A JOURNAL OF HIGHWAY RESEARCH AND DEVELOPMENT
U.S. Department of Transportation
Federal Highway Administration

public roads

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arch 1980 Vol. 43, No. 4

public roads

A JOURNAL OF HIGHWAY RESEARCH AND DEVELOPMENT

March 1980 **Vol. 43, No. 4**

COVER:
Artist's concept of confusing parking signs.

IN THIS ISSUE

Articles

Departments

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

Public Roads is published quarterly by the Offices of Research and Development

Gerald D. Love, *Associate Administrator*

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Public Roads Magazine, HDV-14
Federal Highway Administration
Washington, D.C. 20590

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The Secretary of Transportation has determined that the publication of this periodical is necessary in the transaction of the public business required by law of this Department. Use of funds for printing this periodical has been approved by the Director of the Office of Management and Budget through March 31, 1981.

Motor vehicles – Parking signs
Marking of roads – " "
Signs and symbols

The Development of Improved Parking Signs

by

Donald A. Gordon[1]

Introduction

"Laboratory Studies of Lane Occupancy Signs," by Donald A. Gordon, in the December 1979 issue of *Public Roads* describes Federal Highway Administration research on laboratory testing of drivers' decisions on lane occupancy.

This article summarizes the results of laboratory studies on parking signs. Subjects indicated whether displayed parking signs permitted parking or standing at designated times. Their responses indicated the designs that drivers most accurately and rapidly understood and the designs that caused difficulty for drivers.

see p. 133

Conventional Parking Signs

The Manual on Uniform Traffic Control Devices (MUTCD) permits the parking sign types shown in figure 1. *(1)*[2] Sign types a and c display prohibitions in red letters on a white background; sign types b and d display permissive information in green letters on a white background. The restriction and duration of parking are emphasized in each sign type. Although these signs are effective, difficulties arise when the regulations are applied to complicated parking and standing schedules. *(2)* Double- and triple-paneled conventional signs can be difficult to interpret (fig. 2).

The driver may have to search through two or three panels to find information he or she needs: The top panel may concern standing, whereas the driver may want to park. The driver may have to apply one or more of the following rules: (1) If parking or standing is not prohibited, it is allowed; (2) if the sign explicitly prohibits standing, it implicitly prohibits parking; (3) if the sign prohibits only parking, it allows standing; and (4) if only standing is allowed, parking is prohibited. In some instances the information is intrinsically confusing. The top panel may cover Monday through Friday, whereas the bottom panel may cover Monday through Saturday. It is also confusing if too much information is presented on the sign: Parking and standing may be regulated to the left and right of the sign at different times of day and different days of the week.

[1]This article is a condensation of the report "Regulatory Signs for Lane Occupancy and Parking," by D. A. Gordon, Report No. FHWA-RD-78-89, *Federal Highway Administration,* Washington, D.C., June 1978.

[2]Italic numbers in parentheses identify references on page 133.

Figure 1.—MUTCD-approved parking sign designs.

Time-Referenced Parking Signs

It was hypothesized that the driver could read multipaneled parking signs more easily if the information was organized by time. To interpret a parking sign, a driver must search for the regulations applying at a particular time. If regulation times were prominently displayed on the sign, the driver might be able to make a rapid decision. Time-referenced sign types were developed and tested in a preliminary study. The type giving the fewest errors was selected from three time-referenced designs that differed in format. This design was evaluated in a later phase of the study.

Comparison of Signs

The selected time-referenced sign type was compared with conventional parking signs and changeable message signs (figs. 2–4). The conventional series reproduced actual Washington, D.C., parking signs and included two single-paneled signs, two double-paneled signs, and two triple-paneled signs. The time-referenced series used the sign type shown most effective in the previous trials and presented the same parking regulations as the conventional series. The changeable message series presented the regulations in force at the time stated in the question. For example, if the question read "Can you park to the left of the sign at 8:30 a.m. on Wednesday?" the changeable message sign showed the restrictions applying at 8:30 a.m. on Wednesday. Although changeable message signs are too costly for actual use, they were included in the study to show driver performance when parking information is presented most simply. Changeable message signs showed regulations right and left of the sign even though the question involved parking or standing on only one side. For all three sign series, prohibitory information was printed red on a white background; permissive information was black on a white background.

Subjects and Procedure

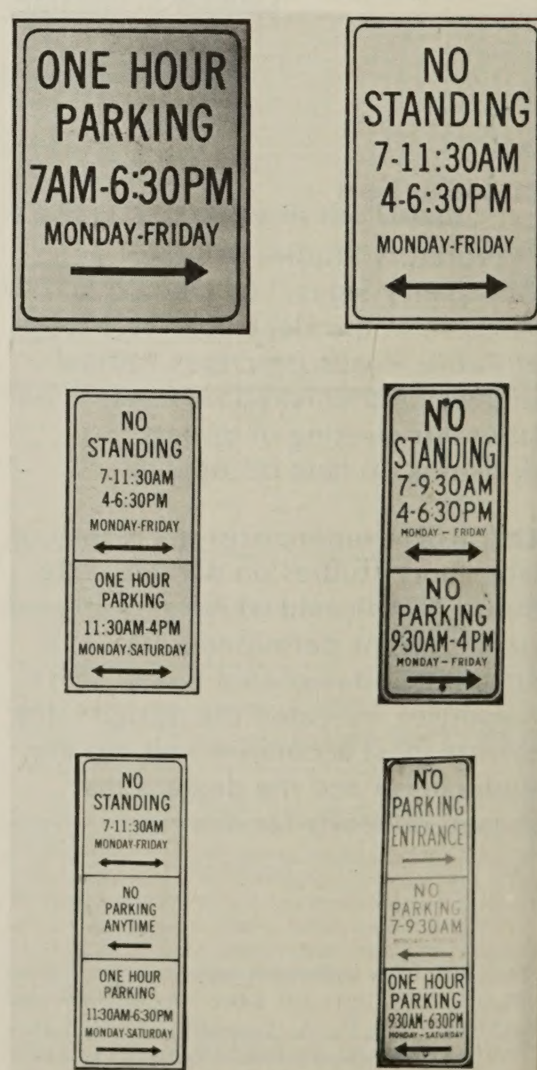
The 48 subjects participating in the study included a range of ages, education, and driving experience (table 1). All of the subjects had valid driving permits and were paid for their participation.

Eighteen questions were asked on the conventional series and on the time-referenced series, three questions on each sign used. The same 18 questions were asked on the changeable message series, but 15 rather than 6 types of signs were required to display the information outlined in the questions. The within-series order of sign testing was random, but each series was completed before a new series was shown. Subjects responded "yes" (parking allowed) or "no" (parking prohibited). Counterbalancing insured that no particular sign series was favored by the presentation order.

Results

Errors and response times are shown in table 2. On the average, the conventional series gave one error per 3.74 trials, the time-referenced series one error per 4.96 trials, and the changeable message series one error per 6.5 trials. The correction for

Figure 2.—Conventional series signs.



chance accounts for the only two possible responses—either a "yes" or a "no"—to the question. On the average, a subject would get 50 percent of the questions correct by chance (guessing) alone. The correction for chance is an indication of the subjects' true understanding of a sign series. These percentages were found using the following formula:

$$\text{Corrected percent} = \frac{100\ (R-W)}{48}$$

Where,
R = Number of subjects giving right answer.
W = Number of subjects giving wrong answer.
48 = Number of subjects.

Table 2 shows that there were fewer errors per question for time-referenced signs than for conventional signs. The difference was statistically significant at the .05 t-test level. Other differences in error scores were not statistically significant.

Table 1.—Characteristics of 48 subjects

Characteristics	Number of subjects
Sex:	
Male	31
Female	17
Years of age:	
Less than 20	13
20–29	24
30–39	6
40–49	2
Over 50	3
Education:	
Completed elementary school	6
High school graduate	16
College student	16
College graduate	10
Years of driving:	
Less than 1	5
1–9	37
10–19	3
20–29	1
Over 30	2

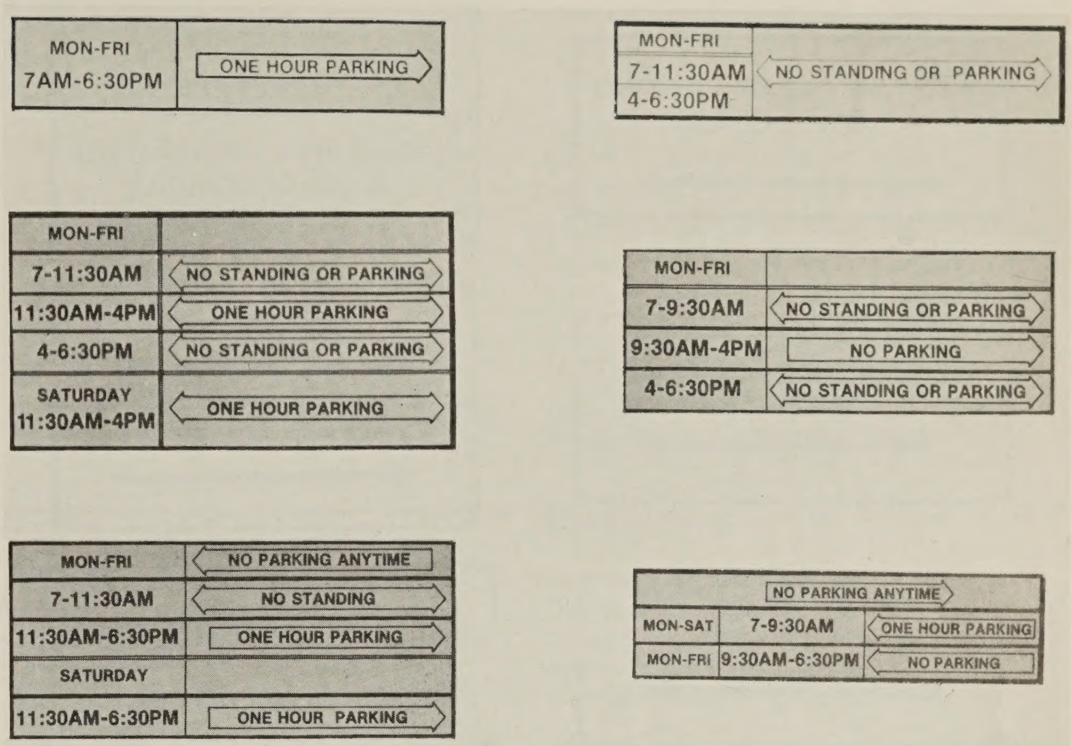


Figure 3.—Time-referenced series signs.

Table 2 also shows that subjects took longer to interpret time-referenced signs than conventional signs. However, the difference was not statistically significant.

Changeable message signs gave significantly fewer errors than the conventional signs and significantly more rapid responses than the other two series. Nevertheless, changeable message signs did give one error per 6.50 trials.

Errors sorted by single-, double-, and triple-paneled signs are shown in table 3. Triple-paneled signs showed almost as many errors as single- and double-paneled signs combined. On the average, subjects made an error every 2.5 trials on triple-paneled signs. It is not known if triple-paneled signs are difficult because of their layout or because they govern inherently complex situations. It is also not known why subjects responded most quickly to triple-paneled signs. It is recommended that triple-paneled signs be used as infrequently as possible.

Driver Difficulties With Parking Signs

Subjects' difficulties with the parking signs were further analyzed to determine the causes of the errors indicated in table 2. Five of the twelve questions and signs that gave the most errors concerned the parking-standing relationship. Of these five, four allowed standing even if parking was prohibited; the fifth prohibited both standing and parking. Two of the problem signs were conventional, two were changeable message, and one was time-referenced. Three signs (two conventional and one time-referenced) gave difficulty because Monday to Friday regulations conflicted with Saturday regulations.

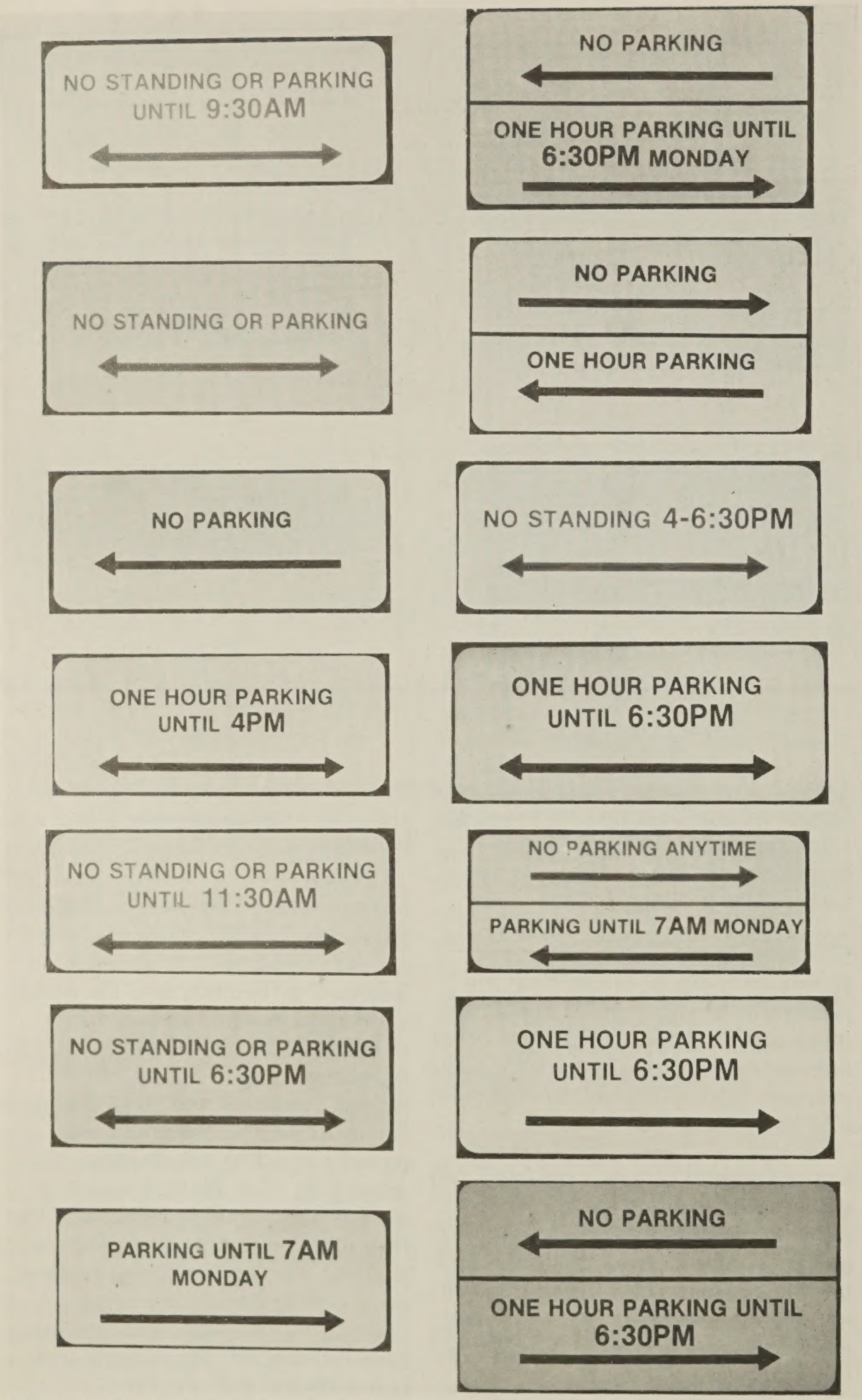


Figure 4.—Changeable message series signs.

The other questions that gave difficulty concerned 2-hour parking and the rule that parking is allowed if not prohibited. One high error changeable message sign gave a premature warning of a regulation change, which was interpreted as having occurred.

Summary

Parking signs govern the stopping and standing of vehicles. Single-paneled parking signs described in the MUTCD are effective, but double- and triple-paneled signs, which present complex parking schedules, give difficulty. The concept was tested that drivers could better understand complex parking signs if the information was arranged by time because in interpreting a sign the driver must first determine the current regulations. Three time-referenced sign types that were translations of single-, double-, and triple-paneled conventional signs were experimentally compared. Measures of speed and accuracy were determined in a preliminary laboratory study. The most successful time-referenced sign was then tested against conventional parking signs and against changeable message signs. The changeable message signs showed only the regulations in force at the time of the question. These signs served as experimental controls to indicate how close time-referenced performance came to "best" performance. The following conclusions were made:

- Triple-paneled parking-standing signs give difficulty. Triple-paneled conventional signs give more errors than single- and double-paneled signs combined. Of the signs giving numerous wrong answers, five were triple-paneled signs, and one a double-paneled sign. No single-paneled sign had a high frequency of errors.

Table 2.—Parking sign study results

	Sign series Conventional	Time-referenced	Changeable message
Total errors	231	174	133
Errors per question	0.27	0.20	0.15
Mean trials per error	3.74	4.96	6.50
Percent right corrected for chance	50.50	59.70	69.30
Mean response time (seconds)	6.03	6.67	4.28

Table 3.—Errors and response times related to number of sign panels

Sign series and number of panels	Total errors	Trials per error	Mean response time
			Seconds
Conventional			
1	55	5.2	6.44
2	62	4.6	6.51
3	114	2.5	5.13
Time-referenced			
1	46	6.3	7.01
2	48	6.0	7.73
3	80	3.6	5.28
Changeable message			
1	35	8.2	4.67
2	35	8.2	4.14
3	63	4.6	4.04

- Organizing parking sign information by time is favored. The average number of errors with time-referenced signs was three-fourths the number of errors with equivalent conventional signs. The findings of the study suggest that complex parking regulations might be better communicated by a rearrangement of the conventional MUTCD-approved signs to give prominence to time information. However, the adoption of time-referenced signs should not be expected to result in error-free interpretations.
- The parking-standing relationship should be clarified. Subjects' misunderstandings of these regulations were the most important source of error in the study. If standing is forbidden, the sign should read: "No Parking or Standing." The public also needs a clear definition of "standing."
- The signs should be simplified, and unusual signs should be avoided. Subjects had difficulty with 2-hour signs and with signs where Saturday regulations conflicted with Monday to Friday schedules. Although not specifically investigated in this study, it is recommended that "Entrance," "Loading Zone," "Embassy," and "Towaway Zone" messages should be used infrequently on parking signs. The signs are often already burdened with information.

These conclusions indicate public difficulty with many parking signs. However, most signs are of the easily understood, single-paneled type. Parked cars also serve as an important clue to parking permission, even if the sign itself is ambiguous. However, a regulatory parking sign must stand on its own. A driver who has attempted to read triple-paneled signs from a moving car will be aware of the difficulties investigated in the study.

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p. 133

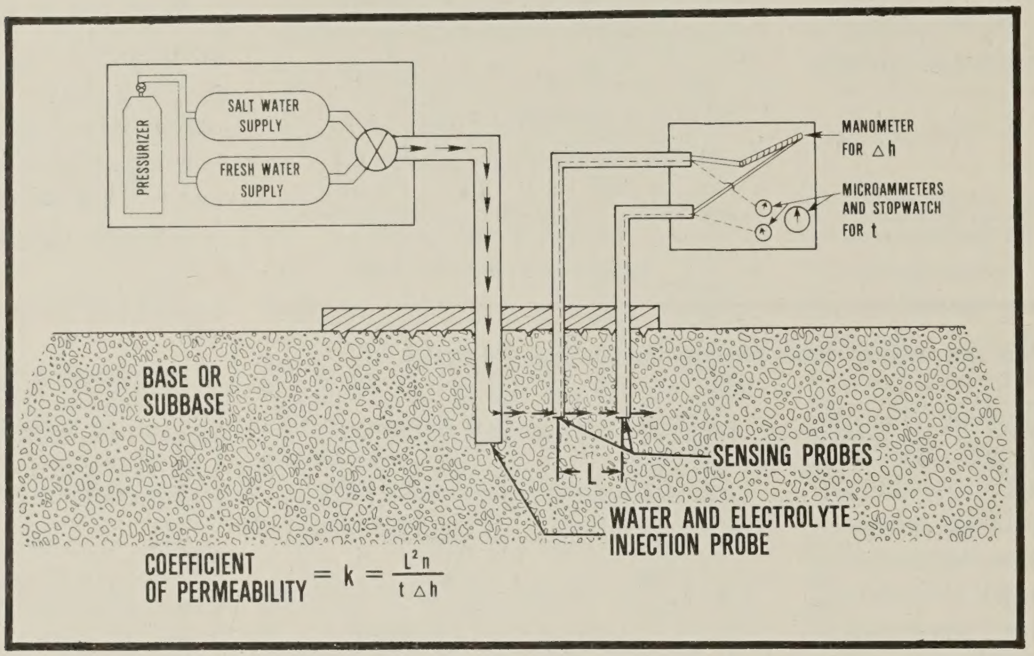
(1) "Manual on Uniform Traffic Control Devices for Streets and Highways," *National Advisory Committee on Uniform Traffic Control Devices, U.S. Department of Transportation,* Washington, D.C., 1978.

