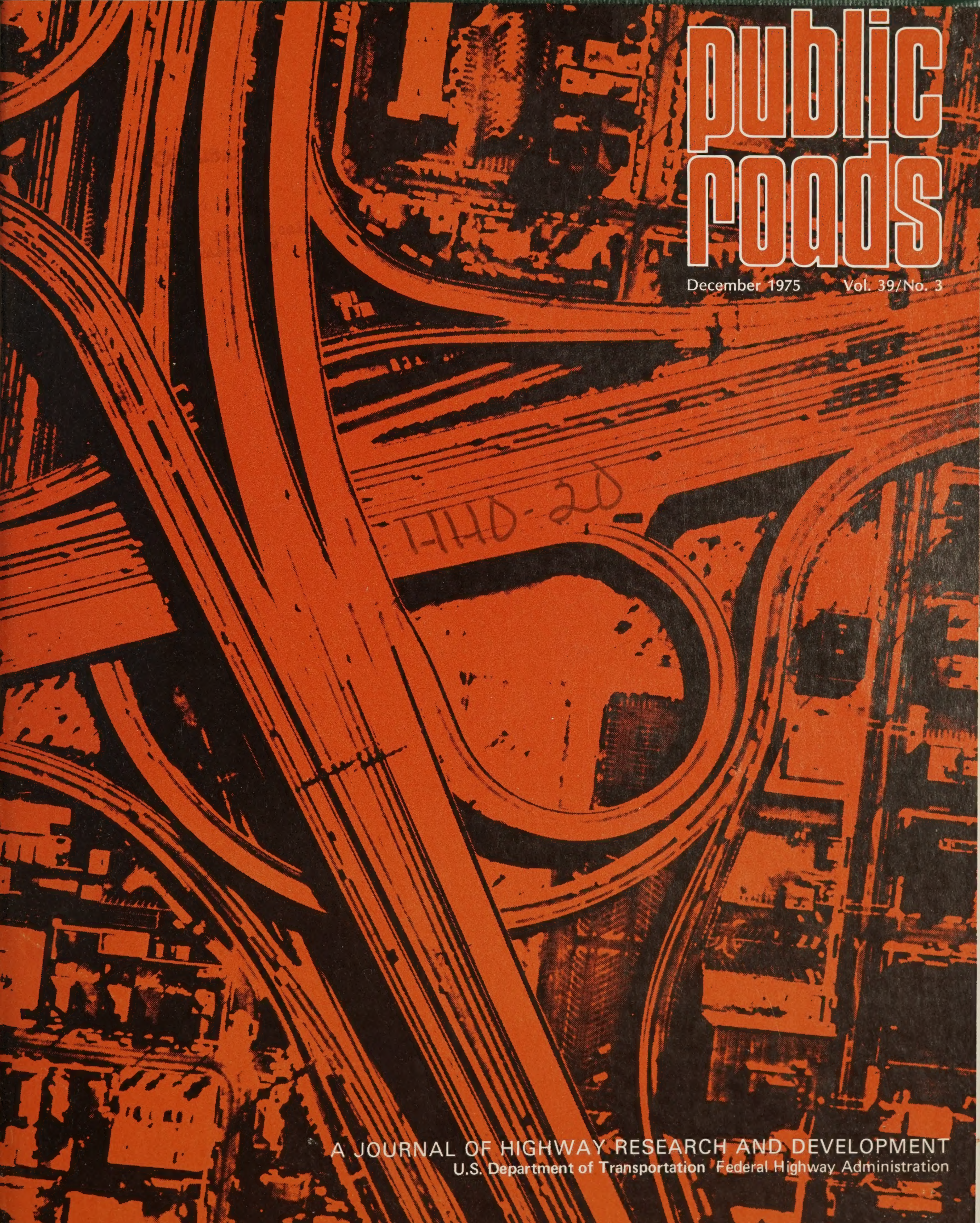
public roads

December 1975 Vol. 39/No. 3

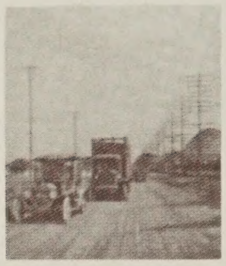


A JOURNAL OF HIGHWAY RESEARCH AND DEVELOPMENT

U.S. Department of Transportation Federal Highway Administration public roads

A JOURNAL OF HIGHWAY RESEARCH AND DEVELOPMENT

December 1975 • Vol. 39, No. 3



BACK COVER:
Artist's concept of the first Federal-aid road—1918. This section of road completed under the authorization of the Federal Aid Road Act, approved by President Wilson on July 11, 1916, was California Federal-Aid Road Project No. 3, situated in Contra Costa County and known locally as the "Alameda County boundary to Richmond road." Artist: Carl Rakeman. (See page 131.)

U.S. Department of Transportation
William T. Coleman, Jr., *Secretary*

Federal Highway Administration
Norbert T. Tiemann, *Administrator*

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

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

Gerald D. Love, *Associate Administrator*

Editorial Staff

Technical Editors
C. F. Scheffey, R. C. Leathers

Editor
Fran Faulkner

Assistant Editors
Judith Ladd, Debbie DeBoer

Advisory Board
J. W. Hess, R. F. Varney,
D. Barry Nunemaker,
C. L. Shufflebarger, R. J. Betsold

Managing Editor
C. L. Potter

IN THIS ISSUE

Articles

Departments

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of an article.

