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# public roads

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U.S. Department of Transportation Federal Highway Administration



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**COVER:**

The *Federal Highway Administration's Research and Development Program, 1974* was distributed at the January 1975 Transportation Research Board meeting in Washington D.C. For details and information on availability, see page 151.

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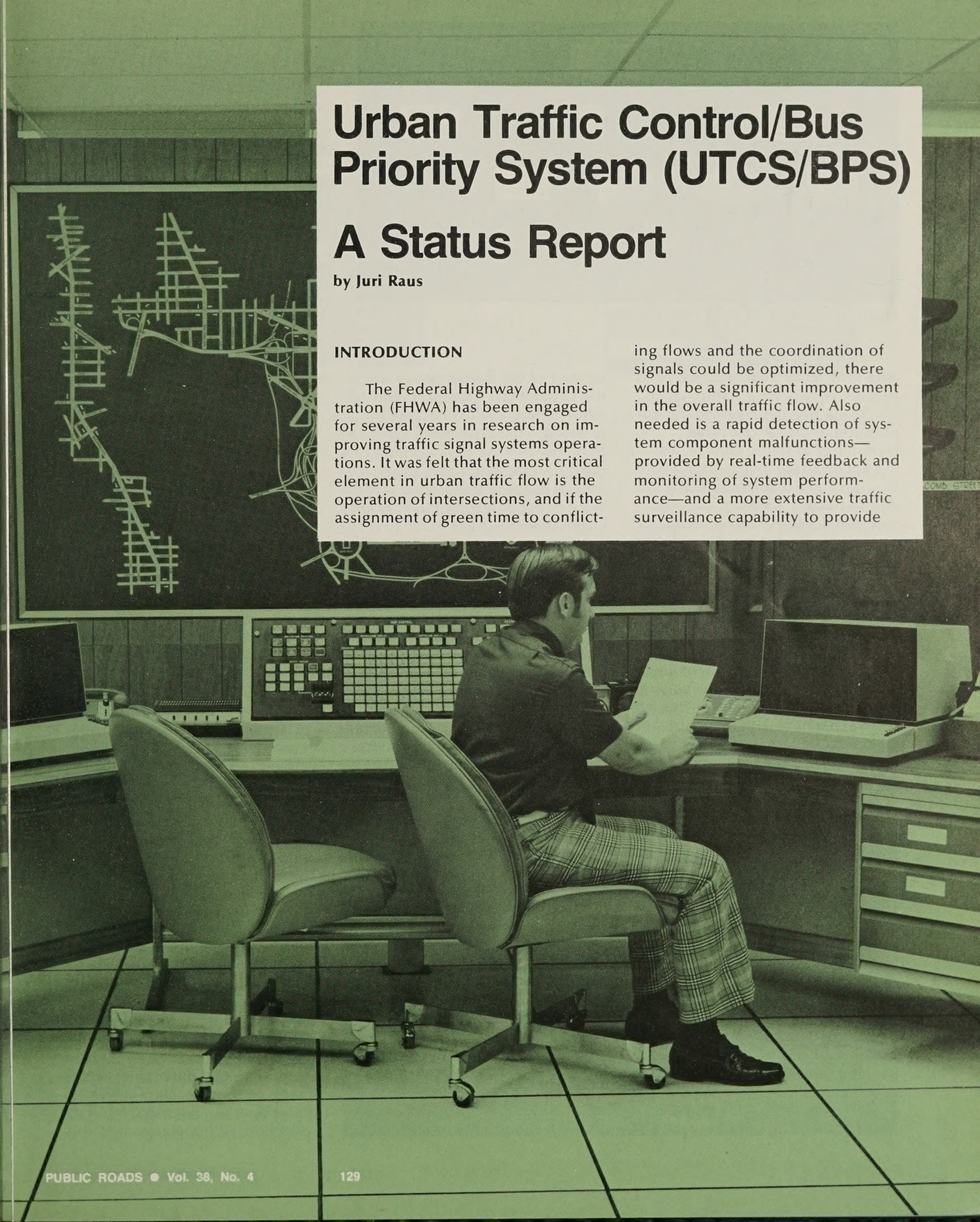
# Urban Traffic Control/Bus Priority System (UTCS/BPS)

# A Status Report

by Juri Raus



## INTRODUCTION

The Federal Highway Administration (FHWA) has been engaged for several years in research on improving traffic signal systems operations. It was felt that the most critical element in urban traffic flow is the operation of intersections, and if the assignment of green time to conflicting flows and the coordination of signals could be optimized, there would be a significant improvement in the overall traffic flow. Also needed is a rapid detection of system component malfunctions—provided by real-time feedback and monitoring of system performance—and a more extensive traffic surveillance capability to provide

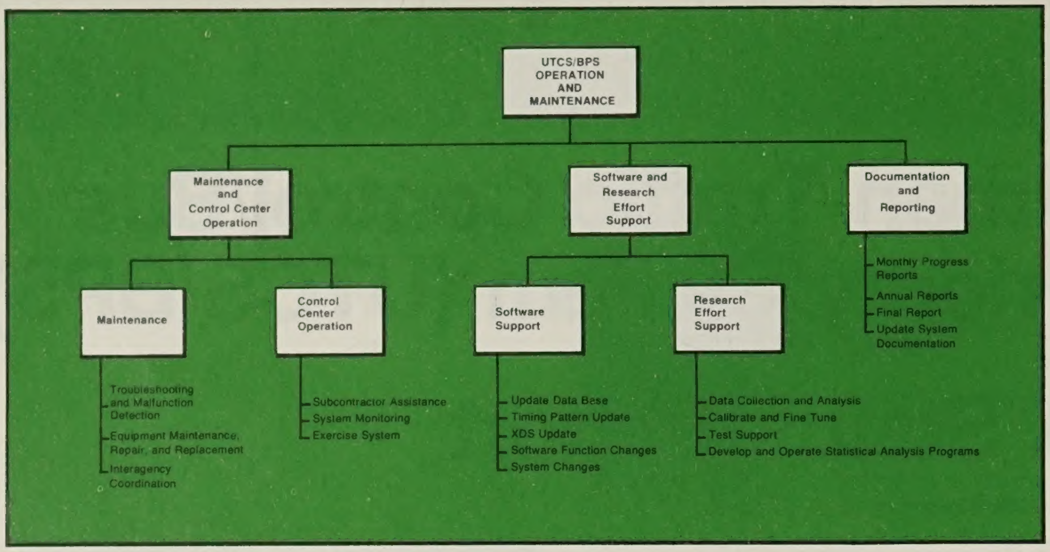



*Figure 1.—UTCS/BPS work plan structure.*

data for a more intelligent decision process in switching traffic signals.

These needs suggested the application of digital computer technology to traffic control. This did not mean the invention of a new concept since a few pioneering cities—notably Toronto, Canada; San Jose, Calif.; Glasgow, Scotland; and others—had already established the basic design of system operation. Rather, the FHWA research was geared toward the development of advanced control strategies to be translated into operational computer software. To accomplish these objectives, the installation of an actual operating system to serve as a test facility was a necessity. This led to an agreement with the District of Columbia Department of Highways and Traffic for the Federal Highway Administration to develop and install a system in Washington, D.C.

## DESIGN AND INSTALLATION

The project management philosophy for design and installation of the system was based on two concepts: (1) The hiring of a systems contractor with responsibility for procurement, installation, and integration of all system components and, (2) the decision to use off-the-shelf hardware. The second concept was determined by the desire to limit the research to software and to obtain higher reliability by using proven equipment. This thinking was slightly modified during the latter part of the design phase when the Urban Mass Transportation Administration (UMTA) became interested in the system and agreed to participate in the development of a bus priority aspect. As a result, a special purpose transceiver was developed for detecting buses in the traffic stream.

System design and bid specifications were completed early in 1970, and the procurement and installation were begun in July of that year. By November 1972, the system was declared operational after the completion of acceptance testing using functional software developed by the systems contractor. The system included 111 intersections, about 500 vehicle detectors, 144 bus detection receivers, and 450 transmitter-equipped buses in downtown Washington, D.C. The control center housed a dual central processing unit (CPU) Sigma 5 computer, the usual peripherals, cathode ray tube consoles, and a map display with a control panel designed for operation by traffic engineers.

In forming a team, the systems contractor, District of Columbia staff, and the FHWA project staff worked on a closely coordinated basis to complete the effort. In this they were largely successful, with all the components installed, interfaced, and operating as designed. One notable exception, which may be worth mentioning, was a snag which developed due to a disagreement with the telephone company on the responsibility for payment of hookup for system communications and the inability to obtain from them accurate data on conduit requirements. There was also a delay in obtaining a facility to house the central equipment. When these matters were finally resolved, an approximately 6-month delay had been inserted into the installation effort with the accompanying increase in cost.

While the system installation was underway, the FHWA designed the concepts and awarded contracts for the development of second and third generations of control software, which made a fully dynamic on-line optimization of traffic signal timings possible. As will be explained later, these efforts—combined with the enhancement of the first generation software—have absorbed a large part of the system's computer operations, reducing the time available for signal control by the computer. Since the Urban Traffic Control/Bus Priority System (UTCS/BPS) is basically a research project, these efforts should have priority.

## POST-INSTALLATION ACTIVITIES

During the approximately 2 years of operation the system has worked remarkably well. Provisions for operations and maintenance, shown in figure 1, have been adequate. Even the reliability of individual components has been quite good as shown in figures 2 and 3. This record seems to support the decision made during the design phase to use only proven and tested equipment.

The functional software has also worked well, allowing the research to be directed toward the control algorithms as originally planned. This has turned out to be quite time consuming. For instance, the first generation control software requires the off-line computation of signal timing patterns, each of which requires a rather extensive input data collection. Although much of this

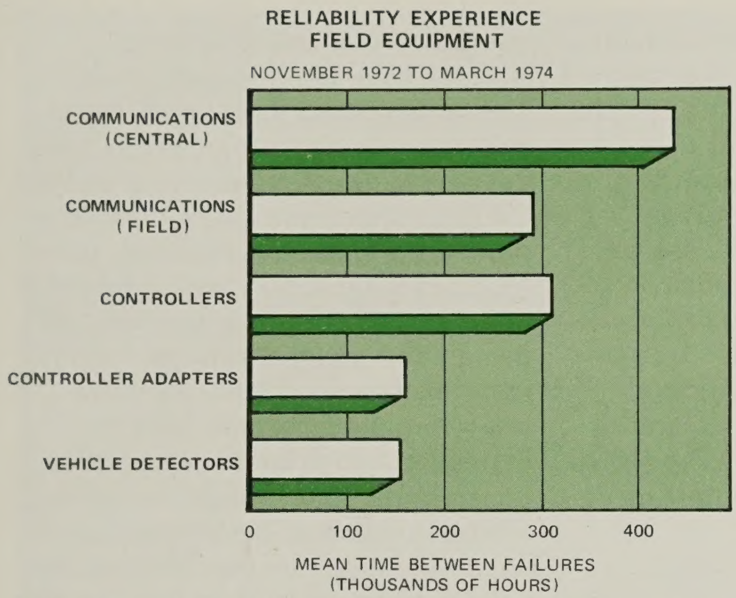



*Figure 2.—Reliability experience—field equipment.*

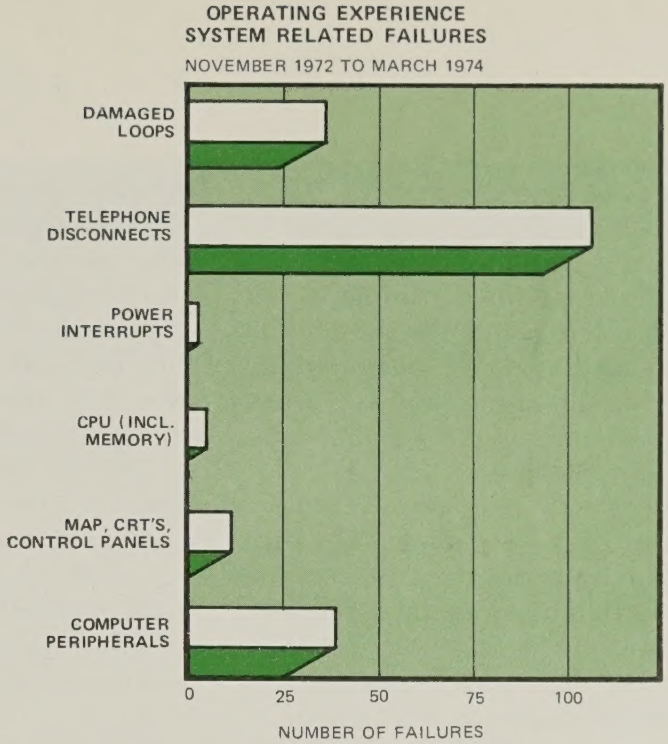



*Figure 3.—Operating experience—system-related failures.*

data could be obtained from system detectors, field counts were still required for turning movements and for street links where there are no detectors.

Initially, the SIGOP program developed by the FHWA in 1966 was used for pattern computations. After a number of trials, analyses, and evaluations, it was found that this program—at least for the Washington, D.C., network—did not produce good patterns. This may be because of short block lengths, but there is also reason to believe that some of the basic assumptions in the optimization algorithm are inaccurate. As a result, the TRANSYT program developed in the United Kingdom was tested and found to produce better results. A further consequence of this testing and evaluation process was the decision by the FHWA to restructure SIGOP based on a new algorithm developed in third generation research. This work is now almost completed and the new SIGOP II will be undergoing field testing soon.

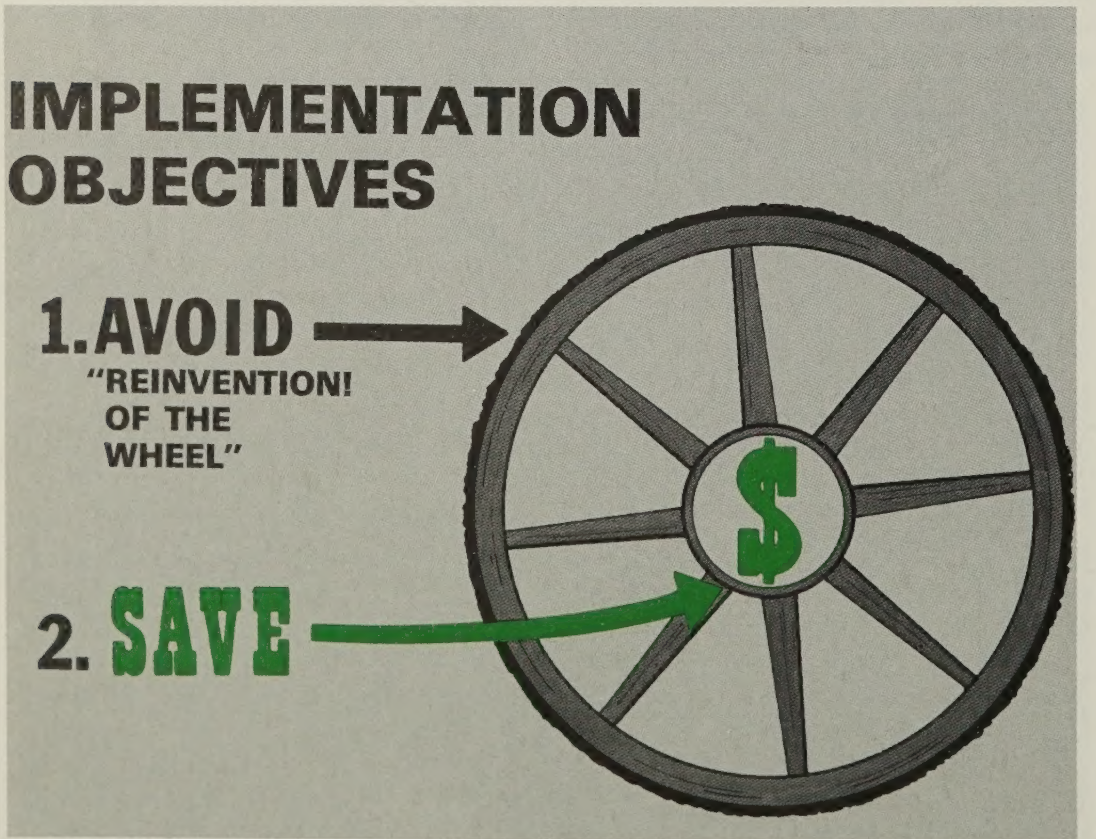
Work has also been underway in evaluating the Critical Intersection Control (CIC) algorithm. One of the problems discovered with the original algorithm was that it looked at average queue demands over several cycle lengths. A quicker, cycle-by-cycle demand response was desirable and a new algorithm has been developed and is being tested. Similarly, with the Bus Priority System, the granting of additional green time has been restructured to give buses a greater preference over automobile traffic.

The initial development in the second and third generations of control software has also been completed. The second generation, which was originally designed to compute a new pattern on-line every 15 minutes, has been programed and a preliminary evaluation has been performed. Also, the optimization algorithm which was based on SIGOP is being reworked. In the third generation software category, the algorithms and basic program structure have been completed and the actual programing effort has begun. This control philosophy is based on a dynamic computation of splits and offsets without the necessity of imposing a common background cycle on the group of signals under consideration.

In all these projects the UTCS-1 network traffic simulation model has been valuable in assessing various control methods. Simulation of street traffic has been treated with some skepticism in the past, but it is now evident that the time and effort spent in developing this model have been worthwhile.

Another development which shows promise, especially in regard to future use in bus priority systems, is the work underway on a Magnetic Gradient Vehicle Detector (MGVD). Laboratory test results show that this detector produces distinct signatures for different types of vehicles. If a bus can be recognized as such, it would be possible to design a passive bus detection system, eliminating the need for transmitters to be mounted on buses as is the case with the present BPS. The impact on costs and the elimination of problems associated with the scheduling of instrumented buses would greatly enhance the attractiveness of bus priority systems.

The goal in all these activities is to improve the flow of traffic. This cannot be accomplished unless some evaluation of flow under different control strategies is made. The FHWA has engaged a contractor who was not involved in the system and software development to make such evaluations. At present, the flow characteristics for various modes of first generation control are being studied. Additional studies will be conducted for advanced control software as first generation software is implemented. The system is also being expanded to include 200 intersections to allow for a more comprehensive testing of control strategies.




## IMPLEMENTATION

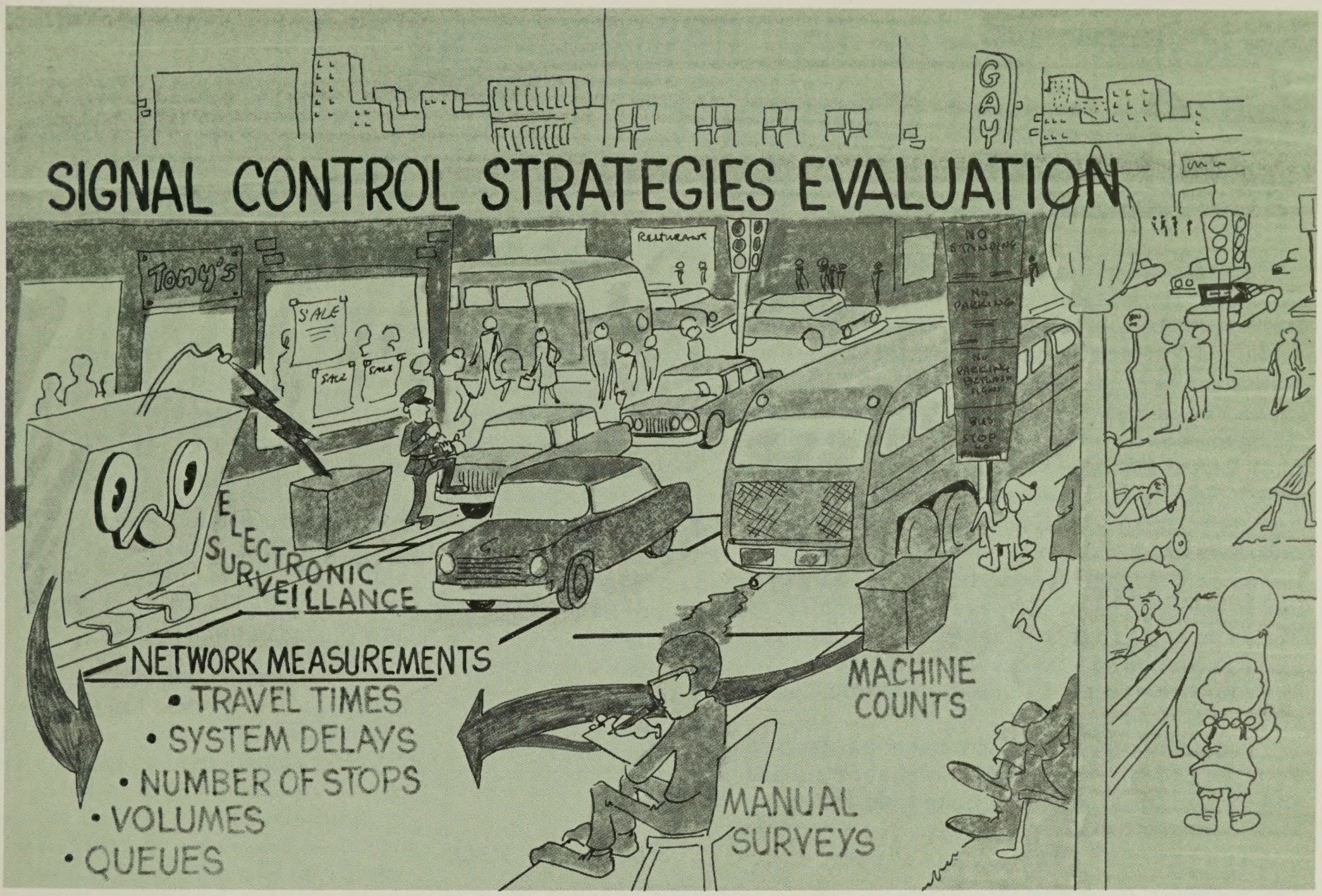
As research products from these activities have become available, the Federal Highway Administration has placed increasing emphasis on implementation of the research results.[1] A nationwide study has been conducted on the type and status of computer-controlled systems. Notices have been issued on the availability of manuals and software, and a long-range program has been developed for dissemination of the UTCS/BPS technology and information to aid in implementation. In response to these notices, approximately 2,000 copies of manuals on design and installation, operations, maintenance, and software have been requested by and sent to States, municipalities, universities, consultants, and foreign countries.

In addition to dissemination of documentation, instructional material has been developed for a seminar on the UTCS/BPS development. This seminar deals with the processes involved in system design and operation and is oriented toward traffic engineers in municipalities where a system of this type will be installed. Five successful seminars have been presented in several FHWA Regions and more are planned.

In the software area, which is the primary development objective, one of the most important products is the FORTRAN IV version of the first generation software which is now available.[2] Where necessary, updating and enhancement of this program will be performed.

[1] Requests for UTCS/BPS reports should be directed to the U.S. Department of Transportation, Federal Highway Administration, HDV-21, Washington, D.C. 20590.

[2] Urban Traffic Control System FORTRAN IV Software Documentation, September 1973—PB 225252/4, and Urban Traffic Control System FORTRAN IV Software—Interface Manual, September 1973—PB 225351/6AS, are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161.




## SUMMARY AND CONCLUSIONS

The specific objective of the UTCS/BPS program is the advancement and implementation of the technology for digital computer control of traffic signal systems. The program meets the needs of many cities whose systems have become obsolete. It is also responsive to the prevailing philosophy of maximum use of existing highway and street facilities.

The program has been uniquely successful in achieving its objective. The system, as installed in Washington, D.C., works well. Even though the work is complex, the development of new control strategies and corresponding computer programs is progressing.

Although the ultimate objective has been interpreted as the improvement of traffic flow by advanced signal timing techniques, the real benefits may be gained in somewhat less understood areas, such as the real-time malfunction detection which allows immediate notification of any irregularities of any component or signal timing. In older systems such matters could go unnoticed for weeks—if not months—with resulting penalties to traffic at poorly operating signals.

Another aspect is the potential elimination of the need for extensive work in retiming the signals manually as traffic patterns change over months and years. The advanced generations of software should be able to adjust to these changes automatically.

Finally, the UTCS is the first system in which the traffic engineer has complete surveillance and control of his signal system and real-time data on traffic flow. This should lead to a much better understanding of flow and control interaction and should allow the traffic engineer to continue to improve the operation.

The computer-controlled signal systems are here to stay. Much work still needs to be done and the progress may be slow at times, but there is no way of turning back the clock.