(2) D. C. Hanson, C. Bennett, and G. Radelat, "Curb Parking Sign Study," Highway Research Record No. 151, *Highway Research Board,* Washington, D.C., 1966, pp. 18–40.

Donald A. Gordon is a research psychologist in the Traffic Systems Division, Office of Research, Federal Highway Administration. He has been involved in research on the driving process and the development of improved signs and roadway delineations. Dr. Gordon has published articles on topics such as perception in vehicular guidance, experimental isolation of the driver's visual input, and the contribution of psychology to the traffic flow theory. Lately, he has been concerned with the development of improved highway guide signs.

Moulton, Lyle K.
Seals, Roger K.
Field permeability testing device
X FPTD

Determination of the In Situ Permeability of Bases and Subbases



by

Lyle K. Moulton and Roger K. Seals[1]

This article discusses the development and evaluation of the field permeability testing device (FPTD), a prototype in situ test device for determining the permeability of highway bases and subbases. The prototype device, based on the velocity method of in situ permeability determination, was evaluated extensively in the laboratory and field. Based on these evaluation results, it was concluded that the prototype FPTD satisfied stipulated performance criteria and provided a convenient, accurate, and reproducible means for determining the in situ coefficient of permeability of highway bases and subbases. However, the equipment and procedure need further development before the device can be adopted for routine use.

Introduction

Many of the problems associated with the unsatisfactory performance of pavement systems are attributable to excessive moisture in the subgrade and the structural section of the pavement. Recognizing this situation, many highway agencies specify that granular bases and subbases have outlets that drain water from the pavement section as quickly as possible. However, the base and subbase layers are not always permeable enough to prevent damage to the pavement under saturated conditions and normal traffic loads. (*1*) [2]

As part of the effort to develop effective subsurface drainage systems for highway pavements, rational procedures have been developed for estimating the amount of water that enters the pavement section and designing the drainage layers to rapidly remove this water. (*1*) The principal material property required to use these procedures is the coefficient of permeability. Minimum coefficients of permeability must be specified to meet design requirements of the drainage system.

[1] This article is a condensation of the report "Determination of the In Situ Permeability of Base and Subbase Courses," by L. K. Moulton and R. K. Seals, Report No. FHWA-RD-79-88, *Federal Highway Administration*, Washington, D.C., May 1979. The report is available from the National Technical Information Service, 5285 Port Royal Rd., Springfield, Va. 22161 (Stock No. PB 300908).

[2] Italic numbers in parentheses identify references on page 143.

Existing laboratory testing methods can be used to determine the permeability coefficients of candidate drainage layer materials; these values can be compared with the design requirements. Although these laboratory methods are well known and quite reliable, relatively small variations in gradation and density, such as those normally encountered in construction, can produce large changes in the coefficient of permeability. (*2, 3, 4*) Thus, the field permeabilities of these materials can differ from the values determined in the laboratory. Therefore, the coefficients of permeability of base, subbase, and subgrade materials should be determined in situ. Proven methods for such determinations must be available before the coefficient of permeability can be routinely specified in construction contracts to control materials and construction practices.

Recognizing this need, the Federal Highway Administration (FHWA) contracted for the development of a test apparatus and procedure for determining the in situ permeability of highway base, subbase, and subgrade materials. In Phase I of the project, feasible measurement techniques were developed and investigated in the laboratory; the optimum technique was used as a basis for the Phase II construction, laboratory, and field evaluation of the prototype FPTD.

During the study, several important facts about the problem and the required operating characteristics of the prototype FPTD were given special consideration:

- The flow or seepage domain in pavement structural systems consists of layered, nonhomogeneous, anisotropic media. A knowledge of coefficient of permeability (saturated hydraulic conductivity) in the transverse or longitudinal direction (while keeping in mind that the vertical permeability influences the amount of surface water that infiltrates the pavement structural system) is of primary concern in designing the drainage of these layers. The overriding influence of the horizontal flow limits the usefulness of techniques that measure only vertical permeability.
- The prototype FPTD should measure the coefficients of permeability of individual layers ranging in thickness from 75 mm (3 in) to 460 mm (18 in), with the coefficients of permeability ranging from 10^{-4} cm/sec to 10 cm/sec (0.4×10^{-4} in/sec to 4 in/sec), under various boundary conditions. These boundary conditions included both initially saturated and unsaturated layers, as well as underlying layers that were either more or less permeable than the layer being evaluated.
- The measurement technique adopted should be nondestructive or disturb the layer being evaluated as little as possible.
- The prototype FPTD must be simple to operate and durable.
- The device should measure the coefficient of permeability within a factor of 2 of the true permeability 90 percent of the time.

Phase I of the research was completed in December 1977 and an interim report was published. (*5*) The final report for the project was published in May 1979.

The Velocity Technique

An intensive search of the research literature revealed no in situ permeability test method that met all the performance criteria necessary for highway bases and subbases. Several candidate methods were identified, however, and the project was directed toward the development and testing of a "velocity technique" for the in situ determination of the permeability of highway bases and subbases. (*6–11*)

Fundamental considerations

The velocity technique involves the direct application of Darcy's Law, which can be stated as follows:

$$v = ki$$

Where,

v = The discharge velocity.
k = The coefficient of permeability (in units of velocity).
i = The dimensionless hydraulic gradient.

The hydraulic gradient, i, can be expressed in finite difference form as follows:

$$i = \frac{\Delta h}{L}$$

Where,

Δh = The loss in total head between two points on a flow path (streamline) in the flow domain.
L = The distance measured along the flow path between these two points.

The discharge velocity, v, can be expressed as follows:

$$v = n \times v_p$$

Where,

v_p = The seepage velocity (the actual average velocity of flow within the pores of the soil).
n = The porosity of the soil.

Thus, Darcy's Law can be rewritten and solved for the permeability, k, to give the following:

$$k = \frac{n \times v_p}{\Delta h / L}$$

Further development of the velocity technique required the following: (1) A method for the establishment of saturated steady state flow within the layer of base or subbase to be evaluated; (2) a method for measuring the average seepage velocity, v_p, along a flow path between two points a known distance, L, apart; (3) a method for determining the head loss, Δh, between these two points; and (4) a method for determining the in situ porosity, n, of the base or subbase being evaluated.

Development of the technique

Studies were conducted to provide the equipment and procedures necessary for developing a practical in situ permeability measurement system based on the velocity technique. The following conclusions were reached:

- Saturated steady state flow could be established by injecting water under constant pressure through a perforated injection tube located in the center of a circular plate. Flow net studies, conducted using electric analogs, showed that the flow pattern and the configuration of streamlines and equipotential lines could be controlled by regulating the plate diameter and injection depth relative to the existing boundary conditions—that is, the base and subbase layer thicknesses and their relative permeabilities. Ideally, streamlines of the flow pattern within the layer being evaluated should be essentially parallel to the surface. Flow net studies showed that this condition was best achieved by injecting water over the full depth of the layer when an impervious or much less permeable layer is under it. Under these boundary conditions, full depth injection was not absolutely necessary to establish a sizable zone of essentially horizontal flow.

- Electrical conductivity could be used to measure seepage velocity. Once saturated steady state flow has been established, an electrolyte solution is introduced through the injection tube, and electric conductivity probes are used to time the flow rate between two selected points on a streamline. A two-wire probe and a microammeter system was simpler and more effective and economical for both laboratory and field use than were the other conductivity measurement systems investigated.

- Two possible methods were considered for determining the head loss, Δh, between the velocity measuring probes in the flow domain: (1) The analytical (mathematical) evaluation of the head loss between the two points as a function of the measured flow rate and total head loss through the system and (2) the direct measurement of the head loss between the two points. The analytical solution required knowledge of the ratio of the permeabilities of the various layers in the flow domain. Therefore, the head loss had to be determined by directly measuring the fluid pressures at the ends of the electric conductivity probes. Either a manometer or a differential pressure gage (DPG) could be used to measure the head loss.

- Using measured values of the dry density, γ_d, and the specific gravity of solids, G_s, of the soil, the porosity, n, could be calculated using the following expression:

$$n = 1 - \frac{\gamma_d}{G_s \times \gamma_w}$$

Figure 1 shows the principal components of the field permeability test device. As shown in figure 2, the pressure taps were incorporated into the electric conductivity probes.

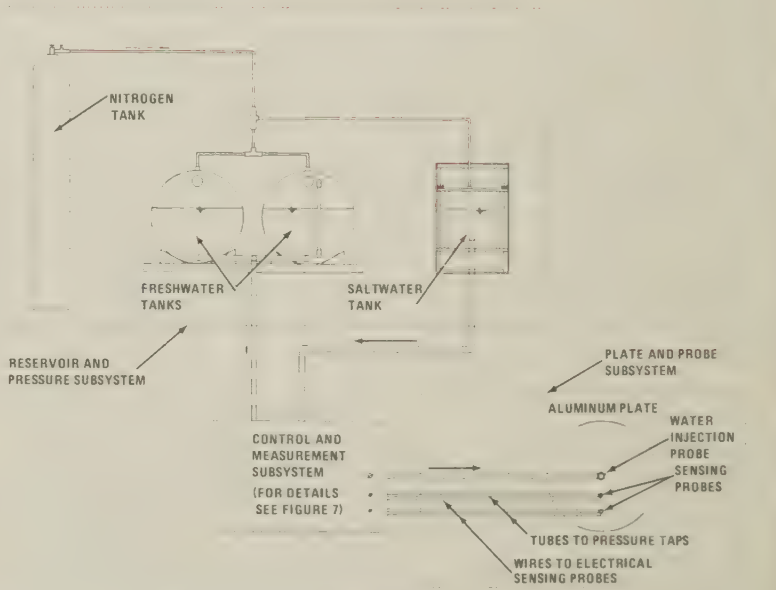


Figure 1.—The FPTD and its subsystems.

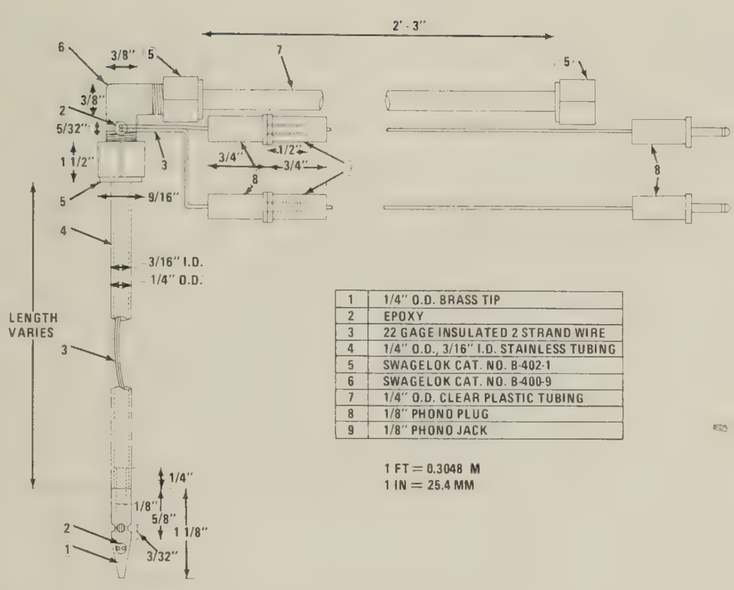


Figure 2.—Sensing probe.

Preliminary laboratory studies

The accuracy and reliability of the technique were studied initially by placing electric conductivity/pressure probes in the side of a modified constant head permeability test device and then comparing the coefficient of permeability values based on the velocity technique and the conventional constant head method. In addition to verifying the viability of the velocity technique, these studies produced the following two significant observations:

- Some error is introduced into the velocity determination by hydrodynamic dispersion and diffusion of the salt solution. Thus, the apparent velocity of flow between the two probes measured by the initiation of conductivity change was slightly higher than the actual average velocity determined in the constant head permeameter. The magnitude of this error was time dependent and could be minimized by using a combination of probe spacing and hydraulic gradient that allowed the test to be run in the shortest possible time.
- The best electrolyte solution tested consisted of 25 mg (8.75×10^{-4} oz) of ammonium chloride (NH_4Cl) in 100 ml (3 oz) of water.

The data, summarized in figure 3, compare the coefficient of permeability, k_{ch}, measured by the modified constant head device with that determined by the velocity technique, k_p, using the new electric probe with pressure tap system installed in the modified constant head permeameter. The linear regression equation (shown as the solid line in figure 3) can be expressed as the following:

$$k_{ch} = 0.64 k_p^{0.958}$$

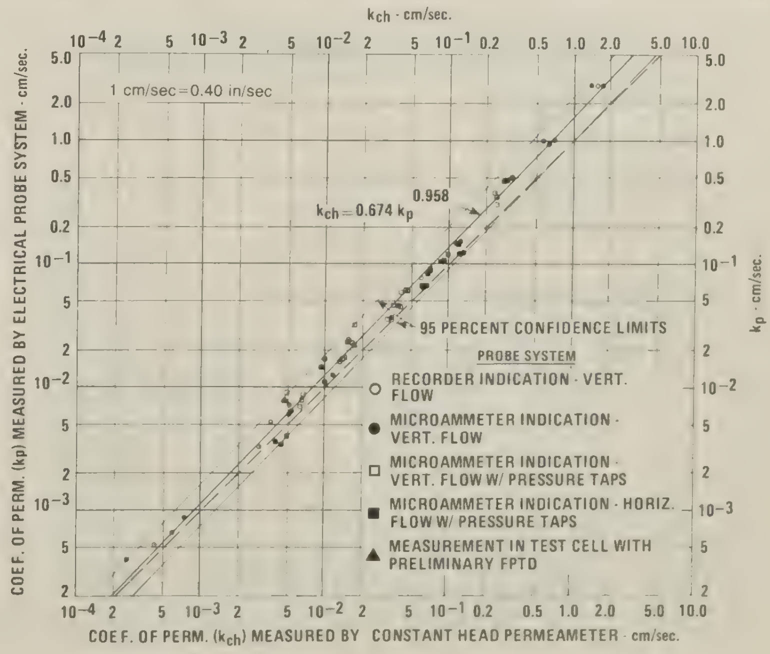
This equation fits the experimental data well, as evidenced by a coefficient of determination, r^2, of 0.991 and a coefficient of variation, CV, of 5.08 percent. The velocity technique slightly overpredicts the coefficient of permeability because of the dispersion and diffusion phenomena noted previously. Even with this problem, the data show that the two observations agree very well, which confirms the practicality of the velocity technique for in situ permeability measurements.

Before fully developing the prototype FPTD, a preliminary device was tested in 1.5 m × 1.5 m (5 ft × 5 ft) cells. (5) These cells were designed to allow direct determination of coefficients of permeability for simulated bases and subbases under saturated horizontal sheet flow conditions. Results obtained with the preliminary device agreed very well with the direct determinations when corrected to account for the effects of hydrodynamic dispersion and diffusion.

Development and Evaluation of the Prototype FPTD

The remainder of the project was devoted to completing the development of the prototype FPTD, evaluating the accuracy and reliability of the method, and establishing the suitability of the equipment for the field.

Figure 3.—Comparison of coefficients of permeability measured by modified constant head device with two-wire electric probe system.



Description of FPTD

The prototype device consists of three major subsystems: (1) The reservoir and pressure subsystem, (2) the control and measurement subsystem, and (3) the plate and probe subsystem (fig. 1).

The reservoir and pressure subsystem consists of the freshwater supply tanks, a saltwater supply tank, and a pressure source. The freshwater supply tanks provide the water for saturating the base or subbase and establishing steady state flow during permeability testing. The saltwater supply tank provides the electrolyte solution that initiates the conductivity change. The pressure source, which maintains the gas pressure of the system, is a regulated nitrogen gas cylinder. For field use, the reservoir and pressure subsystem was mounted in the rear of a West Virginia University (WVU) mobile research van.

The control and measurement subsystem consists of the hydraulic controls, the electric sensing system, and the pressure sensing system (fig. 4). The hydraulic controls can shut off the water supply or precisely regulate the flow of either freshwater or saltwater (electrolyte) to the water injection probe. The two electric sensing circuits provide an adjustable response to the conductivity change that occurs as the electrolyte solution passes the electrodes in the sensing probes. The pressure sensing system consists of a differential manometer that determines the head difference between the pressure taps in the sensing probes.

Figure 4.—Closeup of the control and measurement subsystem.

The plate and probe subsystem consists of the horizontal plate, water injection probe, and sensing probes. The 460 mm (18 in) diameter aluminum plate is equipped with a central port through which the water injection probe is inserted and with radially located ports through which the sensing probes are inserted. To minimize the amount of piping at the interface between the plate and the base or subbase, the plate was prepared with annular projections on its bottom surface.

The water injection probe consists of closed-end tubing with holes at regular intervals along its length. During testing, the probe is oriented so that these holes point in the direction of the row of plate ports, that is, in the direction of testing.

The sensing probes (fig. 2) were constructed from stainless steel tubing with a brass tip. The tip contains four ports to permit the access of water to the manometer for head measurement. A two-wire electrode is brought down through the sensing probe and secured in the tip. Both the water injection probes and the sensing probes were made in various lengths to suit the geometry of the test situation.

Operation of the FPTD

Once the plate has been positioned on the surface of the bases or subbases, the central water injection and sensing probes are inserted into predriven holes. The probes are positioned at preselected depths and oriented to produce a consistent flow/measurement direction. The fresh- and saltwater reservoir lines are connected through the control/measurement system to the water injection probe. The piezometer and electric conductivity lines are connected between the probes and the control/measurement system. The plate is then jacked against the test surface using the equipment vehicle for reaction. Figure 5 shows the test setup.

When freshwater begins to flow through the central probe, the development of saturated steady state flow is determined by observing seepage adjacent to the edge of the plate as well as by a stable differential manometer reading. The differential head, and thus the quantity of flow, can be adjusted by a regulator on the nitrogen pressure system. Once a stable flow is established, a "slug" of the salt solution is introduced into the injection probe flow system at the same head as the freshwater. The salt slug is followed by a continuous flow from the freshwater reservoir.

Timing is begun when the microammeter for the upstream probe deflects and is stopped when the microammeter for the downstream probe deflects. After

Figure 5.—Test setup before start of the flow of water.

the initial test, the freshwater that follows the salt slug "flushes" the salt solution from the flow domain causing the microammeter needles to return to their original undeflected positions. The data that are recorded and used for calculation of the coefficient of permeability are as follows: Travel time, t (seconds); differential head, Δh (centimetres); and travel distance, L (centimetres).

Once the system returns to the original condition, the flow (and thus the differential head) is adjusted and another test can be conducted.

Field evaluation of the FPTD

The performance of the FPTD was evaluated under actual field conditions. The field testing program consisted of investigations at 18 test sections in 13 locations in 8 States (Kentucky, Maryland, Michigan, North Carolina, Ohio, Pennsylvania, Tennessee, and West Virginia). Almost all of the test sections consisted of a single base or subbase layer overlying an impervious subgrade. Samples were collected at each test location and returned to the WVU laboratories for physical properties and permeability testing. In addition, field nuclear moisture-density determinations were made at each test location. These tests were conducted to calculate the in situ porosity of the layer and to provide the target dry density values for the laboratory permeability tests.

The FPTD performed satisfactorily in the field on all but 3 of the 18 test sections. In two tests, the flow required to maintain steady state flow in the base exceeded the flow capability of the FPTD. Laboratory time-lag permeameter tests (*2*) on these materials revealed average permeability coefficients of 2.76 and 8.27 cm/sec (1.1 and 3.3 in/sec), both near the proposed upper limit of the operating range for the equipment. The third failure occurred on a dense graded aggregate base that had a laboratory permeability coefficient of 2.73×10^{-3} cm/sec (1.1×10^{-3} in/sec), which is near the proposed lower operating limit for the equipment. In all three failures, excessive piping at the plate-base course interface was found to be one of the limiting conditions. As a result, the annual serrations previously noted were machined into the base of the plate in an attempt to develop a better interfacial seal. Although subsequent performance improved, none of the remaining test sections exhibited particularly high or low permeability values, so the interfacial seal was not tested under either extreme. It was also noted that a better interfacial seal could be achieved on freshly compacted material than on bases or subbases that had been in place and under traffic for some time.

Comparison of the field and laboratory results revealed that for 6 of the 14 measured coefficients of permeability (43 percent), the field values were within a factor of 2 of the laboratory values, and for 10 of the 14 measured coefficients of permeability (71 percent), the field values were within a factor of 10 of the laboratory values. These comparisons were not judged to be particularly good, but certain inherent problems exist in comparing field and laboratory test results. There may be differences in dry density (porosity), differences in direction of fluid flow, and differences in fabric (particle orientation). Even though the field results could not be directly correlated with the laboratory results on the same material, the laboratory evaluation (discussed below) on carefully controlled samples established that the prototype FPTD could produce consistent and accurate results over a relatively wide range of material types and boundary conditions.

The field evaluation program did identify potential minor problems with the equipment, demonstrate its ruggedness and durability, and assist in developing a systematic test procedure. The program also identified possible refinements to improve equipment portability and operation. The sensing probes were the only components that presented problems during the field tests, but the probes are inexpensive and easy to replace when failures occur.