Address changes (send both old and new) and inquiries concerning the *FREE* mailing list should be directed to: *Public Roads* Magazine, HDV-14
Federal Highway Administration
Washington, D.C. 20590

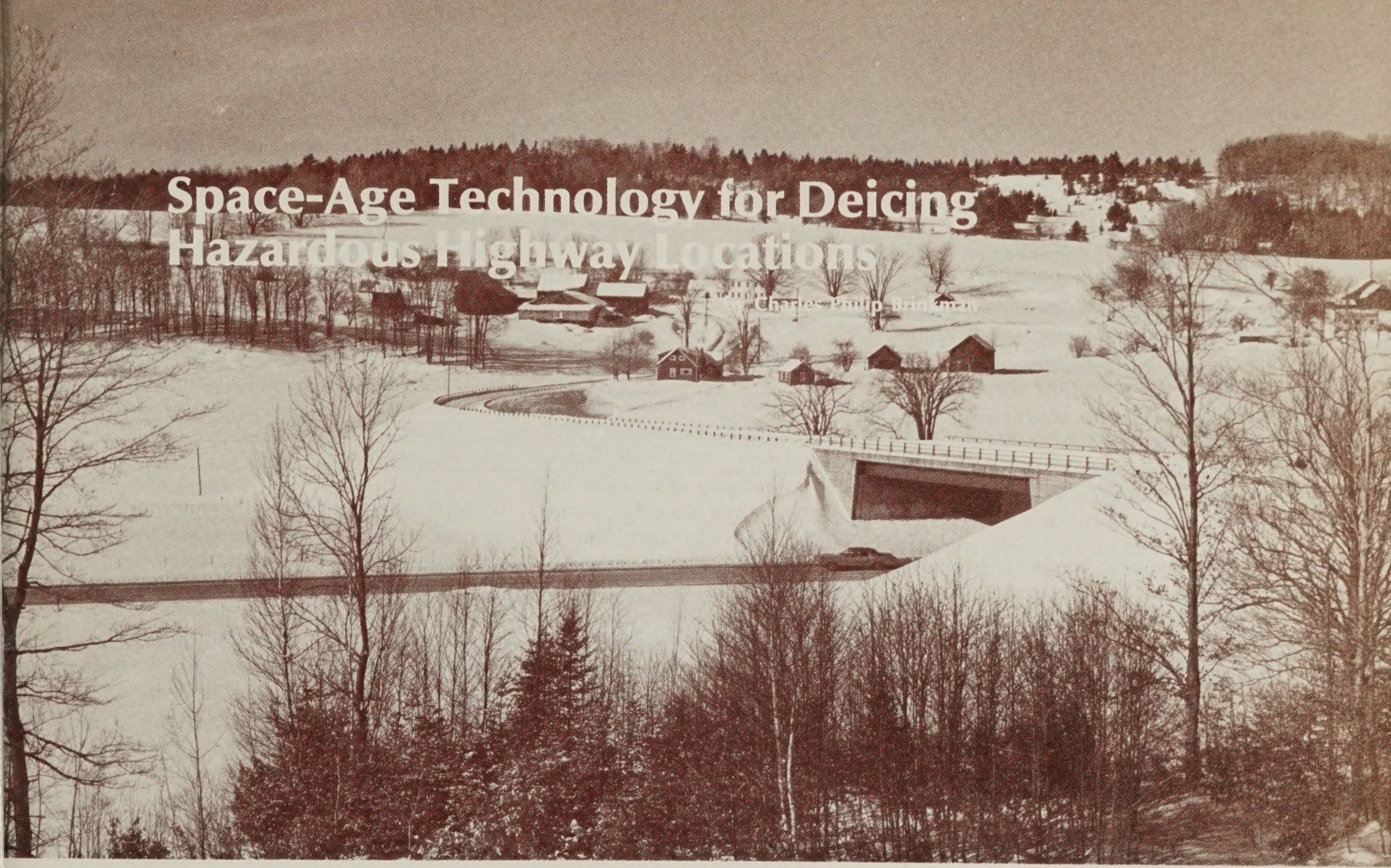
Public Roads, A Journal of Highway Research and Development, is sold by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, at $6.10 per year ($1.55 additional for foreign mailing) or $1.55 per single copy. Subscriptions are available for 1-year periods. Free distribution is limited to public officials actually engaged in planning or constructing highways and to instructors of highway engineering. A limited number of vacancies are available at present.

The Secretary of Transportation has determined that the publication of this periodical is necessary in the transaction of the public business required by law of this Department. Use of funds for printing this periodical has been approved by the Director of the Office of Management and Budget through March 31, 1976.

Contents of this publication may be reprinted. Mention of source is requested.

Space-Age Technology for Deicing Hazardous Highway Locations

by Charles Philip Brinkman



—courtesy, Vermont Department of Highways.

Introduction

Until now, pavement heating has not been considered a viable option for deicing highway pavements for both technical and economic reasons. There are critical locations, however, where pavement heating appears attractive because of safety hazards, design constraints, or operational considerations. For example, where the availability of land prevents redesign, pavement heating might improve winter operations on an unusually steep or sharply curved ramp. Pavement heating might also be considered at particularly crucial interchanges where snowplowing, sanding, and salting cannot prevent severe operational difficulties. It appears space-age technology has provided a solution, at least to the technical aspect of the problem. This solution is the heat pipe, although some developmental work remains to determine the most economical heat-pipe deicing system.

Early Pavement Heating Systems

Various systems of heating pavements have been tried in Europe and the United States. The most common systems employed embedded electric resistance elements or pipes carrying a heated fluid. Because these systems have either poor reliability, high costs, or restrictive power sources, they have not had widespread application.

Various types of electric heating systems have been used, but their reliability is low (*1, 2*).[1] For example, shielded resistance wires embedded in the roadway are susceptible to wire breakage due to concrete cracking, to shorting due to moisture, and to corrosion due to salt penetration. Bare electric resistance wire is even less reliable. The high cost of electric power makes operating costs very high. Even if the system is activated only when needed, standby power costs are incurred. These costs are often high enough that continuous operation at a lower power—keeping the pavement above freezing—may be less expensive. The high thermal resistivity and large heat capacity of the roadway pavement necessitates either several hours lead time or a high start-up wattage to warm the pavement so snow or ice will melt. It is usually preferable to maintain the surface at a temperature above freezing, and continuous operation at low wattage may be desirable.

[1] Italic numbers in parentheses identify the references on page 95.

A modern electric pavement deicing system is being constructed for a 165,000 ft^2 (15,000 m^2) interchange in Louisville, Ky. The system uses embedded resistance cables consisting of a copper conductor with magnesium oxide insulation in a copper sheath. These cables are able to provide 60 W/ft^2 (650 W/m^2). The initial cost of the system is about \$12/ft^2 (\$129/m^2). Power costs will contribute significantly to the total cost.

