Appendix

by Office of Implementation

There has been an increasing awareness on the part of the Federal Highway Administration that practicing engineers are not taking advantage of the research and experience gained in the use of traffic detectors. Proper design, installation, operation, and maintenance of detectors can significantly improve traffic flow and reduce fuel consumption, vehicle emissions, and operating costs.



These reports consolidate information on the best current practices for the design, installation, operation, and maintenance of three kinds of traffic detectors—the widely used inductive loop detector, the magnetometer, and the magnetic detector. Included are answers to some previous misconceptions about detector theory concerning inductive loops. Also, innovative installation techniques are presented for all three kinds of detectors.

Limited copies of the reports are available from the RD&T Report Center.

Tunnel Lighting Design Procedures, Report No. FHWA-IP-85-9

by Office of Implementation

Bottlenecks in traffic commonly occur at tunnel entrances because the width of the road changes and the road shoulders are discontinued. These restrictions can cause congestion and accidents. An adequate lighting system is required to reveal the location of tunnel walls and curbings.

To facilitate the design of a lighting system that allows for the transition from a brightly illuminated roadway during the day to the darker tunnel with a much lower luminance level, five transition zones are considered. The approach zone, the threshold zone, the transition zone, the interior

zone, and the exit zone each have specific lighting levels depending on the tunnel wall materials, tunnel dimensions, wall color, portal landscaping, and traffic characteristics. Luminance requirements can vary from 100 fL to 250 fL depending on the tunnel orientation with the sun.

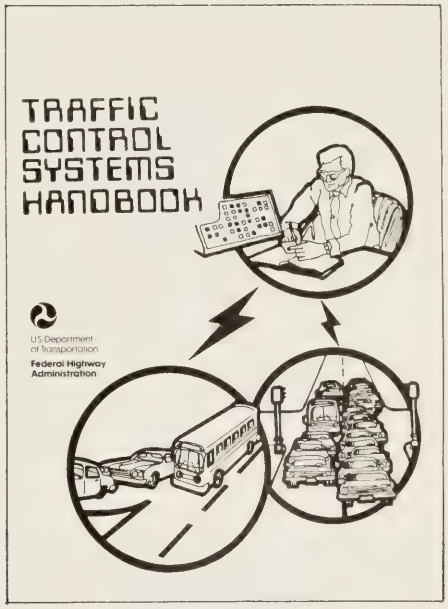
Limited copies of the report are available from the RD&T Report Center.

Traffic Control Systems Handbook Revised Edition 1985, Report No. FHWA-IP-85-11, and Executive Summary, Report No. FHWA-IP-85-12

by Office of Implementation

Within the broad spectrum of transportation systems management, traffic control systems play a key role in the efficient operation of urban streets and freeways. In the mid-1970's, FHWA published the original "Traffic Control Systems Handbook" as a compendium of available technology and practice. In the intervening years, control systems technology and hardware advances, permitted by the application of the microprocessor, have contributed to widespread use of such systems.

This revision retains much of the valuable material and basic scope of the original Handbook, but updates discussions of concepts and hardware to reflect the state-of-the-art. Further, it is focused toward the more experienced signal and control systems designer and user, with discussions of actual experience and pitfalls. Topics addressed in the Handbook include: Available systems technology, control concepts (urban streets and freeways), detectors, local controllers, system masters, driver information systems, and system management.



Limited copies of the Handbook and Executive Summary are available from the RD&T Report Center.

New Research in Progress

The following new research studies reported by FHWA's Offices of Research, Development, and Technology are sponsored in whole or in part with Federal highway funds. For further details on a particular study, please note the kind of study at the end of each description and contact the following: Staff and administrative contract research—*Public Roads* magazine; Highway Planning and Research (HP&R)—performing State highway or transportation department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, NW., Washington, DC 20418.