Although the subbase layer in Tennessee contained 5 percent calcium chloride for stabilization, there was no problem in achieving steady state conditions and obtaining a satisfactory permeability measurement.

Combined setup and testing times for a given layer ranged from 45 to 90 minutes.

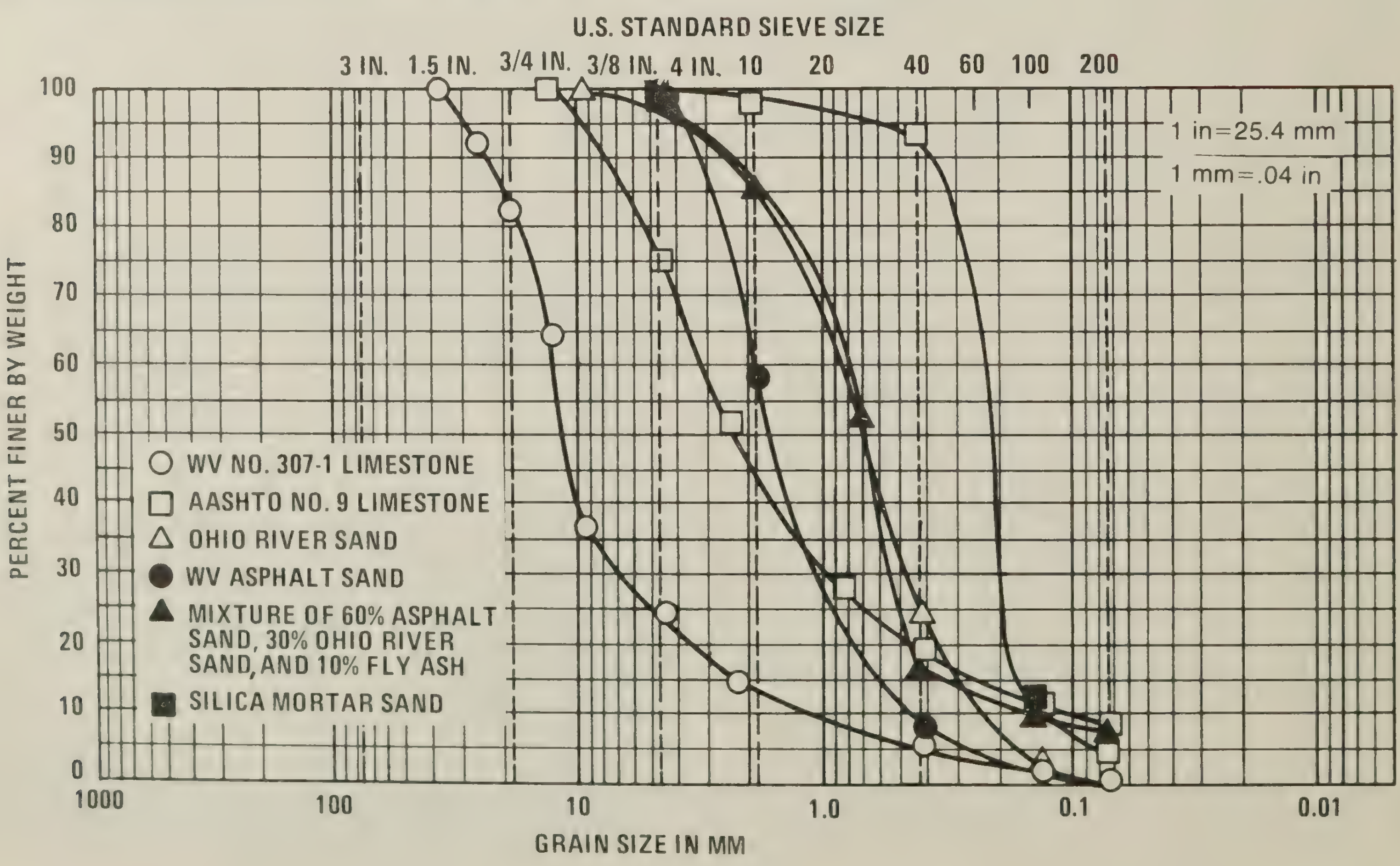
Laboratory evaluation of the FPTD

Because of the difficulties anticipated in trying to correlate field and laboratory results, the study included a laboratory evaluation of the FPTD. The prototype FPTD's performance was evaluated for a variety of materials and physical and hydraulic conditions.

Six different materials were selected, more on their permeability—between 10^{-4} and 10 cm/sec (0.4×10^{-4} and 4 in/sec)—than on their suitability as a base or subbase. These materials were as follows, in order of decreasing permeability: (1) A crushed limestone aggregate, satisfying West Virginia Department of Highways (WVDOH) 307-1 base course requirements, (2) a crushed limestone aggregate meeting the American Association of State Highway and Transportation Officials (AASHTO) No. 9 gradation requirements (washed), (3) a limestone sand meeting the WVDOH requirements for fine aggregate in asphaltic concrete, (4) an Ohio River sand meeting the WVDOH requirements for fine aggregate in portland cement concrete, (5) a silica mortar sand supplied by the WVU physical plant, and (6) a blend of 60 percent asphalt sand, 30 percent Ohio River sand, and 10 percent fly ash. The average test-cell-determined coefficients of permeability in cm/sec of these materials were, respectively: (1) 3.56 (1.4 in/sec), (2) 2.70×10^{-1} (1.1×10^{-1} in/sec), (3) 1.10×10^{-1} (0.43×10^{-1} in/sec), (4) 3.51 to 5.90×10^{-2} (1.4 to 2.3×10^{-2} in/sec), (5) 1.80×10^{-2} (0.7×10^{-2} in/sec), and (6) 3.75×10^{-3} (1.5×10^{-3} in/sec). The grain size distribution curves for these materials are shown in figure 6.

Physically, the boundary conditions were varied by using either a homogeneous or layered system with different layer thicknesses. The physical location of impermeable, moderately permeable, and very permeable materials was varied within the layered system. The location of the free water surface was varied relative to the position of the layer being tested. In addition, the effects of FPTD test parameters, such as direction of testing, plate size, probe location, and probe spacing, on permeability coefficients were evaluated in the laboratory.

Figure 6.—Grain size distribution curves for the materials used in the test cells to evaluate the FPTD.



The test results indicated that neither layer thickness nor water table depth significantly affects the measured coefficient of permeability if saturated steady state flow can be established. Similarly, if the underlying material was either impervious or moderately permeable, it did not significantly influence results.

Some problems were encountered in obtaining reliable measurements in 75 mm (3 in) and 150 mm (6 in) layers of Ohio River sand overlying a 300 mm (12 in) layer of WVDOH No. 307-1 crushed limestone. In this test, the permeability of the underlying layer was over 100 times that of the layer being tested. Consequently, the bulk of the flow was found to move abruptly downward and then horizontally through the very pervious layer. Other tests showed, however, that permeability measurements of a layer that is above a much more permeable layer are reliable if a condition of steady state saturated flow is maintained in both layers.

The influence of the direction of testing was evaluated by running tests at the same location and placing the sensing probes at different directions. As expected, some materials exhibited considerable variations, whereas others showed only small differences. These results suggest that considerable anisotropy might exist, particularly under field conditions where placement and compaction of bases and subbases might not be as uniform as in the laboratory test cells. Consequently, in actual practice it would be desirable to perform tests in orthogonal directions at a given test location and then take the permeability as the geometric mean of the results.

The influence of the plate size, the depth of the water injection probe, and the depth, location, and spacing of the sensing probes are interrelated. Ideally, these parameters should be controlled to produce a zone of essentially horizontal flow so that the tips of the sensing probes can be located on a single streamline. Plate size can be held constant if the depth of the water injection probe and the depth and location of the sensing probes are properly controlled. Therefore, the 460 mm (18 in) diameter plate was selected for most of the laboratory and field tests.

For layers 300 mm (12 in) thick or less, full depth penetration of the water injection probe was required. For layers from 300 to 460 mm (12 to 18 in) thick, a 300 mm (12 in) penetration depth was found to be satisfactory.

For layer thicknesses less than 300 mm (12 in), placing the sensing probes at the center of the layer proved satisfactory. For layer thicknesses exceeding 300 mm (12 in), the sensing probe depth should not exceed 150 mm (6 in). However, averaging measurements made at several depths is desirable for such layers.

Results of tests to determine the influence of sensing probe location and spacing were somewhat erratic but showed that better results were produced with 50 mm (2 in) and 75 mm (3 in) probe spacing, with the interior probe within the center third of the plate, that is within 75 mm (3 in) of the center. This was particularly true where a layer of highly permeable material is under the layer being tested.

The overall accuracy of the FPTD and the reproducibility of the results achieved were evaluated by comparing coefficients of permeability measured by FPTD, k_d, with the coefficients of permeability for the same materials measured in the test cells, k_{tc}, using steady sheet flow. These data are compared in figure 7. The linear regression equation (shown as the solid line in figure 7) can be expressed as follows:

$$k_d = 1.023\, k_{tc}^{\,1.023}$$

The equation fits the experimental data well, as evidenced by a coefficient of determination, r^2, of 0.959. On the average, the FPTD produced values very close to those measured by the test cell technique, with only a slight tendency for underprediction in the low permeability range and a very slight tendency for overprediction in the high range. The overprediction of coefficient of permeability, which showed up earlier as a result of dispersion and diffusion phenomena, did not show up here.

Figure 7 was prepared and the statistical analysis was performed using all 410 test results that were obtained during laboratory evaluation of the FPTD. Although the accuracy of certain data was questioned, the data were included in figure 7 and the analysis so that the resulting comparison between k_d and k_{tc} would represent the "worst condition" and thus could represent the lower limit of the accuracy and reproducibility of the values obtained with the FPTD.

The shaded area in figure 7 represents the zone where the data would fall if the FPTD measured the coefficient of permeability within a factor of 2 of the true value. When all of the test results are considered, 336 of the 410 test values (82 percent) fall within the shaded zone. However, as noted earlier, some of the test data can be questioned, including data obtained with what proved to be unsatisfactory locations and spacings of the sensing probes. If these 44 pieces of data are excluded from the total, then 336 of the remaining 366 test values (91.8

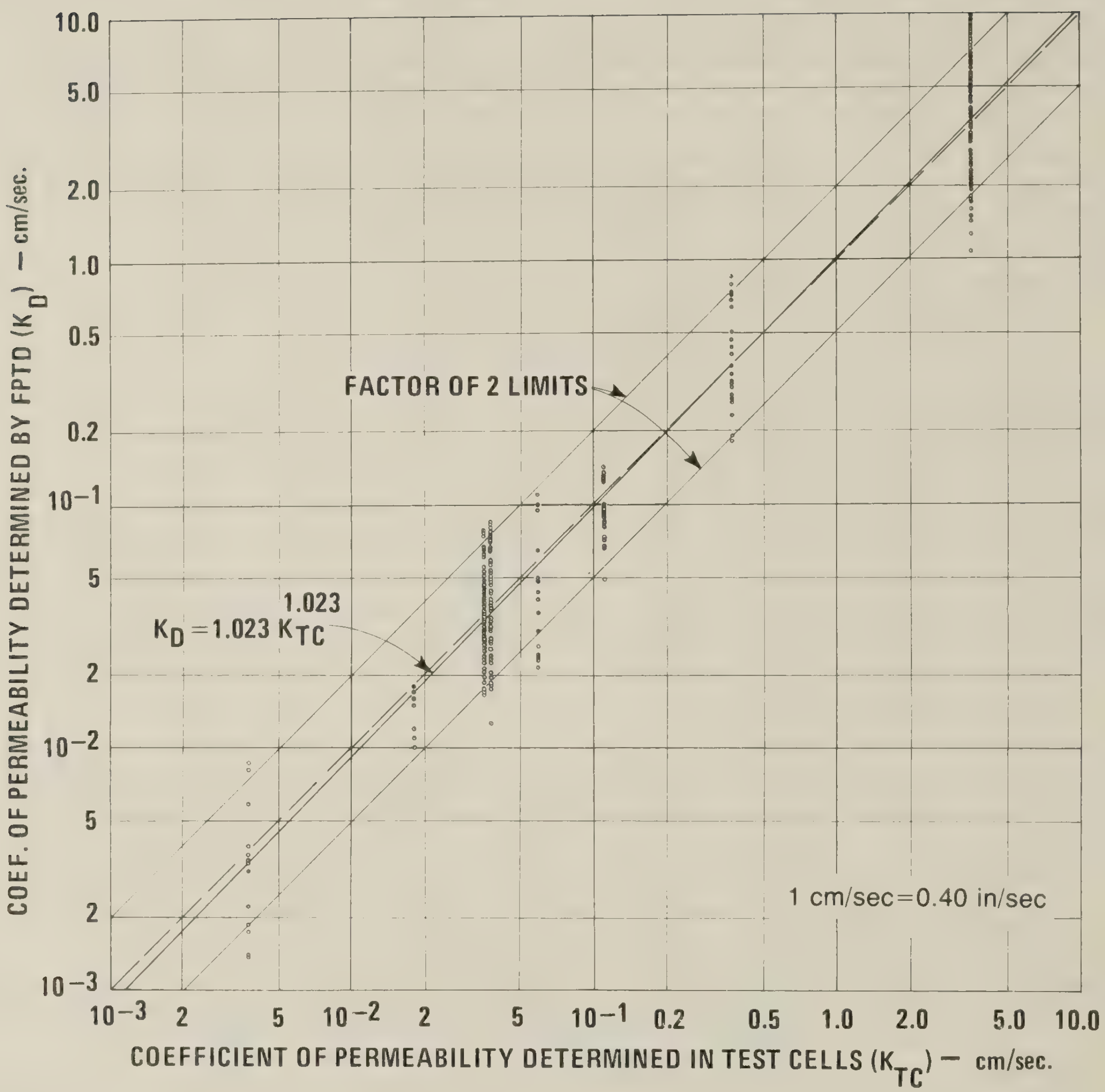


Figure 7.—Comparison of permeability determined in test cells with permeability measured by FPTD.

percent) fall within the shaded zone. Thus, the prototype FPTD satisfies the requirement that it measure the coefficient of permeability within a factor of 2 of the true value 90 percent of the time.

Conclusions and Recommendations

The prototype FPTD can measure, with satisfactory accuracy and reproducibility, the coefficient of permeability of typical bases and subbases under a variety of physical and hydraulic boundary conditions. Measurements are reliable if a zone of saturated steady state flow can be established and maintained during testing.

Although the FPTD can measure the coefficient of permeability of bases and subbases within a practical range, at the present state of development it cannot measure permeabilities below about 10^{-4} cm/sec (0.4×10^{-4} in/sec) or above about 10 cm/sec (4 in/sec).

The equipment proved to be rugged, reliable, and easy to operate. In addition, the components are inexpensive and easy to construct.

Although the results of the investigation were generally favorable, additional equipment and procedural improvements are needed before the test is routinely used. The FPTD should be widely field tested under diverse conditions that might be encountered in routine use. FHWA is currently initiating an evaluation program in which the prototype FPTD is being loaned to State highway agencies for field testing.

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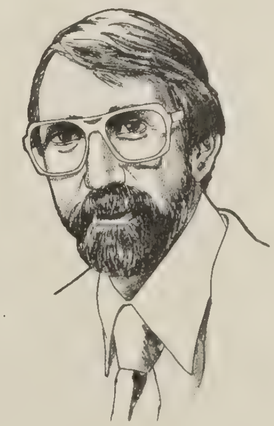
Lyle K. Moulton is a professor of civil engineering at West Virginia University where he specializes in geotechnical engineering. His principal areas of interest are groundwater and seepage, earthwork design, and foundation engineering. His recent research work includes studies on in situ permeability measurement and tolerable bridge movements.



Roger K. Seals is a professor of civil engineering at West Virginia University where he specializes in geotechnical engineering. His principal areas of interest are soil properties and behavior and foundation design. Much of his recent research has been devoted to the use of coal-associated residuals as construction materials.

[3]Reports with PB numbers are available from the National Technical Information Service, 5285 Port Royal Rd., Springfield, Va. 22161.

The Seventh Annual FCP Conference

by

Debbie DeBoer

Although the near completion of the Interstate Highway System has led to the general assumption that an intensive program of highway research and development (R&D) is no longer justified, the opposite is true—highway R&D is needed more urgently now than ever. The highway program must redirect itself toward goals that reflect the changing complexion of the transportation field: Use of smaller cars; the fuel crisis; a greater number of pedestrians, bicyclists, and moped users; the need for rehabilitation of the existing highway system; and the ever increasing interest in and importance of safety for users of all modes of transportation. (*1*)[1]

As a result, R&D is still an important function of many highway agencies. Because this is the case, the efforts of various highway agencies and those of the Federal Highway Administration must be coordinated to eliminate duplication and insure proper direction of R&D efforts. This coordination is the mission of the Federally Coordinated Program (FCP) of Highway Research and Development[2] of the Federal Highway Administration.

[1] Italic numbers in parentheses identify references on page 148.

[2] For further information on the FCP, write to the Associate Administrator for Research and Development (HRD-3), Federal Highway Administration, Washington, D.C. 20590.

Because participants in the FCP include R&D personnel from diverse areas of the highway community, communication among participants is vitally important. For this reason, annual review conferences have been held since 1973. The objective of the FCP conference, in review of selected projects from the FCP, is threefold: (1) To bring together members of each project team in an atmosphere of open discussion; (2) to test the research approach of each project by discussion with individuals from State highway agencies, operating offices, and FHWA field and headquarters offices; and (3) to test the plans for appropriate implementation of results.

Each project reviewed at the FCP conference goes through one of the three types of reviews: Initial, midstream, or final. An initial review is conducted when a new project has been outlined by FHWA staff and a budget request has been placed for the project, but before a significant level of contract funds is available. When approximately half of the planned contract funds have been committed, substantial Highway Planning and Research Program (HP&R) activity has been initiated, and substantive intermediate results have been obtained for a project, a midstream review is conducted. This review is held no later than the third year of funding. A final review is held when essentially all contract research has been completed, major implementation efforts are in preparation or in process, and HP&R activity on the project has passed its peak. The final review must be held no later than the second year after final contract funding.

The seventh annual FCP Review Conference was held in Williamsburg, Va., the week of December 3, 1979. Eighteen projects were reviewed in 15 sessions. The first half of the week dealt mostly with the review of projects from FCP Categories 1 and 2 ("Improved Highway Design and Operation for Safety" and "Reduction of Traffic Congestion, and Improved Operational Efficiency"). One project from Category 5 ("Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety") also underwent review during the first half of the week. Except for review of one project in Category 2, the second half of the week concentrated on Categories 3 ("Environmental Considerations in Highway Design, Location, Construction, and Operation"), 4 ("Improved Materials Utilization and Durability"), 5, and 7 ("Improved Technology for Highway Maintenance").

The review sessions began with an introduction and project overview by the project manager. These were followed by presentations on different elements of the project. After these presentations and some general discussion, the reviews of most of the projects followed a format different from that of previous FCP conferences. The attendees of the reviews met in small groups (breakout sessions) to discuss, critique, and make recommendations on the projects. Attendees then reconvened to review the discussions conducted in the breakout sessions. In past years most review sessions consisted of only large group discussions, and this year's change in format was to promote more open, indepth discussion of the projects under review. The general reaction of the conference attendees was that the review sessions benefited from this format change.

Table 1 lists the projects reviewed at the 1979 conference, their titles, and the type of review conducted for each project. Following is a brief description of the topics discussed at each project review, in some cases including problems that were encountered and recommendations that were made.

FHWA project manager Ken Clear leading review session of Project 4K.

Table 1.—Projects reviewed at the 1979 FCP Review Conference

Project	Title	Type of review
1A	Traffic Engineering Improvements for Safety	Midstream
1J	Improved Geometric Design	Final
1N	Safety Improvements for Bicyclists, Moped Operators, and Pedestrians	Initial
1T	Advanced Vehicle Protection Systems	Midstream
1W	Measurement and Evaluation of Pavement Surface Characteristics	Midstream
2C	Requirements for Alternate Routing to Distribute Traffic Between and Around Cities	Midstream
2D	Priority Techniques for High Occupancy Vehicles	Final
2N	Improved Traffic Signing and Motorist Information Systems	Initial
3H	Social and Economic Considerations in Highway Development and Improvement	Initial
4C	Use of Waste as Material for Highways	Midstream
4K	Cost-Effective Rigid Concrete Construction and Rehabilitation in Adverse Environments	Initial
5E	Premium Pavements for Zero Maintenance	Midstream
5K	New Bridge Design Concepts	Midstream
5L	Safe Life Design for Bridges	Midstream
7A	Physical Maintenance	Midstream
7B	Traffic Services	Midstream
7C	Management	Midstream
7D	Equipment	Midstream

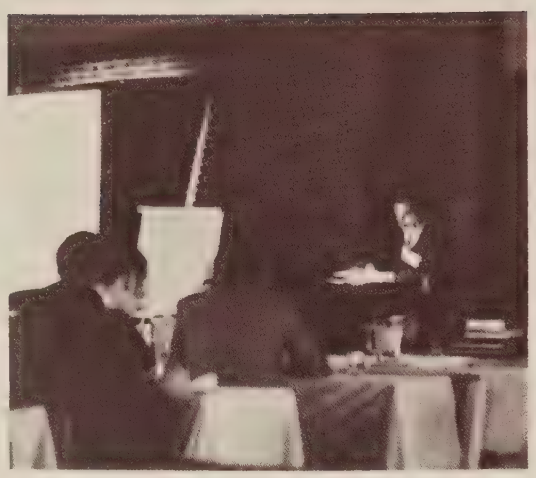
• 1A— In this review, the attendees discussed the project's 15 ongoing research studies, the process by which such studies were selected and evaluated, and how the results of such studies are implemented. Changes will be made to the direction and scope of five of the studies, as well as to the solicitation and evaluation process for candidate 1A studies. It was felt that the solicitation notice did not reach enough local jurisdictions and an effort should be made to correct this situation.