# Nuclear Gage for Measuring the Cement Content of Plastic Concrete

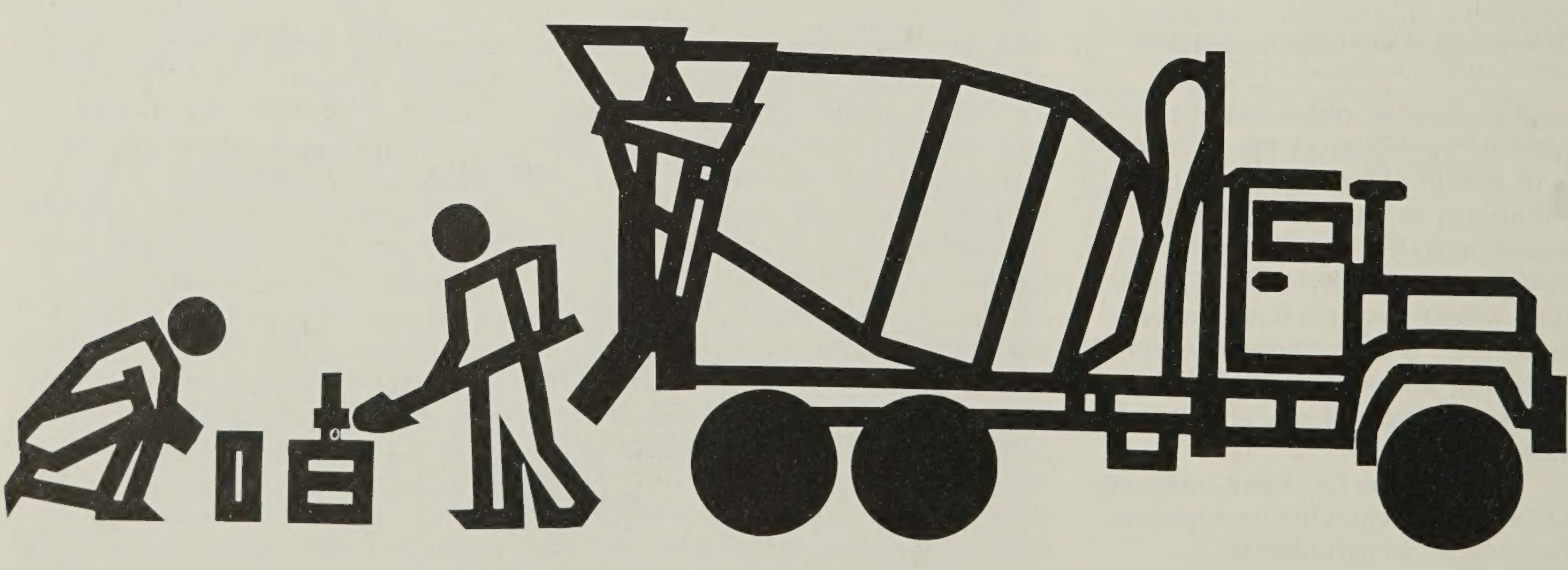
by Terry M. Mitchell

**A nuclear (gamma-ray backscatter and absorption) gage for measuring the cement content of fresh portland cement concrete (PCC) has been evaluated and modified to achieve the desired accuracy and field applicability. Accuracy obtainable varies from standard errors of 22 lbs cement/yd³ (13 kg/m³) concrete with siliceous aggregate mixes to 31 lbs/yd³ (18 kg/m³) with calcareous aggregate mixes. Results reported include the effects of aggregate composition, ambient temperature, bulk density, and other parameters on gage performance. The gage is expected to be a valuable tool in the exercise of early age quality control of PCC. The author summarizes the results of a report, "A Radioisotope Backscatter Gauge for Measuring the Cement Content of Plastic Concrete," FHWA-RD-73-48 *(1)*.[1]**

**Two additional gages have been constructed from the Federal Highway Administration's plans and specifications and have been field-tested by State transportation departments.**

Since this article was prepared, the Maryland State Highway Administration and the Georgia Department of Transportation have completed field performance evaluations of two prototype nuclear gages. Both gages have been returned to the Federal Highway Administration's Office of Development. One is available for additional evaluation, and the Louisiana Department of Highways plans to work with it this spring. The other will be available for promotion, with operation manuals, brochures, and the recommendations of Maryland and Georgia. The results of any additional evaluations will be published in *Public Roads* at a later date.

[1]Italic numbers in parentheses identify the references on page 139.



## INTRODUCTION

### The problem

Quality control of portland cement concrete (PCC) now depends primarily on tests such as strength measurements on cured cylinders. The results are not available until days or weeks after placement. Preplacement control can only be exercised by overseeing the weighing-in of the cement, aggregates, admixtures, and water. In automatic batching plants which lack interlocks, however, it is almost impossible to exercise even that kind of regulation. Gravimetric control obviously leaves the final material still subject to scale errors, erratic or erroneous mixing techniques, and changes in the air and water contents of the concrete prior to placement. A rapid, simple, and accurate onsite test for the cement content—the cement factor—of wet concrete would be a valuable tool for early age quality control of PCC.

Several test methods are available for cement factor determinations. Most, however, are based on a physical separation (sieving) of the coarse aggregate from the mortar followed by chemical or physical determinations of the amount of cement present in the mortar *(2–4)*. Unfortunately the tests are either very slow or highly susceptible to testing errors, or both.

### The solution

This article is a summary of the results of a Federal Highway Administration (FHWA) staff research study in which a practical *nuclear*—gamma backscatter and absorption—gage for cement content determinations was developed *(1)*.[2] The overall goal of the study was to develop a gage capable of reliably and quickly determining the cement content of typical concrete mixes in the field within 28 lbs cement/$yd^3$ concrete (17 $kg/m^3$) of the actual value while the concrete is still plastic. This accuracy is equivalent to $\pm 0.3$ sack cement/$yd^3$ and corresponds to about $\pm 5$ percent of typical cement factor values for concrete used in the highway industry.

Before this study began, the Texas Nuclear Division, Nuclear-Chicago Corporation, did the basic research exploring the practicality of such a gage and constructed the first prototype. That research, performed under a contract with the Federal Highway Administration and the U.S. Atomic Energy Commission, was summarized in an earlier issue of *Public Roads* (5). The FHWA study reported in this article was organized: (1) To evaluate the acceptability of the prototype nuclear cement content gage for use in the field and (2) to make and evaluate such modifications to the gage as were necessary to meet the overall design goals.

## BASIC PRINCIPLES

The principles underlying the operation of the cement content gage are quite similar to those employed in the widely used nuclear density gages. Both gages employ gamma ray sources and detectors, but they rely on different proportions of the common gamma ray attenuation reactions.

In the density gage, the source—typically Cesium-137 ($^{137}Cs$)—emits high energy gammas (667 Kev). At this energy, the dominant attenuation process is Compton scattering. The amount of scattering[3] depends primarily on the density of the scattering material. As shown in figure 1, detection of the quantity of radiation scattered by a sample to a specific location is the basic mechanism of operation of nuclear backscatter density gages.

*Figure 1.—Nuclear density gage, backscatter type.*

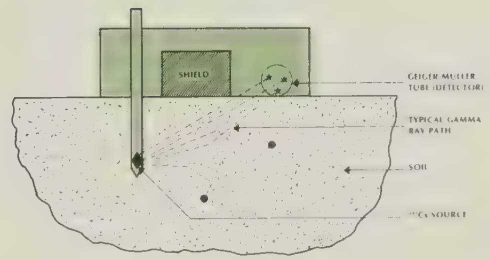


*Figure 2.—Nuclear density gage, direct transmission type.*

Direct transmission density gage operation, in contrast, is based on the detection of the proportion of the original radiation remaining in an unscattered beam after it passes through a sample, as shown in figure 2.

The cement content gage, on the other hand, employs a low energy source—Americium-241 ($^{241}Am$) (60 Kev)—for which the photoelectric absorption process is the dominant attenuating mechanism. Compton scattering still occurs and is, in fact, necessary to divert the original radiation into

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[2]Several other nuclear methods such as neutron activation analysis and neutron capture gamma ray analysis have shown potential for cement content determinations but are as yet unproven.

[3]Scattering is defined as the change of direction of the original gammas accompanied by partial loss of energy.

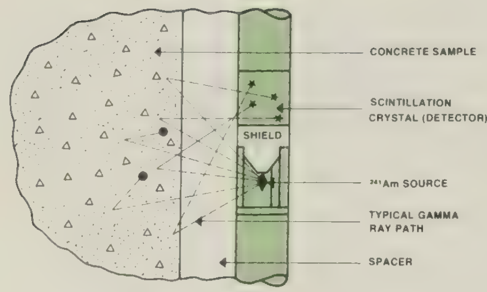


*Figure 3.—Nuclear cement content gage.*

the detector, as shown in figure 3. But photoelectric absorption is a far more important determinant of how much radiation reaches the detector than is the density-dependent scattering process. The amount of absorption depends primarily on the chemical composition of the sample material and particularly on the concentrations of the elements of highest atomic number ($Z$). The absorption per unit path length by any single element is proportional to $Z^4$. Therefore, in a mixture of elements such as concrete, the per atom contribution of high-$Z$ elements to the total absorption of gamma rays in the sample is much greater than the contribution of low-$Z$ elements.

In concrete the attenuating medium is a mixture of cement, aggregates, and water. Calcium ($Z=20$), which occurs in fairly constant amounts in portland cements of various types and sources, is generally among the highest-$Z$ elements present in significant quantities in concrete. It therefore plays a very important role in the absorption of the gammas and sensitively indicates changes in cement content.

In short, the operation of the cement content gage can be stated as follows (fig. 3): Low energy gamma radiation is both scattered and absorbed by a concrete sample. The more cement present in the sample, the larger is the fraction of the original radiation absorbed and the smaller is the fraction which eventually reaches the detector to be counted.

## INSTRUMENT DESIGN AND OPERATION

### Design

Figure 4 shows the components which make up the most recent model of the gage. These include a polymer-impregnated concrete (PIC) test standard, a probe, a sample holder, and an analyzer. A count-ratio procedure, which employs the ratio of the count on a sample to the count on the PIC standard as the gage-determined variable, is used to compensate for error-producing changes in the electronics with time and temperature. The probe and sample holder are also shown schematically in figure 5. The probe contains a 14 millicurie $^{241}$Am radioisotope source, a 1-in. diameter by 1-in. long (25-mm by 25-mm) NaI(Tl) scintillation crystal (the radiation detector), and a high gain photomultiplier tube. The sample holder is a 1-ft$^3$ (0.03-m$^3$) unit weight bucket, modified to position an annular acrylic (Lucite) spacer. The spacer fixes the probe position relative to the concrete sample. The analyzer is a portable single-channel analyzer whose main function is to count the pulses which arrive from the probe.

In addition to fixing the probe position, the spacer serves two other functions. Low energy gamma radiation has a relatively short range in concrete; those gammas which reach the detectors are quite unlikely to have penetrated much further than 1 in. (25 mm) into the sample. The spacer, which is relatively transparent to 60 Kev gammas, effectively increases the size of the sample sensed by the radiation before detection, thus reducing the effects of the heterogeneity of concrete samples. Of equal importance, the spacer minimizes the dependence of the gage count rate on sample density.

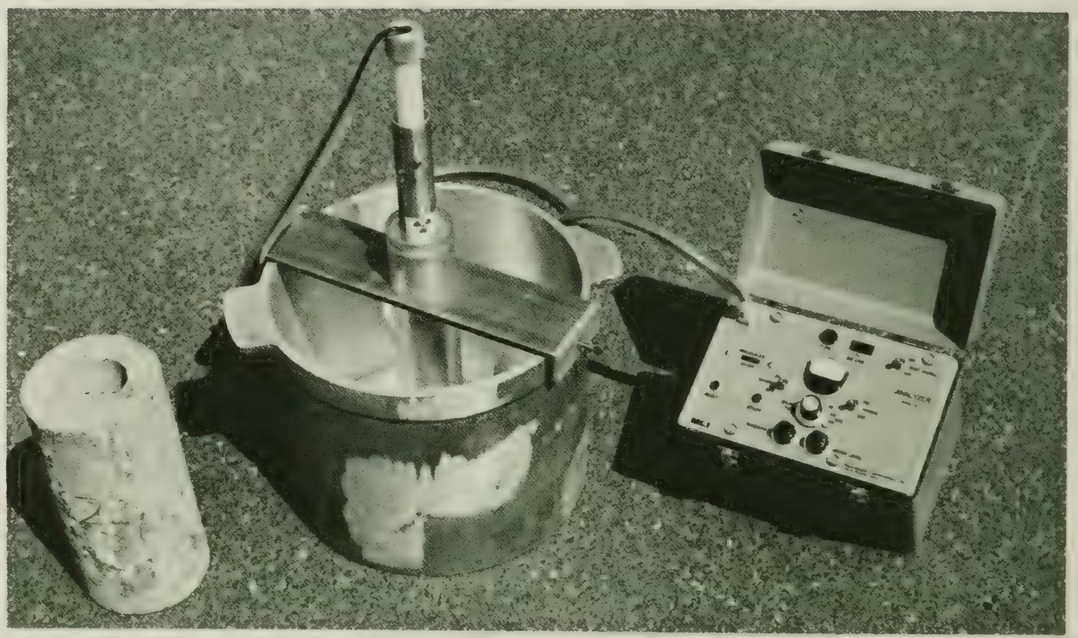

*Figure 4.—Cement content gage: PIC test standard, sample holder and probe, analyzer.*

The gage model described is considerably simpler in both design and operation than the contractor's prototype which was evaluated in the initial stages of this study. The contractor's gage required a second source—0.5 millicurie of $^{137}$Cs—for a density correction (5). In the original geometry, the count from the $^{241}Am$ source had been strongly dependent on the sample's density as well as its cement content. Addition of the spacer, as noted before, allowed removal of the $^{137}Cs$ source. That removal in turn (1) led to simplification of the analyzer, the probe, and the sample holder; (2) resulted in significant time savings during construction of calibration curves for new aggregates, during calibration checks, and during cement content determinations on samples; and (3) improved the accuracy of cement content determinations on certain concretes such as those containing limestone aggregates.

## Operation

A single cement content determination can be completed in less than 15 minutes including the time required to fill and to empty and clean the sample holder. Briefly outlined, the procedure is as follows:

- After the operability of the gage is checked, the PIC standard is installed around the acrylic spacer in the sample holder. A series of 20-second counts is taken with the probe inserted in the spacer; their average is calculated and used as the *standard* count.
- The PIC standard is then removed and the sample holder is loaded with the fresh concrete sample following the standard procedure for filling unit weight buckets.
- A sequence of 20-second counts is then made with the probe at each of six vertical positions 1 in. (25 mm) apart relative to the sample. These positions are maintained by engaging the slot locating pin (see fig. 5) on the locating sleeve with each of six horizontal slots in the nylon probe support rod. The average of these six readings is then calculated for use as the *sample* count. Averaging reduces the effect of sample heterogeneity which would arise from the combination of large aggregate pieces and the short range of the low energy gamma radiation.

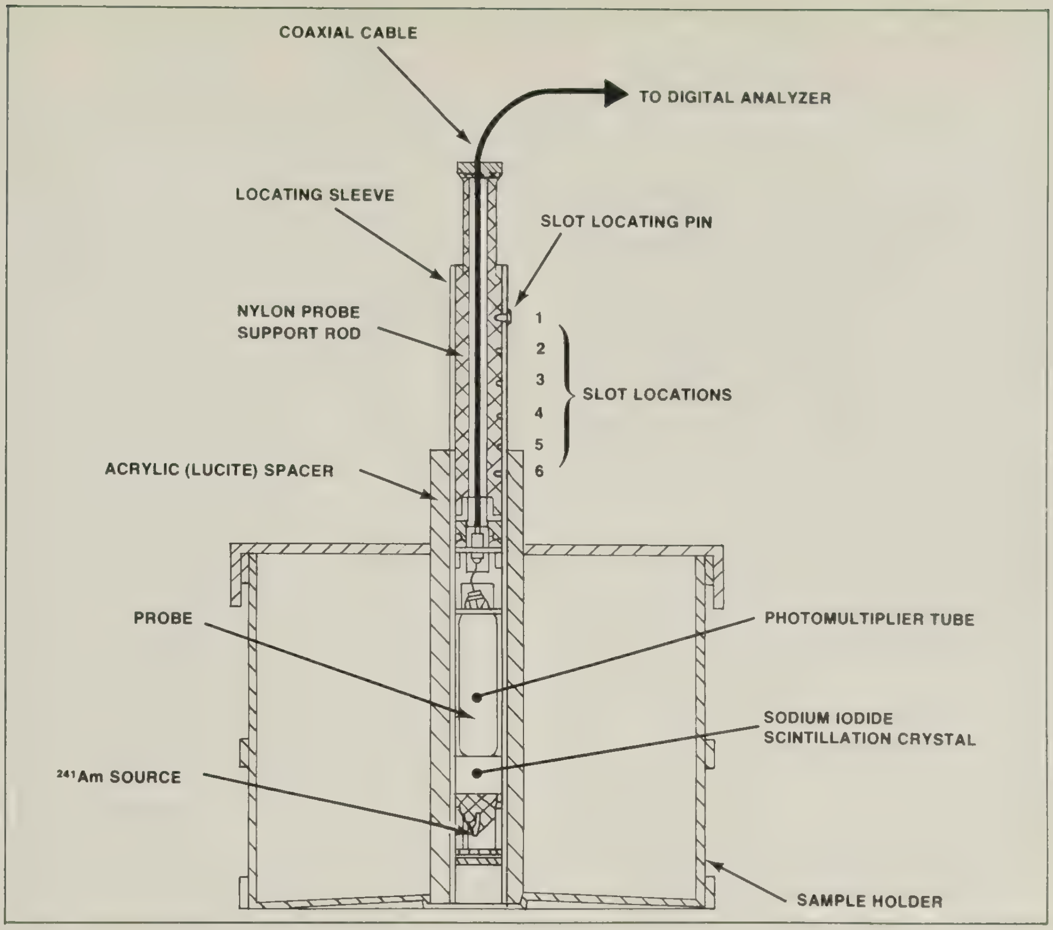

*Figure 5.—Schematic, sample holder and probe.*

- The operator then calculates the ratio of the *sample* count to *standard* count and finds the corresponding cement content from a previously established calibration curve.

Calibration curves, such as the one shown in figure 6, are constructed in the laboratory for each concrete job. A different curve will be obtained for concretes from each

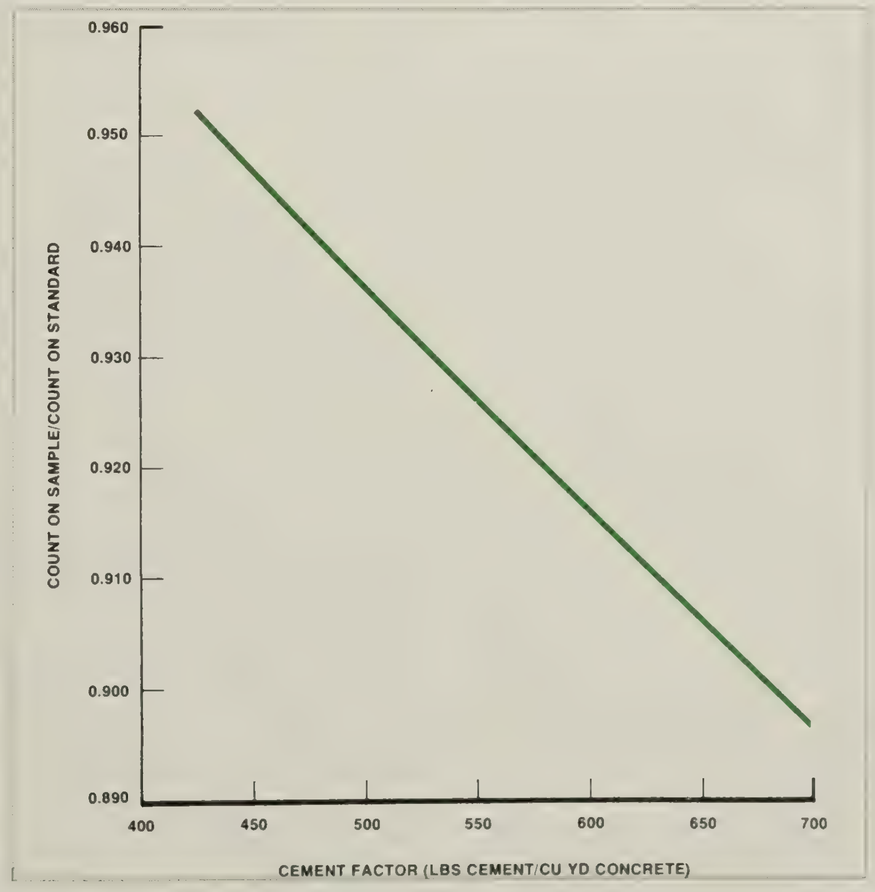

*Figure 6.—Typical calibration curve—coarse aggregate: Riverton, Va. limestone.*

distinct aggregate source and from each ratio of coarse to fine aggregate when the two sizes are unlike chemically. Calibration curves are constructed with small, carefully controlled laboratory batches for which the actual cement factor can be established from the weights of the components. Typically, mixes of three different cement factors are made. For example, for a job design cement factor of 564 $lbs/yd^3$ (335 $kg/m^3$), the calibration curve can be established with laboratory mixes of 470, 564, and 658 $lbs/yd^3$ (279, 335, and 390 $kg/m^3$).

Detailed information on the instrument design and operation will be available in the operating manual for the gage, to be published by mid-1975.

## SUMMARY OF GAGE FEATURES

- Components—four (sample holder, probe, analyzer, and PIC standard).
- Total weight—68 lbs (31 kg).
- Total test time—less than 15 minutes per sample.
- Total counting time—2 minutes.
- Precision—5 lbs cement/$yd^3$ (3 $kg/m^3$) concrete.
- Accuracy (standard error; single sample)—22 to 31 $lbs/yd^3$ (13 to 18 $kg/m^3$).
- Operation—20 hours from rechargeable silcad batteries or continuous 110 V AC line operation.
- Full battery recharge time—15 hours.
- Operating temperature range—35° to 120° F (2° to 49° C).
- Radiation hazards—minimal.
- Digital readout on analyzer—converts to cement factor with use of laboratory-constructed calibration curve.
- Gage response—independent of concrete bulk density, water content, and air content.

## RESULTS

At present, the cement content gage has been evaluated mainly in the laboratory. The laboratory

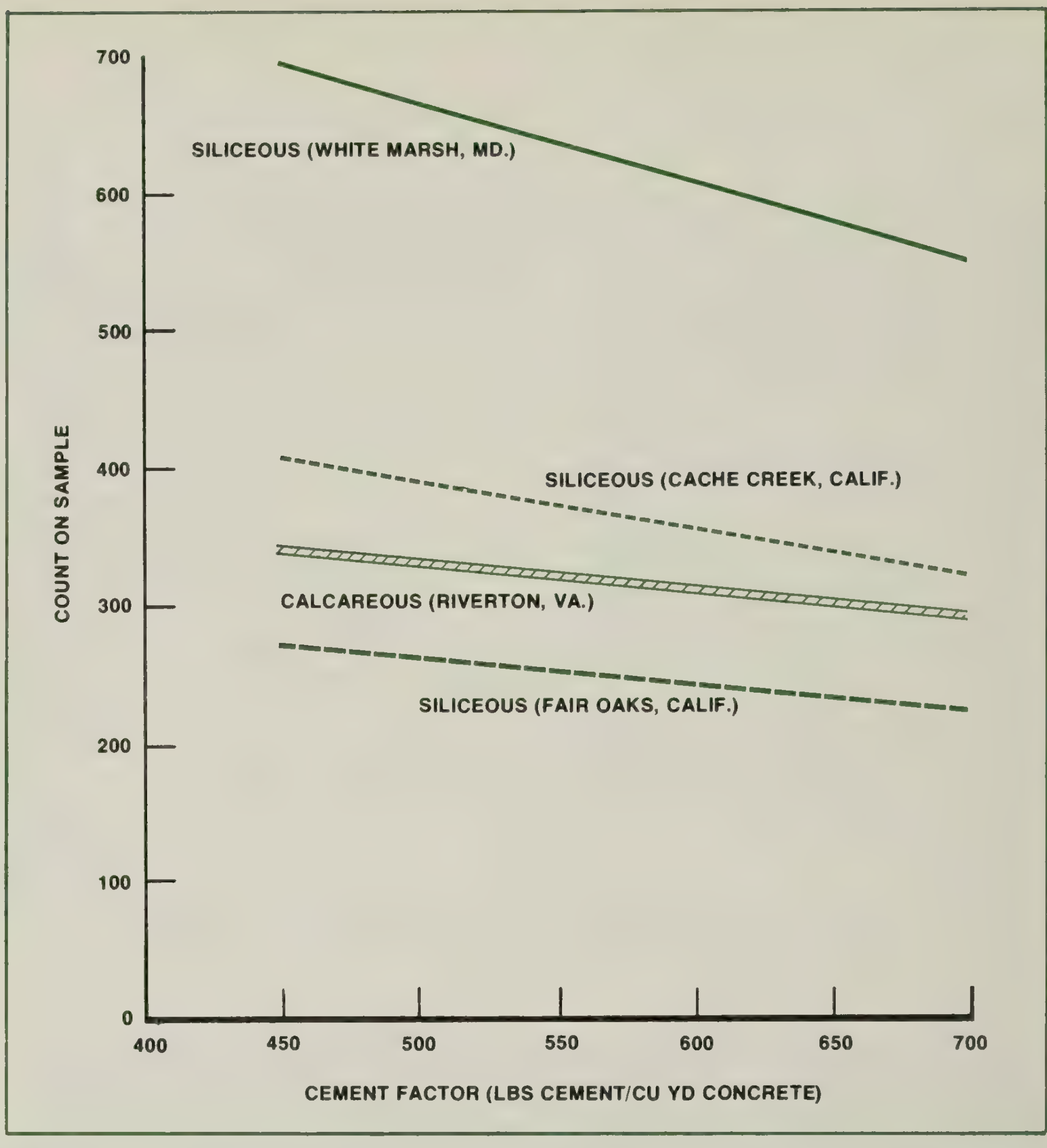


*Figure 7.—Calibration curves for concretes made with four different aggregates (data for first prototype gage).*

evaluations have considered all of the parameters which are expected to significantly affect gage performance, including aggregate composition, gage temperature, bulk density, and water content.