FCP Category 1—Highway Design and Operation for Safety

FCP Project 1K: Accident and Countermeasure Analysis

Title: Development of Alternative Accident Costs. (FCP No. 31K4042)
Objective: Derive traffic accident costs based on an improved theoretical framework. Survey the willingness of individuals to pay to reduce the risks of traffic accidents.
Performing Organization: The Urban Institute, Washington, DC 20037
Expected Completion Date: January 1988
Estimated Cost: $200,000 (FHWA Administrative Contract)

FCP Project 1N: Safety of Non-Motorists

Title: Measuring Pedestrian Volumes and Conflicts. (FCP No. 31N1082)
Objective: Develop a method of counting pedestrians for a short period of time and extrapolating these counts to longer time periods. Investigate conflicts between pedestrians and motor vehicles and other criteria as substitute measures of pedestrian accidents. Use these predictions to identify those locations most in need of pedestrian safety improvements.
Performing Organization: Analysis Group, Inc., Washington, DC 20010
Expected Completion Date: December 1987
Estimated Cost: $250,000 (FHWA Administrative Contract)

FCP Project 1T: Roadside Safety Hardware

Title: Force Deflection Characteristics of Guardrail Posts. (FCP No. 31T2382)
Objective: Provide adequate foundation support for strong posts and weak posts, including large soil plates, wider flange posts, anchor ties, longer posts, and decreased post spacing. Identify the most economical solutions in weak and strong soils. Develop soil/post analytical models. Conduct pendulum tests of guardrail posts and perform a few full-scale guardrail tests to verify the results.
Performing Organization: ENSCO, Inc., Springfield, VA 22151
Expected Completion Date: August 1987
Estimated Cost: $176,900 (FHWA Administrative Contract)

FCP Project 1U: Large Truck Safety

Title: Effectiveness of Truck Roadway or Lane Restrictions. (FCP No. 31U2122)
Objective: Determine jurisdictions and roadways where all trucks or a specific class of trucks is restricted in some manner (for example, restricted to a specific lane, prohibited from a specific lane or roadway, prohibited from operating during certain hours, or separate facilities). Examine the purpose, effectiveness, and the compliance levels of the restrictions and the traffic volumes (both total and truck) under which the restrictions are justified.
Performing Organization: Transportation Research Corporation, Haymarket, VA 22069
Expected Completion Date: August 1987
Estimated Cost: $193,994 (FHWA Administrative Contract)

Title: Calibration of Weigh-in-Motion (WIM) Systems. (FCP No. 31U4132)
Objective: Use controlled laboratory tests and field tests at actual installations to determine the degree of accuracy expected from a WIM installation on an unmodified section of pavement and from an installation on a section of pavement that has been resurfaced on the approach to the WIM. Determine the length of resurfacing required to attenuate the bouncing effect of most vehicles.
Performing Organization: Sparta, Inc., Laguna Hills, CA 92653
Expected Completion Date: October 1986
Estimated Cost: $175,708 (FHWA Administrative Contract)

FCP Category 2—Traffic Control and Management

FCP Project 2P: Urban Freeway Management

Title: Freeway Simulation Model Enhancement and Integration. (FCP No. 32P1042)
Objective: Reprogram the freeway portion of the INTRAS traffic simulation model according to the format of the TRAF simulation system and integrate it into TRAF. Enhance the model to include a more adequate representation of some freeway bottleneck situations (for example, ramp merging) and a more efficient sequence of vehicle processing. Incorporate improvements in the FREFLO model (for example, modeling of off-ramp backups).
Performing Organization: JFT Associates, Culver City, CA 90230
Expected Completion Date: December 1988
Estimated Cost: $210,000 (FHWA Administrative Contract)

FCP Category 3—Highway Operations

FCP Project 3C: Calcium Magnesium Acetate as an Alternate Deicer

Title: Ice Melting Characteristics Versus Water of Crystallization of Calcium Magnesium Acetate (CMA) Solids. (FCP No. 33C2032)
Objective: Develop recommendations for the optimum crystalline properties of CMA solids relative to ice melting. Obtain solid CMA materials from CMA solutions using various evaporation and other drying techniques. Determine the percent water of crystallization, user characteristics, storage capabilities, and various deicing properties including rate of dissolution, solubility, heat of solution, crystalline strength, shape, hygroscopicity, and cohesiveness.
Performing Organization: Energy and Mineral Research Company, Exton, PA 19341
Expected Completion Date: June 1986
Estimated Cost: $114,984 (FHWA Administrative Contract)