• 1J—Discussions in this session exhibited a concern for improved design and operation of horizontal curves especially in relation to superelevation, spirals, length of curves, and transitions. Also, an evaluation of the design elements proposed in the new American Association of State Highway and Transportation Officials' (AASHTO) design guide was recommended.

• 1N—One problem which arose in this review was that of transmitting research results to the local level. The attendees were also concerned with improving followup efforts to determine how research is being implemented and what further research is needed in Project 1N. It was recommended that the Federal Highway Administration work jointly with the National Highway Traffic Safety Administration on future R&D efforts within this project.

• 1T—Computer simulation programs were discussed in this review and the consensus was "let the user beware." The development of these programs is in its early stage and many pitfalls may be encountered due to the current form and state of validation of the programs. Accurate input parameters must be determined for these programs and computer results must be compared carefully with experimental test data to assure reasonableness of results. Attendees did support further research with these tools because of the programs' potential for solving many highway safety problems.

• 1W—Skid resistance and hydroplaning, pavement texture, and road roughness were discussed in the breakout sessions of this project's review. There was also considerable discussion on the need for determining the hydroplaning potential of pavements by texture or speed gradient measurements. The policy implications of making the latter measurement with a bald tire to obtain greater sensitivity caused a lively interchange of ideas and opinions.



Review session of Project 5L being led by Jerar Nishanian, FHWA project manager.

• 2C—This review included intense discussions on motorist information systems and the possibility of overcoming problems that arise as an attempt is made to lessen congestion on highways. These problems include resistance by residents near freeways to improved lighting, perceived inequities between suburban and downtown ramp metering users, diversion from congested toll facilities to nearby free highways, and the need for commitments from politicians and transportation officials for funds for operation and maintenance of new traffic management and information systems.

• 2D—One recommendation arising from this review was that further research is needed on problems associated with operating high occupancy vehicle (HOV) facilities, such as accident prediction, the need for improved equipment for inserting and picking up HOV lane stanchions, and what future actions can be taken when HOV capacities are reached. Personnel from field offices indicated that the "users guide" which is being developed on priority techniques for HOV's will be most welcome if it presents recommendations that the user can accept, reject, and/or modify.

• 2N—In this review, it was recommended that more research be done to understand how drivers find unfamiliar destinations because drivers appear to use various methods when trying to find an unfamiliar location. A knowledge and understanding of these methods is necessary to the design of navigational aids so the new aids will be accepted and used by the motoring public.

• 3H—Discussions in the breakout sessions of this review resulted in recommendation of the following activities: Identify examples of

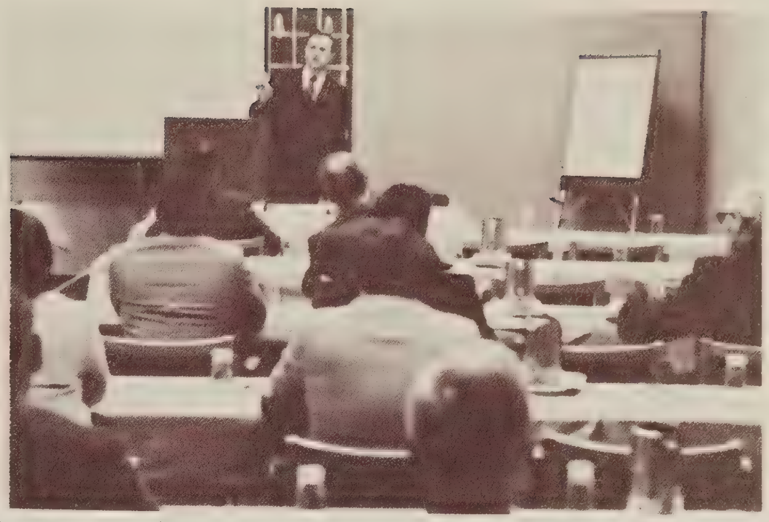
Monday morning session break.

successful social and economic (SE) analyses in the environmental impact statement; identify examples of effective early community involvement at the systems level; perform detailed research on survey techniques, existing and proposed, for SE analyses; perform research on the effectiveness of citizen involvement; and determine the value of predictive models for SE impact identification.

• 4C—It was concluded at this review that further study of waste materials such as fly ash and incinerator residue should be conducted by the States by experimental application. However, there is still a need to continue to develop mix design methods using reclaimed asphaltic concrete so a mixture having the physical and chemical properties and durability of virgin asphaltic concrete mixes can be produced.

• 4K—The need to preserve the national investment in highway bridges by stopping the corrosion of reinforcing steel in decks and other structural members caused considerable discussion at this review. The attendees agreed on the importance of further development of simple, lightweight cathodic protection systems to save structures already contaminated by road salt, but on which the process of spalling and delamination has not yet occurred to any major degree.

• 5E—In general, the attendees of this review were appreciative of the results that have already been achieved by this project, especially those showing that high traffic density pavements may warrant greater initial investment to reduce "life cycle" costs. Strong interest was shown in the adaptation of zero maintenance pavement concepts to the pavement rehabilitation process; this would result in an extension of the benefits of this project.

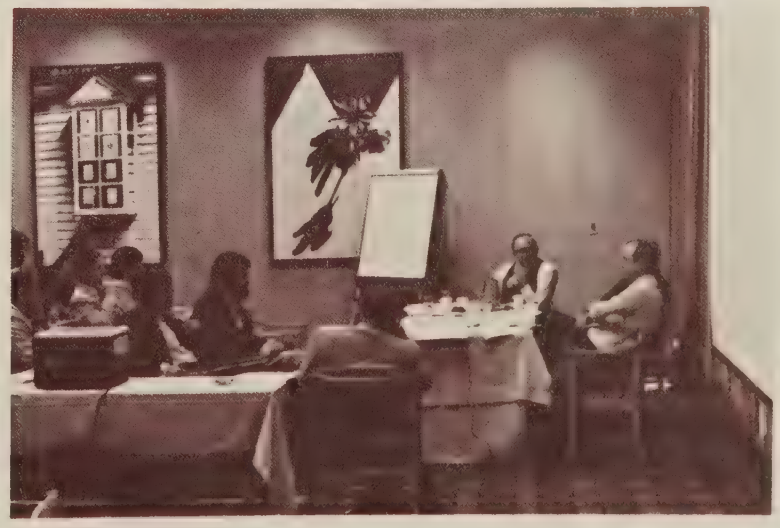


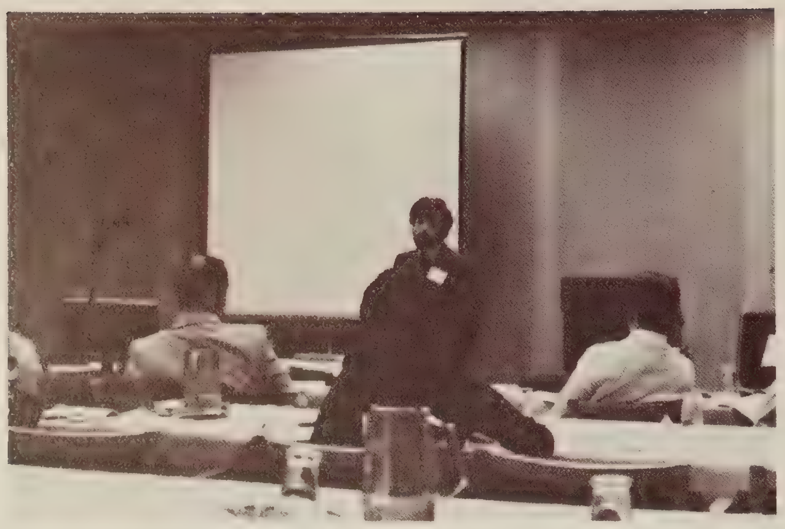
Project 1J review being led by George Pilkington II, FHWA project manager.

• 5K—The recommendations resulting from this project review included the consensus that the project is necessary and important, that it should be expanded to be truly representative of new bridge design concepts in both concrete and steel, and that inspection problems on existing concrete bridges should be transferred to Project 5L.

• 5L—During this review, a great deal of attention was focused on a fracture control plan for new steel bridges with fracture critical members. Most of the participants agreed that more work is needed both on determining the significance of the fracture toughness characteristics of the bridge steels used and on the level of quality control and inspection required during the fabrication of steel bridge members. There was also considerable discussion on how to avoid critical details created by improper design which no amount of quality control or toughness in the steel can make completely safe.

Breakout session of Project 1A.





Project 1N review being led by FHWA project manager John Fegan.

• 7A, B, C, D—The following subjects under the present maintenance R&D program were discussed: Equipment Management System—Test and Evaluation; Litter Pickup Machine; Pavement Patching Demonstration and Evaluation; Salt Brine Deicer; Value Engineering of Selected Maintenance Activities (Rest Area Maintenance); and Mechanization of Pothole Patching. In addition to these reviews of Category 7 projects, the steering committee for the Highway Maintenance Research Needs Study met to begin work on developing a new list of R&D maintenance needs that will replace the list of 27 items already acted on. State and field maintenance personnel will be involved as much as possible in developing the new list to insure immediate, effective response by R&D to future maintenance needs. (*2*) The general framework for regional needs workshops was planned and meeting locations were established, including Atlanta, Ga.; Hartford, Conn.; San Francisco, Calif.; and Champaign, Ill. A national meeting is scheduled for August 1980 in Minneapolis, Minn., at which the maintenance R&D needs for the next 5 to 10 years will be finalized.

In addition to the discussions in these formal review sessions, there was opportunity for informal discussion during the session breaks and the two receptions held during the week. As in past years, the 1979 FCP Review Conference was a forum for discussion and exchange of information between research and operations personnel and gave participants a chance to evaluate and discuss the progress made in the FCP since its formation in 1970.

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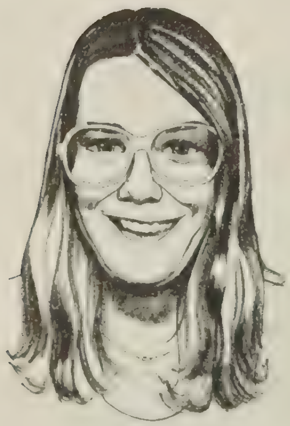

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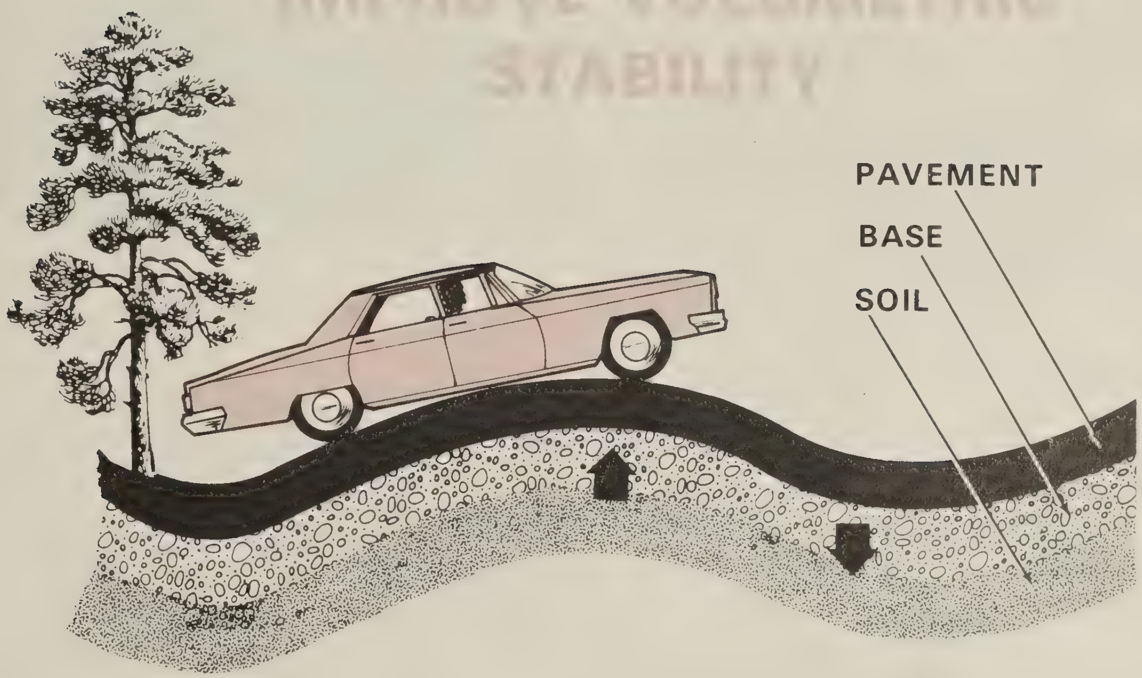
The Frost Action Problem—An Overview of Research to Provide Solutions



by
Albert F. DiMillio and Donald G. Fohs

Introduction

The ravages of frost action on roads and streets is well documented by the news media each spring and by county and district maintenance engineers throughout the Northern States. For example, The Road Information Program (TRIP) estimated that $1.8 billion was required to rebuild the 9 600 km (6,000 miles) of pavement in the Northern United States that was destroyed during the winter of 1977. This expenditure was in addition to the cost of filling potholes and surfacing pavements with minor damage. (*1*)[1] According to the TRIP report, automobile repairs resulting from rough pavements and increased cost to transport goods because of detouring to avoid damaged roads should also be added to the $1.8 billion to full assess the impact of severe winter weather.

The problem of maintaining roadways and airfield pavements in areas of seasonal frost has long been a major concern to pavement design engineers. Although pavement designers have attempted to provide protection against the detrimental effects of frost action, the severe winters of the past several years have demonstrated that a basic and rational methodology for analyzing and designing pavement systems in cold regions does not presently exist.

The detrimental effects of frost action on subgrade soils contribute significantly to pavement distress and failure. During the past 5 years, Federal and State transportation agencies have made an effort to mitigate the effects of frost action on subgrade support capacity. Although the solutions have not been verified, it is important to periodically review current research efforts to assess the progress that has been made and to examine future plans that might need to be altered or redirected.

Proper coordination of the overall research and development (R&D) efforts is essential for efficient and prudent use of government funds and resources to solve the frost action problem. Various States and the Federal Highway Administration (FHWA) have joined forces

[1] Italic numbers in parentheses identify references on page 158.

through the Federally Coordinated Program (FCP) of Highway Research and Development to develop a comprehensive and well-coordinated program of R&D in this area. Also, in recent years the Federal Aviation Administration (FAA) and the U.S. Army Corps of Engineers (OCE) have joined forces with the States and FHWA to address this complicated problem. Current cooperative efforts of these Federal agencies extend previously separate R&D programs in this area. Significant past contributions of State highway department and university researchers also have been incorporated into the current program, and efforts are underway to expand the interest and involvement of these researchers.


Figure 1.—Typical pothole problem.

Before 1972, FHWA played a passive role in the development of new technology and improved predictive techniques to address frost action. The principal contribution of FHWA's Office of Research was to coordinate the efforts of the various State highway agencies and universities conducting separate research studies in this area. As the number of studies increased and significant interest was generated during the Interstate construction program, FHWA researchers became actively involved in the overall effort.


Figure 2.—Typical edge cracking problem.

In August 1973, FHWA organized a frost action research conference in Kittery, Maine, to discuss the status of ongoing research. An important objective of this conference was to determine the interest of the highway research community in participating in a large field investigation program for correlating actual heave measurements with the various available predictive techniques.

The Kittery conference brought together practicing engineers and researchers from universities, State highway agencies, FHWA, FAA, and OCE. It was agreed that field data on actual measurements of frost heave and the resulting loss of bearing capacity (thaw weakening) were needed to compare with predicted values. The consensus was that sections of inservice pavements be selected as sites for sampling, testing, and periodic measurement of frost heave. FHWA's Office of Research was assigned the task of planning an experiment to acquire and correlate the data.

FHWA initiated a Federally coordinated effort to develop a field testing program to validate or disprove existing prediction methods and stimulate the development of improved techniques. This article discusses the development of the field test program and the new predictive techniques.

In 1977, FHWA organized a frost action research review meeting at the FCP conference[2] in Atlanta, Ga., to review the progress of current efforts and plan for future investigations. Plans for many of the current research efforts were formulated or conceptualized at this meeting.

Nature of the Problem

The seasonal variation in the serviceability of a pavement is very pronounced in areas subject to alternating

[2] FHWA conducts annual research review meetings to assess the progress of the Federally Coordinated Program of Highway Research and Development.

Figure 3.—Concrete pavement breakup.

Figure 4.—Differential surface frost heave.

freezing and thawing. The combination of freezing and thawing of pavement subgrades is commonly called frost action. Differential pavement surface heaving (poor rideability) frequently is the effect of freezing, and subsequent thawing may lead to a greatly reduced load-carrying capacity—thaw weakening. (*2*) Many potholes and other pavement breakups (distress) result from thaw weakening (figs. 1-3).

Some soils are more susceptible to frost action than others and the amount of heave that occurs is not a good indication of how much strength loss will occur during the thaw period. It is also probable that a soil of lower frost susceptibility will experience greater heave than a soil of higher frost susceptibility if placed under more adverse temperature and water conditions. In fact, a highly frost-susceptible soil will not heave at all if either one of these two conditions (temperature and water) is missing. Conversely, clean granular materials not normally classified as frost susceptible will heave if the temperature and water conditions are sufficiently adverse.

Differential heaving

Because the amount of heave is dependent on three conditions that can be quite variable—frost susceptibility of the soil, freezing temperatures, and access to groundwater—uniform heaving cannot be expected. The differential heaving that results causes surface irregularities and general surface roughness in the form of bumps, waves, and distinctive cracking (fig. 4). Severe cases of differential heave will usually reduce traffic speeds significantly and may cause damage to vehicles or loss of control of the vehicle. The potential for abrupt differential heave at cut-to-fill transitions or culverts requires special design considerations. (*2*)

The amount of heave that occurs is not entirely a result of the expansion of free water in the soil voids when freezing temperatures penetrate the subgrade soil mass. This can often be a small percentage of the total heave. In severe cases of heaving, the extent and rate of growth of ice lenses are determined by the soil's ability to draw water from below by capillarity and also by the rate and depth of penetration of the freezing temperatures. The formation of ice lenses responsible for heaving is governed by the interaction of heat and mass transfer (moisture movement) in porous soil media—a very complicated phenomenon.[3] The growth of ice lenses also results in decreased soil density. After several cycles of freezing and thawing, the soil fabric can be adversely changed depending on the type of soil and the amount of ice lens buildup.

Thaw weakening

Thaw weakening is considered by many to be the more critical manifestation of frost action. It is just as complicated as the heave problem and it is probably more difficult to evaluate or predict. This problem occurs when the ice lenses formed in the subgrade during freezing begin to thaw from the surface downward. This thawing results in melt water being trapped between the pavement and the still frozen portion of the subgrade, which accompanied by loading of the soil in its loosened state generates excess pore water pressure and a corresponding decrease in load-carrying capacity. The duration and frequency of load application (static versus

[3] "Mathematical Modeling of Simultaneous Transport of Moisture and Heat in Soils," by B. J. Dempsey. Unpublished report presented at the FCP Research Review Conference, Atlanta, Ga., 1977.

dynamic) may also impact load-carrying capacity; that is, dynamic loading may be more destructive to soil structure, thereby reducing strength.

The increase in water content resulting from freezing and subsequent thawing is more detrimental for some soils than for others. The stability of fine-grained soils is more sensitive to changes in moisture content than is the stability of granular materials; that is, very slight increases in moisture content for silts and clays significantly decrease their stability while similar changes in water content do not affect the performance of granular materials. However, soil moisture content cannot be used as an indirect measure of thaw weakening because certain clay soils lose significant supporting capacity during thawing without significant increase in bulk moisture content. (*2*) A different set of physical and environmental factors influence heave and cause subgrade weakening, thus requiring separate evaluations.[4]

Frost susceptibility indicators

The frost action problem is comprised of a series of interdependent factors or parameters that vary over a range of values. Understanding the mechanism of frost action in soils requires a knowledge of soil behavior including soil physics. The frost susceptibility of soils is still a relatively unknown quantity; however, it is generally recognized that a soil is susceptible to frost action only if it contains fine particles. Most studies have shown that soils free of fines (particles smaller than the 200-mesh sieve) do not develop significant ice lens buildup or ice segregation. As a result, the engineering community has used various indirect measures or indicators based on particle-size distribution, pore-size distribution, grain shape, and plasticity characteristics. All of these contribute to frost susceptibility or ice lens buildup in varying degrees. One of the best known indicators is the Casagrande Criterion. (*2*)

The Casagrande Criterion, based on particle-size distribution, gives a high assurance that frost action problems will not occur; however, in many cases it rejects soils that are not a problem in the frost environment. Because sieve analyses are simple and inexpensive to run, many highway engineers prefer to use the Casagrande Criterion when an unexpected change in the soil profile is uncovered during construction. An answer is soon given on the soil's suitability for use within the roadway.