### Aggregate composition

The earliest results with the Texas Nuclear prototype gage indicated that aggregate composition would cause some difficulties in the operation of the cement content gage. As explained previously, the gage's sensitivity to cement content depends on both the level of calcium in the concrete and that of other high atomic number ($Z>20$) elements in the aggregate. It was anticipated that large quantities of calcium and other high-*Z* elements in an aggregate would result in low count rates from concretes made with the material, reduced sensitivities (changes in count rate per unit change in cement content), and less accurate cement content determinations.

Two coarse aggregates were employed in the main part of the evaluation, one *siliceous* (a river gravel) with very little intrinsic high-*Z* material, the other *calcareous* (a dolomitic limestone) with more than 20 percent calcium. Mixes with each over a range of cement factors (450 to 670 $lbs/yd^3$—270 to 400 $kg/m^3$) and densities (136 to 150 $lbs/ft^3$—2,180 to 2,400 $kg/m^3$) gave a standard error for cement factor determinations of 22 $lbs/yd^3$ (13 $kg/m^3$) for the siliceous aggregate mixes and 31 $lbs/yd^3$ (18 $kg/m^3$) for calcareous aggregate mixes.[4] When the cement factors of three samples from the same batches were averaged, the standard error of the determinations was reduced to 19 lbs/yd³ (11 kg/m³) for the siliceous aggregate mixes and 22 lb/yd³ (13 kg/m³) for the calcareous aggregate mixes.

Some additional data were recorded with two other nominally *siliceous* aggregates from California. These contained sizable quantities of iron ($Z=26$), titanium ($Z=22$), and calcium ($Z=20$), and one contained several hundred parts per million (ppm) of barium ($Z=56$). Because of its high atomic number, 163 ppm of barium has a gamma absorption equivalent to 1 percent of calcium. Mixes with these aggregates confirmed the hypothesis that concretes containing calcium and significant quantities of other high-$Z$ elements will show reduced gage sensitivity to changes in cement content and will give less accurate cement factor determinations.

Figure 7 shows sample calibration curves for the four aggregates mentioned above. Separate calibration curves must be generated for individual aggregate sources because of the indicated sensitivity of the cement content gage to chemical composition. In addition, whenever the coarse and fine aggregates in a mix are of significantly different chemical composition, a separate calibration curve is required for each significant change of their relative proportions in a mix design.

### Temperature

The other major parameter which affects the gage's performance is its temperature. Changes in the gain of the photomultiplier tube and in the analyzer electronics with temperature produce significant changes in gage count. Data indicated that when no temperature compensation was available, the error in a cement factor determination made at 40° F (4° C) caused by using a calibration curve generated at 72° F (22° C) was approximately 170 lbs/yd³ (100 kg/m³).

In the model of the gage described here, temperature compensation is achieved by using the count-ratio method with the PIC standard. When counts on a fresh concrete sample and on the PIC standard are taken at roughly the same time and temperature, experimental results have indicated that the temperature effects will approximately cancel out when the ratio of the two counts is used as the gage-determined variable.

### Other variables

On theoretical grounds, the bulk density of concrete samples was expected to significantly affect gage performance and did, in fact, in the Texas Nuclear prototype evaluation. For the most recent gage model, data taken over a range of densities typical for highway concretes—136 to 150 lbs/ft³ (2,180 to 2,400 kg/m³)—indicated no significant dependence of count on density when cement factor was held constant.

The cement content gage response does not vary with either water content or air content over the usual range of those variables in highway concrete.

## FIELD EVALUATION

With the original research essentially completed, FHWA's Office of Development contracted for the construction of two additional prototype gages. These gages were built to the detailed plans and specifications developed by FHWA. The two units were evaluated in both the laboratory and the field by the Maryland State Highway Administration and the Georgia Department of Transportation during the 1974 construction season. Additional implementation programs are planned for the cement content gages.

## SUMMARY AND CONCLUSIONS

A nuclear gage for determining the cement content of plastic (fresh) PCC has been developed and evaluated. The results indicate that the gage establishes cement factors to the accuracy needed for structural concrete on highway projects.

FHWA's Offices of Research and Development foresee a number of practical applications for a test method based on the use of this gage. The most important application is insuring that PCC delivered to a construction site has the proper cement content, thereby providing improved job control. The gage could also be used in the qualification of PCC mixing equipment and procedures, and it will be a valuable aid in field or laboratory research investigations on concrete.

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[4]The standard error is the root mean square of the differences between the cement factor as determined with the nuclear gage and the actual cement factor of a batch as determined from the weights of the components.

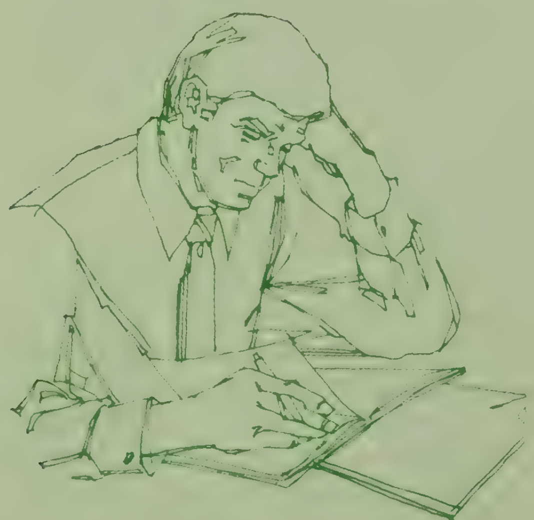
# Our Authors

**Juri Raus** is a senior implementation manager in the Implementation Division, Office of Development. Mr. Raus has been employed by the Federal Highway Administration since 1963 and was the project manager for the Urban Traffic Control/Bus Priority System throughout its conception, design, and installation.

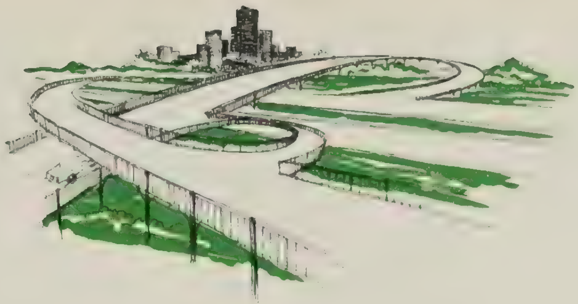
**Terry M. Mitchell** is a materials research engineer in the Materials Division, Office of Research, Federal Highway Administration. His work on the cement content gage is part of a staff research study in which he is currently developing a similar gage for determining the water content of fresh concrete. In addition to his work in applying nuclear analysis methods and radioisotopes to highway materials problems, Dr. Mitchell is manager of the FCP project aimed at developing more significant and rapid test procedures for controlling the quality of highway materials.

**Stanley R. Byington,** Chief of the Systems Requirements and Evaluation Research Group, Office of Research, Federal Highway Administration, is currently responsible for direction of research pertaining to rural two-lane highways, urban grid and corridor traffic control systems, carpool-bus priority lanes, and traffic engineering improvements for safety.

**Craig A. Ballinger** is a structural research engineer in the Structures and Applied Mechanics Division, Office of Research, Federal Highway Administration. He is the manager of Project 5F, "Structural Integrity and Life Expectancy of Bridges," in the Federally Coordinated Program of Research and Development. Mr. Ballinger has been associated with the Office of Research since 1960.



# Reducing Uncertainty in Interchange Design Evaluations



by Stanley R. Byington

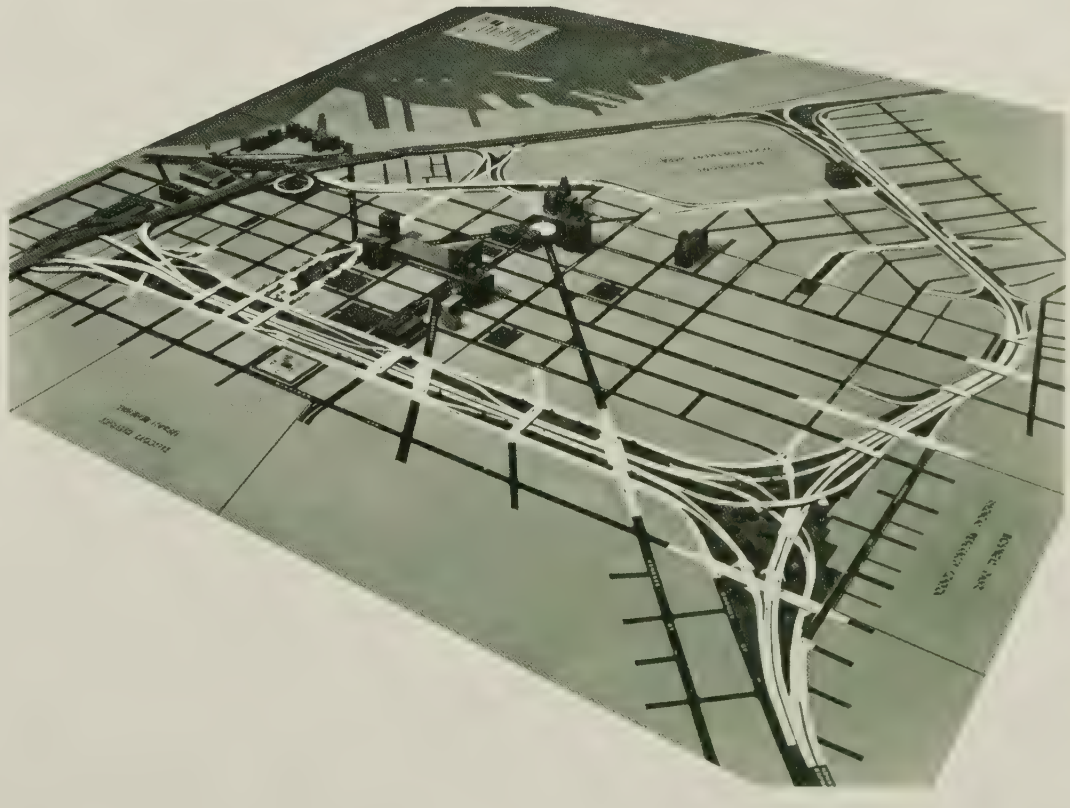
**This article is a condensation of Appendix E, "Decision Theory Approach to Interchange Design," *(1)*[1] which outlines an approach that can be used by State highway or transportation departments in evaluating complex interchange design alternatives. It should reduce the possibility of a wrong decision and enable the decision maker to better explain the reason for the final choice. The approach, which draws heavily on decision theory analysis, is demonstrated through an example.**

[1] Italic numbers in parentheses identify the references on page 149.

## INTRODUCTION

Rising costs in our society are increasing the need to be correct more often the first time; it is usually too expensive to patch up or correct an initial mistake. Often decisions must be based on information whose accuracy is uncertain, increasing the chances of incorrect, or less than optimal, decisions. This is true in the evaluation of alternative designs for freeway-to-freeway interchanges—hereafter referred to as major interchanges—with initial construction costs ranging from $3 to $65 million.

As a result of Federal environmental quality legislation, highway projects—including those for the construction of major interchanges—must be evaluated using 24 factors. These factors—shown as



| GOAL HIERARCHY (more explicit subgoals →) | | | | | PERFORMANCE MEASURES |
|---|---|---|---|---|---|
| "GOOD TRANSPORTATION" | Convenient Transport | | Low travel times | | Reduced time (min.) |
| | | | Free flow | | Level of service (A-D) |
| | | | Reduce user stress | | Direct worth |
| | Safe Transport | | Low fatalities | | Reduced fatal accidents |
| | | | Low injuries | | Reduced injury accidents |
| | | | Low property damage | | Reduced PDO accidents |
| | Aesthetically Pleasing | User | Low noise | | Decibels at ℄ |
| | | | Visually pleasing | | Direct worth |
| | | | Comfortable ride | | Roughness index (1-10) |
| | | Non-User | Low noise | | Decibels at ROW line |
| | | | Visually pleasing | | Direct worth |
| | | | Low water pollution | | Percent increased (%) |
| | | | Low air pollution | | Percent increased (%) |
| | Beneficial to the Community | Economically | Increase industry | | Increased payroll (%) |
| | | | Decrease unemployment | | Increased jobs |
| | | | Increase tax base | | Increased assessed value |
| | | | Increase fire protection | | Decreased average time |
| | | Socially | Improve neighborhood | | Direct worth |
| | | | Improve poor & aged mobility | | Direct worth |
| | | | Improve recreation | | Direct worth |
| | | | Permit desired growth | | Direct worth |
| | Low Cost Transport | Construction | | | Dollars |
| | | Operating | User cost | | Dollars/year reduced |
| | | | Facility cost | | Dollars/year reduced |

*Figure 1.–Example goal structure and performance measures (1).*

*goals* in figure 1—stress *quality of life (2)* and many are difficult to measure objectively. This adds to the uncertainty of the information used to select major interchange designs. In addition to the environmental factors, the designer must consider public sentiment, available resources, political influence, traffic operations, and suitability of engineering materials. All these factors make it difficult to select a feasible interchange design. The designer must quantify what factors he can and simply judge the effects of the remaining factors based on his experience. If the effects of the factors are not sufficiently understood, then operational problems may be encountered in the selected major interchange.

The decision maker needs an evaluation method which will reduce the possibility of making wrong decisions and which will help him to better explain his reasons for the final interchange design choice. Decision theory techniques provide such a method. These techniques, briefly described in this article and demonstrated through an example, have been successfully employed in the fields of business, space, and medicine. They are now being used by the Federal Highway Administration's Offices of Research and Development to determine the priority of projects to be undertaken.

The theory has proved useful in problems where (1) several interrelated factors affect the decision, (2) many key factors are only partially known, and (3) decisions regarding solutions to the problems have long run implications and will involve a significant part of an organization's resources. All these characteristics are evident in the problem of evaluating alternative complex interchange designs.

The following general, simplified discussion of decision theory emphasizes its applicability in evaluating major interchanges. Readers who desire to explore more deeply the theoretical aspects of decision theory techniques can find detailed discussions in most any operations research or management decision book. Two which are particularly informative are "The Analysis of Management Decisions" *(3)* and "Introduction to Operations Research" *(4)*.

## DECISION THEORY—WHAT IS IT?

Decision theory presents a method for making decisions where the information available is uncertain. It structures problems to incorporate, rather than ignore, estimates of immeasurable factors. The decision theory approach seeks to identify all factors relevant to the decision and to judge what effect each factor will have on each alternative. By quantifying factors and values, the decision maker is able to approach the problem systematically, leading to a better understanding of the problem and, therefore, increased confidence that his decision is correct. Decision theory methodology does not replace judgment in evaluation, but assesses alternatives explicitly and systematically.

DESIGN ALTERNATIVES

| | | | A | B | C | D |
|---|---|---|---|---|---|---|
| STATES OF NATURE | $\theta_1$ | Weighting Scheme 1 | $R^*_{A,1}$ | $R_{B,1}$ | $R_{C,1}$ | $R_{D,1}$ |
| | $\theta_2$ | Weighting Scheme 2 | $R_{A,2}$ | $R_{B,2}$ | $R_{C,2}$ | $R_{D,2}$ |
| | $\theta_3$ | Weighting Scheme 3 | $R_{A,3}$ | $R_{B,3}$ | $R_{C,3}$ | $R_{D,3}$ |
| | $\theta_4$ | Weighting Scheme 4 | $R_{A,4}$ | $R_{B,4}$ | $R_{C,4}$ | $R_{D,4}$ |

*$R_{i,j}$ is the cumulative worth of alternative i combined under weighting scheme j

*Figure 2.–Payoff matrix for interchange evaluation problem (1).*

The basic tool of a decision theory analysis is a payoff matrix, like that shown in figure 2, involving alternative choices available and various *states of nature* or uncertain future events. The states of nature must be independent of the alternative choices.

Examples of the three matrix components, when considering interchange evaluation as a decision theory problem, are as follows:

*Alternative Actions:* Several entire interchange configurations (cloverleaf vs. direct connection configuration) or, on a finer level, different designs for one approach leg of an interchange (exit ramp on right vs. exit ramp on left).

*Payoffs:* Measures of performance for the 24 separate categories or attributes referred to earlier, and shown as performance measures in figure 1.

*States of Nature:* Weighting schemes which reflect feelings of society in reference to transportation goals; for example, safety conscious, esthetic conscious, cost conscious.

In decision theory analysis, uncertain future events are handled through use of *subjective probabilities* obtained from the decision maker or from someone who has had objective experience. For the example shown in figure 2, subjective probabilities, $P(\Theta_j)$, must be set for each of the four shown states of nature, $\Theta_1 - \Theta_4$. Using these probabilities, the decision maker should then choose the alternative, i, so that

$$\sum_{j=1}^{4} R_{i,j} \times P(\Theta_j)$$

is the maximum value. $R_{i,j}$ are payoffs, which in the case of figure 2 would each be made up of 24 separate performance measures.

Because many evaluative categories or attributes of a particular alternative state of nature cell within the payoff matrix cannot adequately be expressed in dollar terms, a utility function is employed in decision theory analysis. Utility is defined as a unitless measure of the relative worth of different actions under a given state of nature. This gives the decision maker a normalizing scale for comparing unlike quantities; for example, minutes and decibels which are associated with travel times and noise level respectively and are two measures of interest in interchange evaluations. Utility also permits ranking of those immeasurable factors which must be considered in the analysis; for example, neighborhood disruption and visual impact on the nonuser.

In summary, decision theory analysis involves:

- Determining those goals upon which the alternatives will be evaluated.
- Establishing performance measures or goal quantifiers which include construction of artificial scales for those goals having no scale.
- Reducing all evaluative goals to the same scale.
- Employing a weighting scheme to express the relative importance of each goal to the total.

Through the analysis, a probability distribution for the *total worth* of each alternative is developed and can be compared. Application of the above decision theory principles in the evaluation of alternative major interchange designs is demonstrated below through an example.

## A DECISION THEORY METHOD FOR INTERCHANGE EVALUATION

A step-by-step approach to evaluating alternative interchange designs using the payoff matrix concept follows. An example evaluation directed toward the choice between two hypothetical interchange designs is contained within each step.

### Step 1: Establish a goal hierarchy

Goals for selecting the appropriate major interchange design are best determined by considering a hierarchy of increasingly specific goals, as shown in figure 1. The resulting lowest level subgoals are those which should be considered in the evaluation procedure and are later matched with performance measures.

### Step 2: Establish a performance measure for each lowest level goal

A performance measure must be adopted which reflects how closely each alternative design comes to satisfying the goal. Although expressing goals or goal attainment in terms of physical measures is preferred, this is not always possible because no measure may presently exist. An example of a subgoal with no performance measure might be neighborhood disruption. In this case, the performance measure may have to be a direct worth estimate—as determined by the *expert* or decision maker—of the alternative rather than a physical measure. Figure 1 illustrates matching performance measures for each of the lowest level goals.

### Step 3: Generate alternative designs

Major interchange design is essentially a search and selection procedure—the search is made by generating alternative designs and the selection is made from these alternatives using the evaluation procedure. The alternative designs generated should portray the wide range of goals which appear in the goal structure and also conform with policies and guidelines set forth in the State's design manuals. Each alternative design might be directed primarily toward achieving one of the higher level goals, with secondary consideration of the remaining goals. For example, one alternative might be designed with safety as the ultimate goal (directional interchange) and another designed to stress lower costs (cloverleaf interchange).

### Step 4: Obtain performance distributions

Given the set of alternatives and the measures with which to evaluate them, the decision maker, or expert(s) on his staff, must develop performance distributions such as those shown in figure 3. Cumulative probabilities on each ordinate scale within the figure represent the decision maker's expectation that the displayed alternatives will produce the matched level of performance shown on the abscissa scale. The cumulative distributions portrayed are not necessarily illustrative of two

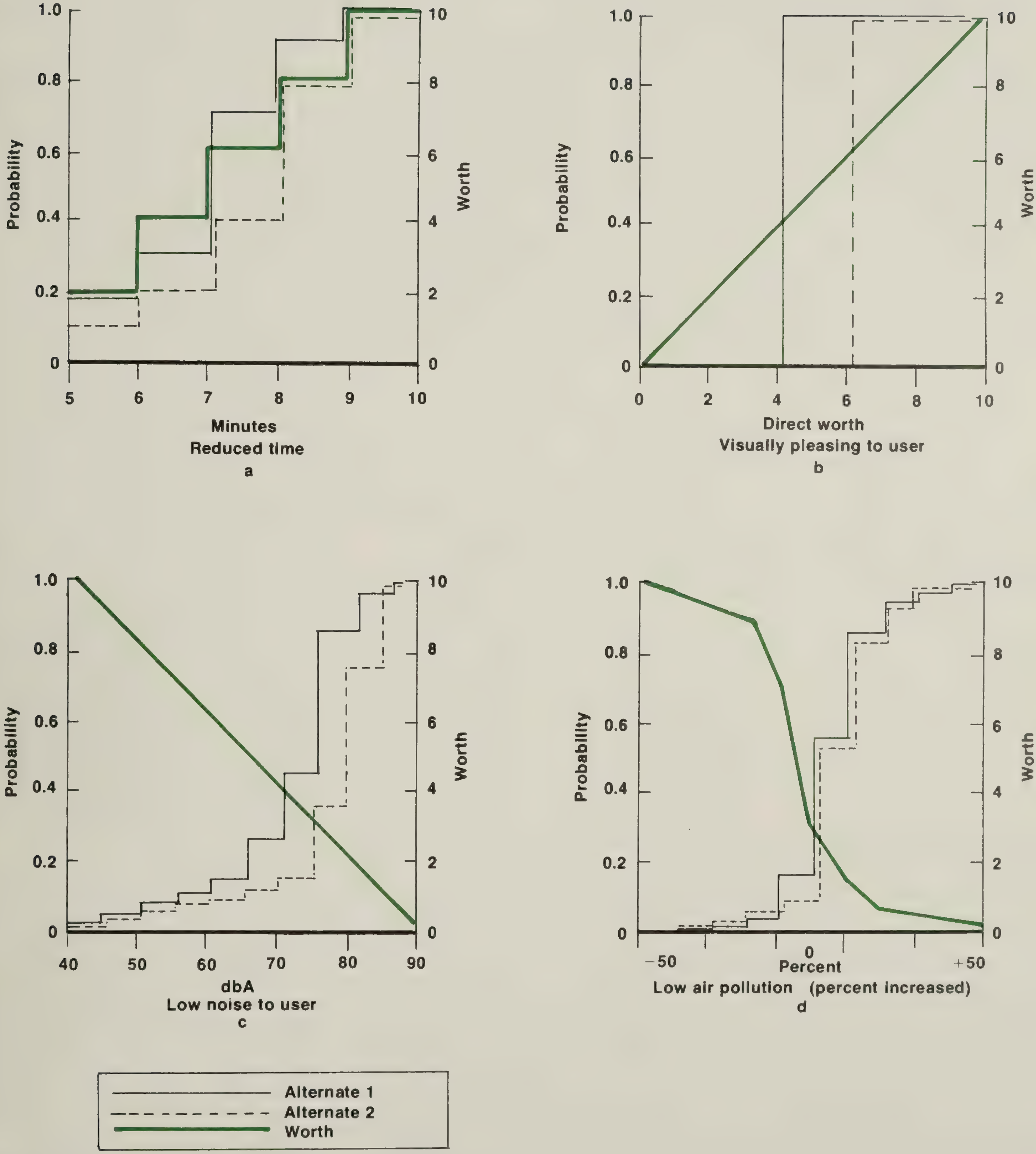



*Figure 3.–Example performance and worth distributions.*

| 1st level goal | 2d level goals | 2d level goal weights | | | 3d level subgoal weights | | Final individual weights | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Scheme | | | | | Scheme | | |
| | | A | B | C | | | A | B | C |
| Good transportation | Convenient transport | 0.4 | 0.1 | 0.2 | | Low travel times [0.3] | 0.12 | 0.03 | 0.06 |
| | | | | | | Free flow [0.4] | 0.16 | 0.04 | 0.08 |
| | | | | | | Reduce user stress [0.3] | 0.12 | 0.03 | 0.06 |
| | | | | | | Total = 1.0 | | | |
| | Safe transport | 0.3 | 0.4 | 0.2 | | Low fatalities [0.6] | 0.18 | 0.24 | 0.12 |
| | | | | | | Low injuries [0.3] | 0.09 | 0.12 | 0.06 |
| | | | | | | Low property damage [0.1] | 0.03 | 0.04 | 0.02 |
| | | | | | | Total = 1.0 | | | |
| | Esthetically pleasing | 0.1 | 0.3 | 0.2 | User [0.4] | Low noise [0.3] | 0.012 | 0.036 | 0.024 |
| | | | | | | Visually pleasing [0.4] | 0.016 | 0.048 | 0.032 |
| | | | | | | Comfortable ride [0.3] | 0.012 | 0.036 | 0.024 |
| | | | | | | Total = 1.0 | | | |
| | | | | | Non-user [0.6] | Low noise [0.3] | 0.018 | 0.054 | 0.036 |
| | | | | | | Visually pleasing [0.3] | 0.018 | 0.054 | 0.036 |
| | | | | | | Low water pollution [0.2] | 0.012 | 0.036 | 0.024 |
| | | | | | | Low air pollution [0.2] | 0.012 | 0.036 | 0.024 |
| | | | | | Total = 1.0 | Total = 1.0 | | | |
| | Beneficial to the community | 0.15 | 0.1 | 0.35 | Economically [0.5] | Increase industry [0.3] | 0.0225 | 0.015 | 0.0525 |
| | | | | | | Decrease unemployment [0.4] | 0.03 | 0.02 | 0.07 |
| | | | | | | Increase tax base [0.2] | 0.015 | 0.01 | 0.035 |
| | | | | | | Increase fire protection [0.1] | 0.0075 | 0.005 | 0.0175 |
| | | | | | Socially [0.5] | Improve neighborhood [0.2] | 0.015 | 0.01 | 0.035 |
| | | | | | | Improve poor & aged mobility [0.2] | 0.015 | 0.01 | 0.035 |
| | | | | | | Improve recreation [0.2] | 0.015 | 0.01 | 0.035 |
| | | | | | | Permit desired growth [0.4] | 0.03 | 0.02 | 0.07 |
| | | | | | Total = 1.0 | Total = 1.0 | | | |
| | Low cost transport | 0.05 | 0.1 | 0.05 | Construction [0.2] | | 0.01 | 0.02 | 0.01 |
| | | | | | Operating [0.8] | User cost [0.6] | 0.024 | 0.048 | 0.024 |
| | | | | | | Facility cost [0.4] | 0.016 | 0.032 | 0.016 |
| Totals | | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

*Figure 4.–Sample weighting procedure.*

real world alternatives, but they do demonstrate the variety of designs which might be encountered in a typical analysis. As shown, certain measures—such as visual pleasure—may be represented as point values, while others—such as reduced travel time—are shown to have a nearly uniform distribution.