Infrared systems can be installed beneath bridge decks without disturbing the pavement, and the bottom can be insulated to reduce heat loss. Such systems have not proved practical because of lengthy lead times necessary to warm the pavement (3). If installed overhead or along the roadside, they must be far enough away so that stopped vehicles are not damaged. Also they must be turned on before any accumulation of snow because the snow's high reflectivity would make the system ineffective. The farther the infrared source is from the road, however, the less efficient it is. Infrared systems can be powered by either electricity or gas. Above-the-road systems are expensive to install and operate and must be made safe against an impacting vehicle. Although such systems have been discussed and designed for application on airport runways, none are in highway use.

In some systems, heated fluids are circulated through pipes in the pavement. The temperature at which the fluids are transported causes expansion and contraction severe enough that expensive leaks may develop. Such a system is found on the approach ramps to the Port of New York Authority's midtown bus terminal. At rare locations, commercial steam, waste heat, or natural hot springs can be utilized, but it is not feasible to transport such heat for distances greater than about a mile (1.6 km).

Use of Nuclear Waste Materials

A lack of reliability and the high cost of pavement deicing prompted the Federal Highway Administration (FHWA) to investigate alternative heat sources for highway deicing. Dynatherm Corporation was contracted in 1969 to study the use of nuclear waste for deicing of bridges, ramps, and pavements *(1)*. The system consisted of an underground steel-lined vault containing a heat exchange fluid (for example, oil) into which steel capsules containing the fission wastes were placed. An electric pump circulated a fluid through a heat exchanger immersed in the oil bath to the earth beneath the pavement. From this earth, heat pipes transported the heat to the pavement. This system appeared desirable because nuclear decay continuously produces heat which must be dissipated and the earth provides good heat storage. A system without earth storage would have required more radioactive waste and a complex system to prevent overheating during warm weather. In this system, emergency heat dumping was provided by temperature-controlled heat pipes as a safety precaution against failure of the pumps due to electrical disruption or mechanical malfunction.

Unfortunately, a wide application of the nuclear waste system was not possible because of the limited availability of fission waste and safety problems associated with its use. Nuclear waste requires special protective systems for transport to many sites. Subsequent disposal, when the nuclear waste no longer produced enough heat to be effective, would be difficult for a highway agency to handle. During the analysis of the earth's heat storage potential, it became apparent that a heat-pipe system utilizing earth energy from the first 40 ft (12 m) below the pavement could deice pavements in moderate climates (for example, Washington, D.C., New York City) without using nuclear energy or any other supplemental energy source.

The Physics of Heat Pipes

Understanding the basic technology of heat pipes is important since they are essential to both earth and nuclear waste heat systems for pavement heating. R. S. Gaugler, working at General Motors, introduced the heat pipe in 1944 but its importance was not noted until it was proposed for use in the space program in 1961 as a means of achieving isothermal temperatures and dissipating excess heat on spacecrafts: getting them out of the slow roll mode that caused the early astronauts so much trouble.

In 1963, the *heat pipe* was given its name by George Grover and his associates at Los Alamos Scientific Laboratory. Its many nonspace applications range from cooling electronic components to stabilizing permafrost on the Alaska Pipeline project. Heat pipes have also been proposed in conjunction with solar collectors and the cooling of nuclear reactors.

A heat pipe (fig. 1) is a closed container evacuated of all noncondensable gases, having a capillary wick, and containing a *working fluid* which transports heat from a region of higher temperature to one of lower temperature. The choice of fluid is determined by the temperatures of the heat giving and receiving regions. It must be a fluid in two-phase equilibrium (liquid-vapor) for these temperatures. With the proper working

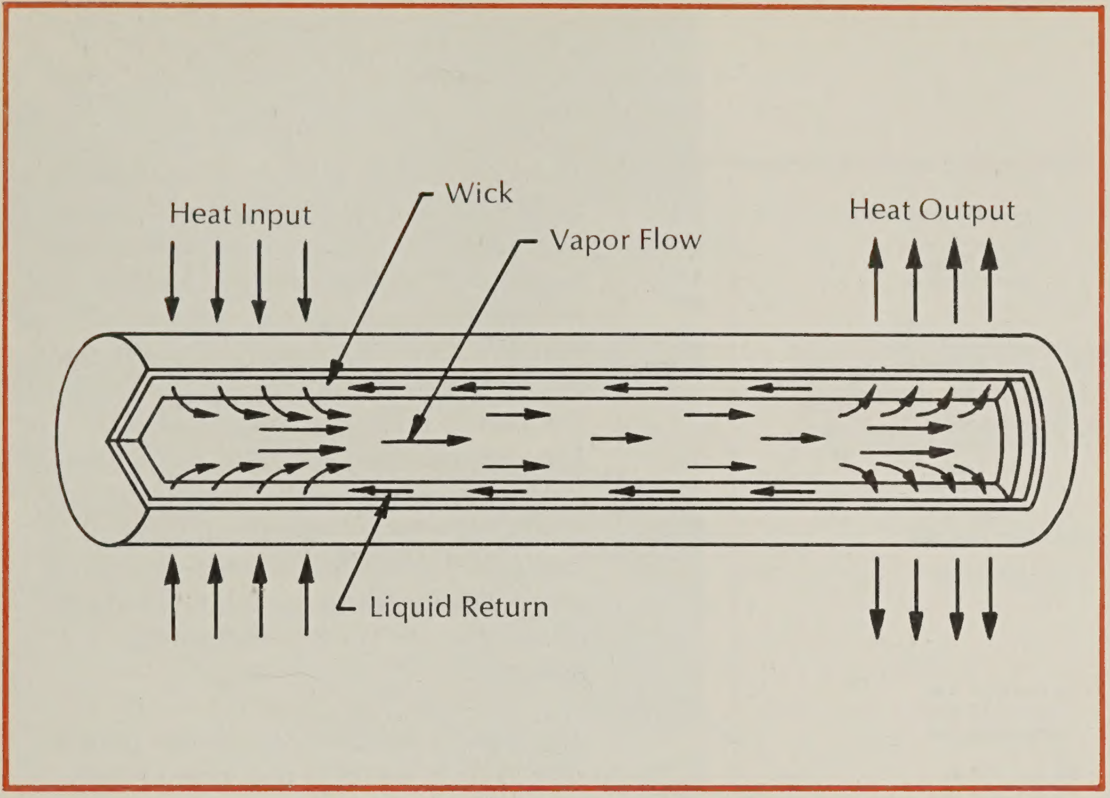


Figure 1.—Schematic representation of the heat pipe.