To avoid detrimental effects of frost action, most agencies require that materials within the frost penetration zone be nonfrost susceptible. This frequently requires that subgrade soils be excavated and replaced with frost-free material. Because excavation and replacement with frost-free material is expensive, and the material being replaced may not be an adequate performer, researchers are developing more accurate and direct methods of measurement. Most of these methods involve the unidirectional freezing of a soil sample and the measurement of heave rate, heave pressure, and moisture tension.

CRREL test

The most widely used test of this type was developed by OCE at its Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, N.H. (*3*) The CRREL test, based on heave rate, is more accurate than the indirect methods; however, it is a long and tedious test to perform and requires large-scale and expensive cold rooms and testing equipment. Many State highway agencies and some foreign countries have developed simpler, more rapid test methods to directly measure frost susceptibility. (*4*)[5] None of these methods has been adequately verified nor has the CRREL test been thoroughly verified by field data comparison studies, thus the need for full-scale field tests is well established.

The frost susceptibility value provides an order ranking for a particular soil and must be considered with the other physical and environmental factors to predict a pavement's performance in seasonal frost areas.

Status of Current Research Efforts

In the past 10 years several advancements have occurred in the determination of frost susceptibility and analytical modeling of frost action. Significant developments in laboratory and field test equipment and instrumentation systems have contributed to these advancements. But the lack of well-documented field data has delayed efforts to determine the best method to use, resulting in confusion and indecision for both designers and construction engineers (fig. 5).

The most significant development occurred in September 1978 when a comprehensive, 5-year research investigation was initiated by FHWA, FAA, and OCE to validate and refine certain selected frost action predictive

[4] "Materials Characterization of Thawed Subgrades," by M. W. Witczak. Unpublished report presented at the FCP Research Review Conference, Atlanta, Ga., 1977.

[5] "Rapid Test for the Determination of Frost Susceptibility of Soils," by R. M. Leary. Unpublished report presented at the FCP Research Review Conference, Atlanta, Ga., 1977.

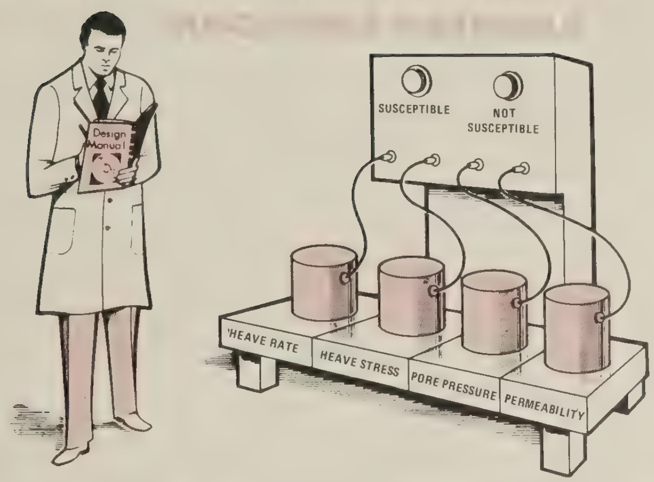


Figure 5.—Criteria for identifying frost-susceptible soils are greatly needed.

techniques. The investigation is being performed by CRREL and includes evaluation of the various devices for measuring frost susceptibility, mathematical modeling, laboratory predictive techniques for assessing strength loss due to thawing, and monitoring full-scale field test sites to provide correlative data.

Phase 1

Phase 1 of the CRREL study involves evaluating and selecting the best test method for determining the frost susceptibility of soils quickly and inexpensively. Three methods will be selected and validated with field test data. Each of the three chosen methods will be used to test six to eight soils that are being studied at the field test sites.

Phase 2

Phase 2 involves the mathematical modeling of frost action and deals with frost heave and thaw weakening. A preliminary computer model of frost heave was developed; an attempt will be made to develop a thaw weakening algorithm to be included in the mathematical model of frost heave.

The existing CRREL finite element model couples heat and moisture transport in freezing soil-water systems and provides quantitative predictions of the frost heave a soil will experience under different moisture and climatic conditions. The model includes algorithms for phase change of soil moisture as well as frost heave and permits several types of boundary and initial conditions. The Galerkin method of weighted residuals was used to simulate the spatial aspect and the Crank-Nicolsen method was used for the time domain portion of the finite element model. (5)

Preliminary verification of the frost heave model was conducted with the aid of laboratory soil column studies and also by comparing model predictions with available field data. Verification and refinement of the model under the current study will expand the laboratory soil column studies (Phase 3) and compare the predicted values generated from the model against field data obtained from Phase 5. The field data used in the preliminary verification phase were obtained from other sources and did not completely suit the study's needs.

The preliminary model was also inconclusively evaluated with respect to the effects of surcharge and overburden. These effects will be more fully evaluated under the present study by the use of the more elaborate soil column device designed and built in Phase 3.

Phase 3

In Phase 3 a laboratory soil column device will be designed and built to nondestructively measure moisture content, density, and soil suction changes that occur during unidirectional freezing of the soil sample. The device will be used to characterize parameters and evaluate and refine the mathematical models developed in Phase 2.

Although expensive to build and operate, the dual gamma energy device will provide greater accuracy, flexibility, and speed of testing because it simultaneously monitors key parameter changes without having to stop a particular test to take a moisture and density sample. The device should more than pay for itself in reduced testing costs during the life of the study.

As previously mentioned, the mathematical model was developed in terms of energy requirements to make water and heat move through soil. The water movement portion of the model is based on Darcy's Law, which requires knowledge of the hydraulic conductivity (coefficient of permeability), and the driving head, which is the sum of the pressure head and position head. Because pressure head can be positive or negative, piezometers and tensiometers will be included in the soil column to measure the pressures that are involved.

Another important input parameter is a diffusivity term, which is a function of the hydraulic conductivity and the slope of the moisture characteristic curve of the soil in question. The interaction of all of these properties of the soil-water system can best be studied by nondestructively monitoring the changes that occur as the freezing front advances in the controlled environment of a dual energy soil column device.[6]

The device will consist of two gamma sources (Cesium will be used to measure moisture content changes and Americium will be used to measure density changes), detectors, signal conditioning and analyzing equipment, recording equipment, and a controller. The controller will permit automatic operation of the system or permit the operator to manually choose the source, vertical position, or counting time, as the situation dictates. In the manual mode the operator may record output from the system manually or have the output recorded on cassette tape. A movable stage is also provided to simultaneously move the radioactive (gamma) sources and their respective detectors vertically.

Phase 4

Phase 4 of this study is concerned with the development of a thaw weakening index of subgrade supporting capacity. This includes field and laboratory testing and is closely connected to the analytical work in Phase 2, which involves the development of a thaw weakening algorithm for the mathematical model of frost action.

The field investigations (Phase 5) include repeated-load plate-bearing (RPB) tests to determine the supportive capacity of subgrade or unbound base course soils during the frozen, thawed, recovered, and partially recovered conditions at the various test sites. Recoverable and nonrecoverable vertical displacements are measured at the plate itself and at various radial distances from the plate under a selected plate load.

FHWA research personnel performed RPB tests similar to the CRREL tests using the FHWA "Thumper." (6) The RPB and Thumper tests are being conducted at a load duration and frequency that represent a vehicle traveling at creep speed. The repetitive load triaxial tests are being conducted using the same load rate as the field tests. The duration and frequency of load application were selected so that no drainage would occur during loading, thus excess pore pressures would develop as under traffic loading.

The principal laboratory investigation for this phase of the work involved repeated load triaxial compression tests on undisturbed samples of the test site soils. The samples were obtained by coring the frozen subgrade soils during the first winter cycle of the test program. The samples remain frozen until tested and, upon completion of the repeated load tests, the samples are allowed to thaw and then are retested in the same manner. The test loads are stopped before the samples fail so that they remain suitable for retesting. The next tests are run on the same samples at different stages of recovery from thaw weakening. Thaw recovery is artificially produced by desaturating the thawed specimen to various partial saturation points. The CRREL researchers monitor moisture content, density, and stress state variables including moisture tension. The deformation moduli will be expressed in terms of these variables.[7]

Various resilient moduli for the soil at various depths in each test section were analyzed to determine which values gave surface vertical displacements that matched the measured field values obtained with the RPB equipment. The CHEVRON computer program (elastic layered systems analysis) and the FHWA VESYS system were used to calculate the vertical displacements.

Phase 5

Phase 5 involves two field test sites used by CRREL researchers to verify the analytical and laboratory predictive techniques. The Massachusetts test site is located in Winchendon at an off-road site on State Highway Department property behind a district maintenance depot, and the New York site is located at the Albany County Airport.

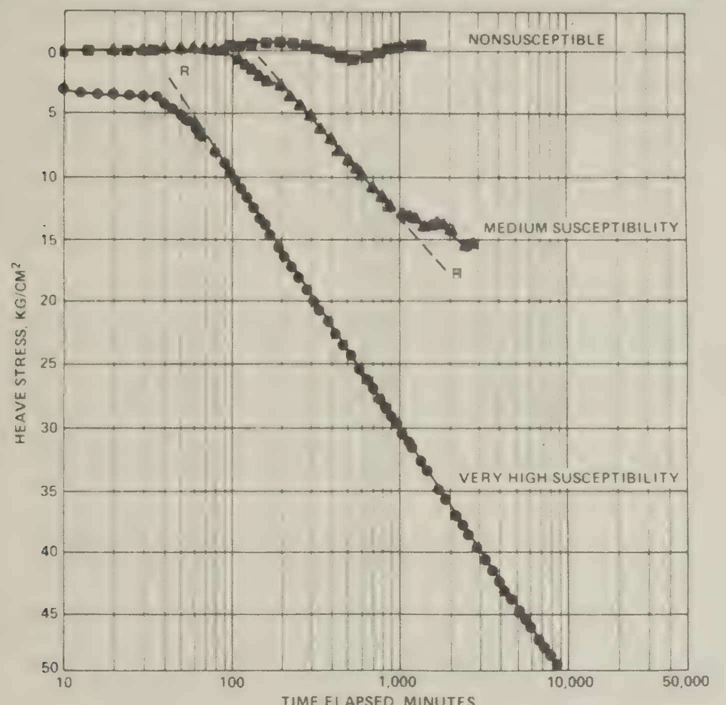
The Winchendon site was constructed in 1977 by the Massachusetts Department of Public Works (MDPW) to evaluate an improved test apparatus that was developed for MDPW by Massachusetts Institute of Technology (MIT) to determine the frost susceptibility of soils. The new device, the Freezing Soil Heave Stress System (FSHSS), was delivered to the MDPW in 1974 for in-house evaluation. Figure 6 shows typical test results. Although the FSHSS test results were reproducible, they did not correlate with CRREL heave rate test results. Because of the lack of field test results to validate either of the methods, it became necessary to conduct the additional field studies at Winchendon.

To minimize site-associated difficulties it was decided that a number of different soils would be studied under the same environmental conditions by importing

[6] "Mathematical Modeling of Simultaneous Transport of Moisture and Heat in Soils," by B. J. Dempsey. Unpublished report presented at the FCP Research Review Conference, Atlanta, Ga., 1977.

[7] "Proposed Investigation of Thaw Weakening of Subgrade Soil and Granular Unbound Base Course," by T. C. Johnson. Unpublished report presented at the FCP Research Review Conference, Atlanta, Ga., 1977.

TYPICAL RESULTS FOR VERY HIGH, MEDIUM, AND NONSUSCEPTIBLE SOILS



1 Kg/cm^2 = 14.2 psi

Figure 6.—Typical heave stress versus log time plots.

Figure 7.—Each of the 12 soil types tested at the Winchendon site was placed in separate cells at two different elevations above groundwater level.

selected problem soils to the Winchendon site and placing them in prepared trenches (cells). The Winchendon site was chosen because it has a high natural groundwater table, granular subsurface soil with a relatively high permeability, and a relatively deep frost penetration.

Twelve different soils were obtained from various parts of Massachusetts and several neighboring States. Each soil was placed in a cell at two different water table elevations (0.9 and 1.5 m [3 and 5 ft]) and capped with a 75 mm (3 in) bituminous surface course. Figure 7 shows a partially completed soil test cell on the left and a completed cell on the right.

The data being collected in the field tests are as follows:

- Precipitation.
- Ambient temperature.
- Depth of frost penetration.
- Water content profile.
- Moisture tension.
- Frost heave.
- Subsurface temperatures.

In addition to the above data, RPB tests will be run by CRREL and FHWA during each seasonal variation to obtain appropriate pavement response data (deflections) under certain selected loads. As previously mentioned, undisturbed samples have been taken for use in the laboratory characterization program at the CRREL facility. Frost susceptibility and other soil tests not requiring undisturbed samples will be performed on soil samples gathered from stockpiles at the Winchendon site.

The Albany County Airport site, under observation since the fall of 1979, involves the construction of an extension to an existing taxiway and an existing but little-used taxiway pavement that has experienced detrimental frost effects.

The cross section of the extension will comprise 330 mm (13 in) of asphaltic concrete, 584 mm (23 in) of crushed stone base, and approximately 305 mm (12 in) of a granular subbase. The pavement cross section of the little-used taxiway is 102 mm (4 in) bituminous aggregate base and 406 mm (16 in) of granular base. The subgrade varies among a silty sand, silt, and clay at both sections.

The sampling and testing programs for the Albany site are very similar to those for the Winchendon site, except that sampling and instrumentation programs will be complicated because no construction work is planned for the little-used taxiway and because of the traffic on the existing taxiway.

Test pits were excavated along the little-used taxiway to obtain bag samples of each layer of soil and base material and to install instrumentation. The installation of instrumentation and collection of bag samples for the existing taxiway took place during construction operations. Borings were also taken during the first winter to obtain frozen samples of the subgrade soils to be used in the laboratory triaxial testing program.

Phase 6

Phase 6 involves formulating preliminary design and construction guidelines for pavements in seasonal frost areas. These guidelines will be prepared for practicing highway and airfield pavement design engineers. The preliminary guidelines will be expanded by CRREL under a separate contract with the Implementation Division of FHWA's Office of Development.

Potential Solutions to Frost Action Problem

Potential solutions may be classified into three main groups that will address the previously mentioned three major factors that control frost action in and beneath pavement systems—freezing temperatures, access to water, and frost-susceptible soil. All three factors must be present simultaneously to cause frost heave and thaw weakening problems; eliminate any one of them and you remove the problem. If the severity of any or all three of the factors is reduced, a corresponding reduction in frost action severity will occur—usually on about a one-to-one basis.

For example, freezing temperatures can be excluded or significantly reduced by using thermal barriers or insulators. The most popular insulating materials are extruded polystyrene boards (fig. 8) and foamed-in-place polyurethane. Many public works agencies have used this approach successfully; however, some have experienced serious problems with differential surface icing conditions between insulated and uninsulated pavement sections. Proper design of transition sections is required. (2)

Moisture barriers have also been used to cut off the supply of subsurface water that can migrate to the freezing front. This is another case of one theoretically sound solution creating another problem—the use of a capillary cutoff layer below the freezing zone but above the water table will trap infiltrating surface water between the pavement and the impervious layer.

Figure 8.—Placing polystyrene boards on a soil subgrade to provide a thermal barrier.

The most popular method for treating frost action involves removing or modifying the frost-susceptible soil element. Perhaps the best general source of information on this topic and the frost action problem in general can be found in reference 2.

In most cases public works agencies will control frost action damage by specifying nonfrost-susceptible material beneath pavements within the frost zone. For example, the MDPW specifications for soil and unbound base course materials within the frozen zone are as follows:[8]

- When the in situ soil within the frost depth contains more than 12 percent by weight passing the No. 200 sieve (0.074 mm [0.0029 in] opening) it shall be excavated and replaced with special borrow containing less than 10 percent passing.
- Embankment material within the frost depth shall consist of borrow material with less than 10 percent by weight passing the No. 200 sieve.

As previously mentioned, these specifications have proven to be very effective in excluding frost-susceptible soils; however, they are very expensive. One way to reduce the costs is to improve the accuracy and speed of frost susceptibility measurement equipment so that nonfrost-susceptible soils are not classified with the "bad actors" under the same specification that is based on particle-size classification.

A rapid test method is necessary to eliminate long delays whenever an unexpected change in the soil profile is uncovered during construction operations. The test should also be simple and inexpensive; many public works agencies will not invest in large-scale and expensive cold rooms and testing equipment.

Solution Selection

Collective efforts to solve the frost action problem have produced many new developments and many refinements of older processes or materials. However, the interaction of the soil element and the various environmental factors is not thoroughly understood. Until it is reduced to solvable mathematical expressions,

[8] "Full Depth Testing of Frost Susceptible Soils," by D. C. Rice. Unpublished report presented at the FCP Research Review Conference, Atlanta, Ga., 1977.

it will not be possible to rationally select from the available solutions.[9]

The proper solution may involve a combination of the various techniques that are available or are being developed. What is needed then is a rational decisionmaking methodology that includes appropriate tests and predictive techniques for assessing the potential for and consequences of frost action.

The mathematical model of frost heave potential should be a useful tool in selecting the proper course of action. This model will be especially valuable if an algorithm for thaw weakening can also be added to it.

The importance of the development and verification of an accurate, rapid, and inexpensive device or methodology for determining the frost susceptibility of soils is well established. It was previously explained to be both a design and construction control tool. The CRREL study will attempt to identify the best available tool and provide the required field measurements for verification. The carefully controlled and well-documented field studies will provide the necessary data base for improving any of the existing methods or the development of a newer, improved method. These data will be the first of their kind and will be valuable in the research community. (*4*)[10] [11] [12]

The development of a thaw weakening index of subgrade supporting capacity will also be a valuable design tool. This engineering approach to thaw weakening will supplement the scientific approach of the mathematical modeling phase. The empirical index will probably be based on the observed relationships between the resilient modulus and one or more of the following parameters:[13]

- Moisture tension.
- Moisture content.
- Density.
- Temperature.
- Permeability.
- Confining stress.
- Poisson's ratio.
- Various indices of material type.

The success of this work task depends on the correlation between the laboratory triaxial test results, the field RPB test results, and the soil column results. It also depends on the capability of the frost heave model to predict heave and changes in water content and density in the field.

The above discussion shows that it is not possible at this time to select the right "solution" to the "problem" of frost action beneath pavements. This is not to say that current design techniques are based on "guesswork" but rather that they are too conservative. The CRREL study is expected to provide answers that will form the basis for an improved design procedure for pavements in seasonal frost areas.

Summary

The damage to U.S. highways from frost action amounts to several billion dollars annually. Despite many years of research the problem has not been adequately defined, and therefore, rational solutions are unavailable.

FHWA is attempting to coordinate the resources of other Federal agencies and State highway departments to address this problem. The CRREL study is the major thrust of this effort, and a major breakthrough is anticipated.

Although each phase of the study is very important and each could stand alone, the most important aspect of the investigation is the soil column study. The results obtained from this portion of the investigation will tie together all of the other major aspects and provide the means for understanding the complicated frost action problem.

The analytical and laboratory testing programs that support the field testing programs are expensive, and the field testing and instrumentation monitoring costs are also high. It is unlikely that any Federal or State agency could afford to take on this challenge alone. Thus, the need to coordinate and combine resources is well established.

The results of the Winchendon and Albany field studies will provide valuable verification data; however, the resultant data base may be only marginally adequate. A

[9] "Mathematical Modeling of Simultaneous Transport of Moisture and Heat in Soils," by B. J. Dempsey. Unpublished report presented at the FCP Research Review Conference, Atlanta, Ga., 1977.

[10] "Rapid Test for the Determination of Frost Susceptibility of Soils," by R. M. Leary. Unpublished report presented at the FCP Research Review Conference, Atlanta, Ga., 1977.

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[13] "Proposed Investigation of Thaw Weakening of Subgrade Soil and Granular Unbound Base Course," by T. C. Johnson. Unpublished report presented at the FCP Research Review Conference, Atlanta, Ga., 1977.

series of satellite field studies in various parts of the Northern United States must be developed to validate and regionally adjust the findings of the CRREL studies at the two northeastern sites. Support and technical guidance will be provided to research personnel who are interested in conducting this type of study.