FCP Category 4—Pavement Design, Construction, and Management

FCP Project 4A: Pavement Management Strategies

Title: Resilient Properties of Arkansas Soils. (FCP No. 44A1433)
Objective: Develop the resilient modulus test parameter for Arkansas so that the revised AASHTO design can be used. Examine the effects of moisture content, density, stress state, and freeze-thaw cycles. Establish recommendations for lab testing procedures. Develop a method for estimating the resilient modulus with falling weight deflectometer data. Develop correlations between resilient modulus and other more convenient soil properties.
Performing Organization: University of Arkansas, Fayetteville, AR 72701
Funding Agency: Arkansas State Highway and Transportation Department
Expected Completion Date: June 1988
Estimated Cost: $105,314 (HP&R)

Title: Truck Size, Weight, and Tire Pressure on Pavement Deterioration. (FCP No. 44A1443)
Objective: Compare and assess three scenarios—first, characterized by traffic operating within current legal weight limits and pre-1973 tire pressures; second, the existing condition, characterized by traffic estimated from current weight-tire pressure survey data; and third, characterized by vehicle configurations designed to increase payloads but to reduce damage.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: July 1987
Estimated Cost: $110,000 (HP&R)

FCP Project 4B: Design and Rehabilitation of Rigid Pavements

Title: Development of Subbase Friction Information for Use in Design of Concrete Pavement. (FCP No. 44B1312)
Objective: Construct test slabs in the laboratory and at construction sites on the most important subbase types. Take measurements to develop force-movement curves for the various types of subbase.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1987
Estimated Cost: $80,000 (HP&R)

FCP Project 4C: Design and Rehabilitation of Flexible Pavements

Title: Implementation of a Dynamic Deflection System for Rigid and Composite Pavements in Ohio. (FCP No. 44C1193)
Objective: Purchase a falling weight deflectometer. Develop software and hardware to allow data transfer from an HP computer to an IBM PC computer. Review available pavement evaluation and design procedures for use in Ohio. Compare results, and implement the new equipment into Ohio's pavement evaluation program.
Performing Organization: Ohio Department of Transportation, Columbus, OH 43215
Expected Completion Date: May 1987
Estimated Cost: $222,505 (HP&R)

Title: Development of an Overlay Design Procedure for Pavements in Indiana. (FCP No. 44C1202)
Objective: Develop an easily implemental overlay design technique, and determine the input required for this technique to predict the optimum overlay design thickness. Emphasize the use of nondestructive testing devices for ascertaining pavement deflection and determining the limiting pavement deflection that may be used in a design for a given set of conditions.
Performing Organization: Purdue University, West Lafayette, IN 47907
Funding Agency: Indiana Department of Highways
Expected Completion Date: January 1988
Estimated Cost: $79,900 (HP&R)

Title: Recycling and Rehabilitating Low-Volume Roads—Phase II. (FCP No. 44C3074)
Objective: Investigate the use of cold, inplace recycling using emulsified asphalt and cement-fly ash binders on field sites in Bradford County, Pennsylvania.
Performing Organization: Pennsylvania Department of Transportation, Harrisburg, PA 17120
Expected Completion Date: November 1986
Estimated Cost: $543,000 (HP&R)

Title: Field Evaluation to Obtain Density in Asphalt Mixtures. (FCP No. 44C6304)
Objective: Evaluate current practices associated with the compaction of asphalt mixtures in Texas, and establish procedures and guidelines to assure satisfactory compaction and density on future projects.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: September 1987
Estimated Cost: $260,000 (HP&R)

FCP Category 5—Structural Design and Hydraulics

FCP Project 5H: Highway Drainage and Flood Protection

Title: Development and Testing of an Interactive Real-Time Computer-Based System for Statewide Hydrologic Analysis—Phase II. (FCP No. 45H3812)
Objective: Develop and implement the hardware, software, and data bases derived from remote sensing technology that will allow the State highway engineers to conduct real-time hydrologic modeling on a Statewide basis.