Because the performance measures are predicted—using, for example, expert judgment, existing quantitative information available in reports like the Highway Capacity Manual, and/or presentation models to assess nonuser and user visual impacts—a degree of uncertainty exists. The decision maker can represent his estimate of uncertainty through the shape of his performance measure distribution; the width or range of the distribution increasing with an increase in uncertainty.

## Step 5: Obtain worth transformation functions

In order to combine the performance measures of the individual attributes into a single overall measure for each alternative, the performance units must be transformed into worth. Worth functions can be developed by employing a lottery scenario which involves asking the decision maker to choose between two constructed lotteries. In this process, the end points—worth values of 0 and 1—are first identified, its being quite obvious which end of the scale is preferable over all other points. For example, in figure 3d, the lowest and highest air pollution levels have the maximum and minimum worth values respectively. To determine intermediate worth values, the decision maker is offered the choice of having for example, 10 percent less air pollution for certain or of taking a chance where there is *P* probability of having 50 percent less air pollution, but $1-P$ probability of having 50 percent more air pollution. The *P* value where the decision maker is indifferent to the choice offered is the worth value for achieving a 10 percent reduction of air pollution. Several points for other levels of decreases and increases of air pollution can be determined in the same manner to determine the entire worth function.

Worth transforms can be step functions such as those shown in figure 3a, or continuous forms, either sloping positively or negatively as shown in figures 3b and 3c respectively.

Direct worth transforms, for those attributes which cannot be physically measured, are simply one-to-one transformations. This is demonstrated in figure 3b as a positively sloping 45° line.

### Step 6: Generate a number of weighting schemes

Different weighting schemes should be devised to reflect the diversity of opinion within the affected community. Three systems for weighting the performance measures are shown in figure 4. The numbers at the left- and right-hand side of the figure are three alternative weighting schemes intended to demonstrate a user-convenience-oriented strategy (Scheme A), a safety-oriented strategy (Scheme B), and a community-benefits-oriented strategy (Scheme C). The numbers at the right-hand side of the figure are derived by giving different weights to the five second-level goals (convenient transport, safe transport, etc.). The only restriction on generating weighting schemes is that the sum of the second-level goal weights for each scheme and the subgoal weights (third level) within a goal must all sum to unity. The final individual weights are the products of the second-level goals and subgoal weights.

Figure 4 shows that Scheme A gives more weight to user convenience and only slightly less to safety. Scheme B is primarily safety and esthetics oriented, while Scheme C is intended to give most consideration to benefiting the community.

### Step 7: Assign prior probabilities to the weighting schemes

In assigning the weighting scheme prior probabilities, the decision maker must decide how certain he is that an individual scheme represents the majority opinion. For this example problem, it is assumed that the probability of Scheme A being representative of community desires is 0.3; Scheme B is 0.2; and Scheme C is 0.5. This would mean that Scheme C, the community-benefits-oriented strategy has the highest likelihood of representing the public's wishes, followed by user convenience, and then safety.

### Step 8: Monte Carlo sample the performance measure distributions

The decision maker now has, for each alternative, a set of subgoal performance distributions and means for transforming them into worth functions (examples shown in figure 3) and a distribution of weighting strategies to combine the worths of all subgoals (figure 4). These distributions must next be combined into a single distribution of a single payoff variable. This can be accomplished by employing a Monte Carlo sampling technique in which a random number between 1 and 100 is selected for each of the performance measures, for each alternative, by consulting a random number table.

Table 1 shows one sample set for each of the two example alternatives. The worth values shown were obtained by entering the probability scale of the cumulative performance distribution curves, using the random number selected (divided by 100); moving to the right from the ordinate until it intercepts the appropriate alternative cumulative curve; moving vertically to the worth line and reading this intercept on the worth scale. This procedure,

**Table 1.—Example problem performance measures and weighting schemes**

| Goal | Performance measure | Alternative 1 Random No. | Alternative 1 Worth | Alternative 2 Random No. | Alternative 2 Worth |
|---|---|---|---|---|---|
| Low travel time | Reduced time . . . . . .minutes | 21 | 4 | 25 | 6 |
| Free flow | Level of service (A, B, C, or D) | 84 | 3 | 40 | 6 |
| Reduce user stress | Direct worth | 78 | 5 | 50 | 7 |
| Low fatalities | Reduced fatal accidents | 38 | 3 | 77 | 7 |
| Low injuries | Reduced injury accidents | 18 | 2 | 48 | 7 |
| Low property damage | Reduced property-damage-only accidents | 33 | 3 | 23 | 3 |
| Low noise (user) | Decibels at centerline | 63 | 3 | 96 | 1 |
| Visually pleasing (user) | Direct worth | 17 | 4 | 71 | 6 |
| Comfortable ride (user) | Roughness index (1–10) | 68 | 3 | 22 | 4 |
| Low noise (nonuser) | Decibels at right-of-way line | 53 | 3 | 92 | 1 |
| Visually pleasing (nonuser) | Direct worth | 12 | 8 | 26 | 9 |
| Low water pollution | Percent increase | 64 | 5 | 87 | 3 |
| Low air pollution | Percent decrease | 25 | 3 | 55 | 3 |
| Increase industry | Increased payroll . . . . .percent | 14 | 3 | 52 | 6 |
| Decrease unemployment | Increased jobs | 64 | 2 | 98 | 9 |
| Increase tax base | Increased assessed value | 94 | 7 | 26 | 6 |
| Increase fire protection | Decreased average time | 67 | 9 | 15 | 0 |
| Improve neighborhood | Direct worth | 65 | 8 | 74 | 6 |
| Improve poor and aged mobility | do | 76 | 9 | 19 | 7 |
| Improve recreation | do | 16 | 7 | 47 | 7 |
| Permit desired growth | do | 55 | 8 | 78 | 8 |
| Construction cost low | Dollars | 93 | 8 | 99 | 6 |
| User cost reduced | Dollars/year reduced | 80 | 6 | 1 | 2 |
| Facility cost reduced | do | 57 | 6 | 98 | 9 |

demonstrated in figure 5, must be repeated, preferably more than 30 times, to obtain a distribution of sample sets; each sample set, in effect, represents an interchange of the type defined by the alternative. As the sample size is increased, the

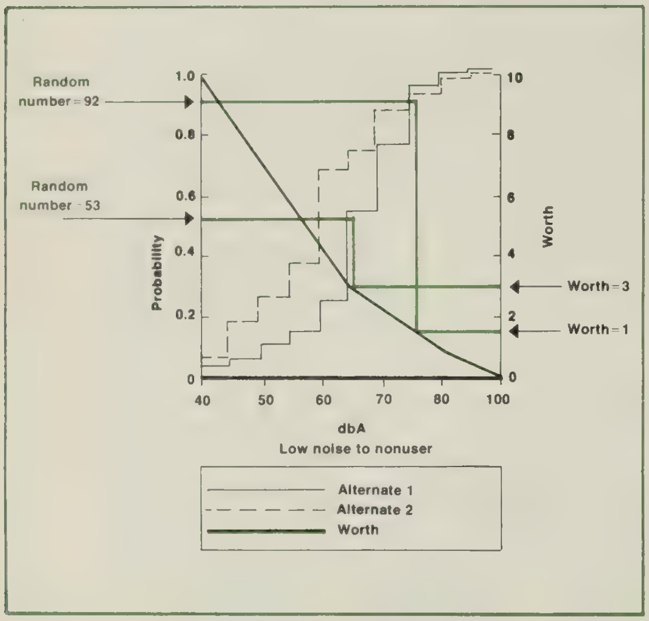



*Figure 5.–Applying Monte Carlo sampling techniques.*

average of the sample set worths obtained would approach the expected worth of the alternative.

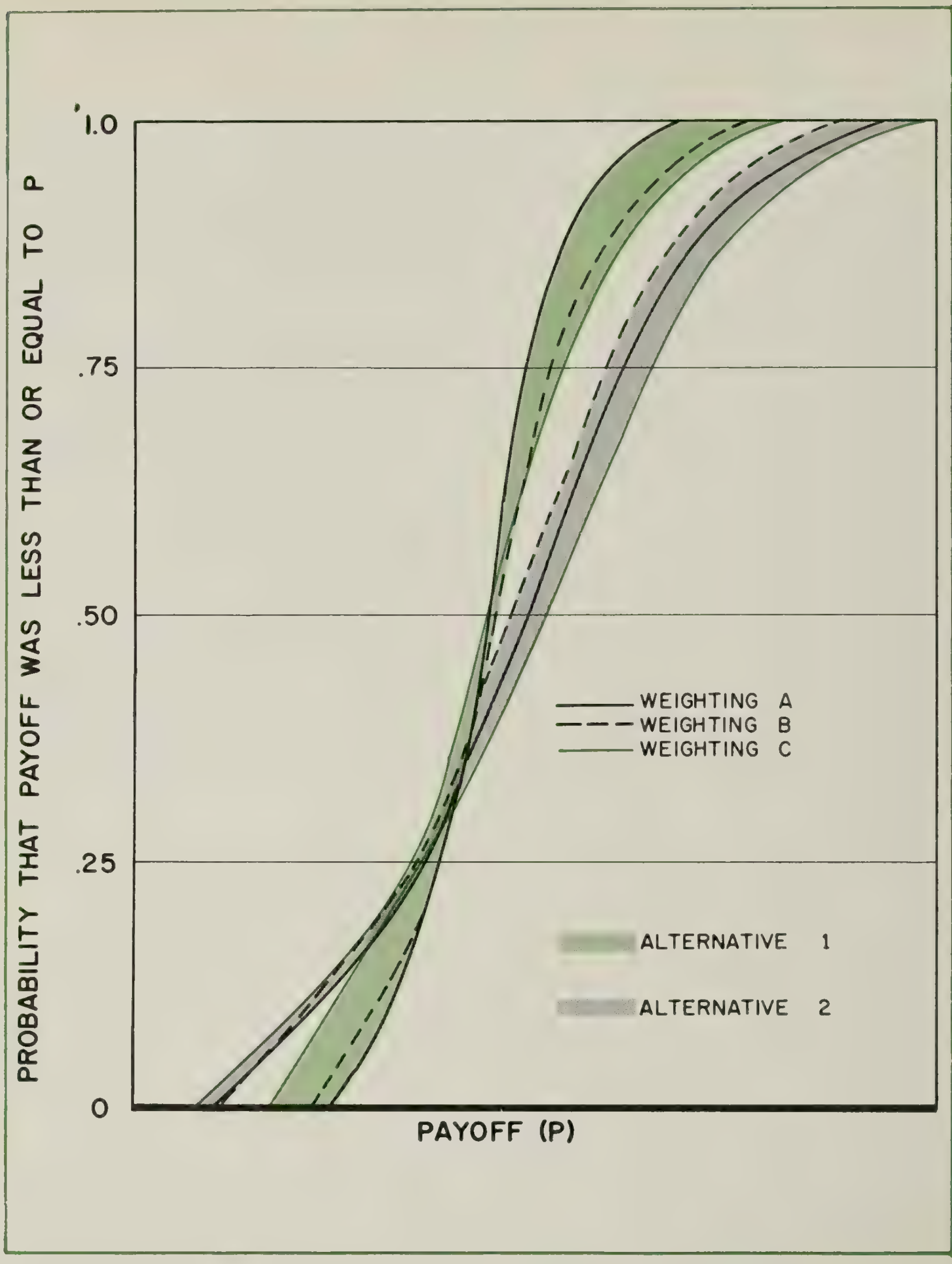



*Figure 6.–Sample payoff distributions with weighting bands.*

### Step 9: Monte Carlo sample the weighting distribution

Monte Carlo sampling can also be used to select different weighting strategies, enabling the decision maker to test the sensitivity of his weights. A weighting procedure can be chosen randomly according to the prior probability distribution discussed in Step 7 (Scheme A=0.3; Scheme B=0.2; and Scheme C=0.5). In this example, a random number between 1 and 100 is generated. If it is less than or equal to 30, it indicates Scheme A, a number 31 through 50 indicates Scheme B, and a number greater than 50 fixes the weights according to Scheme C.

These weights, together with each sample set of worth measures obtained in Step 8, will be used in Step 10 to produce a distribution of payoff points for each alternative which forms the basis for decision.

### Step 10: Produce payoff distributions

The final step in the evaluation (except the decision itself) is to multiply the appropriate weighting strategy, as obtained in Step 9, by the worth values, obtained in Step 8, and add the scores to get a total worth. If the sample of interchange worth sets is multiplied by the sample of various weighting schemes, then a distribution of payoffs results for each alternative. A graph of the payoffs' total computed worths for all 24 performance measures for each alternative in a cumulative format, as shown in figure 6, provides the decision maker with more information than a simple *mean* payoff or total worth value. The payoff distribution gives ranges and the shape of the entire function and enables the decision maker to evaluate each alternative under the best or worst weighting conditions.

In this example, the decision maker sees that Alternative 1 is the best alternative in about 70 percent of the sampled cases. However, it can be seen that there is a chance that Alternative 1 will yield the lowest worth of the two alternatives under some combinations of performance measure values. Thus, one can accept Alternative 1 on the basis that it is most likely to produce the higher payoff, or Alternative 2 on the basis that at least some minimum payoff will be assured.

The shaded bands represent the outer limits of each alternative as defined by the individual weighting strategies. It can be seen that Alternative 2 is generally more sensitive to the different weighting schemes as the band widths of payoffs are larger.

## CONCLUSIONS

If this decision theory approach is adopted and executed properly in the selection of interchange designs, it will force informal evaluation to be better focused, leading to a better understanding of the reasoning process. It makes the assumptions inherent in the decision explicit and, therefore, subject to scrutiny. Both these characteristics of decision theory approaches are desirable if one accepts the notion that the more one knows about a process, the better the process will work.

Additional details on applying decision theory techniques in evaluating complex alternative interchanges are available in the complete report *(1)*, copies of which are available from the Federal Highway Administration, Traffic Systems Division, HRS-30, Washington, D.C. 20590. A summary of the research effort leading to the report appears in the March 1974 issue of *Public Roads, A Journal of Highway Research and Development*, vol. 37, No. 8.

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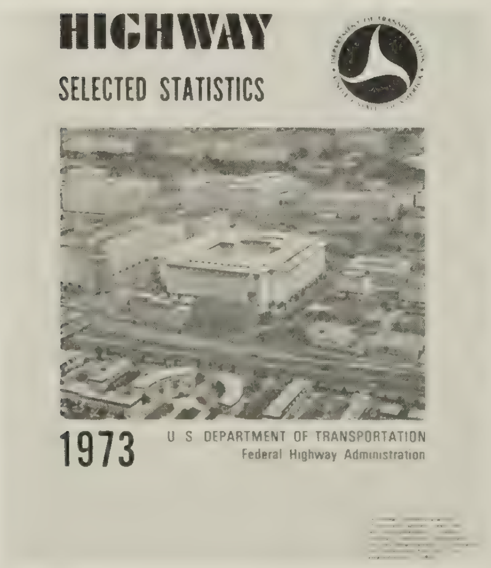
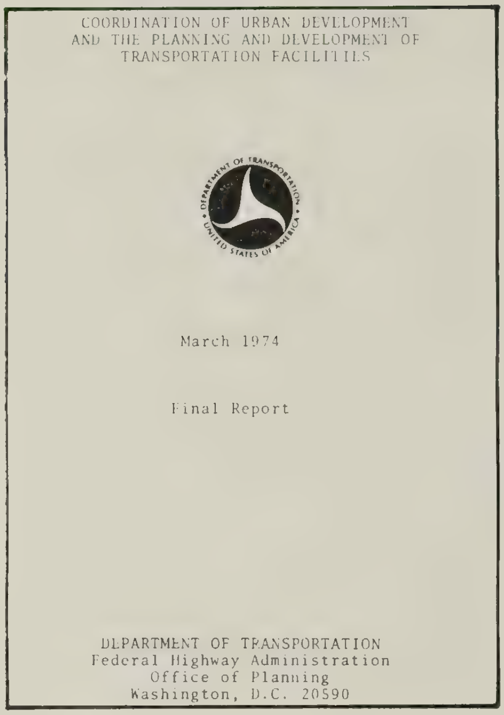
# New Publications

**Selected Highway Statistics, 1973** is a 19-page booklet, the third in an annual series providing most-used statistics in a handy pocket-sized form. (The complete bulletin, **Highway Statistics, 1973,** will be published early in 1975.) Included in the booklet are data on vehicles, fuels, drivers, finances, contracts awarded, and mileage. Estimates for vehicle registrations, motor-fuel consumption, drivers licensed, and highway-user revenues are provided for 1974.

This publication may be obtained from the U.S. Department of Transportation, Federal Highway Administration, Office of Public Affairs (HPA-1), Washington, D.C. 20590.




**Coordination of Urban Development and the Planning and Development of Transportation Facilities** is the result of a contract between the Federal Highway Administration and the International Road Federation to investigate the procedures followed in certain other countries in coordinating urban transportation planning with general urban planning. The study also investigated the manner in which these plans are realized through control of public and private development. The effort involved visits to eight European countries, Australia, and Canada; talks with officials; and observations of the results of their approaches to their problems.

This report should be of interest to anyone concerned with planning, location, and design of urban development and the necessary transportation facilities to serve such development. It is available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 for $2.50 (Stock No. 5001-00076).


**Bicycles and Pedestrian Facilities in the Federal-Aid Highway Program** provides basic information about the Federal-aid highway program and how it may assist in the planning and construction of bikeways and walkways. Eligible features of such facilities, such as drainage, paving, lighting, right-of-way, curb-cut ramps, and grade separations are discussed and illustrated. The publication also contains a reference list of publications which may be of assistance in the development of bikeways and walkways.

This booklet is available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock No. 5001-0082) for 45 cents.

## New Report on 1974 Highway R&D

Published in time for the Transportation Research Board's annual meeting in January 1975, the Federal Highway Administration's *Research and Development Program, 1974* presents program highlights for the fiscal year. The 102-page report provides an overview of the program, summarizes its chief accomplishments for the year, and forecasts its future direction. It explains how, through the Federally Coordinated Program of Research and Development in Highway Transportation (FCP), FHWA cooperates with many other organizations to work toward highway R&D objectives on a national scale. The report provides basic information on FHWA's R&D organization and how the organization, through the FCP, coordinates the widely scattered activities of the nationwide highway R&D program. Detailed reports on the individual categories and projects of the FCP are also included.

The report, which FHWA plans to update and reissue annually, replaces the nearly 500-page annual "Highway Transportation Research and Development Studies" (HTRDS). Official distribution of the new report to the Washington office of FHWA and to Region and field Division offices has been completed. It may be purchased for $2.30 a copy (Stock No. 5000—00091) from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

**Woodrow J. Halstead** has been Chief of the Materials Division, Office of Research, since 1966. Since its inception in 1905 the division's major emphasis has been determining the characteristics of materials used in highway construction and the relation of their characteristics to their performance in pavements or other highway structures. Mr. Halstead's Federal career began in 1935 with the Bureau of Public Roads, where his work dealt with asphalt research. From 1944 to 1946 he served as an electronics officer in the U.S. Navy. Upon his return to the BPR in 1946 he was assigned as head of the chemical laboratory dealing primarily with testing and research on cements and paints.

Mr. Halstead has been active in a number of technical societies and associations. He was chairman of the Committee C-1 of ASTM from 1963 to 1968 and a member of the Board of Directors of the Association of Asphalt Paving Technologists from 1967 to 1974, serving as its president in 1971. He is a member of the Transportation Research Board's Group 2 Council on Design and Construction of Transportation Facilities and has been Secretary of the AASHTO Subcommittee on Materials since 1967.

In 1969 he received the Award of Merit from ASTM and was named a Fellow of the Society, and in 1972 he received the Industry Recognition Award of the National Asphalt Pavement Association for his work in establishing viscosity graded specifications for asphalt cements.

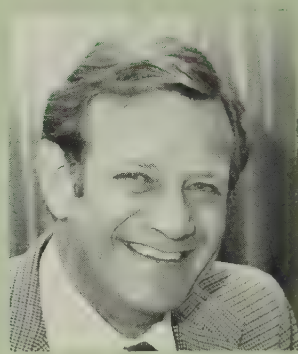
Mr. Halstead is a 1934 graduate of the University of Virginia, with a B.S. degree in chemical engineering.

**David Solomon,** Chief of the Environmental Design and Control Division, Office of Research, has had 22 years of research experience with the Federal Highway Administration. His contributions encompass traffic, safety, and the environment. At present he is responsible for research in such diverse areas as pedestrian safety, air and water quality, geometric design, noise, hydraulics and hydrology, bicycle safety, snow, ice, rain, fog, safety of heavy vehicles, separate bus and truck roadways, utilization of urban transportation space, and ecological problems associated with highways.

Mr. Solomon's research efforts have included studies of highway signing, night visibility, vehicle sizes and weights, economic evaluation of comfort, traffic signals and accidents, driver behavior, speed relationships, and driver and vehicle characteristics. He has participated in the work of several Organisation for Economic Co-operation and Development groups and completed a 1-year assignment to the British Transport and Road Research Laboratory.

Mr. Solomon is a member of ASCE and ITE, where he has served as president of the Washington section. He has also served on TRB committees and participated in evaluation panels of the National Cooperative Highway Research Program.

He attended Florida Southern College and received a Bachelor of Civil Engineering degree from the University of Colorado in 1949 and a Certificate in Traffic Engineering from the Yale Bureau of Highway Traffic in 1954.



**Milton P. Criswell,** Chief of the Implementation Division, Office of Development, since 1973, is responsible for developing and administering programs to stimulate and expand the application and the practical use of the products of research and development. Prior to this assignment he was Chief of Administrative Control for the Associate Administrator for Research and Development. His career with the Bureau of Public Roads and the Federal Highway Administration has spanned over 20 years. Field positions have included area engineer in New Hampshire, New Jersey, and Massachusetts and planning and research engineer and assistant to the chief of the Planning and Research Section in Region 1. Central office positions have included highway engineer and program officer for the Office of Research and Development from 1965 to 1970 and a 6-month detail to the Bureau of the Budget in 1969.

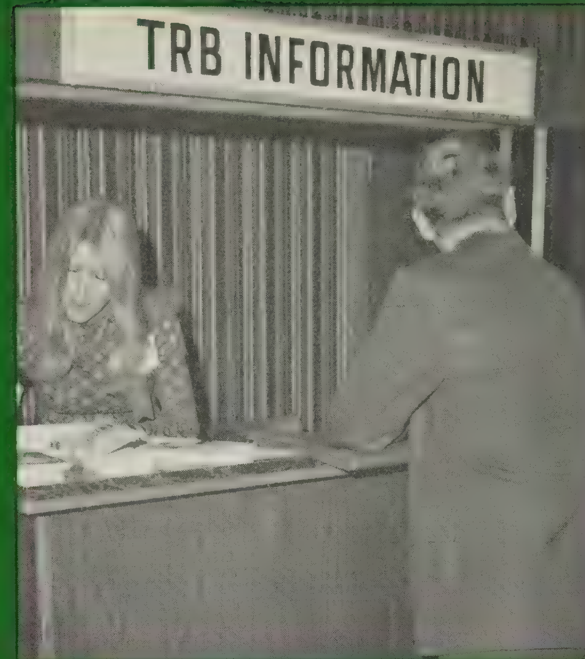
After 2 years of service in the U.S. Marine Corps, Mr. Criswell received a B.S. degree in civil engineering in 1953 from Denver University. He obtained a Master of Engineering Administration from George Washington University in 1968. His awards in the course of his employment have included the Bureau of Public Roads Special Acts or Services Award in 1962 and Outstanding Performance ratings in 1966 and 1971.