The use of physical models (full-scale field tests) to validate theoretical and laboratory models remains the most popular verification tool used by the highway industry. To be effective, these field testing programs must be planned, coordinated, constructed, and monitored as closely as possible with the way the predictive techniques were developed. The same assumptions must be used and all variables that cannot be controlled must be measured. If a series of field tests is to be conducted by various agencies at different locations, special care must be taken to insure uniformity of purpose and scope.[14]

Acknowledgments

The authors wish to thank Dr. Richard Berg and Mr. Thadeus Johnson who are directing the cooperative study for CRREL. As coprincipal investigators, they are leading a team of highly qualified researchers who are conducting the large and comprehensive investigation of frost action beneath pavements. Appreciation is also extended to Mr. Carl Schulten, Chief, Airport Pavements and Facilities Branch, FAA, and Messrs. Stephen A. Cannistra and Aston McLaughlin of the Airport Pavements and Facilities Branch. Special thanks are extended to members of the special board of consultants which was established to provide guidance to the researchers. The members of this board are Dr. B. J. Dempsey, University of Illinois; Dr. D. G. Fredland, University of Saskatchewan; Dr. M. E. Harr, Purdue University; Mr. E. Penner, Canadian National Research Council; and Dr. M. W. Witczak, University of Maryland. Dr. E. J. Barenberg has also contributed significantly to this investigation through his role as special consultant to FAA. The authors would also like to thank the MDPW and the Albany County Airport manager for their cooperation in the use of their facilities.

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Development and Testing of Advanced Control Strategies in the Urban Traffic Control System

by
John MacGowan and Iris J. Fullerton

This is the last of three articles that trace the evolution and accomplishments of the Urban Traffic Control System (UTCS) research project. This series of articles highlights the research activities undertaken in the past 10 years and stresses the potential application and anticipated benefits accruing from this major research project. The first article, published in *Public Roads,* vol. 43, No. 2, September 1979, described the development of offline signal timing programs, the provisions of the real-world fully instrumented test laboratory established in Washington, D.C., and the first generation control strategy. The second article, published in *Public Roads,* vol. 43, No. 3, December 1979, summarized the hardware and strategies of the Bus Priority System (BPS), the second and third generation software systems, the evaluation of the various strategies, simulation model development, and vehicle detection. This article presents the technical accomplishments of the UTCS research project.

Introduction

The primary purpose of the UTCS project was to generate knowledge and experience in the design and implementation of computer-based traffic control systems. The preceding articles of this series detailed the activities undertaken within the UTCS project. The following are the major results of these activities and their application to traffic control in urban areas.

The UTCS project makes available significant data on planning digital computer-based traffic systems. The advantages to the users are as follows: Technical information that assists the explicit preparation of design specifications; successful system procurement by specifying proven software; easier staged construction without tying the agency to the original contractor; better system changes nationwide; reduction of procurement costs by eliminating the costs of new commercially developed software; and an interchange of operators among similar systems in various cities.

In addition to these advantages associated with the overall planning and implementation of a computer-based system, the UTCS system provides significant operational advantages to the user agency. For example, the UTCS system provides the following:

- Capability to use many signal timing plans designed for special problems or periods of the week.
- Operational flexibility because of operator-in-the-loop functions.
- Immediate awareness of operating status using a map display or other available display devices.
- Surveillance information for recurring traffic problem locations.
- Instant notification and diagnosis

of system element malfunction to facilitate hardware maintenance.

- Automatic data recording for engineering analyses.
- Computation of measures of effectiveness that may be correlated with other contemporary measures such as fuel consumption, vehicle emissions, or safety.

Results of the Development of Advanced Strategies

The research results are summarized in perspective. First generation control (1-GC) improved operations in Washington, D.C., in the phase I evaluation; in the phase II evaluation, second generation control (2-GC) performed approximately equal to a well-timed pretimed system. Third generation control (3-GC) was disappointing when compared to the well-timed pretimed system. Critical intersection control (CIC) strategies did not improve overall system performance for any system with which it was evaluated. However, net benefits were derived during certain periods of the day by judicious application of CIC. Bus delays were reduced at intersections by granting preferential treatment. A preemptive scheme of allowing additional green time to buses until they cleared the intersection approach or granting an early green signal indication worked well when properly designed for existing conditions.

Summary of findings—phase I

The results of the 1-GC alternatives evaluation are summarized in table 1. *(1)*[1] The traffic responsive (TRSP) alternative generally matched or exceeded the performance of the other traffic control alternatives. The differences in traffic delays were relatively small, ranging from 2 percent better than TRSP to 4 percent worse. These small differences may have resulted because the three time periods tested were not truly representative of the total potential for improvement. This indicates that longer periods of the day should be considered in evaluations.

Table 1.—Summary of performance of tested strategies—phase I

Comparison[1]	Time period 7:00–9:45 a.m.	1:00–3:00 p.m.	4:00–6:30 p.m.
TRSP versus DCP	−4.0	+0.3[2]	−3.9[3]
TRSP versus TOD	−1.8	−2.8[3]	+2.0
TRSP versus CIC	+0.7	−0.5	−2.8[4]
TRSP versus BPS	−2.5	−0.8	−0.3

[1] In terms of aggregated delay.
[2] The overall delay reduction in the dense grid portion of the network; the total increase in delay in other portions of the networks. A positive sign indicates less delay with alternative when compared with TRSP.
[3] Statistical significance at 5 percent level.
[4] Statistical significance at 1 percent level.

Despite little difference in performance, the computer-based system remains an attractive alternative. Fewer person-hours are required to develop the timing using a computerized optimization program than are required for manual preparation of timing. Also, the computer-based system has greater operating flexibility and improved hardware maintainability. In addition, the effectiveness of user-generated signal timing plans is site-specific. The impact of these plans on traffic flow efficiency may vary considerably, depending on the efficacy of the original plans to which they are compared.

The phase I evaluation also indicated that the CIC alternative equally distributed delay on the approaches to a given intersection. Under TRSP, approaches with good offset relationships and low delay were generally degraded by the CIC algorithm. Approaches with poor offset relationships and high delay were improved. CIC can be more useful on arterials than in grids because of the fewer offset and capacity conflicts.

The BPS algorithm worked well; bus delays were reduced as much as 42 percent (from 0.831 to 0.481 minutes) on a 1.5 km (0.93-mile) section of a given route. There is a level of bus activity beyond which the BPS operation would be unstable. More than 30 to 50 buses per hour or nearly 1 bus per cycle would lead to congestion at the BPS intersection. Automobiles, as well as buses, would be penalized by the intersection congestion, and the BPS algorithm should be switched off. At the higher bus levels, fixed time plans could be developed to account for constant bus presence.

Summary of findings—phase II

The results of the comparisons between the advanced control strategies (2-GC and 3-GC) and the base case (Washington, D.C., timing plans [DCP]) during phase II are given in table 2. *(2)* Differences in the performances of the strategies are based on a direct comparison of vehicle-minutes of travel in the

[1] Italic numbers in parentheses identify references on page 165.

Table 2.—Summary of performance of tested strategies—phase II

Comparison[1]	Time period: 8:00–9:45 a.m.	10:15–1:00 p.m.	1:00–3:45 p.m.	3:45–6:15 p.m.	7:00–8:00 a.m. 9:45–10:00 a.m. 6:15–7:00 p.m.
2-GC versus DCP	+ 3.5[2]	+3.2	+1.1	+9.3[3]	+ 1.9
3-GC versus DCP	+13.4[3]	+9.8[3]	+3.4	+9.1	+15.2[3]

[1] In terms of vehicle-minutes of travel.
[2] A positive sign indicates greater vehicle-minutes of travel when compared to DCP.
[3] Statistical significance at 5 percent level.

network.[2] When two data sets are compared, the vehicle-minutes of travel represent a combination of travel time and volume, resulting in a "total travel time difference."

The 2-GC control strategies were the first of the advanced control algorithms to be tested. Although networkwide it showed 4 percent degradation in performance relative to the DCP alternative, 2-GC performed better than all other alternatives on the arterial portion of the network showing approximately a 2 percent improvement.

When evaluated over a 10-year period, estimated costs for using 2-GC are 10 to 15 percent higher than for 1-GC. After 10 years, the costs become essentially equal. Given the relatively small cost difference between 2-GC and 1-GC and the self-adapting characteristics of 2-GC, 2-GC offers promise and warrants further experimentation on its application and effectiveness.

During all time periods, 3-GC was less efficient than DCP; 3-GC experienced approximately 10 percent more vehicle-minutes than DCP. Its performance was comparable to DCP in only one case (mid-afternoon, in the dense grid portion of the network). Possible explanations of 3-GC's poor performance relative to the other strategies include the following:

- 3-GC depends on good surveillance and historical traffic data, and they may not have been accurate.
- The saturated network portion of 3-GC was not tested. The unsaturated portion was not intended for congested flow operations and, as expected, performed poorly during these conditions.
- There was not enough calendar time available after 3-GC development to permit the necessary fine tuning and calibration.

The conclusion is that 3-GC must still be considered in the "research and development" stage, and the basic concept of variable background cycle networkwide should be reexamined.

Summary of findings—New Orleans

The evaluation results of the UTCS 1-GC system implemented in New Orleans, La., are presented in table 3. (3) This table compares strategies for each time period for the total network. The comparison of New Orleans timing plans (NOP) with time of day (TOD) indicated a statistically significant 8.8 percent improvement of TOD over NOP. The comparison of NOP with TRSP indicated a statistically significant 8.5 percent improvement of TRSP over NOP. A negligible 0.2 percent difference resulted from a comparison of TOD with TRSP.

These results show a more substantial and consistent improvement in traffic flow in New Orleans with UTCS computer control than in traffic flow in Washington, D.C., with UTCS. The direction of change is generally consistent for UTCS 1-GC evaluations, but the improvement was greater in New Orleans.

Given that the procedures were similar, the differences are probably related to the less congested network conditions found in New Orleans. Under these conditions, the traffic signal system has a more direct impact on traffic flow. Additionally, it is likely that the DCP plans more closely matched existing conditions than did the NOP plans. The New Orleans results are probably typical of cities with populations less than one million because the base signal system and traffic characteristics are

[2] The comparison between DCP and TRSP is given in table 1. That comparison is given in terms of aggregated delay.

Table 3.—Summary of performance of tested strategies—New Orleans, La.

Comparison	Time period 7:00–9:00 a.m.	9:00–11:30 a.m.	11:30–1:45 p.m.	1:45–3:30 p.m.	3:30–6:30 p.m.	6:30–9:00 p.m.	7:00 a.m.–9:00 p.m.
TOD versus NOP	+15.5[1]	+ 9.8	+ 9.1	+2.5[2]	+7.9[2]	+ 8.7	+8.8[2]
TRSP versus NOP	+18.4[2]	+15.2[2]	+10.8	+2.7	+0.4	+13.2	+8.5[2]
TRSP versus TOD	+ 2.9	+ 5.5	+ 1.7	+0.2	−7.5	+ 4.5	−0.2

[1] A positive sign indicates less vehicle-minutes of travel with the first alternative when compared with the second alternative.
[2] Statistical significance at 5 percent level.

more typical than those found in Washington, D.C.

Results of System Design and Specification Research

The system design and specification phase of the research project provided much information and contributed significantly to the development of techniques that are used today. The hardware and software configurations used for the UTCS test area may be applied, in whole or in part, to any urban traffic control system. The size and complexity of the system installed in the test area required additional detectors and computer data handling for evaluation. The UTCS software and its data base, however, can be scaled to suit each local application. The programing of the UTCS software in FORTRAN language provides the maximum flexibility to use various computers as well as the minimum programing for machine-related routines and data base requirements. It also can accommodate future modifications and updates.

When implementing the system, the number of required detectors and controllers and the data handling capability of the central data processor would depend on the number of intersections to be controlled and the local traffic characteristics. The peripheral equipment at the data processing site and the sophistication of the software package can be tailored to reflect data collection needs and budget limitations. UTCS results should be adapted to suit the particular application.

Preliminary surveys and studies of the local area would be needed to derive a street installation design providing the maximum benefits. However, the street installation design affects certain aspects of the central design including the built-in growth capability of the computer configuration. The network size, communication technique selection, and logic signal levels for interfacing through the computer interface unit (CIU) have considerable impact on the communications subsystem design. The CIU must be designed to accommodate the computer-generated commands for the total number of planned intersections and any special functions such as signal preemption. In addition, it must accommodate logic signals to computer peripheral equipment and other control and display devices such as the map display. (*4*)

Although the basic UTCS map display design can be utilized—including the symbols, legends, and lighting—the actual map, the number of displays, and the scaling must be appropriate to the locality.[3]

Results of Research in System Operation and Maintenance

Because objectives of the UTCS research project included providing guidelines and disseminating information to prospective users, much attention was given to the collection of operations and maintenance data. The following are some of the relevant aspects of the UTCS/BPS system operating experience from November 1972 to June 1976. (*5*)

A typical operational system should be readily accommodated in an approximately 110 m^2 (1,200 ft^2) area. If possible, the control center room should be isolated from building entrances by partitions or separated rooms to avoid severe temperature variations and dust accumulation. The control center should be separated from any office facilities and located in a controlled access area to keep out unauthorized personnel. A fire protection system

[3] Map displays are discussed in detail in "Map Displays for Traffic Systems," by D. Sundberg, *Public Roads*, vol. 42, No. 1, June 1978, pp. 6–16.

for the computer system components should be part of the control center design. Also, acoustical design factors should be used to minimize ambient noise; air conditioning units should be located outside the center to minimize noise.

Each unit of peripheral equipment should have an individual circuit breaker, and where power outages frequently occur, a backup power source should be provided.

Continuous operation of a system requires onhand supplies of expendable materials (tapes, cards, paper) and various stored program materials (disks, tapes), which should be conveniently stored.

The UTCS control panel was useful in determining system and equipment status and in facilitating maintenance activities. Similarly, a dynamic map display aided in troubleshooting the system, debugging and refining control techniques, and evaluating performance.

Responsibilities should be clearly designated to a specific individual or position for both operations and maintenance. It should be the operations manager's responsibility to establish and enforce procedures for emergency situations, special traffic situations, coordination with police, correcting malfunctions, alerting appropriate personnel of system status, and incorporating system changes. Another important role of the operations manager is communication with the media (press, television, radio) to keep the public informed of the system's status and improvements and to aid motorists. A staff of three people can adequately handle a normal, single-shift operation (peak-to-peak attended). A system operator can program, and a field maintenance technician can carry out normally required functions. The third person can serve as a backup in various troubleshooting activities.

The maintenance manager is responsible for systematic identification and isolation of malfunctions, direction of repair, parts procurement, and vendor warrantee processing. Other necessary tasks in effective maintenance management include arranging the required services, monitoring and verifying their completion, validating invoices, and updating as-built drawings.

The system operator should maintain a log of all system activities for tracing the operational performance history and maintenance and troubleshooting. A procedure that keeps the traffic engineering and maintenance personnel informed of all changes is essential.

It should be recognized that a computer-controlled signal system will have more stringent requirements and deployed equipment than a conventional system. Proper consideration should be given to budgeting for this.

The key factor of adequate maintenance staffing is the early assignment and training of personnel. Negative effects of turnover in staff are alleviated by good replacement training and system documentation.

The reliability of equipment and turnaround time for repairs should be projected. A repair strategy for field equipment must be established. In UTCS, when field repairs were necessary, a new unit replaced the faulty one in the field. The faulty unit was returned to a depot for repair or cycled back to the supplier for warrantee servicing. It was found that many units could be repaired by replacing a unit component. This resulted in significant cost savings and required fewer unit and module spares.

One item considered essential is a two-way communication link between the field and the control center to evaluate operation and performance. Both radio and voice line to intersection techniques are available but in any case, a communication link is a cost-effective and timesaving aid in troubleshooting a system.

System Costs and Benefits

Comparing system costs is difficult because of the variability in procurement, the extent of implementation activities, and the amount of recurring operations and maintenance costs including the following: Operating staff costs, maintenance staff costs, service contract costs, and replacement hardware costs.

As a result of the UTCS research conducted over the past 10 years, approximately 150 U.S. cities are in some stage of implementing UTCS or similar systems. Several cities have determined that installing the systems reduces traffic congestion and increases fuel efficiency. Table 4 shows these benefits for three medium-sized cities and relates the benefits to the time required to recover installation costs.

The New Orleans, La., system used UTCS; the Greensboro, N.C., system used a software package functionally equivalent to UTCS; and the Raleigh, N.C., system used a software package similar to UTCS. Fuel savings alone will recover installation costs within a 10-year lifespan of these systems (table 4). When savings from reduced congestion are considered, the installation costs can be recovered in 1 to 2 years.

The variability in system costs makes it difficult to extrapolate these data for other cities. However, it should be noted that the cost of the computer complement combined with

Table 4.—Example benefits from three medium-sized cities *(3, 6, 7)*

City	Number of intersections	Installation costs	Benefits per year[1] Reduced fuel consumption		Reduced person-hours	Travel time cost savings	Total cost savings	Years to recover investments[2] Fuel savings only	Travel time savings only	Total
		Millions	*Gallons*	*Millions*	*Thousands*	*Millions*	*Millions*			
New Orleans, La.	202	$4.40	926,000	$0.93	1,924	$5.10	$6.03	4.7	0.9	0.7
Greensboro, N.C.	159	1.35	360,000	0.36	260	0.50	0.86	3.7	2.7	1.6
Raleigh, N.C.	153	0.66	286,000	0.29	364	0.80	1.09	2.3	0.8	0.3

[1] Based on actual field data and the following conversion factors: 1 gal=3.8 l
1.3–1.4 persons per vehicle.
260 work days per year.
Cost of fuel $0.95–$1.05 per gallon.
Value of time $2.00–$2.65 per hour.

[2] Does not include recurring costs, benefits from enhanced operations and maintenance. Life-cycle of these systems is figured at 10 years, although many conventional systems with same life-cycle have been operating for more than 20 years. No attempt has been made to convert future savings to present dollar value.

programing is usually less than 25 percent of system cost.

Application Conclusions

The application conclusions of UTCS-type strategies and concepts in urban areas are summarized below:

- 1-GC (TRSP) is a viable software system and should be given primary consideration. 1-GC is also the least expensive to apply.
- 2-GC is a potentially effective online control strategy. It should be considered and tested on arterials and networks outside the Washington, D.C., UTCS site.
- 3-GC has the potential for improving traffic performance but needs further research.
- CIC proved effective with the 1-GC (TRSP) alternative at equalizing delays on competing approaches to individual intersections. Although the 1-GC CIC algorithm did not show consistent improvement networkwide, CIC can be used effectively at a limited number of intersections—particularly arterials because of fewer offset and capacity conflicts.
- BPS proved effective at locations insensitive to offset changes and where peak hour bus volumes average 30 or less buses per hour.
- Design concepts developed during the UTCS project provide guidance for system specification preparation and more successful system procurement.
- Operational flexibility is enhanced, allowing higher productivity of staff and budget.
- Maintainability—detection, diagnosis, and repair—is improved, providing motorist benefits from greater uptime for system components.
- Because of direct and indirect benefits to motorists, UTCS systems "pay for themselves" within their life cycles. System efficiencies and flexibility allow more effective control of traffic signals than was ever possible with conventional systems and at a greater savings to the public.

REFERENCES[4]

(1) J. L. Kay and J. C. Allen, "Evaluation of First Generation UTCS/BPS Control Strategy, Volumes 1, 2, and Executive Summary," Report Nos. FHWA-RD-75-26, -27, and -28, *Federal Highway Administration,* Washington, D.C., February 1975. PB Nos. 244111, 244112, and 244110.

(2) R. D. Henry, R. A. Ferlis, and J. L. Kay, "Evaluation of UTCS Control Strategies, Executive Summary and Technical Report," Report Nos. FHWA-RD-76-149 and -150, *Federal Highway Administration,* Washington, D.C., July 1976. PB Nos. 275044 and 275045.

(3) R. D. Henry, R. A. Ferlis, and R. M. White, "Application of UTCS First Generation Control Software in New Orleans, Executive Summary and Final Report," Report Nos. FHWA-RD-78-2 and -3, *Federal Highway Administration,* Washington, D.C., January 1978. PB Nos. 287359 and 287360.

(4) "Urban Traffic Control System Hardware, A Specifications Checklist," Implementation Package 76-1, *Federal Highway Administration,* Washington, D.C., February 1976.

(5) "UTCS/BPS Operations and Maintenance Final Report," Report No. FHWA-RD-76-160, *Federal Highway Administration,* Washington, D.C., June 1976. PB No. 276377.

(6) JHK & Associates, "Greensboro Traffic Control and Surveillance System Before and After Evaluation—Draft Final Report, Project 8.6070811," *North Carolina Department of Transportation,* Raleigh, N.C., December 1977.

(7) JHK & Associates, "Raleigh Traffic Control and Surveillance System Before and After Evaluation—Final Report, Project 8.6052014," *City of Raleigh,* Raleigh, N.C., May 1977.