☆U.S. Government Printing Office: 1985—491-825/40001

Performing Organization: University of Maryland, College Park, MD 20742
Funding Agency: Maryland State Highway Administration
Expected Completion Date: November 1987
Estimated Cost: $234,700 (HP&R)

FCP Project 5K: Bridge Rehabilitation Technology

Title: Behavior and Design of Steel-to-Steel Bonded Connections on Bridges. (FCP No. 45K3252)
Objective: Develop preliminary material specifications, fabrication procedures, and procedures for design of bonded connections.
Performing Organization: Case Western Reserve University, Cleveland, OH 44106
Funding Agency: Ohio Department of Transportation
Expected Completion Date: June 1987
Estimated Cost: $97,000 (HP&R)

Title: Structural Concrete Overlays in Bridge Deck Rehabilitation. (FCP No. 45K3262)
Objective: Conduct theoretical and experimental investigations to develop design recommendations and guidelines for structural concrete overlays for bridge rehabilitation.
Performing Organization: University of California—San Diego, LaJolla, CA 92093
Funding Agency: California Department of Transportation
Expected Completion Date: June 1988
Estimated Cost: $110,000 (HP&R)

FCP Project 5Q: Bridge Maintenance and Corrosion Protection

Title: Development of Performance Tests, Criteria, and Specifications for Coatings. (FCP No. 35Q1182)
Objective: Prepare standard performance-type specification clauses to be used for procuring new, high-performance coating systems such as urethanes, latexes, and zinc-rich and modified vinyls. Evaluate previous studies, and develop performance tests to obtain performance or composition-performance specifications for these coatings including quality assurance test methods.
Performing Organization: U.S. Department of Commerce, Gaithersburg, MD 20899
Expected Completion Date: July 1988
Estimated Cost: $200,000 (FHWA Administrative Contract)

FCP Category 9—R&D Management and Coordination

FCP Project 9B: New Concepts Development and Systems Characterization

Title: Feasibility of Integrating Urban Traffic Operations Techniques. (FCP No. 39B2342)
Objective: Determine the feasibility and implementation potential of an integrated traffic management system for large urban areas. Consider the following kinds of traffic control for implementation: Signal control, reversible lanes, bus priority, alternate routing, and parking advisory.
Performing Organization: Farradyne Systems Inc., Silver Spring, MD 20904
Expected Completion Date: November 1986
Estimated Cost: $115,096 (FHWA Administrative Contract)

FCP Category 0—Other New Studies

Title: Selection and Use of Fly Ash for Highway Concrete—Phase II. (FCP No. 40M3962)
Objective: Study details of the performance and behavior of concrete produced with fly ashes for use in highway concrete in Indiana. Obtain a maximum of objective scientific information about the general behavior and influence of fly ash in concrete. Record the behavior and determine the reasons and mechanics behind the effects produced. Report the findings and results to provide the maximum possible use to the Indiana Department of Highways construction engineers involved in specifying the placement of fly ash concrete in highways and associated structures.
Performing Organization: Purdue University, West Lafayette, IN 47907
Funding Agency: Indiana Department of Highways
Expected Completion Date: December 1987
Estimated Cost: $115,800 (HP&R)

Title: Superplasticized White Concrete Curbing. (FCP No. 40P5014)
Objective: Assess the effect of superplasticizers on the properties of typical New Jersey white barrier curb concrete. Evaluate compressive strength, freeze-thaw resistance, workability, and air content (with void spacing and specific surface).
Performing Organization: New Jersey Department of Transportation, Trenton, NJ 08625
Expected Completion Date: September 1988
Estimated Cost: $128,000 (HP&R)

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