fluid, heat pipes can operate at temperatures from the cryogenic region to about 2,000° F (1,100° C). In the cryogenic region, the fluid is a gas such as nitrogen. For high temperatures, the fluid is a metal. At the higher temperature end of the heat pipe the liquid evaporates. The vapor fills the portion of the tube not occupied by liquid and condenses in the lower temperature end. Evaporation takes heat, and condensation releases this heat, called the latent heat of vaporization.

The condensed liquid must then be returned to the evaporation section. The orientation of the pipe may allow for gravity return. In the gravity-free situation in space, a wick is used to accomplish liquid return via capillary action. The practical limit for liquid return against gravity using conventional wicking materials is approximately 1 ft (0.3 m).

The criteria for a good fluid consist of a large latent heat of vaporization allowing large amounts of heat to be transported, high surface tension in its liquid state for best wicking action, and low viscosity for best liquid flow. The fluid must be chemically stable in the temperature range for which the heat pipe will be used, and compatible with the outside wall and capillary wick. The chemical properties of the fluid, the mechanics of flow, and the wick's capillary pumping impose conductance limits on heat pipes.

Heat pipes can transport heat at a rate several thousand times greater than the best solid conductors or a convective system. The vaporization-condensation cycle is essentially isothermal (with only a very small temperature drop associated with the slight vapor pressure drop between the evaporator and the condenser). Heat pipes can transport heat considerable distances with only a slight drop in temperature. Because heats of vaporization are typically large, heat pipes can be relatively small devices.

The heat pipe does not consume energy—it transports energy. The Second Law of Thermodynamics as formulated by Clausius forbids a transformation whose only final result is to transfer heat from a body at a lower temperature to a body at a higher temperature. Such a device would be a perfect refrigerator which would make low-grade heat energy available to perform work and thus be a panacea to our energy problems. However, a perfect refrigerator does not exist. The heat pipe does not violate the Second Law of Thermodynamics, since it can only transport heat energy from a region of higher temperature to one of a lower temperature. The heat pump, which transfers heat from a region of lower temperature to one of higher temperature, also does not violate the Second Law of Thermodynamics because it is not a closed system. It requires energy from an outside source.

Advantages of Heat Pipes

The use of heat pipes overcomes many problems associated with pavement heating systems. Steel or black iron pipe used for heat pipes is durable and not easily broken by small movements in the pavement. Transporting heat involves no mechanical or electrical parts so heat pipes should last many years without maintenance. Also, the multiplicity of the heat-pipe network means that failure of one pipe is not critical to the system. Their high conductance allows heat pipes to operate at moderate temperatures—even while utilizing high temperature heat sources—and utilize low-grade energy sources such as earth heat. Severe pipe expansion-contraction and concrete cracking associated with high temperature in pavement elements is also eliminated. A test installation using this system (*4*) was designed for the Fairbank Highway Research Station (FHRS) in McLean, Va.

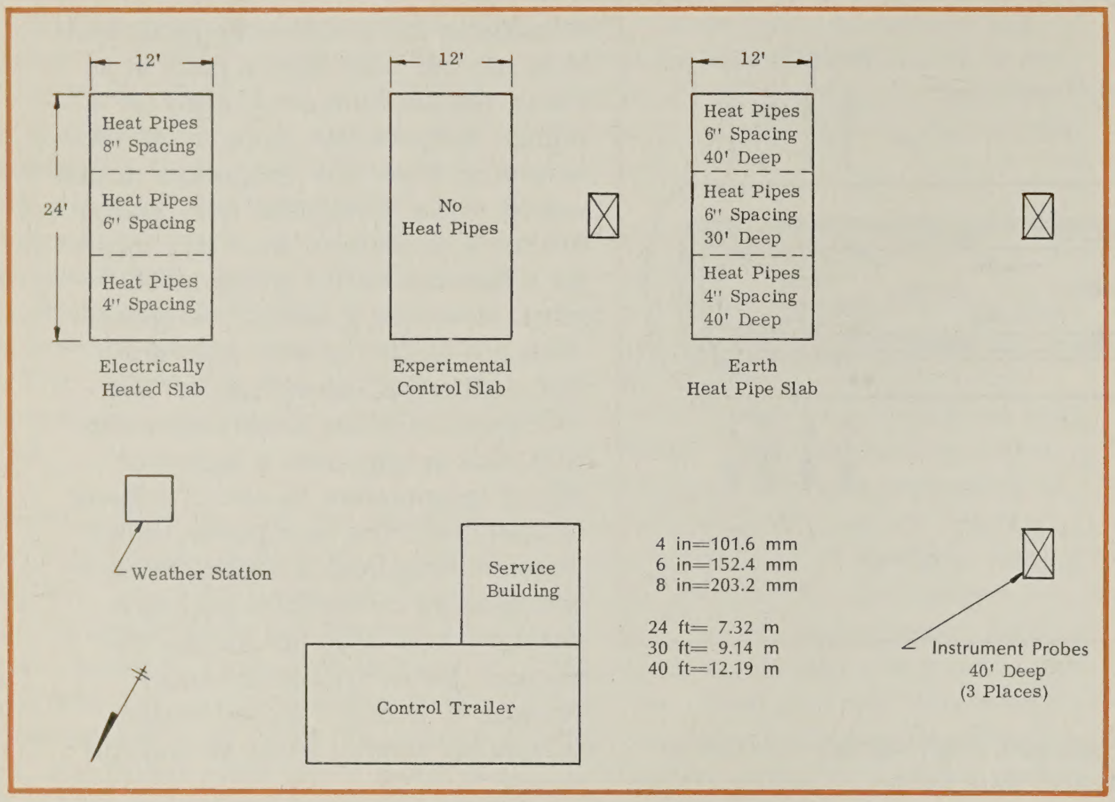


Figure 2.—General site arrangement.