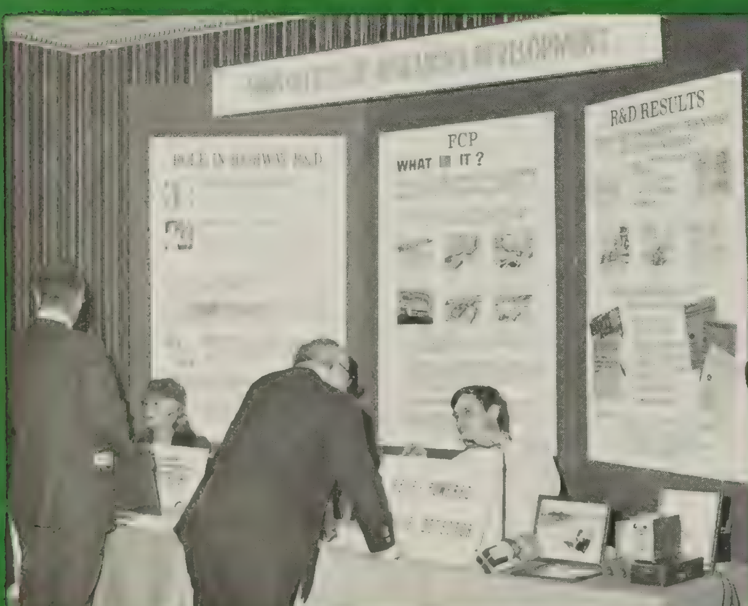
## EDITOR'S NOTE:

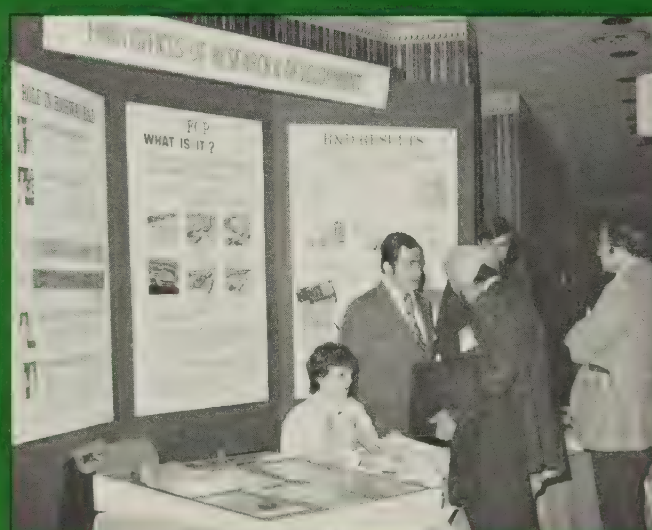
In the past few issues of *Public Roads* we have made significant changes in the content, format, and design. As reader interest is essential in planning a more effective publication, we want to know what you now think of our magazine and how we can make it even more responsive to your needs. The following questionnaire will help us in our efforts to make the magazine more interesting and more relevant to all members of the highway community. Remove this page and the next (perforated along center fold) to leave your magazine intact. Please complete the questionnaire, fold as indicated on the reverse, and staple. Postage is prepaid.

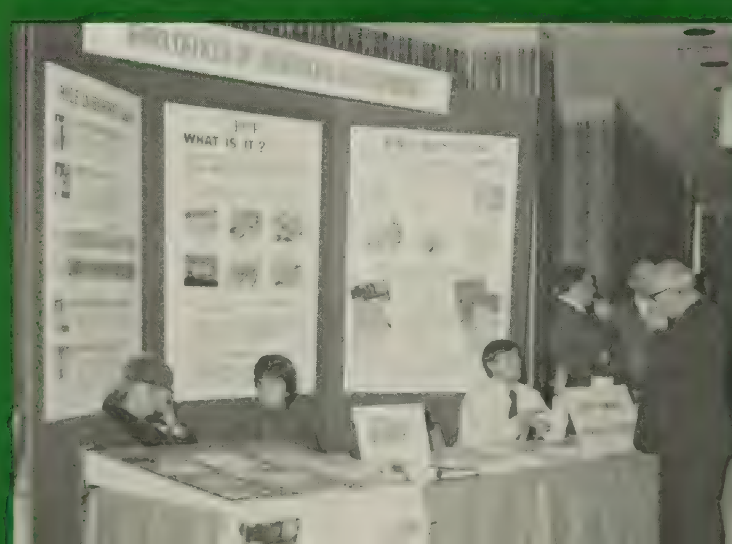
# TRANSPORTATION RESEARCH BOARD FIFTY-FOURTH ANNUAL MEETING

**January 13-17, 1975**
**Sheraton-Park Hotel**
**Washington, D.C.**



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Since 1966 **William W. Wolman** has been Chief of the Traffic Systems Division of the Office of Research. He is responsible for a broad program of fundamental and applied research, including the development of urban, freeway, and rural traffic controls and systems for the enhancement of safety, alleviation of congestion, and traffic problems related to energy conservation. He is also a professorial lecturer in the Statistics and Operations Research departments of the George Washington University.

For the 6 years before coming to FHWA Dr. Wolman was with NASA's Goddard Space Flight Center and was concerned with the reliability of satellites. Before that assignment he was Head of Reliability of NASA's Office of Manned Space Flight. Before 1960 he spent 10 years with the Department of the Navy as a statistical consultant. His military service was with the Navy's Seabees.

Dr. Wolman is a member of the Institute of Traffic Engineers. He also belongs to the American Statistical Association and the Institute of Mathematical Statistics. He has been a U.S. delegate to several road research groups of the Organisation for Economic Co-operation and Development and is presently delegate and chairman of its Group T-9, International Corridor Experiment. He received degrees from City University of New York, Columbia University, and a Ph.D. in mathematics from the University of Rochester.

**F. J. Tamanini** has been Chief of the Structures and Applied Mechanics Division of the Office of Research since 1971. The division plans, promotes, and coordinates research to obtain greater insight into the structures used in the highway transportation system, to develop new structural concepts, extend life expectancy and reduce costs, and to improve design methodology. This research relates to bridges; tunnels; pavements; drainage structures; and protective highway appurtenances such as traffic railings, impact attenuators, lighting standards, and sign supports. His career with the Federal Highway Administration began in 1966 after approximately 20 years of bridge and structural research and development for the U.S. Army and NATO forces.

Mr. Tamanini is a fellow of ASCE and a member of the National Society of Professional Engineers and the International Association for Bridge and Structural Engineering. He served as vice president of the Virginia Society of Professional Engineers (VSPE) and president of the George Washington chapter.

He is the recipient of the 1968 Engineer of the Year Award in Northern Virginia and the VSPE Outstanding Service Award in 1968 and 1973. He received ASCE's State of the Art Award in 1972 for his paper, "Designing 'Fail-Safe' Structures for Highway Safety." He is listed in *Who's Who in Engineering* and in the Engineer's Joint Council's *Engineers of Distinction.*

Mr. Tamanini received a BSCE degree from Penn State and an MSCE from Catholic University, and is a registered professional engineer.

**C. L. Potter,** as Chief of the Engineering Services Division, Office of Development, is responsible for providing a wide range of engineering and technical services to the other R&D divisions. These encompass the design and fabrication of electronic instrumentation and mechanical systems, computer programing, dissemination of R&D technical information, design of data acquisition equipment, and operation of R&D's computer equipment and the Management Information System. He is also the managing editor of *Public Roads* magazine.

Mr. Potter came to the FHWA in 1967 with over 20 years experience in quality control and reliability engineering of military, space, and consumer products and programs. His government service includes a 5-year assignment with NASA where he was Executive Secretary to the Goddard Space Flight Center's Reliability Assurance Council. Positions in private industry have included senior quality control engineer for Bendix Radio Division, supervisor of the quality engineering department for Melpar, Inc., quality control manager of American Machine and Foundry Company, and product assurance manager of Sanders Associates, Inc.

He is a member of the American Society for Quality Control and was chairman of the Baltimore Section for 2 years. He is active in the Society and has been Certified by the ASQC both as a Reliability and Quality Engineer.

Mr. Potter's awards as a Federal employee include Outstanding Performance ratings in 1970 and 1971 and Quality Increases in 1966, 1970, and 1973.

# Structural Behavior of Typical Highway Inlet Grates

by Craig A. Ballinger

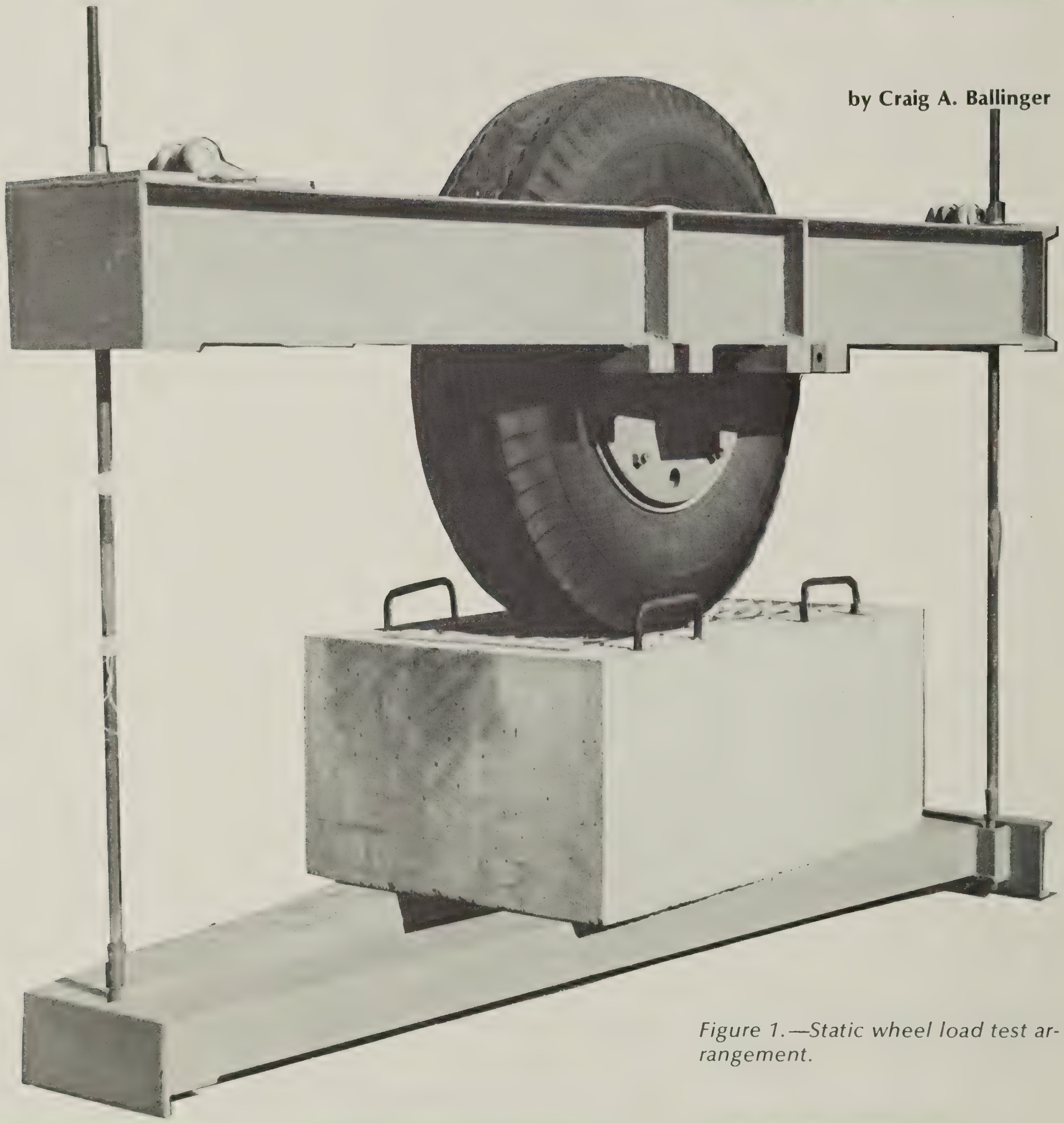

Figure 1.—Static wheel load test arrangement.

This article summarizes a study involving the load testing and structural analysis of eight typical State highway department inlet grates—six roadway and two median. Other grate variables included the composition material, the shape of grate members, and either flat or sloped installed surfaces.

The inlet grates were subjected to incremental static wheel loads and rolling and impact dynamic wheel loads at various vehicle speeds. Each grate was also subjected to flat plate load tests to determine its ultimate load capacity and mode of failure. Computer analyses were made to determine whether the behavior of the subject grates under static wheel loads could be predicted.

Study results indicated that the load capacity of most

**of the grates tested greatly exceeded current vehicle loadings, and that inlet grates may be designed using modern structural design methods. Grates may also be effectively evaluated with a plate load test.**

**The complete report on this study, "Evaluation of the Structural Behavior of Typical Highway Inlet Grates, with Recommended Structural Design Criteria" (*1*),[1] is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock No. PB 236435).**

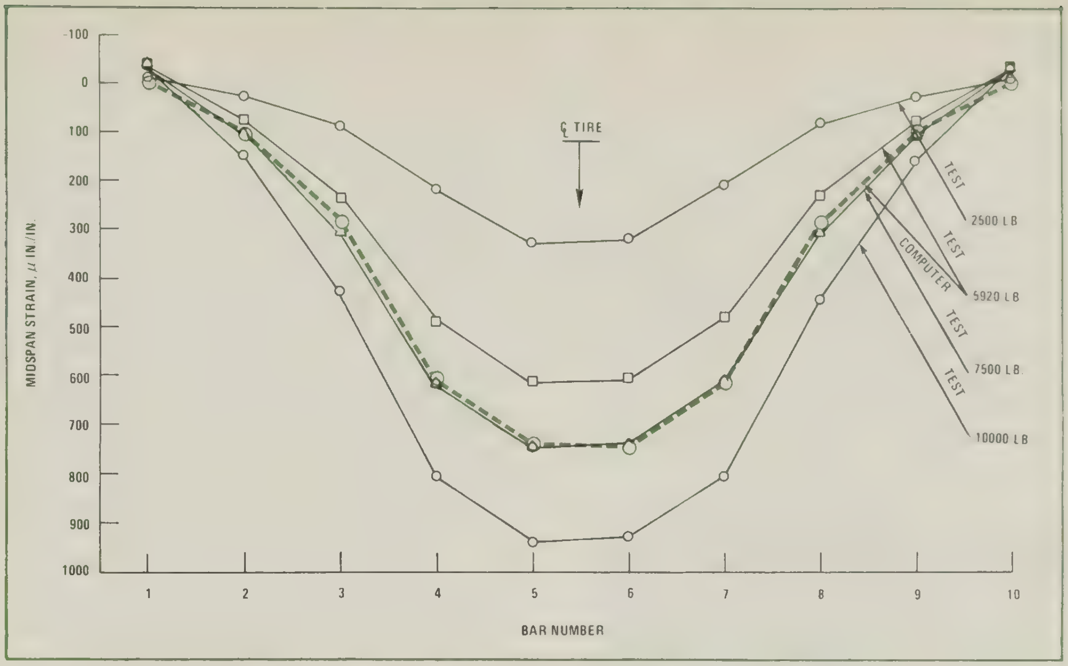


*Figure 2.—Static wheel load strains on transverse centerline (four-bar loading).*

## INTRODUCTION

The Federal Highway Administration's (FHWA) Office of Engineering conducted a survey on inlet grates which indicated the following:

- Most inlet grates in service throughout the United States are very heavy, often requiring two men and lifting devices to place them.
- Few State highway departments have *modern* criteria for designing inlet grates on a structural basis. Some grates are designed for hydraulic capacity.
- Some State highway departments fabricate grates and then proof test them in accordance with Federal Specification RR–F–621b; however, this is not a requirement for Federal-aid construction (*2*).
- Many State highway departments do not have standard designs for inlet grates. In at least one State, over 100 different sizes and shapes of inlet grates are used.

Although some State highway departments have conducted limited studies on certain aspects of commonly used inlet grates (*3*), the Office of Engineering survey indicated the need for a structural research study on highway inlet grates. Consequently, the State highway departments were requested to supply the Office of Engineering with copies of the plans for their most typical inlet grates. These plans were reviewed and eight styles of inlet grates from seven States were selected for study.

The highway departments of the selected States supplied two duplicate sets of the grates and frames for testing. These grates provided the following variables for evaluation:

- Location—roadway and median.
- Material—steel and cast iron.
- Shape of structural members—plate, I-beam, double-extra-strong pipe, variable sections.
- Surface position—flat and sloped.

As a result of the survey, the Office of Engineering requested FHWA's Office of Research, Structures and Applied Mechanics Division, to conduct a structural research study on typical highway inlet grates. In general, the optimum design of inlet grates includes hydraulic efficiency, vehicle safety, protection against vandalism, and structural adequacy. The research study was primarily concerned with structural adequacy.

## TEST METHODS AND ANALYSIS

### Static wheel load tests

In the laboratory each roadway grate was subjected to incremental static wheel loading tests up to 10,000 lbs (44,480 N) to determine its structural response characteristics. Figure 1 shows a general view of the test arrangement. The tire used for these tests was an 11.00-20, 12-ply, triple-tread truck tire, inflated to 85 psi (590 kPa). As a safety precaution, 90 percent of the tire volume was filled with water prior to inflation with air. Each inlet grate frame was cast into a reinforced concrete box, which served as a mounting fixture for the inlet grate. Each grate was set into a thin layer of plaster grout to provide uniform bearing.

The loading assembly consisted of two parallel, triangular, structural steel frames which were connected at the apexes by steel rods. The concrete box was placed between the frames and oriented as the grates are installed in the field—so that the longitudinal grate bars were parallel with the longitudinal axis of the wheel. The load was applied by drawing the two frames together by turning the nuts on the connecting rods, thereby forcing the wheel down onto the inlet grate. The wheel loads were adjusted by monitoring full-bridge SR–4 strain gages on each of the previously calibrated rods.

During the load tests the midspan deflection and bending strain of each longitudinal grate bar were recorded. Figure 2 shows a typical plot of the strains recorded in the longitudinal bars at various loads, with the wheel located at the center of the grate.

[1] Italic numbers in parentheses identify the references on page 159.

## Dynamic wheel load tests

At a field installation each inlet grate was subjected to 6,000-lb (26,700-N) rolling and impact truck wheel loading tests to determine its response to typical dynamic (in service) loading conditions. The test site is shown in figure 3.

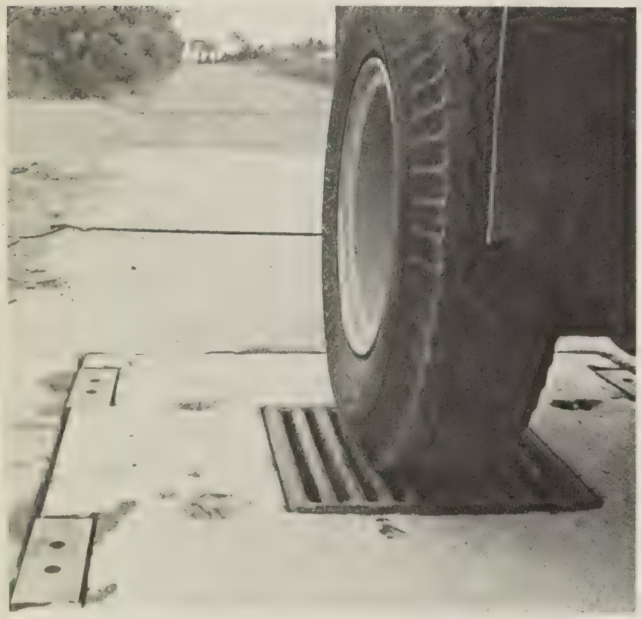

*Figure 3.—General view of the test site.*

For these tests the right rear dual wheels of a dump truck were removed and replaced with the single 11.00-20 tire and wheel which was used for the laboratory tests. The truck was loaded with sand to provide a 6,000-lb (26,700-N) load on the test wheel, which simulated an AASHTO HS-15-44 truck loading. Rolling and impact wheel loads were applied to each grate at speeds ranging from 1 to 50 mph (1.6 to 81 km/h). Impact loads were obtained by driving the truck over a 2.25-in. (57-mm) high ramp.

During these tests deflection of the centerpoint of the grate and bending strain at the midspan of each grate bar were recorded on an oscillograph. Lateral positions of the wheel loads were recorded on heavy brown paper taped over the grates. Figure 4 shows a typical plot of the midspan strains which were recorded in the grate bars at various truck speeds and positions over the grate.

## Static plate load tests

In the laboratory each inlet grate was subjected to static plate loading tests to determine its behavior in accordance with the requirements of Federal Specification RR-F-621b, and its ultimate load capacity and mode of failure. The following is excerpted from the specification (2):

Proof-load test. The frames and covers or gratings selected . . . shall show no permanent deformation when the proof-load [25,000 lb.] is concentrated on a 9- by 9-inch area placed on the cover or grate [through a rubber pad]. The specified load shall be applied by a suitable testing machine and held for a period of one minute. Upon removal of the load, the cover or grating and frame shall be examined for cracks, or permanent deformation, such as buckling. Any cracks or permanent deformation shall be cause for rejection.

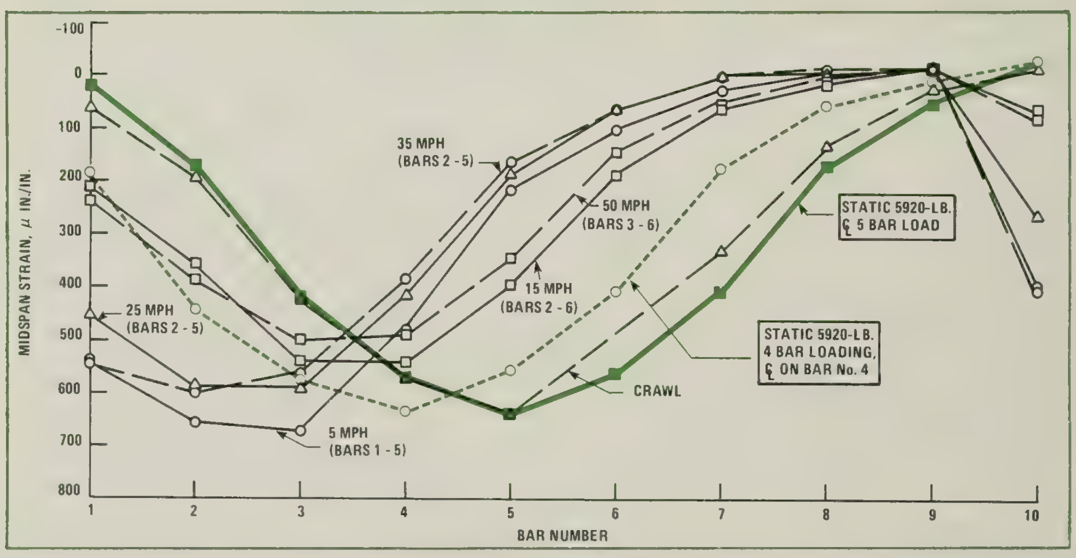


*Figure 4.—Rolling load strains on transverse centerline.*

For these tests loads were applied to grates in reinforced concrete boxes which were used for static wheel load tests. Loads were applied through 9.0- by 9.0- by 1.5-in. (230- by 230- by 38-mm) thick steel plate and a 0.5-in. (13-mm) thick, 60-durometer hardness rubber pad. To apply vertical loads to sloped surface grates an additional trapezoidal, high-strength mortar

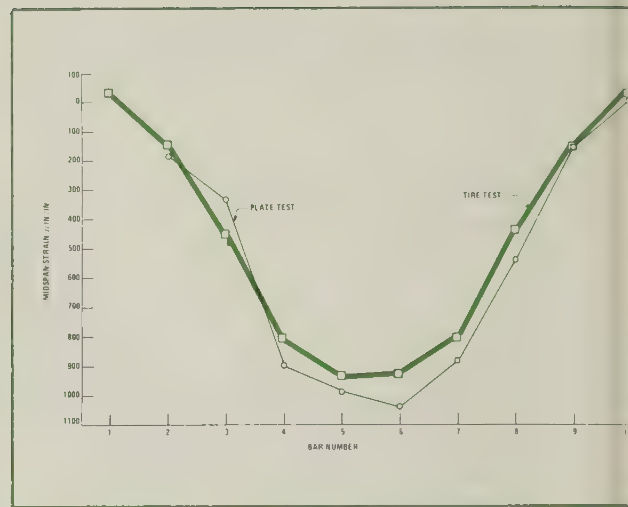


*Figure 5.—Comparison of static tire and plate load test results.*

block was used. These tests were conducted in a universal testing machine.

As with the dynamic wheel load tests, deflection of the centerpoint of the grate and bending strain at the midspan of each grate member were recorded on an oscillograph. In addition, mode of failure and location of yield hinges were recorded. Figure 5 shows a typical plot of midspan strain versus bar number for a plate load test compared to the results from a static wheel load test.

## Computer analysis

A structural analysis of the grates subjected to simulated static wheel loads was made by using the computer program "Analysis of Two-Dimensional Grid Structures" (4). This analysis provided computer values for flexural and torsional moments, shear, and deflection for each position of the wheel on the grates for the selected load increments. Midspan strain in the longitudinal and transverse grate members was subsequently calculated from bending moments, assuming a linear strain distribution. Loading for the computer analysis assumed that the effective width of tire tread contact is equal to the grate member width. Analyses were based on the data from special load/tireprint tests and measured length of tire contact on each of the grate members.