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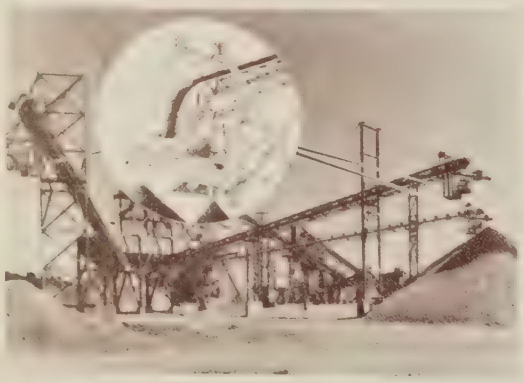
[4]Reports with PB numbers are available from the National Technical Information Service, 5285 Port Royal Rd., Springfield, Va. 22161.

Recent Research Reports You Should Know About

The following are brief descriptions of selected reports recently published by the Office of Research, Federal Highway Administration, which includes the Structures and Applied Mechanics Division, Materials Division, Traffic Systems Division, and Environmental Division. The reports are available from the address noted at the end of each description.

Techniques for Automatic Aggregate Gradation, Report No. FHWA-RD-79-118



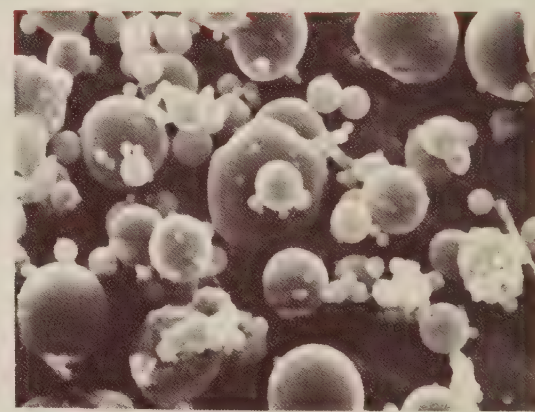
by FHWA Materials Division

This report evaluates techniques for automatic gradation of mineral aggregate used in highway construction. The report provides information on aggregate gradation for process control and producer certification of highway aggregate.

Six potential techniques for automatic particle-size identification were studied after an extensive review of industrial methods. Two of these six techniques—the vidicon and the optical shadow—were used to develop a conceptual system design. The design includes technique modification, system component identification, structural considerations, compatibility with existing plant equipment, system reliability analysis, cost estimates, and analysis of technique limitations.

No commercially available technique meets all the industry-specified criteria for automatic gradation, however, the vidicon and optical shadow techniques appear viable. Engineering model development and field testing are recommended to improve their performance.

The report is available from the Materials Division, HRS-22, Federal Highway Administration, Washington, D.C. 20590.



The Application of Brown Coal Fly Ash to Road Base Courses, Report No. FHWA-RD-79-101

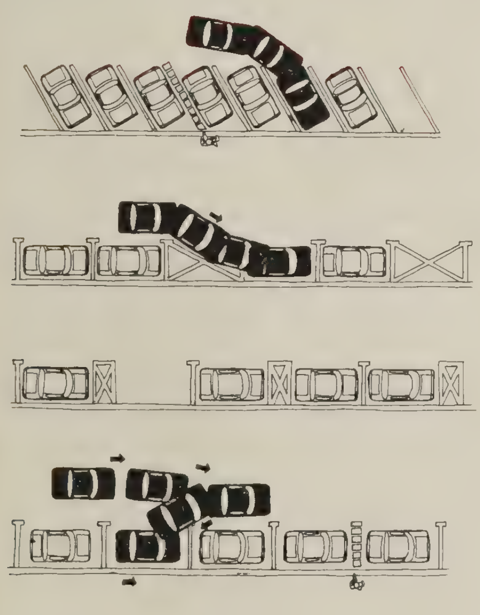
by FHWA Materials Division

This report describes research performed at the Polish Ministry of Transport's Road and Bridge Research Institute. The research should be useful to highway construction and maintenance engineers in the Midwest and Southwest United States where increasing quantities of fly ashes from subbituminous and lignitic coals are being generated in power plants.

The research findings indicate that reactive brown coal fly ash can stabilize cohesive soils to improve subgrades for all-purpose roads and subbases for lightweight roads. Free lime, the reactive ingredient in these fly ashes, can range from 7 to over 20 percent by weight. Noncohesive soils can be stabilized using both reactive and nonreactive fly ashes, with corresponding decreases in cement requirements. The report recommends investigating potential uses of nonreactive brown coal fly ash as a filler in portland cement concrete and bituminous mixes for road embankments.

The report is available from the Materials Division, HRS-23, Federal Highway Administration, Washington, D.C. 20590.

Safety Aspects of Curb Parking, Executive Summary (Report No. FHWA-RD-79-75) and Final Technical Report (Report No. FHWA-RD-79-76)



by FHWA Traffic Systems Division

These reports describe the effects of onstreet parking on safety and traffic operations. An analysis was made of over 4,800 accidents on 273 km (170 miles) of major, collector, and local streets in 10 cities with varying street widths, land uses, and types of parking. Field studies compared the effects of different types of parking on operating speeds, parking times, and pedestrian conflicts. The types of parking examined were no parking, conventional parallel parking, paired parallel parking, flat angle parking, and high angle parking. The study found that angle parking is no more hazardous than parallel parking when land use, parking turnover, and street type are considered.

The executive summary highlights the study findings and the final technical report details the research techniques and analyses.

Limited copies of the reports are available from the Traffic Systems Division, HRS-33, Federal Highway Administration, Washington, D.C. 20590.

Guidelines for the Application of Arrow Boards in Work Zones, Report No. FHWA-RD-79-58

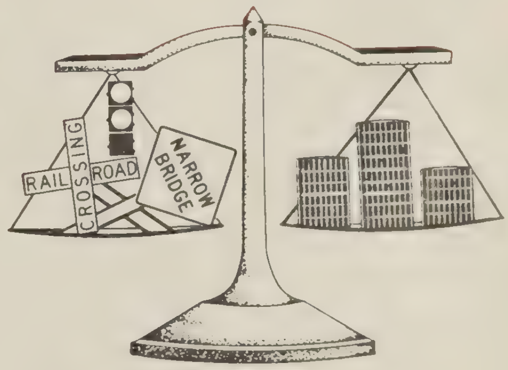
by FHWA Traffic Systems Division

This report contains guidelines for the application of arrow boards in highway work zones, including design specifications, warrants for use, and placement details. Human factors investigations were conducted in the laboratory to determine driver information requirements, expectancy, and understanding of arrow boards. Field studies of driver responses to arrow boards were conducted in 78 construction and maintenance zones in California and Illinois.

The research determined that arrow boards were effective in lane closure work zones when placed on the shoulder of the highway near the start of the lane closure taper because they prompted earlier. merging into the open lane. Arrow boards were not found to be generally effective in traffic diversions or splits or for shoulder closures; however, they did reduce some specific operational problems in these types of work zones.

Limited copies of the report are available from the Traffic Systems Division, HRS-33, Federal Highway Administration, Washington, D.C. 20590.

Assessment of Techniques for Cost-Effectiveness of Highway Accident Countermeasures, Executive Summary (Report No. FHWA-RD-79-52) and Final Report (Report No. FHWA-RD-79-53)



by FHWA Environmental Division

These reports describe the accuracy, sensitivity, and usefulness of cost-effectiveness analysis methods for evaluating highway-related accident countermeasures. The executive summary highlights the findings in the five-part final report.

Part one contains a classification and discussion of available methods of cost-effectiveness analysis.

Part two reviews highway safety activities at the Federal, State, and local government levels.

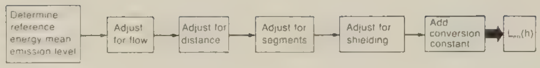
Part three evaluates the usefulness of cost-effectiveness submodels in identifying accident locations and estimating countermeasure effectiveness. The sensitivity and importance of accurate, reliable information on accident costs, highway user benefits, and costs of countermeasures are discussed.

Part four describes methods for determining countermeasure effectiveness and reviews the effectiveness and cost of seven countermeasures: Adding shoulders to two-lane highways; resurfacing pavements with inadequate friction; installing signals at a stop-controlled, simple intersection on a moderate-volume highway; installing flashing lights at railroad-highway grade locations; installing delineators on horizontal curves; installing impact attenuators at raised gore areas; and widening bridges.

Part five gives recommendations regarding cost-effectiveness analysis and recommends three specific cost-effectiveness methods—a dynamic programing algorithm, an improved incremental benefit-cost algorithm, and an integer programing algorithm.

The same techniques recommended for use by State and local governments can also be used to perform nationwide highway safety needs studies. To perform evaluations at the Federal level, accident data for selected locations must be collected from sampling data available in the States.

The reports are available from the Environmental Division, HRS-41, Federal Highway Administration, Washington, D.C. 20590.



Users Manual: FHWA Level 1 Highway Traffic Noise Prediction Model SNAP 1.0 (Report No. FHWA-RD-78-139) and Users Manual: FHWA Level 2 Highway Traffic Noise Prediction Model STAMINA 1.0 (Report No. FHWA-RD-78-138)

by FHWA Environmental Division

The SNAP 1.0 report describes the FHWA level 1 highway traffic noise prediction model. The model allows rapid calculation of highway traffic noise emissions for simple roadway-receiver configurations. Computed output is presented in tables for direct inclusion in reports.

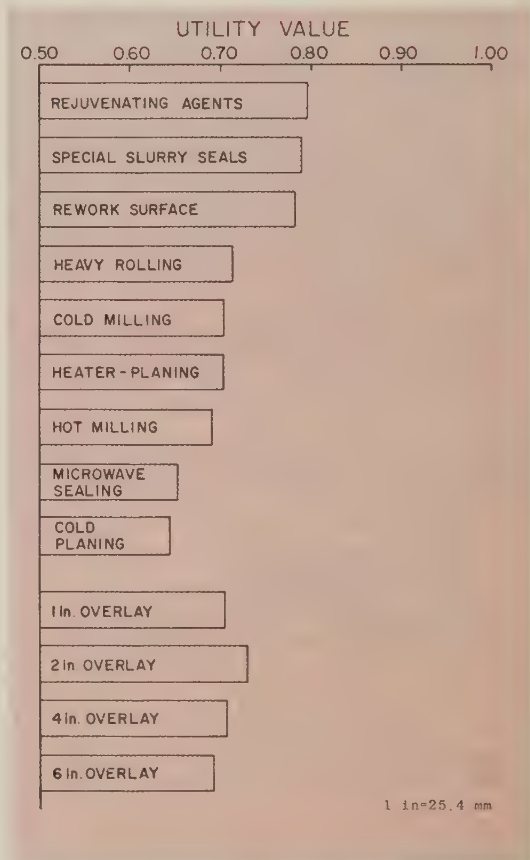
The report describes the formulation and format of input data and the predicted traffic noise estimates. Noise attenuation is considered for traffic lanes parallel to both "thin screen" and "berm" type barriers. Vehicle noise emissions are estimated by vehicle type and vehicle speed.

The STAMINA 1.0 report describes the FHWA level 2 highway traffic noise prediction model and modifications to the TSC MOD-04 highway traffic noise prediction program. The level 2 model extends the scope of problem formulation. It features revised vehicle reference noise emission levels; specification of site-specific excess attenuation; English, metric, and metric/English conversion of engineering units for both input and output data; common input data format with the TSC MOD-04 model; and user options to improve operating efficiency.

The report describes problem formulation, input data requirements, output error messages, examples of usage, and computer program documentation.

The reports are available from the Environmental Division, HRS-42, Federal Highway Administration, Washington, D.C. 20590.

Techniques for Rehabilitating Pavements Without Overlays—A Systems Analysis, Volume 1—Analysis (Report No. FHWA-RD-78-108) and Volume 2—Appendixes (Report No. FHWA-RD-78-109)



by FHWA Structures and Applied Mechanics Division

These reports identify 92 promising techniques for rehabilitating deteriorated pavements in place without using overlays. Sixty-two of these techniques are analyzed in detail. A utility value for each technique was established through computerized decision analysis methodology, which considered 17 feasibility factors grouped into four categories: Costs, performance, energy implications, and safety or environmental impacts. Nineteen of the techniques analyzed exhibit excellent pavement rehabilitation potential and warrant field evaluation. The use of rejuvenating agents and the reworking of pavement surfaces were rated highly as flexible pavement rehabilitation techniques for particular pavement distress problems. Applying rejuvenating agents was most beneficial for flexible pavement surface loss and deterioration; surface reworking was more effective for pavement holes or indentations, profile distortion, and asphalt bleeding.

Two methods were recommended for repair or replacement of failed joints in rigid pavements. At joints over granular bases where spalling, faulting, or pumping is present, the pavement structure near the distress is strengthened by drilling a horizontal opening under each joint and backfilling with a strong, permeable material to provide a sleeper slab. The second method involves a new precast replacement joint assembly design that maintains load transfer along a single new transverse joint rather than along two joints.

Transferring traffic wheel load concentrations from distressed paths by laterally shifting the lane markings is a technique for extending pavement service life without structural change. This preemptive method may be used where deterioration has not progressed significantly and where the pavement is wide enough to permit such a remedy.

The reports are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock Nos. PB 297403 and PB 297404).

Extending the Service Life of Existing Bridges by Increasing Their Load Carrying Capacity, Report No. FHWA-RD-78-133

by FHWA Structures and Applied Mechanics Division

This report identifies typical structural deficiencies of older inservice bridges and presents new techniques for increased load carrying capacity of such bridges through repairs, strengthening, improved geometrics, and other upgrading measures.

One hundred and forty older, substandard steel, concrete, and timber bridges, ranging in span from 6 m (20 ft) to 60 m (197 ft) and located in five States, were inspected to categorize bridge types and deficiencies. Two classes of deficiencies are defined: Those resulting from poor design and those resulting from age and wear. Deficiencies are further cataloged as structural, mechanical, geometric, or safety related.

Bridge rehabilitation practices in nine States and innovative measures for upgrading the structural adequacy of existing bridges are reviewed and evaluated. The most applicable techniques were used to prepare example rehabilitation plans for five typical bridges. Estimates of rehabilitation costs for four of the five bridges are as low as one-tenth of the cost for span replacement.

The proposed structural modifications for increasing live load capacities fall into four general classes: Strengthening critical members, adding supplemental members, reducing dead loads, and modifying the structural systems. Innovative measures investigated include applying external reinforcing plates with adhesives, making a series of simple spans into a continuous span, and adding supplemental supports to reduce span length. Further development of other new and unique techniques is recommended.

Cost-effective measures to improve traffic safety and capacity are available for geometrically modifying all bridge types except through-truss structures.

The report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock No. PB 294508).

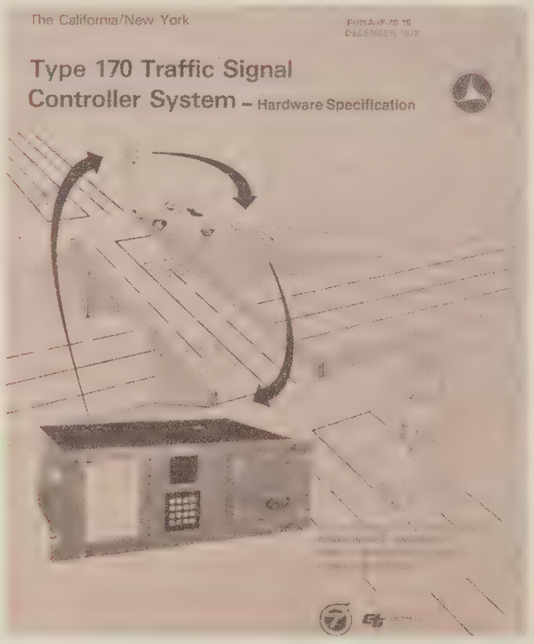
Implementation/User Items "how-to-do-it"

The following are brief descriptions of selected items which have been recently completed by State and Federal highway units in cooperation with the Implementation Division, Office of Development, Federal Highway Administration (FHWA). Some items by others are included when they have a special interest to highway agencies.

**U.S. Department of Transportation
Federal Highway Administration
Office of Development
Implementation Division (HDV-20)
Washington, D.C. 20590**

Items available from the Implementation Division can be obtained by including a self-addressed mailing label with the request.

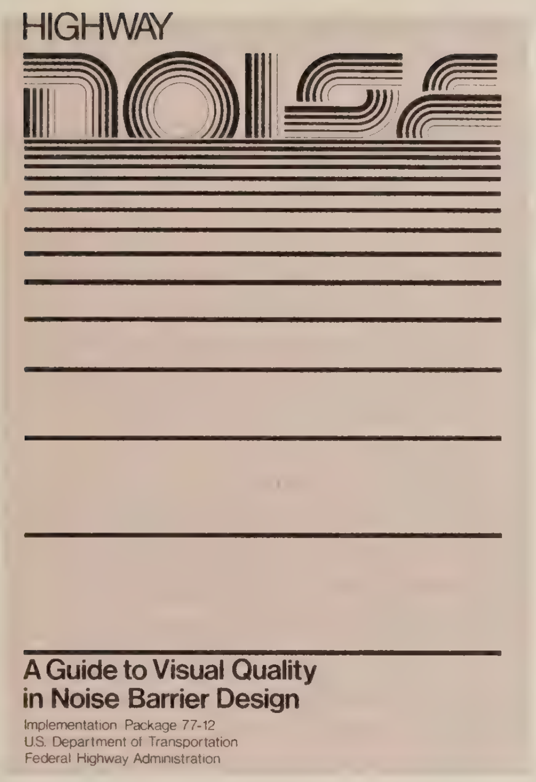
The California/New York Type 170 Traffic Signal Control System—Hardware Specification, Implementation Package 78-16



by FHWA Implementation Division

This report constitutes the completed hardware specification used by California and New York to purchase Type 170 traffic signal controller systems. California and New York purchased over 1,000 microcomputers, performed acceptance testing, installed software, and installed the microcomputers as intersection controllers. The concept reduced purchase cost and improved flexibility and expediency. California and New York have prepared three sets of software with appropriate documentation for the microcomputer-based controllers. This software will control two- to eight-phase intersections, diamond interchanges, and ramp meter locations. Diagnostic maintenance and acceptance testing programs to be used with the controllers are being developed.

Limited copies of the report are available from the Implementation Division.



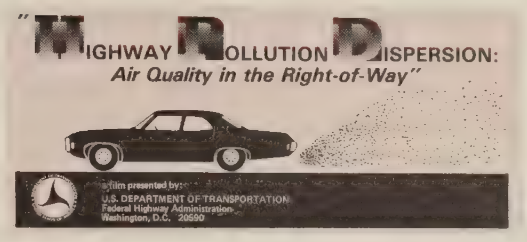
A Guide to Visual Quality in Noise Barrier Design, Implementation Package 77-12

by FHWA Implementation Division

This guide explains how visual design principles can be incorporated into the design of highway noise barriers. The three current forms of noise barriers—earth berms, walls, and combinations of berms and walls—can create visual problems because of acoustical requirements. Potential visual problems and design measures that minimize the visual disruption are illustrated. This guide will aid highway engineers in designing noise barriers that are functional, attractive, and visually related to the environment.

Limited copies of the guide are available from the Implementation Division.

Highway Pollution Dispersion: Air Quality in the Right-of-Way

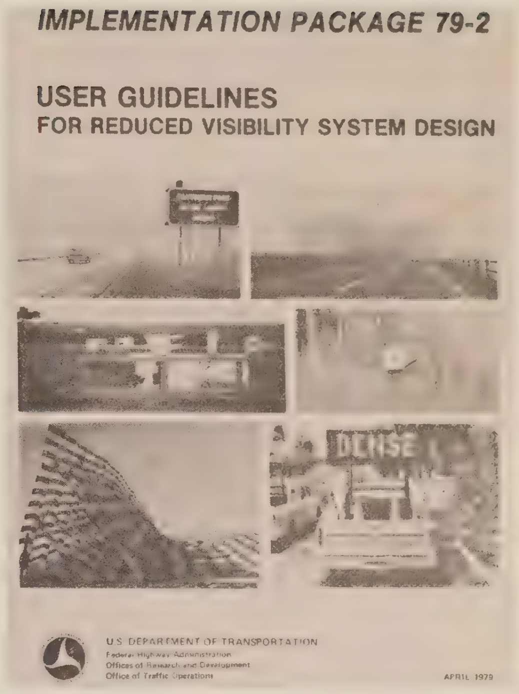


by FHWA Implementation Division

This 16 mm color/sound film examines pollutant dispersion within the highway right-of-way by presenting concepts of air flow patterns around moving vehicles, manmade structures, and adjacent landforms. The effects on dispersion caused by various highway cross sections including street canyons are also presented.

This 20-minute film offers specific research insights on air quality. An important point illustrated in the film is that vehicles emit substantial amounts of waste heat, creating an unstable air mass in the right-of-way. This artificially induced turbulence enhances the dispersion of air contaminants, resulting in lower concentrations in the near roadway environment.

The film is available on loan from the National Highway Institute.



User Guidelines for Reduced Visibility System Design, Implementation Package 79-2

by FHWA Implementation Division

This report contains guidelines for identifying locations with reduced visibility problems, quantifying the extent of the problem, establishing candidate systems, and estimating costs.