Earth Heat Systems

The earth heat-pipe system uses the volume of earth immediately below and adjacent to the road's surface. It could be used with other heat sources where the earth's energy is insufficient to overcome severe climate conditions. For areas having moderate winters, the earth's temperature at 30–40 ft (9–12 m) below ground is about 50°–60° F (10°–15° C), which is approximately the average year-round atmospheric temperature at the ground/air interface.

The system can be passive since it will only work when the earth's temperature at the bottom of the heat pipe is greater than the pavement's temperature—the situation encountered in icing predicaments. For areas having moderate winters, a passive earth heat-pipe system should function effectively all winter and degradation of the heat source over a period of years will not occur. Earth heat is renewable. Such systems will not incur electrical power costs and require minimum maintenance.

Earth heat systems can be built into new highway systems or added during resurfacing. However, the high cost of such a system or of any pavement heating system limits pavement heating to especially critical locations.

Test Installation

The test facility at FHRS was designed to investigate some of the variables associated with pavement deicing and verify that earth heat could be utilized in areas having moderate winters. The test site (fig. 2) consists of three concrete slabs 9 in (229 mm) thick: the electric slab, control slab (unheated, having no heat pipes), and earth slab. All three are heavily instrumented with thermocouples and instrument probes provided to measure the ground temperature inside and outside the heat field.

The electric slab consists of test panels A, B, and C, each of which contains heat pipes with only a short downward evaporator section. Electric heaters wrapped around these downward sections can be controlled from the instrumentation trailer to provide the panels a known amount of heat. Panel A contains 12 heat pipes configured as two-pronged forks making a spacing of 4 in (102 mm). Panel B contains 16 heat pipes on 6-in (152 mm) spacing, and panel C contains 12 heat pipes on 8-in (203 mm) spacing.

The earth slab consists of test panels D, E, and F. Panel D contains 12 heat pipes configured as two-pronged forks identical to panel A of the electrical slab and extending to a depth of 40 ft (12 m) in the ground. Panel E contains 16 pipes of a 6-in (152 mm) spacing with the in-earth portion of the pipe extending to a depth of 30 ft (9 m). The heat pipes extend from both sides of the earth slab in an alternating sequence and enter the earth on a pattern of 3-ft (1 m) centers (figs. 3 and 4). Panel F is identical to panel E, except the pipes extend 40 ft (12 m) into the ground.

At FHRS the in-pavement portions of the heat pipes are ½-in (13 mm) and the down legs 1-in (25.4 mm) nominal black iron pipe. The pipes run parallel to the short sides of the slabs, 1.25 in (32 mm) from the surface and are charged with anhydrous ammonia.

Snowstorm provides a severe test

The most severe test of the Earth Heat Pipe Pavement Deicing System at FHRS occurred in December 1973 with 9 in (229 mm) of snow falling within a 24-hour period, temperatures as low as 17° F (—8° C), and winds

Figure 3.—Pouring earth heat pipe slab.

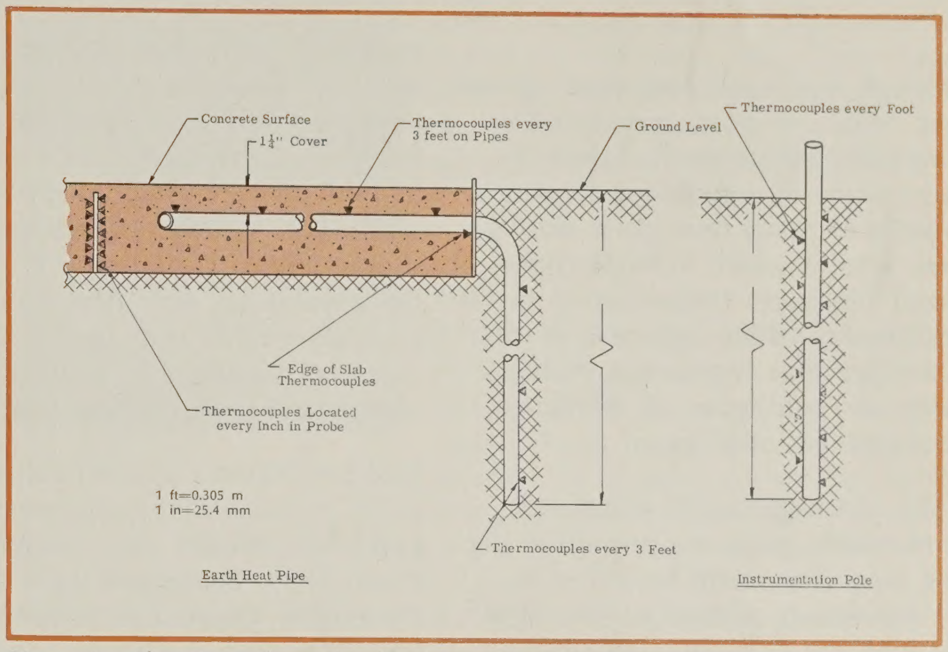


Figure 4.—Elevation schematic of instrumentation.