## Tire contact area tests

In order to make the computer analyses it was necessary to develop tire contact area and contact length data at various load levels. The tire manufacturer provided one tireprint, which was made at the tire's rated load of 5,920 lbs (26,300 N). The print also gave measured pressure intensities over the contact area. By averaging the values of the pressure points over longitudinal strips of the tireprint, the variation in unit tread pressure versus distance from the longitudinal centerline of the tire was calculated. Additional tireprints—made at 2,500; 7,500; and 10,000 lbs (11,100; 33,400; and 44,480 N)—were used to develop a relationship between load and tire contact area. This was not a linear relationship due to the stiffness of the tire sidewalls.

These relationships described the behavior of the truck tire on the flat surface, which does not correctly represent the tire contact area on a grate surface. It was therefore necessary to measure the length of tread contact on each bar in a grate. These measurements were then used with the load and tire contact area relationships to compute tire contact pressures (and loading) on the bars of the grates for input into the computer analyses.

## Description of inlet grate specimens

As noted in the introduction, eight inlet grates were subjected to structural testing and analysis. Six of these were roadway grates and two were median grates. They were all selected on the basis of the variables which they provided, and thus were not necessarily representative of the most popular or efficient designs. However, they are all currently being used by their respective State highway departments. Figures 6 through 13 present dimensional details on each of the inlet grates used in this study. The two sloped-surface grates (shown in figures 8 and 9) were tested in the same relative position as they are installed in the field, in accordance with the State's specifications.

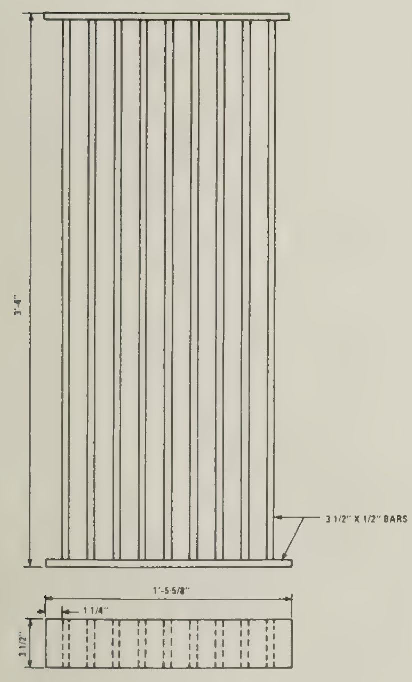


*Figure 6.—Inlet grate A.*

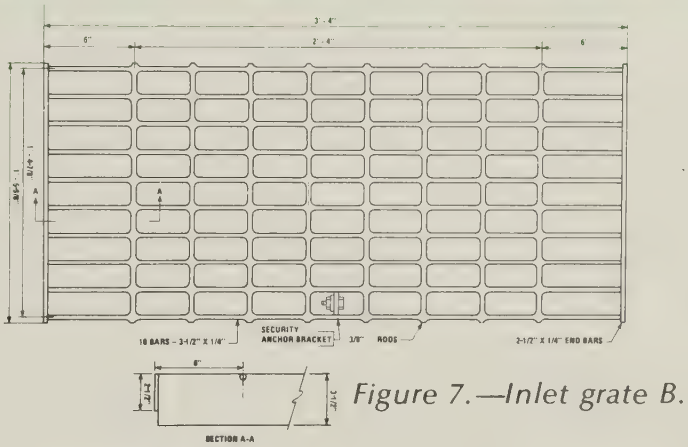


*Figure 7.—Inlet grate B.*

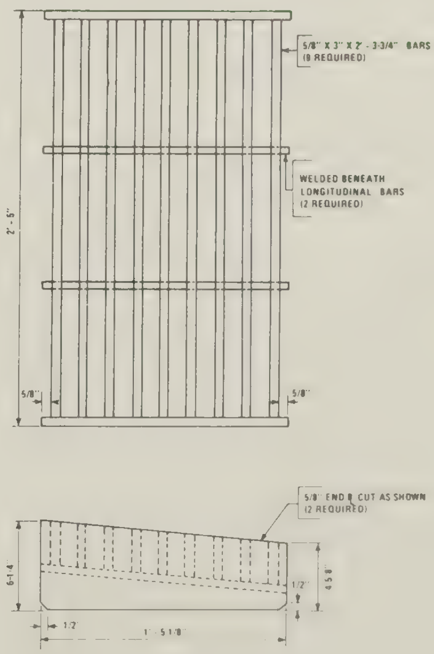


*Figure 8.—Inlet grate C.*

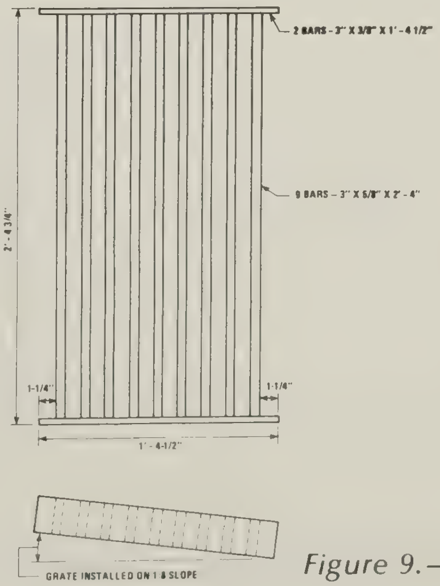


*Figure 9.—Inlet grate D.*

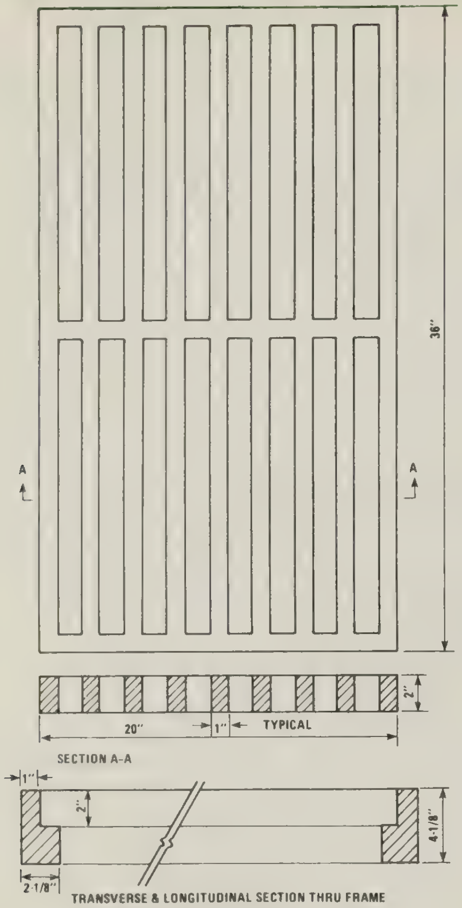


*Figure 10.—Inlet grate E.*

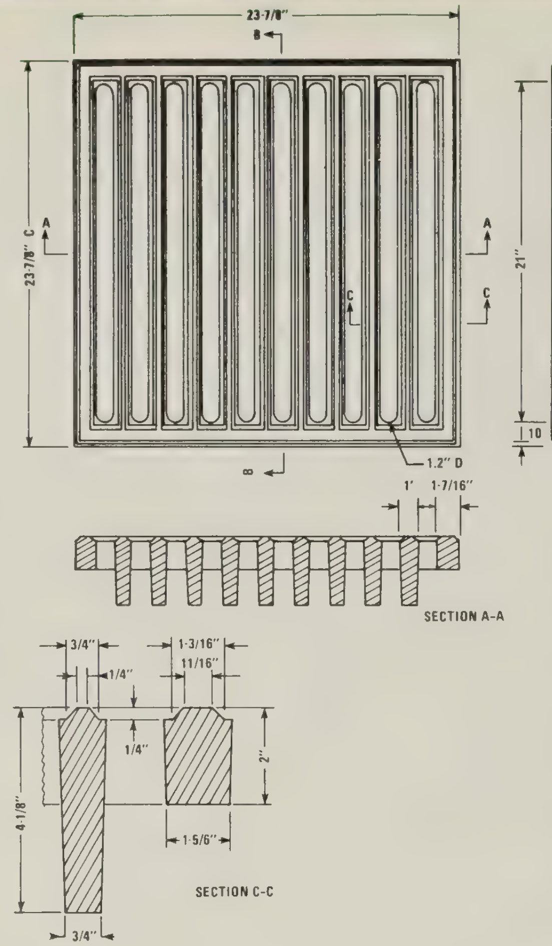


*Figure 11.—Inlet grate F.*

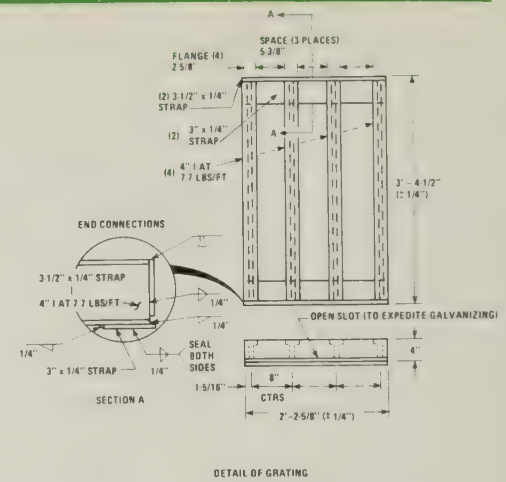


*Figure 12.—Inlet grate G.*

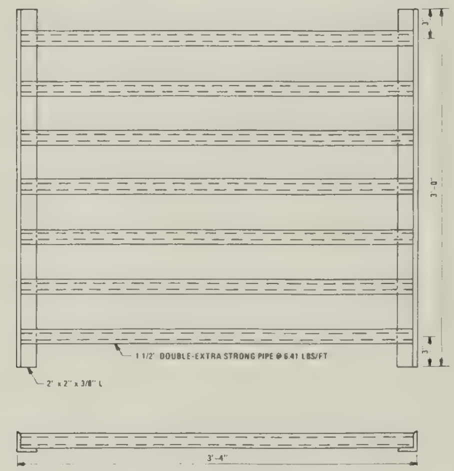

*Figure 13.—Inlet grate H.*

## SUMMARY AND CONCLUSIONS

The study summarized in this article involved the testing and structural analysis of eight styles of highway inlet grates. The objectives of the study were to: (1) Determine the structural behavior of typical inlet grates; (2) develop guidelines for designing such grates on the basis of structural strength and behavior; and (3) make recommendations for possible revision of Federal Specification RR–F–621b.

Table 1 provides a summary of the structural test data obtained from this study. It may be noted that the weight of the inlet grates ranged from 109 to 272 lbs (49.4 to 123 kg); and that the ultimate plate load capacity ranged from 12,700 to 109,300 lbs (56,490 to 486,170 N). Conclusions drawn from this study are as follows:

- Correlations between the computer analyses and the experimental data indicate that the behavior of the highway inlet grates subjected to static wheel (or plate) loads can

**Table 1.—Summary of test data[1]**

| | Grates | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H |
| Type | Roadway | Roadway | Roadway | Roadway | Roadway | Roadway | Median | Median |
| Weight (less grate frame) . . . lbs | 191 | 109 | 168 | 144 | 165 | 224 | 131 | 131 |
| Ultimate plate load . . . . . . lbs. | 76,000 | 40,000 | 98,500 | 109,300 | 12,700 | 90,125 | 68,325 | 25,500 |
| Yield load . . . lbs. | 40,000 | 18,000 | 42,500 | >30,000 | 12,700 | 90,125 | 50,000 | <25,500 |
| Maximum centerline bending stress, 6,000 lb wheel load . . . . . psi | 12,060 | 19,050 | 8,280 | 10,680 | 10,506 | 3,220 | 10,800 | 37,200 |
| Dynamic factors[2] | | | | | | | | |
| Rolling | 1.11 | 1.04 | 1.13 | 1.65 | 1.20 | 1.06 | 1.08 | 1.10 |
| Impact | 1.37 | 1.09 | 1.49 | 2.10 | 2.11 | 1.20 | >1.58 | 2.10 |

[1] Detailed explanation and analysis of test data are contained in subject report *(1)*. 1 lb=4.48 N
[2] Ratios of maximum field dynamic to laboratory static strains. 1 psi=6.89 kPa

be predicted analytically within an acceptable degree of accuracy. However, it was necessary to consider the effect on the analytical model of welds, end connections, and special geometrical shapes and to consider tire loading factors such as variation in unit tire pressure across the tire and the length and number of grate bars contacted by the tire.

- There is close agreement between the results of the plate load and static tire tests up to 10,000 lbs (44,480 N). Therefore, it appears that the plate load test method may be used to evaluate the behavior of inlet grates under service load conditions, as well as in the post-elastic load range.
- Results of the plate load tests indicate that all inlet grates tested are stronger than necessary to meet the requirements of current vehicle traffic, which emphasizes the need for grates to be *designed* to make efficient use of structural materials. Of the eight inlet grates tested in this study, three—B, E, and H—failed to meet the requirements of Federal Specification RR–F–621b. However, there is a strong probability that these *rejected* grates are more than adequate for carrying current highway vehicle loadings.
- Under load the roadway grates acted as a grid system (in plate bending), with the wheel loads being distributed to grate bars not under the wheel. However, the bars of the median grates acted essentially independently, with little transfer of stresses to adjacent bars.
- There are two possible drawbacks for using cast iron for inlet grates: Poor design or casting practices may cause voids in the casting at critical locations—as occurred in both the grate E specimens which were supplied; and cast iron has a low modulus of elasticity and little, if any, ductility.

## RECOMMENDATIONS

- Inlet grates should be structurally designed to make efficient use of materials. The influence of AASHTO HS–15–44 and HS–20–44 vehicle wheel loads on inlet grates may be evaluated by one of two methods: (1) Estimating the actual wheel load distribution over the grate surface—including pressure distribution across the grate, effect of tire sidewall stiffness, and the number and length of grate bars contacted by the tire, or (2) assuming that the wheel load is applied on a 9.0-in. (230-mm) square steel plate. The loading for each grate bar may be represented by two equivalent loads located at 2.25 in. (57 mm) on each side of the transverse centerline of the plate. A design based on the second method will be conservative, but usually more practical to calculate. Design values for shear, moment, and deflection may be calculated by using most modern computer programs for the structural analysis of grid systems.
- Based on findings of this study the following dynamic amplification factors for wheel loads should probably be considered in the design:

  Flat roadway grates:
  rolling=1.20; impact=1.40
  Flat median grates:
  rolling=1.20; impact=2.10
- In lieu of structurally designing inlet grates it appears feasible that an inlet grate *design* might be fabricated and then subjected to a plate load test to evaluate its structural behavior.

An individual State highway department might benefit from surveys to determine the frequency of damage and failure of the various types of inlet grates used on its highways, to better assess the need for revising its present grate designs.

## REFERENCES

(1) C. A. Ballinger and R. H. Gade, "Evaluation of the Structural Behavior of Typical Highway Inlet Grates, with Recommended Structural Design Criteria, " *Federal Highway Administration* Report No. FHWA–RD–73–90, December 1973.

(2) "Federal Specification RR–F–621b—Frames, Covers, Gratings, Steps, Sump and Catch Basin, Manhole," *General Services Administration,* September 1967, available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

(3) E. D. Spartz, "Highway Drainage Inlets (A Value Engineering Study)," *California Department of Transportation, Division of Highways,* Sacramento, Calif., April 1971.

(4) W. P. Doherty and E. L. Wilson, "Analysis of Two-Dimensional Grid Structures," (Computer Program), *University of California,* Berkeley, Calif., September 1967.

# New Research in Progress

**The following items identify new research studies that have been reported by FHWA's Offices of Research and Development. 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 Research)—Performing State Highway Department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.**

## FCP Category 1—Improved Highway Design and Operation for Safety

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**FCP Project 1H:** Skid Accident Reduction

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**Title:** Evaluation of Winter-Driving Traction Aids. (FCP No. 51H3174)
**Objective:** Analysis of surface conditions. Development of traction, braking, and controllability test methods. Performance testing. Evaluation of adverse effects. Cost-benefit analysis.
**Performing Organization:** Pennsylvania State University, University Park, Pa. 16802
**Expected Completion Date:** June 1976
**Estimated Cost:** $150,000 (NCHRP)

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

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**FCP Project 3E:** Reduction of Environmental Hazards to Water Resources Due to the Highway System

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**Title:** Sewage Treatment Methods to Meet the 1977 Requirements of the Federal Water Pollution Control Act—Public Law 92–500. (FCP No. 33E1022)
**Objective:** Develop recommendations and guidelines which will enable State highway departments to bring rest area sewage treatment facilities into compliance with PL–92–500 and the more stringent State and local requirements. Develop design guides and operation and maintenance practices.
**Performing Organization:** Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss. 39180
**Expected Completion Date:** February 1976
**Estimated Costs:** $175,000 (FHWA Administrative Contract)

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**FCP Project 3F:** Pollution Reduction and Visual Enhancement

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**Title:** Highway Operation and Plant Damage. (FCP No. 43F1802)
**Objective:** Quantify the salt concentrations along roadways and correlate this with plant damage. Develop methods for screening between and within plant species for salt tolerance.
**Performing Organization:** University of California, Davis, Calif. 95616
**Funding Agency:** California Department of Transportation
**Expected Completion Date:** June 1977
**Estimated Cost:** $188,000 (HP&R)

**Title:** Highway Location, Design, and Operation to Reduce Photochemical Smog Formation. (FCP No. 33F3092)
**Objective:** Evaluate highway operations, locations, and designs as factors contributing to photochemical smog. Formulate methods to reduce effects of highway sources.
**Performing Organization:** Systems Applications Inc., San Rafael, Calif. 94003
**Expected Completion Date:** June 1976
**Estimated Cost:** $172,000 (FHWA Administrative Contract)

**Title:** Development of Acoustic Attenuation Surfaces and Materials and Artificial Barriers. (FCP No. 33F4012)
**Objective:** Develop an implementable noise abatement system using acoustical attenuation linings, materials, and designs with artificial noise barriers.

**Performing Organization:** Bolt, Beranek, and Newman, Canoga Park, Calif. 91303
**Expected Completion Date:** February 1976
**Estimated Cost:** $225,000 (FHWA Administrative Contract)

**Title:** Determination of Impact from Vibrations Related to Highway Use. (FCP No. 33F4032)
**Objective:** Determine procedures for conducting calibrated vibration measurements using available low-cost, precision portable data recording and analysis systems. Determine vibrations induced by natural phenomena. Determine vibration related to highway construction and maintenance.
**Performing Organization:** Science Applications Inc., Huntsville, Ala. 35805
**Expected Completion Date:** February 1976
**Estimated Cost:** $152,000 (FHWA Administrative Contract)

## FCP Category 4—Improved Materials Utilization and Durability

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

**Title:** Use of Waste Sulfate for Remedial Treatment of Soils. (FCP No. 34C2102)
**Objective:** Determine the suitability of waste sulfate as a soil stabilizer and the effects of sulfate waste on the engineering properties of soils.
**Performing Organization:** Midwest Research Institute, Kansas City, Mo. 64110
**Expected Completion Date:** June 1976
**Estimated Cost:** $132,000 (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:** Management of Air Quality In and Near Highway Tunnels. (FCP No. 35B4012)
**Objective:** Analyses of all factors involved in creating and maintaining satisfactory air quality in and near highway tunnels and development of improved feasible air quality management.
**Performing Organization:** Science Applications Inc., McLean, Va. 22101
**Expected Completion Date:** December 1976
**Estimated Cost:** $309,000 (FHWA Administrative Contract)

**Title:** Social, Economic, and Environmental (SEE) Impacts and Land-Use Planning Related to Urban Highway Tunnel Location. (FCP No. 35B4032)
**Objective:** Develop guidelines for spatial allocation of urban highway tunnel rights-of-way and associated land-use planning concepts which take into account SEE impacts.
**Performing Organization:** Alan M. Voorhees & Associates, McLean, Va. 22101
**Expected Completion Date:** April 1976
**Estimated Cost:** $165,000 (FHWA Administrative Contract)

**FCP Project 5D:** Structural Rehabilitation of Pavement Systems

**Title:** Flexible Pavement Evaluation and Rehabilitation. (FCP No. 45D1164)
**Objective:** Study performance and cost effectiveness of flexible pavements, both new and rehabilitated. Provide Texas Highway Department with information for budgeting and decisionmaking on contract maintenance work.
**Performing Organization:** Texas Transportation Institute, College Station, Tex. 77843
**Funding Agency:** Texas Highway Department
**Expected Completion Date:** August 1978
**Estimated Cost:** $280,000 (HP&R)

**FCP Project 5E:** Premium Pavements for "Zero Maintenance"

**Title:** Zero Maintenance Pavement: Performance Requirements and Capabilities of Conventional Pavements. (FCP No. 35E2012)
**Objective:** Define performance requirements for zero maintenance. Analyze structural aspects of conventional systems (jointed pcc, crcp, flexible, composite) to serve as zero maintenance pavements. Develop design procedures for variable traffic, environment, and age. Determine incremental costs for additional life.
**Performing Organization:** University of Illinois, Urbana, Ill. 61801
**Expected Completion Date:** June 1976
**Estimated Cost:** $182,000 (FHWA Administrative Contract)

**Title:** Field Test and Evaluation of Pavements and Econocrete Base (Low Strength PC Concrete-Composite Pavement). (FCP No. 45E3044)
**Objective:** Approximately 14 sections of experimental pavement will be built on the Federal-aid system. The lower portion of the composite slabs will consist of low strength pc concrete. Wearing surface will consist of either high strength pc concrete or asphalt. Variables are thicknesses, strengths, bond between layers, reinforcement, CRCP, elastic joints, steel fibers, joints.
**Performing Organization:** Florida Department of Transportation, Tallahassee, Fla. 32304
**Expected Completion Date:** October 1976
**Estimated Cost:** $124,000 (HP&R)

**FCP Project 5H:** Protection of the Highway System from Hazards Attributed to Flooding.

**Title:** Feasibility Study of Development of Scour Monitoring Equipment. (FCP No. 35H1053)
**Objective:** Analysis and development of instrumentation required to assess scour around highway bridge piers.
**Performing Organization:** Science Applications Inc., Tullahoma, Tenn. 37388
**Expected Completion Date:** December 1976
**Estimated Cost:** $268,000 (FHWA Administrative Contract)

**Title:** Effects of Urbanization on Runoff from Small Drainage Areas in Ohio. (FCP No. 45H2512)
**Objective:** Launch a 10-year rainfall-runoff data collection program from 30 selected small urban drainage areas in Ohio and develop a regional flow model for estimating peak flow from ungaged small drainage areas less than 5 square miles and with various degrees of urbanization in Ohio.
**Performing Organization:** U.S. Geological Survey, Columbus, Ohio 43212
**Funding Agency:** Ohio Department of Transportation
**Expected Completion Date:** October 1984
**Estimated Cost:** $460,000 (HP&R)

**FCP Project 5J:** Rigid Pavement Systems Designs

**Title:** Development and Implementation of the Design, Construction, and Rehabilitation of Rigid Pavements. (FCP No. 45J1474)
**Objective:** Develop and implement the rehabilitation concepts for rigid pavements. Implement the research accomplished in project NCHRP 1–15, and hence develop theoretical models to optimize the design and rehabilitation of rigid pavements. Continue the performance study made of concrete pavements in Texas in order to establish immediate design criteria.
**Performing Organization:** University of Texas, Austin, Tex. 78701
**Funding Agency:** Texas Highway Department
**Expected Completion Date:** August 1977
**Estimated Cost:** $197,000 (HP&R)

## FCP Category 6—Development and Implementation of Research

**FCP Project 6B:** Construction and Maintenance Methods and Equipment

**Title:** Optimization of Traffic Lane Delineation Systems. (FCP No. 36B1043)
**Objective:** Review existing delineation practices and procedures to determine needs and engineering limits to be used as guidelines for future equipment needs. Develop priorities for equipment development.
**Performing Organization:** California Department of Transportation, Sacramento, Calif. 95814
**Expected Completion Date:** February 1976
**Estimated Cost:** $163,000 (FHWA Administrative Contract)

**Title:** Microwave Heating for Road Construction and Maintenance. (FCP No. 46B4043)
**Objective:** Design, construct, and test a full-size prototype microwave heating unit for use in curing polymer concrete patches. Investigate various patching materials for use with the heater.
**Performing Organization:** Syracuse University Research Corporation, Syracuse, N.Y. 13210
**Funding Agency:** New York Department of Transportation
**Expected Completion Date:** April 1976
**Estimated Cost:** $151,000 (HP&R)

**FCP Project 6C:** Traffic Engineering

**Title:** Computer Controlled Traffic Signals at Diamond Interchanges (FCP No. 36C1043)
**Objective:** Develop, test, and evaluate computer hardware and software for controlling a diamond interchange.
**Performing Organization:** California Department of Transportation, Sacramento, Calif. 95814
**Expected Completion Date:** February 1976
**Estimated Cost:** $127,000 (FHWA Administrative Contract)

# Highway Design for Motor Vehicles— A Historical Review

## Part 2: The Beginnings of Traffic Research

by[1] Frederick W. Cron

**This is the second in a series of eight historical articles tracing the evolution of present highway design practices and standards in the United States. The Introduction and Part 1: The Beginnings of Traffic Measurement were published in the previous issue of *Public Roads*. The remaining parts, to be published in future issues, are 3: The Interaction of the Driver, the Vehicle, and the Highway; 4: The Vehicle-Carrying Capacity of the Highway; 5: The Dynamics of Highway Curvature; 6: Development of a Rational System of Geometric Design; 7: The Evolution of Highway Grade Design; and 8: The Evolution of Highway Standards.**

### EARLY ROAD SYSTEM PLANNING

The combined Federal-State funds which became available for roadbuilding under the Federal-Aid Road Act of 1916 could be spent on practically any rural road that was used for carrying the mail. Not all States had well defined road systems under State control, and by 1920 it was evident that the Federal-aid improvements in many States "were so scattered as to defy any reasonable expectation of a connected improvement" *(1)*.[2] Congress therefore provided in the Federal Highway Act of 1921 that Federal-aid could be spent only on "a system of highways not to exceed 7 per centum of the total highway mileage of such State . . . ." Three-sevenths of this system was to be *primary or interstate highways* and four-sevenths *secondary or intercounty highways.* Following the 1921 Act, cooperative traffic and transportation surveys began providing information for system selection or for determining the utility of systems previously selected. Another major interest was the adequacy of various surface types for the several systems.