Reduced visibility guidance systems were evaluated to determine effective instrumentation, installation techniques, and operational measures. Information was obtained from many operational systems. The report includes information on system configurations, sensing and signing equipment, and communication techniques. The advantages and disadvantages of different equipment types are discussed, and recommendations are made for reduced visibility applications.

The report may be purchased for $4.50 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock No. 050-001-00146-2).

Seismic Retrofit Measures for Highway Bridges, Volume 1 (Report No. FHWA-TS-79-216) and Volume 2 (Report No. FHWA-TS-79-217)

by FHWA Implementation Division

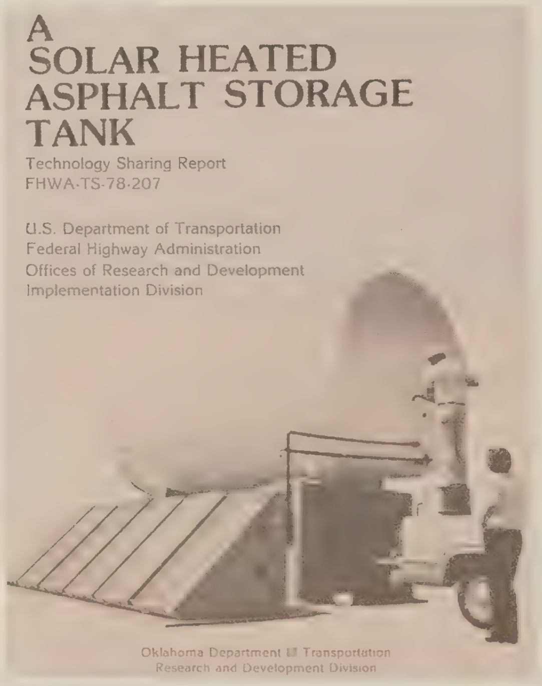
Most highway bridges in the United States have not been designed to resist seismic forces. Since the 1971 earthquake in San Fernando, Calif., highway engineers have been concerned about the potential for earthquake damage to bridges. Bridges are being evaluated to determine if they warrant protection against seismic loading and if so, the appropriate measures to use to retrofit the existing bridges.

The two-volume report provides current information on the theory and techniques for seismic analysis of highway bridges, including background on basic structural dynamics, and demonstrates design details and installation specifications for retrofitting existing highway bridges to minimize earthquake damage.

Volume 1, **Earthquake and Structural Analysis,** includes a definition of terms, seismic risk maps, techniques and equations for analyzing existing bridges prone to earthquake loadings, and criteria for determining if a bridge needs retrofitting.

Volume 2, **Design Manual,** contains illustrations of various retrofit concepts and specific design procedures that can be applied to existing bridges.

Limited copies of the reports are available from the Implementation Division.



A Solar Heated Asphalt Storage Tank, Report No. FHWA-TS-78-207

by FHWA Implementation Division

This report evaluates the design and installation of a solar heated asphalt emulsion storage tank system in Oklahoma. The system, which is simple, inexpensive, and dependable, has been in operation for over a year and has more than fulfilled expectations. Such a solar heating system can be used throughout the year in a wide geographical area.

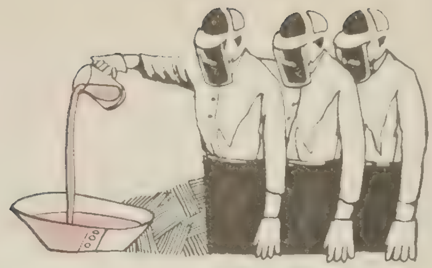
The cost of the solar installation is expected to be recovered in less than 2 years through reduced operating expenses. Cost advantages and uninterrupted heating capability are documented in the report by an analysis between the insulated solar tank and an adjacent uninsulated propane heated tank.

Special instrumentation to evaluate the performance of the solar installation measures the ambient temperature, the amount of solar radiation received on the collector face, the amount of heat circulating through the system at various points, and the temperature of the asphalt in the storage tank.

The report includes schematic diagrams, plans, piping, solar panels, controls, specifications, and performance data for the system. The concepts and data presented will aid those planning to design their own system.

The report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock No. PB 80-116890).

New Research in Progress



The following items identify new research studies that have been reported by FHWA's Offices of Research and Development. Space limitation precludes publishing a complete list. These studies are sponsored in whole or in part with Federal highway funds. For further details, please contact the following: Staff and Contract Research—Editor; Highway Planning and Research (HP&R)—Performing State Highway Department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, NW., Washington, D.C. 20418.

FCP Category 1—Improved Highway Design and Operation for Safety

FCP Project 1I: Traffic Lane Delineation Systems for Adequate Visibility and Durability

Title: Design, Construction, and Evaluation of Installation Equipment for the Recessed Reflective Marker (RRM). (FCP No. 31I3113)
Objective: Modify the design of the experimental design vehicle intended to groove pavement and place recessed reflective markers automatically to eliminate overhanging subassemblies. Construct a prototype and prepare detailed engineering drawings. Verify the performance of the machine in normal field operations. Prepare and furnish an operators manual, maintenance and lubrication manual, and recommended spare parts list.
Performing Organization: B. A. Bodenheimer and Company, Stamford, Conn. 06905
Expected Completion Date: March 1982
Estimated Cost: $309,000 (FHWA Administrative Contract)

FCP Project 1Y: Traffic Management in Construction and Maintenance Zones

Title: Improved Safety Inspection Techniques for Highway Work Zones. (FCP No. 31Y1113)
Objective: Develop improved techniques for inspecting traffic controls in work zones through a review of existing procedures, examination of actual practices, and principles of positive guidance. Provide guidance on how and when to inspect traffic controls and how to recognize deficiencies.
Performing Organization: Transportation Systems Corporation, Vienna, Va. 22180
Expected Completion Date: November 1980
Estimated Cost: $149,000 (FHWA Administrative Contract)

FCP Category 2—Reduction of Traffic Congestion, and Improved Operational Efficiency

FCP Project 2K: Metropolitan Multimodal Traffic Management

Title: Development of Freeway Corridor Evaluation System—Passer IV. (FCP No. 42K2152)
Objective: Develop an integrated battery of analytical methods for evaluating urban freeway corridor transportation systems.
Performing Organization: Texas Transportation Institute, College Station, Tex. 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1981
Estimated Cost: $99,000 (HP&R)

FCP Category 3—Environmental Considerations in Highway Design, Location, Construction, and Operation

FCP Project 3F: Pollution Reduction and Environmental Enhancement

Title: Statistical Analysis of Ozone Data for Transportation/Air Quality Planning. (FCP No. 53F3492)
Objective: Develop methods for quantifying urban ozone levels from historical data and ozone monitoring to establish existing design values upon which ozone reduction strategies are based.
Performing Organization: Stanford Research Institute International, Menlo Park, Calif. 94025
Expected Completion Date: June 1981
Estimated Cost: $190,000 (NCHRP)

FCP Category 4—Improved Materials Utilization and Durability

FCP Project 4C: Use of Waste as Material for Highways

Title: Data Bank for Recycled Bituminous Concrete Pavements. (FCP No. 34C4022)
Objective: Design and establish a comprehensive, cross-reference data bank containing information on construction projects using recycled bituminous concrete materials. Include data categories on location, soil types, drainage, materials, structural section, traffic loads, environmental factors, construction records, maintenance, and performance evaluation.
Performing Organization: Iowa State University, Ames, Iowa 50011
Expected Completion Date: March 1982
Estimated Cost: $100,000 (FHWA Administrative Contract)

Title: Evaluation of Asphalt Paving Recycling in Ohio: A Laboratory and Field Investigation. (FCP No. 44C4233)
Objective: Design recycled asphalt paving mixtures and evaluate asphalt modifiers for three Ohio paving projects. Evaluate the structural engineering properties of laboratory and field compacted test specimens. Predict and evaluate road performance and determine structural layer thickness equivalencies. Develop hot-mix asphalt recycling guidelines for testing, design, and construction.
Performing Organization: Ohio State University, Columbus, Ohio 43210
Funding Agency: Ohio Department of Transportation
Expected Completion Date: April 1982
Estimated Cost: $113,000 (HP&R)

FCP Project 4F: Develop More Significant and Rapid Test Procedures for Quality Assurance

Title: Asphalt Concrete Mixture Design and Specification. (FCP No. 44F2092)
Objective: Review Texas State Department of Highways and Public Transportation's asphalt concrete paving specifications. Attempt to improve density control, aggregate gradation, aggregate requirements, water susceptibility, mixture design methods, and job control and acceptance testing. Evaluate proposed specification changes on field construction projects.
Performing Organization: Texas Transportation Institute, College Station, Tex. 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1981
Estimated Cost: $93,000 (HP&R)

FCP Project 4G: Substitute and Improved Materials to Reduce Effects of Energy Problems on Highways

Title: Economic Skid Resistant Asphalt Surfaces. (FCP No. 44G2122)
Objective: Establish polish value requirements based on better correlations between polish values and field performance. Define polish value requirements based on traffic volumes in average daily traffic per lane.
Performing Organization: Texas Transportation Institute, College Station, Tex. 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1982
Estimated Cost: $160,000 (HP&R)

FCP Project 4J: Controlling Corrosion of Exposed Highway Structural Steel

Title: Low-Solvent Primer and Finish Coats for Use on Steel and Other Structures. (FCP No. 44J1133)
Objective: Evaluate and develop new paint systems, primers, and topcoats so that highway structures will be protected with the best possible coatings under the new air pollution control rules.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95814
Expected Completion Date: September 1982
Estimated Cost: $227,000 (HP&R)

FCP Project 4K: Cost Effective Rigid Concrete Construction and Rehabilitation in Adverse Environments

Title: Superplasticized Concretes for Bridge Decks and Highway Pavements. (FCP No. 34K2314)
Objective: Conduct a factorily designed experiment in the laboratory to determine the properties of superplasticized concretes with and without steel

fibers. Study sensitivities of the properties to water/cement aggregate content, admixture dosage, temperature, cement type, and other variables.
Performing Organization: South Dakota School of Mines and Technology, Rapid City, S. Dak. 57701
Expected Completion Date: August 1981
Estimated Cost: $128,000 (FHWA Administrative Contract)

FCP Category 5—Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

FCP Project 5B: Tunneling Technology for Future Highways

Title: Field and Laboratory Evaluations of Camkometer. (FCP No. 25B2501)
Objective: Evaluate the camkometer for in situ testing of soil parameters and develop users manual for use by FHWA personnel.
Performing Organization: Federal Highway Administration, Washington, D.C. 20590
Expected Completion Date: November 1981
Estimated Cost: $99,000 (FHWA Staff Research)

Title: Evaluation and Design Utilization of Tunnel Instrumentation Data. (FCP No. 35B3122)
Objective: Develop more economical and safer guidelines for planning, designing, and constructing rock chambers and tunnels through collection and interpretation of existing construction records, instrumentation data, and geologic data. Compare with an analytical evaluation of movements and loads around the chambers.
Performing Organization: University of Illinois, Urbana, Ill. 61801
Expected Completion Date: April 1982
Estimated Cost: $100,000 (FHWA Administrative Contract)

Title: Instrumentation and Evaluation of Slurry Wall Construction. (FCP No. 35B3142)
Objective: Collect and summarize instrumentation and geologic data obtained from Red Line Station. Observe Harvard Square construction procedures and evaluate data interpretation plans. Adopt finite element program to slurry wall analysis and implement approved plan for additional instrumentation and data analysis.
Performing Organization: Massachusetts Bay Transportation Authority, West Somerville, Mass. 02144
Expected Completion Date: September 1984
Estimated Cost: $356,000 (FHWA Administrative Contract)

FCP Project 5C: New Methodology for Flexible Pavement Design

Title: Flexible Pavement Data Base and Design. (FCP No. 45C3421)
Objective: Update the Texas flexible pavement data base on performance, distress, deflections, materials properties, traffic, and skid resistance. Convert the flexible pavement system (FPS) to layered elastic theory. Conduct tests to determine material properties of expansive soils.
Performing Organization: Texas Transportation Institute, College Station, Tex. 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: September 1983
Estimated Cost: $295,000 (HP&R)

FCP Project 5K: New Bridge Design Concepts

Title: Reevaluation of American Association of State Highway and Transportation Officials (AASHTO) Shear and Torsion Provisions for Reinforced and Prestressed Concrete. (FCP No 45K1122)
Objective: Make overall evaluation of current design procedures for shear and torsion, perform physical tests to facilitate evaluation, and develop practical design recommendations and proposed AASHTO specification requirements.
Performing Organization: University of Texas, Austin, Tex. 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1982
Estimated Cost: $150,000 (HP&R)

Title: Fatigue Strength of Prestressed Concrete Girders. (FCP No. 45K1132)
Objective: Review current literature, conduct laboratory fatigue tests on full-size prestressed concrete girders, and develop recommended revisions to current design practice.
Performing Organization: University of Texas, Austin, Tex. 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1982
Estimated Cost: $165,000 (HP&R)

FCP Project 5L: Safe Life Design for Bridges

Title: Improving the Reliability and Integrity of Electroslag Weldments in Bridge Structures. (FCP No. 35L1072)
Objective: Improve process control and develop microstructure controls, more reliable nondestructive testing, and special topics to improve the electroslag welding process. Fabricate weldments in accordance with a plan resulting from these studies, and evaluate the effect of process changes on mechanical properties.
Performing Organization: Battelle Memorial Institute, Richland, Wash. 99352
Expected Completion Date: January 1982
Estimated Cost: $332,000 (FHWA Administrative Contract)

Title: Optimization of Existing Nondestructive Bridge Inspection Devices for Routine Highway Bridge Inspection. (FCP No. 35L2012)
Objective: Evaluate existing acoustic crack detector/magnetic crack definer units and make recommended changes to improve performance. Develop breadboard units for laboratory and field tests of the improved units. Fabricate prototype units based on results.
Performing Organization: Southwest Research Institute, San Antonio, Tex. 78284
Expected Completion Date: February 1981
Estimated Cost: $113,000 (FHWA Administrative Contract)

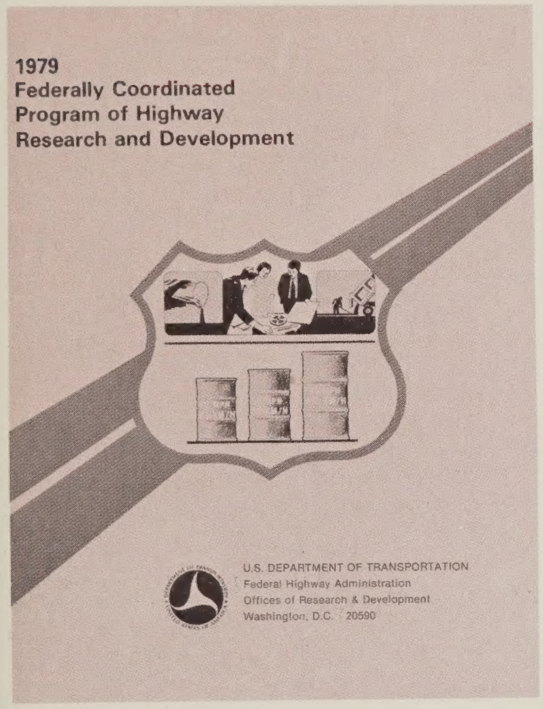
FCP Category 0—Other New Studies

Title: Desirable Asphalt Properties. (FCP No. 40M3603)
Objective: Develop test methods to define desirable asphalt properties and correlate properties with field performance. Investigate asphalt additives that are capable of improving marginal asphalts and determine the associated costs.
Performing Organization: Texas Transportation Institute, College Station, Tex. 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1984
Estimated Cost: $339,000 (HP&R)

Title: Fatigue of End-Bolted Cover Plates. (FCP No. 40S1712)
Objective: Examine the use of high-strength bolts in improving the fatigue life of the critical cover plate detail known to limit the fatigue strength of bridge girders with weldment. Determine experimentally the fatigue resistance of the end-bolted and retrofitted cover plate details. Evaluate test results using fracture mechanics concepts and statistical analysis techniques.
Performing Organization: University of Maryland, College Park, Md. 20742
Funding Agency: Maryland State Highway Administration
Expected Completion Date: December 1980
Estimated Cost: $93,000 (HP&R)

☆U.S. Government Printing Office: 1980—620-316/1

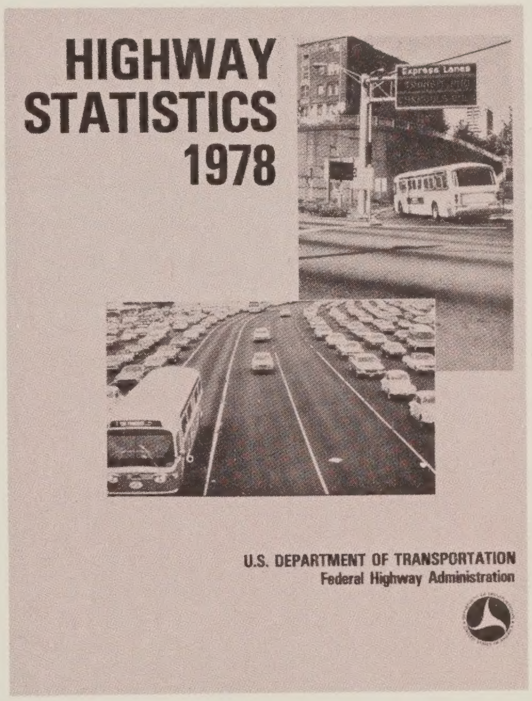
New Publications



The Offices of Research and Development (R&D), Federal Highway Administration (FHWA), have announced release of their fiscal year **1979 Annual Report on the Federally Coordinated Program (FCP) of Highway Research and Development.**

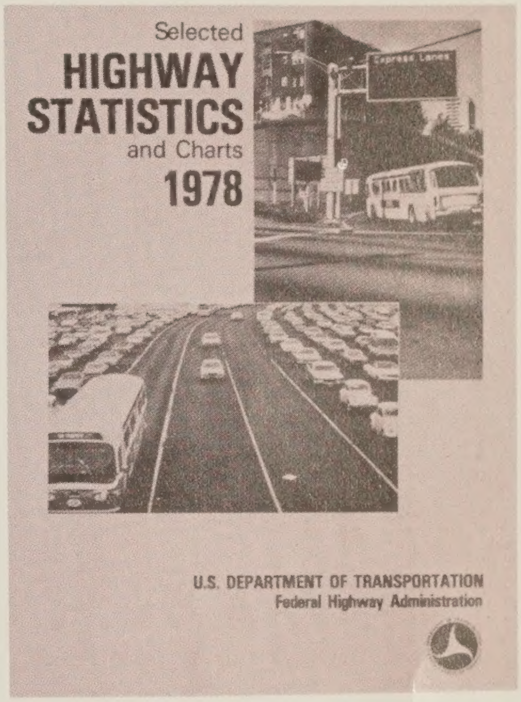
This year's 30-page report consists of two major parts. The first is organized into five major topics—safety research, traffic operations research, environmental research, structural research, and highway maintenance. This part is preceded by a brief statement on the background of the FCP. The second major part deals with organization, funding, and services of the Offices of R&D. The report is prefaced by a message from Federal Highway Administrator Karl S. Bowers.

While supplies last, individual copies of the report will be available free of charge to highway-related agencies and universities. Requests should be sent on agency or institution letterhead to the Federal Highway Administration, Engineering Services Division, HDV-14, Washington, D.C. 20590. Copies of the report are on sale for $2 by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock No. 050-001-00156-0).



Highway Statistics, 1978, the 34th publication in the annual series, presents statistical and analytical tables of general interest on motor fuel, motor vehicles, driver licensing, highway-user taxation, State and local highway financing, road and street mileage, and Federal aid for highways. Also reported are 1977 highway finance data for municipalities, counties, townships, and other units of local government. A listing of the data is given in the table of contents and a brief discussion is given in the text accompanying each section.

The publication may be purchased for $5.50 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock No. 050-001-00157-8). It is also available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Report No. FHWA-HP-HS-78).



Selected Highway Statistics and Charts, 1978, is a 32-page compilation of statistical highlights and charts prepared as a convenient summary supplement to various tables published in **Highway Statistics, 1978,** and previous publications in that annual series. Copies are available from the Highway Statistics Division, HHP-41, Federal Highway Administration, Washington, D.C. 20590.

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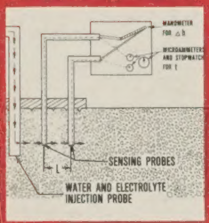
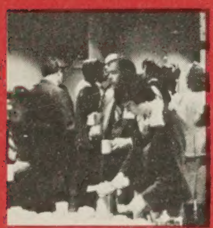
The Development of Improved Parking Signs



Determination of the In Situ Permeability of Bases and Subbases



The Seventh Annual Review of the FCP

The Frost Action Problem—An Overview of Research to Provide Solutions

Development and Testing of Advanced Control Strategies in the Urban Traffic Control System

public roads

A JOURNAL OF HIGHWAY RESEARCH AND DEVELOPMENT