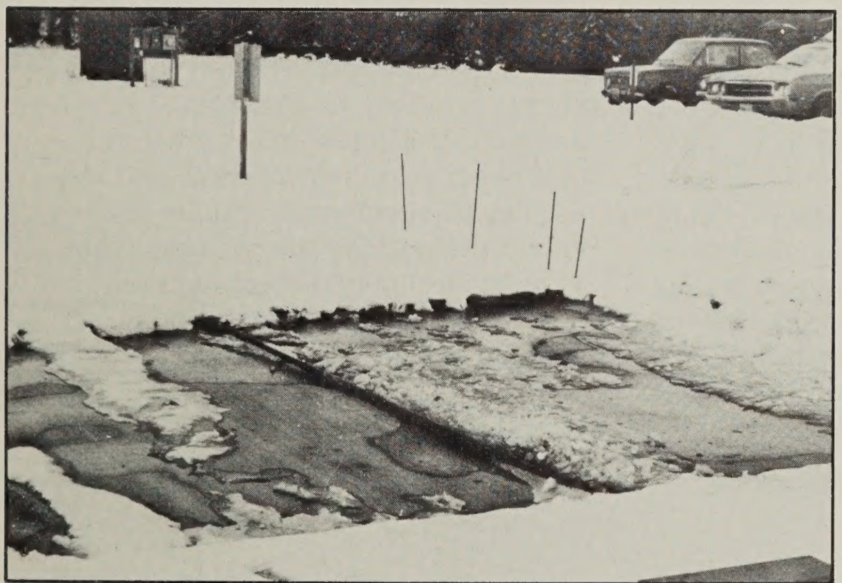


Figure 5.—Earth slab, panels E and F.

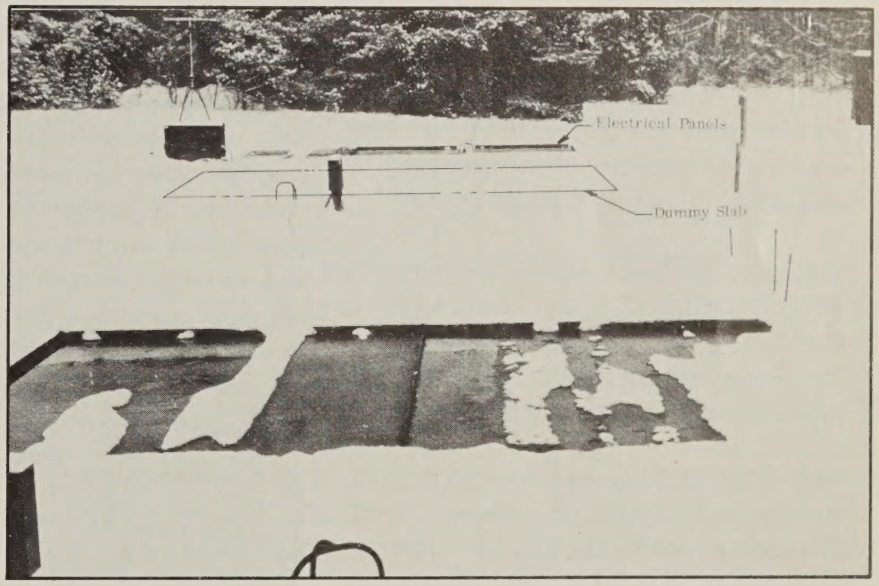


Figure 6.—Earth slab, panels E and F.

up to 27 mph (12 m/s) (fig. 5). The earth heat pipe panels melted most of the snowfall, but considerable drifting occurred. Ridges formed between the heat pipes when melt water wicked up through the snow, freezing on top of the resulting slush. These ridges dislodged easily when stepped on and there was always a film of water between the pavement and these ice ridges. If the test pavement had been subjected to normal traffic, the pavement would have remained clear.

During an ice storm, the heat-pipe pavement remained free of ice. This storm and two major snowfalls which occurred during the winter of 1973–74 demonstrated that the system works (fig. 6). In addition, numerous tests using flaked ice from an ice machine were employed to provide design information.

The next step in developing an earth heating system is an installation on a roadway so that the effects of traffic can be determined. This is being planned for a highway ramp 1,200 ft (366 m) long and 16 ft (4.8 m) wide in West Virginia. The total cost for materials and construction is estimated at \$420,000 or \$22/ft^2 (\$240/m^2). Since no maintenance cost is anticipated, this amount must be prorated over the lifetime of the system to compute the cost per year.

Problems with the heat pipes at FHRS

Although the earth heat-pipe system does work, it does not function completely satisfactorily. Figure 7 shows snow accumulation above portions of many heat pipes during a snowstorm which indicates condenser blockage. Deterioration in the performance of the system over that of the previous winter was visible. There are two types of condenser blockage: gas and liquid.

- Gas blockage occurs when noncondensable gases are present in the heat pipe. They tend to collect in the condenser section of the pipe and interfere with the condensation of the working fluid.

- Liquid blockage occurs when the fluid is caught in the condenser section and cannot return to the evaporator section, thus breaking the evaporation-condensation cycle.

The possibility of liquid blockage has been eliminated at the West Virginia installation by a design that places the in-pavement portion of the heat pipes on the slope of the ramp.

B&K Engineering was contracted to conclusively determine the cause of this poor performance. A clamp-on calorimeter was fabricated. Temperature profiles of the earth slabs indicated substantial blockage of the heat pipes. Only after the pavement was iced down to contract the slug of noncondensable gases was the calorimeter able to extract a significant amount of energy (on short-term basis 150–225 W) from the ground for each heat pipe tested *(5)*. Calorimetric tests verified that the blockage is caused by noncondensable gases inside the heat pipes.

Past performance of the heat pipes at FHRS indicates that noncondensable gases have always been present in them. These heat pipes were not thoroughly cleaned to remove dirt, nor were they baked to accelerate chemical reactions of contaminants that might produce noncondensable gases and then bled to remove any gases. Previous testing had indicated no adverse effects on heat pipe performance. Since then it has become apparent that these cleaning processes cannot be eliminated. Recent accelerated life cycle testing of heat pipes for the Alaska Pipeline has ruled out gas generation due to any chemical reaction between steel and anhydrous ammonia.

There is every reason to believe that the gas blockage exhibited at FHRS resulted from inadequate manufacturing procedures for cleaning and charging the pipes. These procedures have since been refined as a result of testing similar heat pipes for the Alaska Pipeline and adequate specifications have been written for the West Virginia project.