The **Maine Highway Transportation Survey of 1924** showed that the primary system, which had 7.1 percent of the total State highway mileage, carried 53.4 percent of the total vehicle-miles of travel. The secondary system, with 17.5 percent of the mileage, carried 30.9 percent of the traffic, and the third class

[1] Frederick W. Cron's biography appeared with part 1 of his article in vol. 38, No. 3, December 1974.

[2] Italic numbers in parentheses identify the references on page 174.

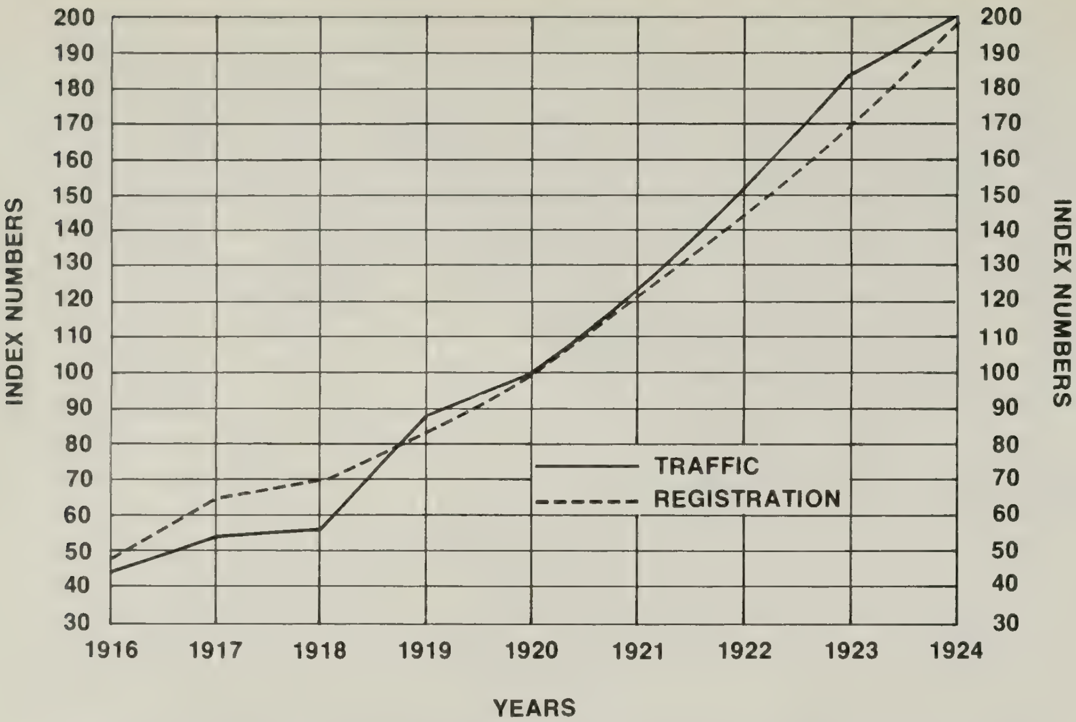



*Figure 1.—Parallel increase of traffic and vehicle registrations in Maine, 1906 to 1924.*

roads, with 75.4 percent of the mileage, carried only 15.7 percent of the traffic *(2)*.

The investigators were careful to point out that these relations were true only for Maine and only for the systems considered as a whole. They showed that within the same system traffic may vary widely from road to road. Thus, 300 miles of the primary system—or 18.4 percent of that system—carried 38.7 percent of all primary traffic.

The investigators concluded that the Maine primary system was well selected, but that several of the secondary roads carried such heavy traffic, especially trucks, that they should be transferred to the primary system.

Clearly, there is need for the creation of traffic zones bringing together for construction and maintenance purposes those sections of the highway system which serve approximately the same amount and type of traffic and to distinguish between those routes which require constant supervision and policing to insure satisfactory service and safety to traffic and those which do not *(2)*.

## ESTIMATING FUTURE TRAFFIC

The Maine State Highway Commission had been counting traffic for 1 week each year since 1916 at 58 stations. This was a very small sample, but the researchers were able to show that there was a relationship between the traffic recorded at these stations and the annual vehicle registration (fig. 1). They also made a trend curve showing the relationship between total population and total vehicles (fig. 2).

Using the predicted population of some future year (obtained from the U.S. Census Bureau), the Maine researchers could predict the future vehicle registration and from this the future traffic at the 58 counting stations and, by analogy, on the entire highway system. These predictions were crude, but they were close enough to show the Highway Commission where it should most effectively spend its funds to stay ahead of traffic demand. Most of the Maine highways were gravel surfaced and the Commission knew from experience that gravel surfaces would not carry more than 500 vehicles per day without excessive maintenance expense *(2)*.

To estimate future demand the investigators projected traffic to 1930 (fig. 3). Then, assuming that all gravel-surfaced roads carrying 1,000 vehicles or more per day in 1930 would be critically deficient, they placed the deficient highways in three priority groups according to traffic density, amount of truck traffic, and the need for immediate improvement. Finally, they suggested improving the deficient roads to an adequate surface standard, financing the improvements either with a bond issue or an increase in the gasoline tax.

This use of the traffic survey to help plan future improvements was not new, but its application in Maine was on a more refined and reliable level than previous efforts. It strongly influenced later studies and, in the following decade, highway administration as well.

## THE FIRST URBAN TRANSPORTATION SURVEY

In 1924 traffic congestion was so bad in Chicago and Cook County, Ill., that the County Commissioners requested that the U.S. Bureau of Public Roads (BPR) cooperate with the County in an investigation of highway traffic and the formulation of a plan of improvement. The **Cook County Transportation Survey** resulting from this request was the first comprehensive study of traffic in an urban region which included a large city *(3)*. The traffic census, first step in the study, showed the researchers the most heavily used roads and the numerous bottlenecks and discontinuities in the road system that were causing congestion. An example was Western Avenue, which then carried 15,000 vehicles per day. This street was blocked by railroad trains at least 17 minutes of every hour and on one occasion it was closed for 30 minutes. The researchers estimated that congestion and interruptions cost vehicle users and the public $3 per hour per vehicle, amounting to $9,900 per day for the 418 miles of county highways.

Using the Maine method, the Cook County and BPR engineers forecast the traffic that might be expected in 1930 and then prepared a plan of improvement that would satisfy the 1930 needs. They also urged advance acquisition of rights-of-way for recommended future highways:

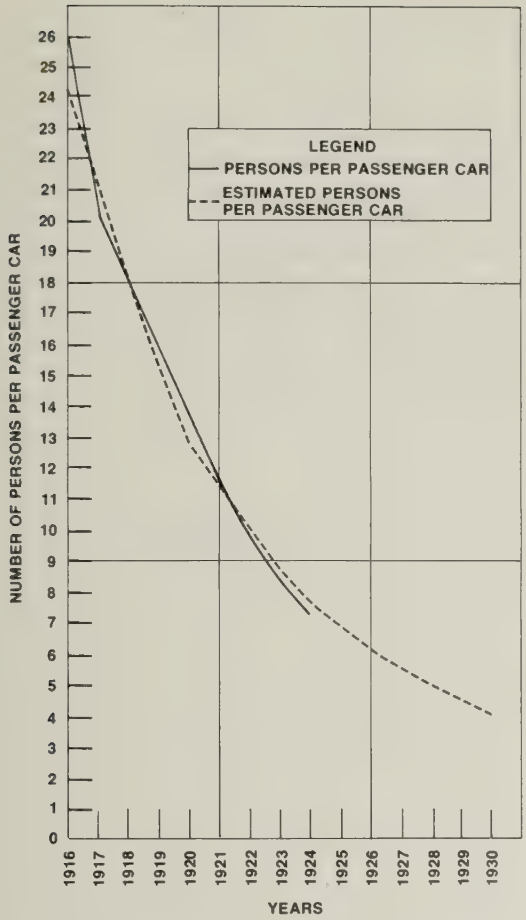



*Figure 2.—Persons per passenger car, in Maine, 1916 to 1930.*

The normal development of an area surrounding a large center of population, such as Chicago, results in the establishment of large special-use areas through which highways cannot be located. Insofar as future highway needs can be predicted, adequate right of way for future improvements should be obtained prior to the establishment of these special-use areas. This procedure will not only reduce the cost of the highway system but will also provide in these areas a highway system so designed as to provide the most efficient highway service *(3)*.

The **Ohio Highway Transportation Survey of 1925** was similar to the Maine survey of a year earlier, but it covered a full year instead of only 4 months. At first, horse-drawn vehicles were recorded at all stations, but there were so few—averaging only seven per day on State highways—that it was decided to ignore them for highway planning *(4)*. Using the Maine method, the Ohio engineers forecast the traffic that might be expected on the State highways in 1930 and 1935 and assigned each State highway to one of three groups:

(1) Major routes carrying 1,500 or more motor vehicles per day. These were assumed to need some form of rigid pavement.

(2) Medium routes carrying 600 to 1,500 vehicles per day. For these the appropriate type of pavement was assumed to depend on the frequency of heavy loads and might vary from bituminous macadam to rigid pavement.

(3) Minor traffic routes carrying less than 600 vehicles per day for which untreated gravel was assumed to be adequate, or at least bearable.

The survey showed that in 1925 only one-third of the State highway system fell into the first or second group, but that by 1935 half of the system would fall into these groups and would need some kind of surface superior to untreated gravel.

An interesting finding of the **Vermont Highway Transportation Survey of 1926** was that *foreign vehicles*—those with other than Vermont registration tags—made up 35.6 percent of the traffic on the State highway system. The investigators doubted that the gasoline tax revenue from these vehicles was "at all commensurate with the increased cost of providing highway service caused by foreign traffic" *(5)*.

## THE FIRST METROPOLITAN REGIONAL TRAFFIC STUDY

The **Cleveland Regional Area Traffic Survey of 1927** brought all levels of government together for the first time in a concerted study of the traffic problem in a single metropolitan region. The U.S. Bureau of Public Roads; the Ohio Department of Highways; the Boards of Commissioners of seven counties; and—within Cuyahoga County—the city of Cleveland, 3 other cities, 42 villages, and 7 townships were involved in this novel experiment in inter-governmental cooperation. The BPR agreed to participate only on condition that the studies be area-wide without regard to political boundaries, that the studies lead to a general highway development

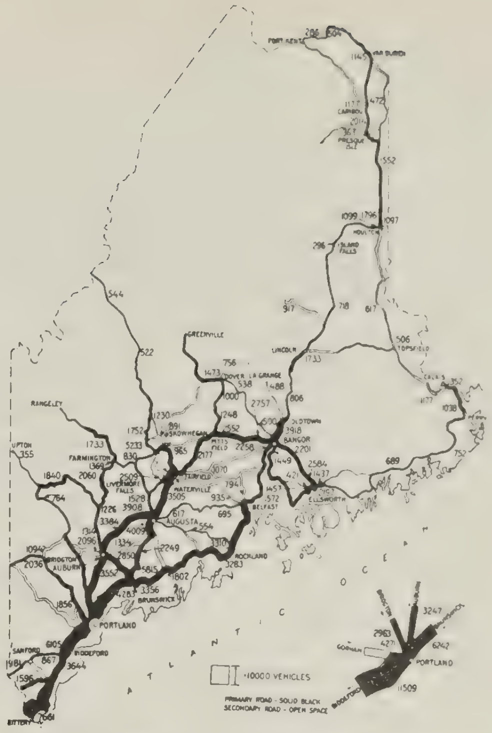


*Figure 3.—Anticipated density of traffic on primary and secondary highway systems of Maine, July to November 1930.*

plan for the region, and that the "studies . . . be continued over a period of years in order to observe the effect which the execution of the plan will have upon the distribution of traffic and upon the efficiency with which traffic is served by a modern highway system" *(6)*. The cost of the survey was shared equally by the BPR and Cuyahoga County.

The Cleveland Regional Survey included the most extensive origin-destination survey made up to that time. It showed that traffic was predominantly local, that the principal movement in Cuyahoga County was between Cleveland and its suburbs, and that traffic between the suburbs themselves was relatively minor.

To further analyze the need for transportation the survey included special studies of population density, distribution and trend of population, and industrial growth in the cities and suburban areas.

The investigators used time and lateral placement studies to estimate the traffic capacity of streets of various widths. These studies showed that the capacity of a two-lane roadway under open-road conditions at a traffic speed of 25 mph was about 10,000 vehicles per day. Under suburban conditions, with a limited amount of parking adjacent to the roadway and a larger volume of local traffic and cross traffic, the capacity dropped to 8,000 vehicles per day. Therefore, streets and roads that were expected to carry more than 8,000 vehicles per day in 1942 (15 years in the future) were planned for four lanes of traffic or 40-foot widths, on the theory that "roads requiring construction or reconstruction should be made adequate for a considerable part of their life period" *(6)*. This is probably the earliest statement of the *design year concept* of pavement type selection.

The Cleveland Regional Survey resulted in a plan for improvements estimated to cost $63 million, distributed over a 10-year period—a budget well within the financial capability of the region. The report of the survey ended with a note of caution:

> Traffic conditions, however, are constantly changing, and the recurrence of present conditions can be prevented only by careful and far-sighted planning based on a definite knowledge of these changing highway and traffic conditions. Proper highway planning must be a continuous process, based on a continuing series of facts in order that the constantly increasing traffic demands may be foreseen and met with improvements as required *(6)*.

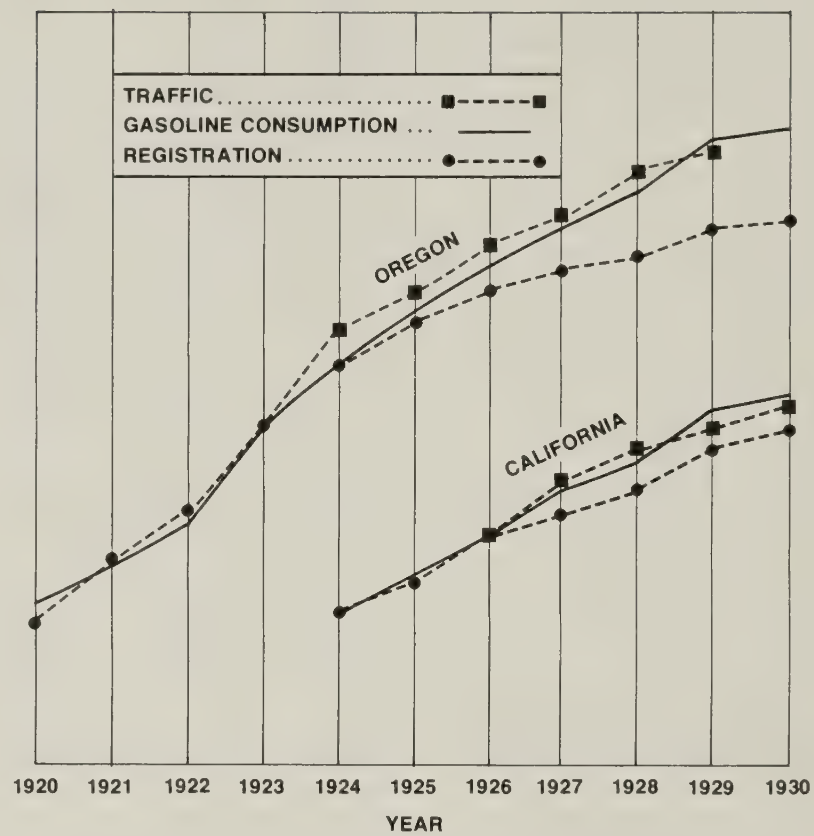



*Figure 4.—Trends of highway traffic, gasoline consumption, and motor vehicle registration in Oregon and California. The vertical scale is logarithmic and the curves have been moved together vertically for comparison of rates of increase.*

## FUEL CONSUMPTION IS BEST TRAFFIC GROWTH INDEX

The **Western States Traffic Survey,** a cooperative effort of the Bureau of Public Roads and the highway departments of 11 Western States was the first interregional traffic study in the United States. Essentially, it was a study of the Federal-aid highway system in the West. Using data gathered at 899 census stations the investigators classified the Federal-aid highways into three traffic density categories such as those used in the Ohio Transportation Survey. They then forecast traffic for 1935 and 1940 to determine what the mileage would be for the three density classes in those years.

For these forecasts the researchers found that gasoline consumption was a more reliable index of traffic growth than motor vehicle registration. The essential data came from Oregon, which had been taxing gasoline as a source of road funds since 1918. (It was the first State to impose a fuel tax.) As shown in figure 4, the three indexes were fairly close together until 1924 when traffic and gasoline consumption began pulling away from registrations, indicating greater use per vehicle *(7)*.

The **New Hampshire Traffic Survey of 1931** gave students of traffic an opportunity to check forecasts made 5 years earlier from population and vehicle registration estimates. On routes carrying over 1,500 vehicles per day the forecast was remarkably accurate, actual traffic being only 3 percent above forecast traffic, but accuracy declined rapidly on the lighter traffic roads, many of which were underforecast as much as 50 percent. The discrepancy arose partly because many of the lighter traffic roads had been paved in the interval between censuses and were attracting traffic from the more congested arterials.

The **Michigan Highway Transportation Survey of 1930–31** was the first to study the traffic on all public roads of a State simultaneously—that is, all city streets, trunkline rural highways under State control, county highways, and township roads. The investigators used standard traffic census methods developed in previous transportation surveys to study traffic at 1,000 rural stations, and 400 stations in 7 cities. They determined township road traffic by making traffic counts in one representative township in each county. Densities measured in the sample township were then applied to all townships in that county to get the total vehicle miles of travel on the township roads *(8)*.

When the Michigan investigators tabulated the results of the survey, they found that 49.7 percent of all the State's traffic was on city streets, with 33.1 percent on trunk highways, 12.2 percent on county highways, and only 5.0 percent on township roads. On 31,000 miles, or about 52 percent, of the township roads, the traffic was less than 20 vehicles per day *(8)*.

Post-card questionnaires were given to the operators of all out-of-State vehicles at the boundary stations. These requested information from the occupants on such matters as accommodations, average expenditures, and length of stay in Michigan. Using the 42,000 questionnaires returned, the researchers determined the average daily expenditure of the several categories of visitors. When applied to the annual influx of 2½ million out-of-State cars, these figures showed that tourists had spent $274,100,000 in Michigan in 1 year—an amazing amount at a time of national depression *(9)*.

In addition to other traffic information routinely compiled, the **Connecticut survey of 1934–35** showed the *maximum traffic densities* at each station, these being the peak loads of heavy summer weekend travel. For the State system as a whole the average maximum density was 162 percent of the average annual daily traffic, but on certain individual roads it ran as high as 200 or even 500 percent. The researchers concluded that: "It is not economical to design surface widths and intersections for a free flow of traffic during those extreme peaks that occur once or twice a year. At such times some sacrifice must be made in freedom of flow to accommodate the increased volume" *(10)*. This was probably the first statement of the *level of service* concept of highway capacity.

## EARLY DRIVER BEHAVIOR STUDIES

During the **Rhode Island 1934 study,** 675,000 speed observations were made by stopwatch timing over a measured course. Average observed speeds ranged from 30.4 mph for buses to 34.2 mph for passenger cars. Practically all drivers drove faster than the advisory safe speeds posted by the State police, and 30 percent of the drivers exceeded the posted limits by 10 to 14 mph. In another study of driver behavior the Rhode Island investigators observed the performance of 622,000 drivers with respect to the white lane lines on the pavements. (At this time Rhode Island was the only State where the entire State system was so marked.) This study showed that lane lines were very effective for keeping drivers in their own lanes on two-lane highways (93 percent stayed in the right lane). On three-lane and four-lane highways there was considerable line-straddling when traffic was light (29 percent of the drivers for four-lane roads); but line-straddling decreased as traffic increased, indicating that lane lines are most effective when they are most needed, that is, in periods of heavy traffic. Wide shoulders induced traffic to stay in the outside lanes; narrow shoulders increased the tendency to straddle; and permanent raised curbs not only increased straddling but tended to cause motorists to drive completely out of their proper lanes.

In a related study of 269,000 drivers at 13 stations at curves and 13 stations at hill crests, 4.8 percent of the drivers took a chance and passed on a hill, but only 1.7 percent passed on curves *(11)*.

## TRAFFIC COUNTING METHODS

Traffic counting for the **Arkansas Traffic Survey of 1935–36** embodied the experience of the 21 preceding surveys and, as with the earlier studies, was a compromise between completeness of results and economy of effort. The standard pattern for counting was to establish *key stations,* also called *regular count stations,* at strategic control points on the highway network. These were operated on a staggered schedule continually for the period of the survey. The less important roads were covered by *blanket stations* which were operated four times during the survey, once in each season of the year. Counts at blanket stations were adjusted to average annual daily traffic (ADT) by correlation with nearby key stations. Finally, *special stations* might be established where the coverage by other stations was in doubt or to extend the coverage beyond a known point. These were operated simultaneously with the nearest key station for a number of days *(12)*.

Beginning with the French traffic censuses in the 1880's a number of sampling schedules were devised by students of traffic. In America the most popular was the *key station schedule,* first used during the Western States Traffic Survey of 1929–30. This schedule was designed to keep a relatively small force of enumerators continuously employed with days of rest equivalent to those received by men in other occupations. This schedule required twenty 8-hour counts per year at each station. To begin the cycle the enumerators might count from 6 a.m. to 2 p.m. on a Tuesday in July. Then they would come back 26 days later and count from 2 p.m. to 10 p.m. on a Sunday in August. The next count would be 26 days after the second, from 6 a.m. to 2 p.m. on a Friday in September, and so on, throughout the year. This schedule gave two 8-hour counts, spaced 6 months apart, for each day of the week. In addition, four night counts, one in each season, were made from 10 p.m. to 6 a.m. At the end of the year all of the 6 a.m. to 2 p.m. counts were averaged to get an average yearly total for those hours; and the 2 p.m. to 10 p.m. and 10 p.m. to 6 a.m. counts were similarly averaged. The sum of these averages was the ADT for the year *(13)*.

The *40-hour schedule,* used principally in urban areas, consisted of forty 1-hour counts scattered throughout the year in a pattern designed to sample the important hourly, weekly, and seasonal fluctuations. A typical schedule is shown in table 1.

The twenty-four 1-hour periods add up to a *statistical day*. The light traffic hours from 10 p.m. to 6 a.m. are covered by only one count, while the others are counted twice during the year and the two counts averaged to get the count for that statistical hour. The total of the 24 statistical hours is the average annual daily traffic *(13)*.

During the era of manual counting other sampling schedules, such as the one used by the French in their traffic censuses, were employed; but the two above illustrate the general principle.

## AUTOMATIC TRAFFIC COUNTERS INTRODUCED

By 1935 the Bureau of Public Roads and the State highway departments were planning a new and more elaborate series of transportation studies, to be called the *Statewide Highway Planning Surveys*. These were to be much wider in scope than the previous traffic surveys, but traffic counting was still a very important part of the total task. The BPR and the States were dissatisfied with manual methods of traffic counting because of the expense and the accuracy limitations of these methods, and there was widespread demand that counting be mechanized. As early as 1928 the Danes had developed a successful traffic counter for the Roskildevej Experimental Road near Copenhagen. This was a concrete trough 1 meter wide and 60 centimeters deep spanned by a timber bridge, the center of which was supported by spring-loaded pistons. As the wheel load passed over the bridge, the pistons depressed slightly making an electric contact that actuated a counting device. Three bridges were installed side by side: one for horsedrawn vehicles, one for motors with pneumatic tires, and one for solid-tired trucks *(14)*. This counter apparently was not used much outside Denmark.