Other Research Underway

Grumman Aerospace Corporation (6) is researching the feasibility of using heat pipes to prevent ice forming on a bridge while the adjacent pavement remains free of ice. This *preferential icing* occurs on structures not in thermal contact with the ground. The use of earth heat appears feasible to prevent preferential icing. The total energy required to eliminate preferential icing is not as great as that needed to melt all snow and ice, but the energy demand can be high for a brief period. The system needs a control to limit the heat required so that the size of the earth field remains within practical limits.

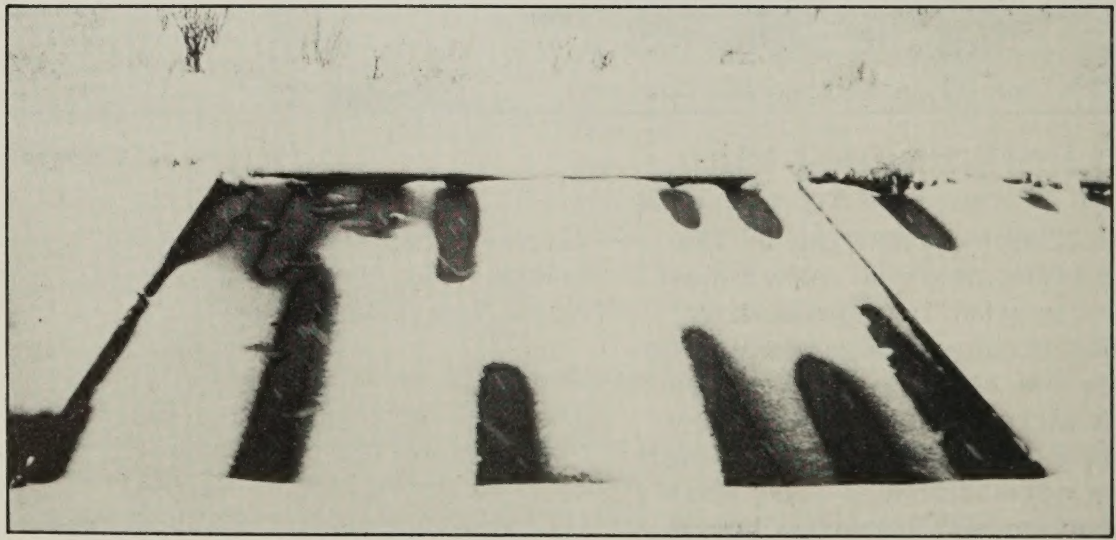


Figure 7.—Snow accumulation on earth heat pipe panels.

Figure 8.—Test site—California State Route 89, 5 miles north of Truckee, Calif.

In other research (fig. 8), MB Associates evaluated the performance of three ice and snow detection systems to determine their utility in conjunction with a motorist warning system (7). The ice detectors evaluated employ three different methods.

- The first system detects frost by applying a thermal pulse to a witness plate, detecting a delay in temperature change due to absorption of latent heat of melting.
- The second system detects the presence of moisture or ice on a witness plate by a change in capacitance compared to air alone, and differentiates between ice and moisture with a conductivity probe.
- The third system detects ice when the road is below 32° F (0° C) by seeking a conductive imbalance between an unheated and a heated probe which is kept above 32° F (0° C) to melt any ice. The system also uses a humidity sensor to predict frost.

Other ice detectors make use of measurements of spectral temperatures and vibration frequency. Systems have been proposed which would use reflectivity.

Results of this 2-year evaluation were disappointing. The devices experienced both electrical and mechanical failures and required modification, recalibration, and adjustment. None of the detectors tested were sufficiently reliable or accurate to operate a motorist warning system. In principle, it should be possible to build a reliable ice detector, but the cost may be too great to be widely used.

Unlike the problem of motorist warning where false alarms cannot be tolerated, the requirements for a detector to activate a deicing system are less stringent. Since some lead time is necessary to warm the pavement, the detector would probably only need to detect temperature or temperature and moisture. For such a system, false alarms can be tolerated, but ice occurrences must be detected with a high reliability.

Future Research

Further development of heat pipe technology might decrease the cost of pavement deicing systems using earth heat and make them practical in cold regions. There are several ways of increasing the amount of available earth heat without using a larger heat field or more heat pipes. By backfilling the holes for heat pipes with a substance having a higher conductivity than the surrounding ground, the rate at which heat pipes could extract heat from the earth would be increased. Also, earth heat could be conserved by shutting off the heat pipes when heat is not needed. Solar energy might be used to augment earth energy.

Summary

A pavement deicing system using heat pipes offers advantages over other systems. A heat-pipe system utilizing earth energy is especially attractive because its operation does not drain energy resources. The West Virginia project, the work being done by Grumman, and further research, particularly augmenting earth energy, will determine whether such systems are practical.

REFERENCES

(1) W. B. Bienert, M. F. Pravda, et al., "Nuclear Wastes in Comparison with Other Heat Sources for Deicing of Bridges, Ramps, and Pavements," Final Report (Phase I), Dynatherm Corporation, *Federal Highway Administration* Report No. DTM–70–6, 1970.

(2) National Cooperative Highway Research Program Report No. 4, "Non-Chemical Methods of Snow and Ice Control on Highway Structures,". *Roy Jorgensen and Associates,* 1974.

(3) R. W. Griffin, "Preferential Icing of Bridge Decks," Interim Report, *Colorado State Department of Highways,* 1974.

(4) W. B. Bienert, M. F. Pravda, et al., "Snow and Ice Removal from Pavements Using Stored Earth Energy," Final Report, Dynatherm Corporation, *Federal Highway Administration* Report No. FHWA–RD–75–6, 1974. This report is available from the Federal Highway Administration, HRS–40, Washington, D.C. 20590.

(5) H. J. Suelau and E. J. Kroliczek, "Examination of Earth Heat Pipes at FHRS," Final Report, *B&K Engineering, Inc.,* 1975.

(6) A. Ferrara, "Preferential Icing on Bridges: Applying Heat Pipe Technology to the Deicing of Bridge Decks," Interim Report, *Grumman Aerospace Corporation,* 1975.

(7) R. C. Mawhinney and R. J. Ruden, "Snow and Ice Detection and Warning Systems," Final Report, *MB Associates,* 1975.