The BPR instrument laboratory began experiments in 1935 with a counter actuated by a photoelectric cell. An electric lamp on one side of the road focused a light beam on an electric-eye sensor on the other side. When the beam was broken by a vehicle (or by a schoolboy's book), the sensor closed a switch which actuated a counter. A year of field testing in all kinds of weather refined this device to a high degree of reliability, and this was the first photoelectric equipment ever to operate outdoors under a wide range of climatic conditions. To avoid counting pedestrians, two parallel beams 1 meter apart were used, both of which had to be broken to actuate the counter. To minimize tampering the counters were located at places remote from schools and heavy pedestrian traffic, but where 100-volt, 60-cycle line power was available. The machines were relatively inexpensive—about $530 each, including installation—and they could operate on paved or gravel roads with an accuracy within 1.5 percent of true volume, and with 95 percent

**Table 1.—A typical 40-hour schedule**

| | *a.m.* | | *p.m.* |
|---|---|---|---|
| 12–1 | April 7 | 12–1 | March 14<br>September 22 |
| 1–2 | May 25 | 1–2 | March 26 (Sunday)<br>October 4 |
| 2–3 | July 12 | 2–3 | April 7<br>October 16 |
| 3–4 | August 29 | 3–4 | April 19<br>October 28 (Saturday) |
| 4–5 | October 16 | 4–5 | May 1<br>November 9 |
| 5–6 | December 3 | 5–6 | May 13 (Saturday)<br>November 21 |
| 6–7 | January 1 (Sunday)<br>July 12 | 6–7 | May 25<br>December 3 (Sunday) |
| 7–8 | January 13<br>July 24 | 7–8 | June 6<br>December 15 |
| 8–9 | January 25<br>August 5 (Saturday) | 8–9 | June 18 (Sunday)<br>December 27 |
| 9–10 | February 6<br>August 17 | 9–10 | June 30<br>January 7 (Saturday) |
| 10–11 | February 18 (Saturday)<br>August 29 | 10–11 | January 1 |
| 11–12 | March 2<br>September 10 (Sunday) | 11–12 | February 18 |

# PUBLIC ROADS

A JOURNAL OF HIGHWAY RESEARCH

UNITED STATES DEPARTMENT OF AGRICULTURE
BUREAU OF PUBLIC ROADS

VOL. 6, NO. 3 MAY, 1925



Approach to Observation Station on Maine Highway Transportation Survey

WASHINGTON : GOVERNMENT PRINTING OFFICE : 1925

mechanical reliability. The annual cost of operating an automatic counter, assuming a 5-year life, was only $578, less than one-tenth of the cost of obtaining the same information manually *(15)*.

Automatic counters revolutionized traffic measurement. By 1940 almost 600 were operating in the United States, replacing manual counting at the *key stations*. Still, there was need for smaller automatic counters that could be moved easily to get the blanket counts at places other than the key stations. A solution to this problem came out of a study in which BPR engineers were trying to measure the maneuvers of cars overtaking other cars on the highway. The instrument laboratory had developed a road switch which could be actuated by a pulse of air from a rubber tube stretched across the road. When a car wheel pressed down on the tube, the pulse of air moved a diaphragm, closing a circuit which in turn controlled a pen recorder on a clockwork-driven chart. Time-distance relationships could then be measured from the chart. The Bureau's chief instrument maker, S. E. Reymer, was concerned about the durability of various makes of rubber detector tubes so he connected the road switch to a counting device which would record the number of times the tube could be compressed before it developed cracks and leaks. Unwittingly, he had also invented a device for counting axles! Because each axle was counted, the count had to be halved to determine the number of vehicles, and, of course, vehicles such as tandem-axle trucks and truck-trailers registered as more than one vehicle. Automatic recording printers made a continuous record on tape, the same as for the electric-eye counters. These portable counters cost only $225 each. They were battery powered, could be installed by one person in about 15 minutes, and counted axles accurately within less than 1 percent of true value. However, it was necessary to know the percentage of multi-axle trucks in the traffic stream to get the true ADT. This percentage was established by periodic manual classification counts *(16)*.

Finally, the BPR developed an accumulating, nonprinting tube counter that required no power and cost only $10. The diaphragm of the air pulse switch was geared directly to a cheap watch which was used as a counter instead of a timepiece. This device could easily fit into a man's pocket, yet could count axles with an error of less than 1 percent. In use, it was buried, out of sight, in the shoulder of the road *(17)*.

## HOURLY TRAFFIC VARIATIONS STUDIED

Automatic counters gave engineers their first insight into hourly traffic variations throughout an entire year. Previously, such information was available only at a few toll bridges, where it was summarized and reported as an annual total or, at best, by monthly subtotals.

By 1940 enough data had been accumulated by automatic recorders to enable the BPR to make a retroactive check on the traffic volumes counted manually during the traffic surveys of the 1920's and 1930's. As noted earlier, the States and the BPR had evolved a number of sampling schedules during those surveys, and it was now possible to check the accuracy of these schedules after the fact by reconstructing what the counts would have been had these schedules been followed. They could also check the accuracy of the *statistical week* schedule devised for use with portable automatic counters to make counts at blanket stations.

This last schedule required a 24-hour automatic count on a Saturday, a Sunday, and either a Monday or a Friday in each of the four seasons. The enumerators then computed the *statistical week* in each season by adding the Saturday and Sunday counts to five times the weekday count. Dividing this week by seven gave the seasonal daily average; they then averaged the four seasons to get average annual daily traffic *(13)*.

For this study the BPR analyzed the records of 89 permanent automatic key stations in 43 States. The analysis proved that all three sampling methods produced remarkably accurate results, with an average percentage of error of less than 6 percent as shown in table 2 *(13)*.

**Table 2.—Accuracy of sampling schedules as compared to continuous automatic counts**

| | Weighted average percentage of error | | |
|---|---|---|---|
| | Key station schedule (manual counts) | 40-hour schedule (manual counts) | Statistical week schedule (automatic counter) |
| State routes with heavy traffic | 3.01 | 3.59 | 4.28 |
| State routes with light traffic | 4.05 | 5.65 | 3.12 |
| Local routes | 4.01 | 5.33 | 4.29 |

As the years passed, traffic engineers refined their counting procedures to get the greatest amount of useful and reliable information with the least cost and effort. However, the backbone of all modern traffic counting systems is still the key station automatic count by permanently installed automatic traffic counters which record traffic every hour of the day. These are now generally called *continuous count stations,* and some of them have unbroken records going back to 1935.

## DETERMINING DESIGN HOURLY VOLUME

Long before the automatic traffic counter was developed, highway engineers and administrators agreed that there would never be enough resources to build roads to accommodate the traffic peaks that occur only occasionally. But where should one place the cutoff point?

To get a feeling for this the BPR in 1940 analyzed the records for 89 permanent automatic stations that had operated continuously for at least 1 year. (These were the same stations that had been used to verify manual counting schedules as described previously.) These stations were spread over 43 States to get a good average picture of United States traffic. When the researchers arranged the hourly traffic volumes at these stations in descending order, they invariably fell into a curve such as the one in figure 5, with the high volumes concentrated in a very few peak hours in the year.

For a typical location with an average annual daily traffic volume of 4,000 vehicles, they compiled the following summary *(13):*

| Hourly traffic volume | Hours during 1 year that hourly volume is equalled or exceeded |
|---|---|
| 950 | 1 |
| 800 | 8 |
| 700 | 20 |
| 650 | 30 |
| 600 | 50 |
| 500 | 115 |
| 400 | 280 |

From this table and figure 5 it is plain that a design based on the peak hour, or even the eighth highest hour, would have considerable surplus capacity, whereas one based on the 115th hour might be frequently congested. The BPR investigators thought the 30th highest hour was a good compromise for designers to use in planning the width of new roads.

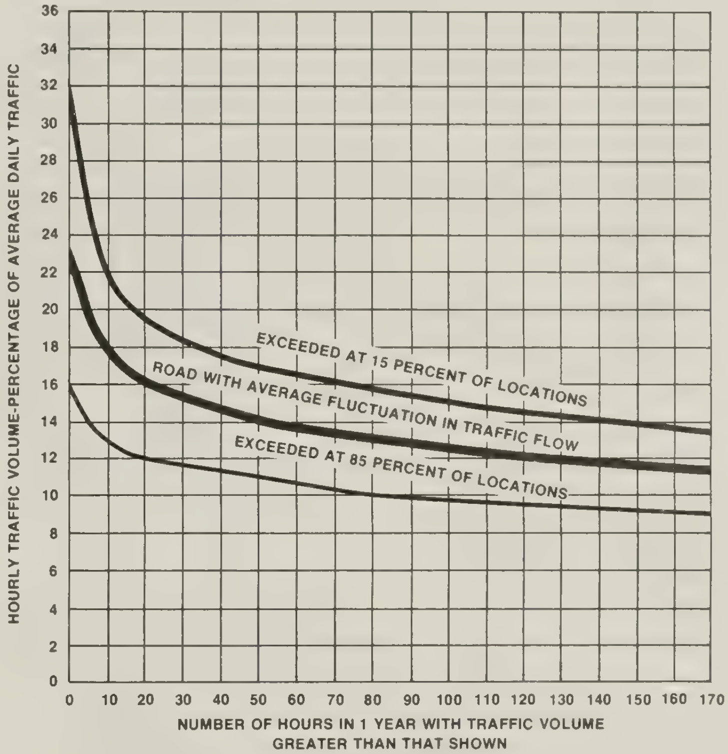



*Figure 5.—Relation between peak hourly flows and annual average daily traffic on rural highways.*

Later studies by the BPR and others showed that the 30th highest hour, expressed as a percentage of ADT, is remarkably stable from year to year on any given highway, ranging from 34 percent of ADT on some highways to as low as 10 percent on others.

In 1945 the American Association of State Highway Officials (AASHO) recommended that the 30th highest hour of a year 20 years from the date of construction be adopted as the standard hourly design volume for the National System of Interstate Highways *(18).* This recommendation with slight modifications has appeared in all subsequent editions of AASHO's design standards for that system.

## THE TOLL ROAD STUDY

By the midthirties there was considerable sentiment in the United States for a few long-distance, controlled-access highways connecting the major cities, modeled somewhat on the Italian autostrade and the German autobahnen. Advocates of such a deluxe system, in and out of Congress, thought the public would be willing to finance much of the cost by tolls, as was contemplated for the newly built Pennsylvania Turnpike. In 1937 President Roosevelt summoned Thomas H. MacDonald, Chief of the Bureau of Public Roads, to the White House and handed him a map of the United States on which he had drawn three east-west routes from coast to coast and three routes traversing the country from north to south. The President asked MacDonald to get started at once on a study of the feasibility of financing and constructing the six routes as toll roads.[3]

[3] As related to the author by E. H. Holmes in January 1974. Mr. Holmes was a member of the task force that prepared the Interregional Highway Report.

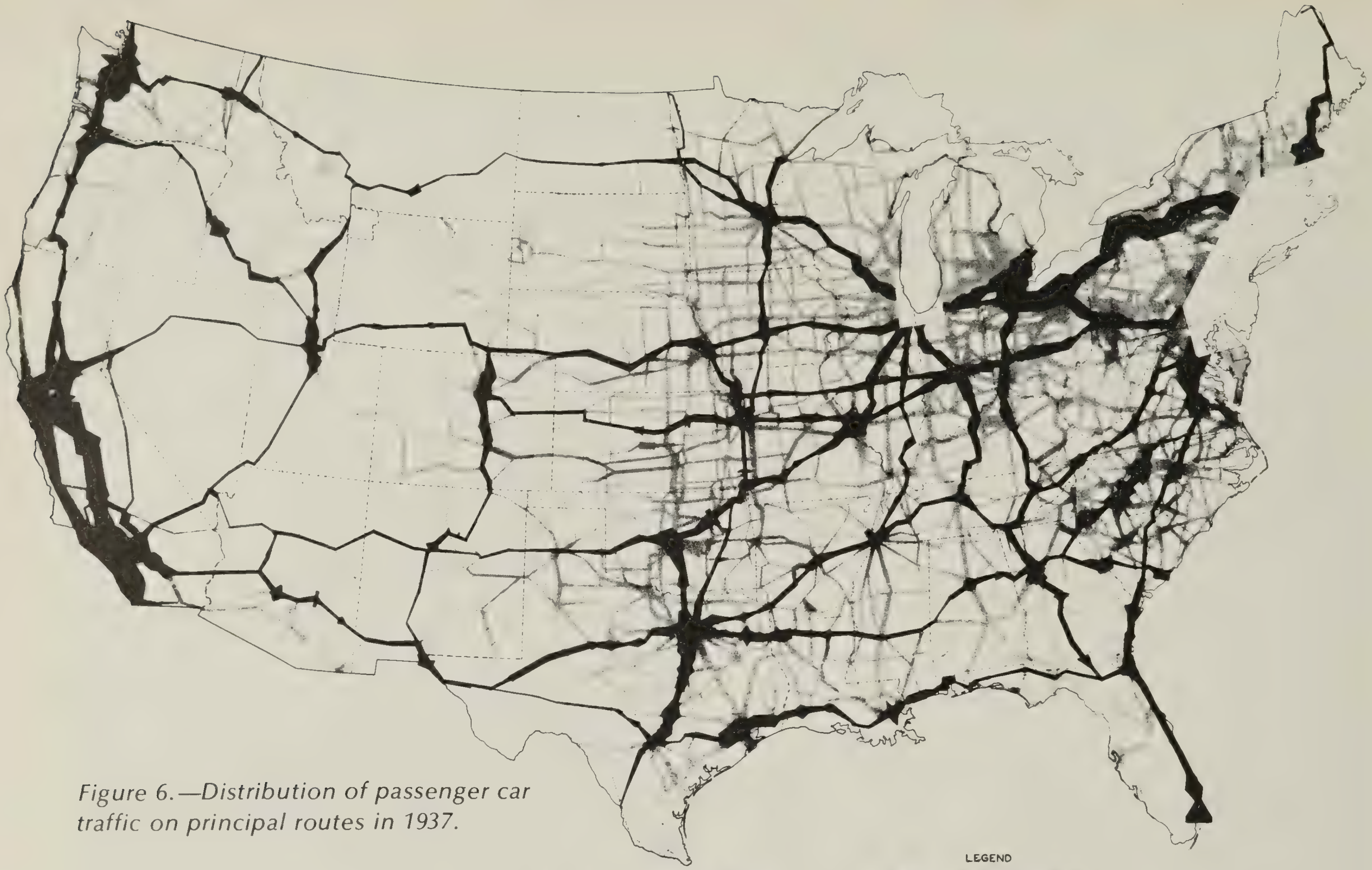
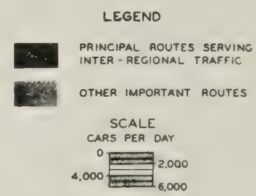
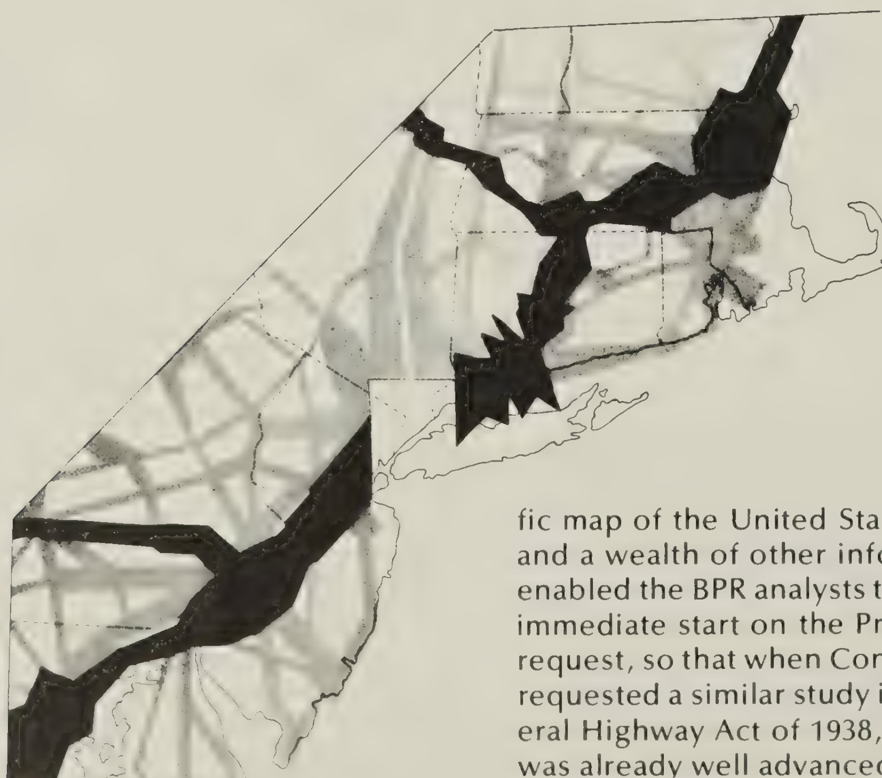


Figure 6.—Distribution of passenger car traffic on principal routes in 1937.



The information needed for such a far-reaching study was available thanks to 17 years of economic and traffic studies by the BPR and the States. By January 1938 the BPR had sufficient information to enable it to assemble the first national traffic map of the United States. This, and a wealth of other information, enabled the BPR analysts to make an immediate start on the President's request, so that when Congress also requested a similar study in the Federal Highway Act of 1938, the work was already well advanced. Because the basic information was already at hand the BPR was able to complete the report by April 1939 *(19)*.

One of the earliest discoveries by traffic investigators—a discovery dating back to the French traffic censuses of the 1870's—was that most of the traffic on any road is local traffic. This principle of traffic distribution was abundantly confirmed by the cooperative State-BPR studies of the 1920's and 1930's as is shown by the 1937 traffic map of the United States (fig. 6). On this map the routes carrying the greatest proportions of long-distance through traffic are shown in black and other main routes appear in gray. (Not all of the traffic on the black routes was through traffic by any means.) From this map the BPR analysts were able to select six transcontinental routes, totaling 14,336 miles, that would satisfy most of the demand for transcontinental travel (fig. 7). According to the predicted traffic, only 3,346 miles, or 23 percent, of the selected routes would require four or more lanes. The estimated cost would range from $63,450 per mile for the two-lane rural sections up to $1,158,400 per mile through the congested megalopolis near New York City, for a total of about $2.9 billion for the system.

Making reasonable assumptions for construction, maintenance, and operation costs, toll-paying usage, and toll rates, the analysts proved that tolls could be counted on to cover less than half of the total annual cost of the system. Only one section of 172 miles from Philadelphia to New Haven would break even by the year 1960, and only 375 additional miles would meet as much as 70 percent of their annual cost by that date.

Although the BPR had shown that toll financing was impractical, it was quick to point out the need for "a special, tentatively defined system of direct interregional highways, with all necessary connections through and around cities, designed to meet the requirement of the national defense in time of war and the needs of a growing peacetime traffic of longer range," and also the need to upgrade the existing Federal-aid highways and the secondary and feeder roads *(19)*. The Bureau tentatively selected a 26,700-mile system of main interregional roads that would connect all of the major population centers. This system, comprising only 1.2 percent of all rural roads, would serve at least 12.5 percent of the annual rural vehicle miles of travel. These roads, the Bureau advised, should be access-controlled, with rights-of-way at least 300 feet wide in the rural sections and without railroad grade crossings. A major recommendation was the establishment of a Federal Land Authority "to acquire, hold, sell, and lease lands needed for public purposes and to acquire and sell excess lands for the purpose of recoupment" *(19)*.

*Figure 7.—Location of transcontinental routes selected for study.*

## THE INTERREGIONAL HIGHWAY REPORT

In 1941 President Roosevelt appointed a blue-ribbon National Interregional Highway Committee to advise the Federal Works Administrator on the need for a limited system of national highways to improve the facilities available for interregional transportation. The Committee's staff was provided by the Public Roads Administration (PRA), successor to the BPR, which placed at the Committee's disposal the men who had been most closely identified with traffic research during the two previous decades.

The appointment of this Committee eventually led to Congressional legislation in 1943 directing the Commissioner of Public Roads to "make a survey for the need for a system of express highways throughout the United States, the number of such highways needed, the approximate routes which they should follow, and the approximate cost of construction," and to report the results of the survey with recommendations for appropriate legislation within 6 months *(20)*.

The required report, a joint effort of the National Interregional Highway Committee and the Public Roads Administration in cooperation with the Department of Defense, was a classic of its kind. The engineers, economists, and analysts—even landscape architects—who compiled it were able to draw not only on the immense reservoir of traffic information accumulated by the States and the PRA, but also on many other sources in the Government. The final choice of routes was influenced as much by strategic necessity and such factors as rural and urban population density, concentrations of manufacturing activity, and agricultural production, as by the existing and anticipated traffic. The Committee and the PRA were able to recommend a system of approximately 33,920 miles that reached all cities of 300,000 or more population and 59 of the 62 cities of 100,000 to 300,000 population (fig. 8). In mileage, this system comprised a little over 1 percent of all the rural roads and urban streets of the Nation *(21)*.

As finally approved by Congress in December 1944, the National System of Interstate Highways totaled 40,000 miles. Its designation was the culmination of a research and planning effort unequalled in the history of transportation.


*Figure 8.—General location of routes for a recommended 33,920-mile interregional highway system.*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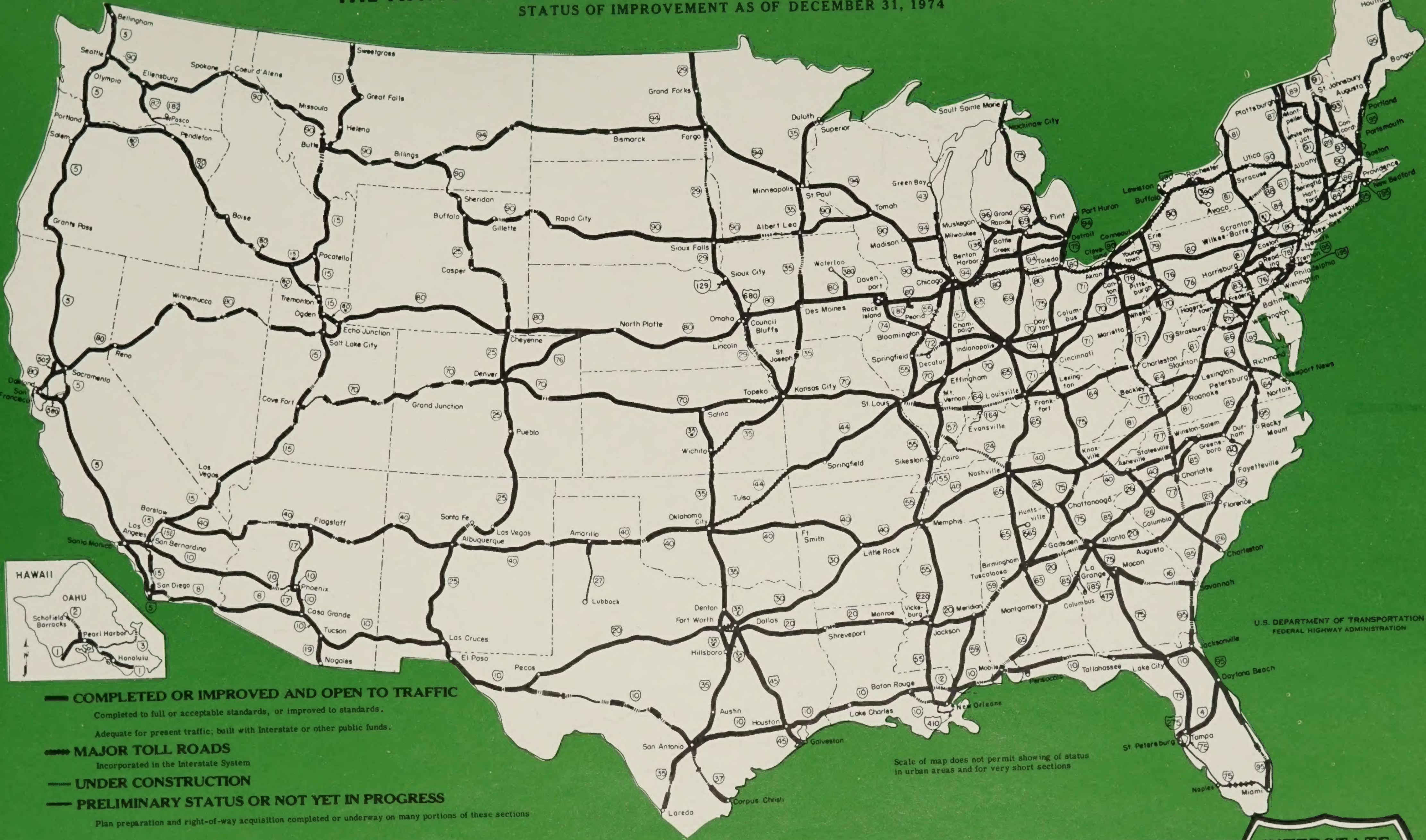
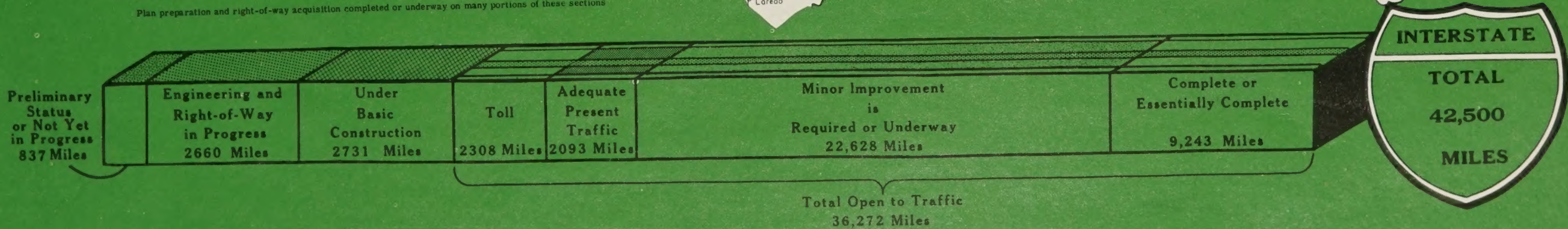



**COMPLETED OR IMPROVED AND OPEN TO TRAFFIC**
Completed to full or acceptable standards, or improved to standards.
Adequate for present traffic; built with Interstate or other public funds.

**MAJOR TOLL ROADS**
Incorporated in the Interstate System

**UNDER CONSTRUCTION**

**PRELIMINARY STATUS OR NOT YET IN PROGRESS**
Plan preparation and right-of-way acquisition completed or underway on many portions of these sections



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