Highway Design for Motor Vehicles— A Historical Review

by [1] Frederick W. Cron

Part 4: The Vehicle-Carrying Capacity of the Highway

This is the fourth 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 vol. 38, No. 3, December 1974. Part 2: The Beginnings of Traffic Research was published in vol. 38, No. 4, March 1975. Part 3: The Interaction of the Driver, the Vehicle, and the Highway was published in vol. 39, No. 2, September 1975. The remaining parts, to be published in future issues, are 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.

Traffic congestion is not new; the streets of Imperial Rome were indescribably congested, day and night. But until the advent of the automobile, seldom did enough vehicles assemble on a single stretch of road—except in the largest cities—to cause serious congestion; or seldom did the congestion continue long enough to raise doubts as to the capacity of the road to handle the traffic using it.

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

Early Capacity Research

In the United States serious congestion began to be felt on certain inter-city rural roads by 1920. In that year 9,200,000 motor vehicles—not including 239,000 motorcycles—were registered, and the number was increasing at an annual rate of 22 percent *(1)*.[2] Most of the rural roads of this period were two-lane roads, 14 to 18 feet wide, and a number of engineers were beginning to question the roads' adequacy to handle the rapidly increasing volumes of motor traffic. One of these engineers was A. N. Johnson, dean of the University of Maryland Engineering College, who, perhaps more than anyone else, deserves to be called the father of the science of traffic analysis.

Johnson was one of the first engineers to advocate the widespread and systematic use of traffic research to collect factual data on which to base highway decisions: "Even a brief study of the problems of highway research shows that many of them of the most fundamental character require for their solution a comprehensive knowledge as to the traffic which moves over the highways" *(2)*. In 1921 from a study of the meager data then available, he concluded that except for a very small fraction of the State highway systems, two-lane roads would suffice for years to come and that "highway plans contemplating an extended system of highways of greater width than is required for two lanes of traffic are extravagant and have no economic basis" *(3)*.

[2] Italic numbers in parentheses identify the references on page 108.

To arrive at this conclusion Johnson first calculated the theoretical capacity or *vehicle discharge* of a single lane of traffic based on the following:

$$N=\frac{5,280V}{D}$$

Where,

N=Total vehicles passing in 1 hour.
V=Vehicle speed in miles per hour.
D=Average spacing center to center of vehicles in feet.

Thus, if all of the vehicles were 15 feet long and there was 15 feet between them, D would be 30 and for a speed of 15 mph the discharge of a single lane would be 2,640 vehicles per hour. From observation of actual traffic on the Baltimore-Washington Road, Johnson noted that the clearance between vehicles traveling 10 to 15 mph was only about 15 feet, whereas at 25 to 30 mph the average clearance was 50 to 60 feet. He therefore concluded that the average minimum spacing of vehicles in a traffic stream varies as the square of the speed; and that if all the vehicles are 15 feet long, the formula for maximum discharge of a single lane at uniform flow would be:

$$N=\frac{5{,}280V}{15+\frac{V^2}{15}}$$

Paradoxically, according to this formula a larger number of vehicles will pass a given point at a speed of 15 mph than at 30 mph (fig. 1, curve B).

For a speed of 30 mph with an average center-to-center vehicle spacing of 75 feet, the theoretical discharge would be 2,100 vehicles per hour per lane. This, Johnson realized, did not allow for passing and normal interruptions under real driving conditions, so he arbitrarily set the comfortable discharge at 500 to 750 vehicles per hour per lane or 1,000 to 1,500 vehicles per hour in both directions for a two-lane highway. Such a road, he explained, could if necessary handle double this traffic during special rush hours.

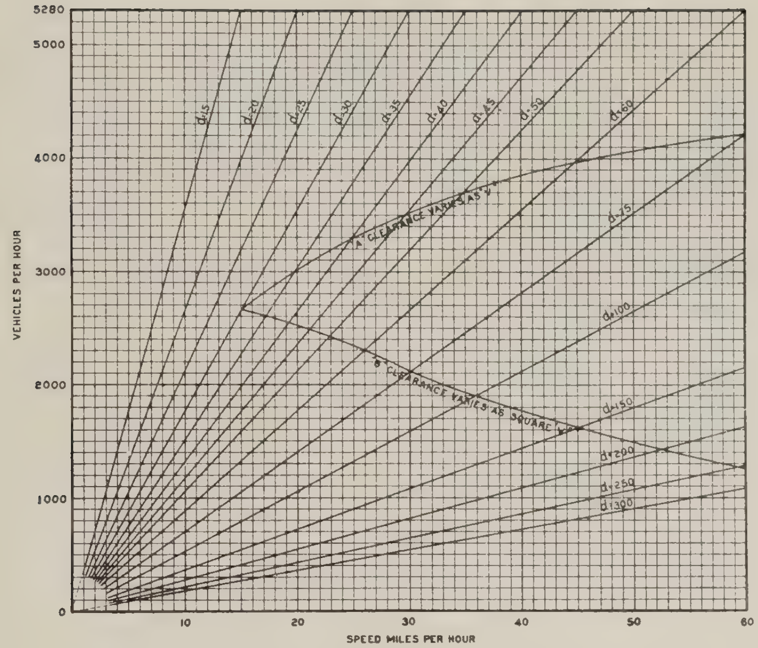


Figure 1.—Traffic discharge diagram. d=distance center to center of vehicles. d—15=clearance between vehicles (3).

Estimated Traffic for a Connected National Network

From the known or surmised information about traffic, Johnson then built up an estimate of what average traffic might be for a connected national network of main highways. His procedure was as follows:

- Total U.S. registration of motor vehicles, including motorcycles, in 1920 was 9,471,000 units.
- According to the American Automobile Association (AAA) average usage per vehicle was 6,000 miles per year. (No one knew exactly, and the Bureau of Public Roads' guess was only 4,500 miles per year.)
- At 6,000 miles per vehicle, annual usage in the United States in 1920 was 57 billion vehicle miles.
- The total mileage of rural roads in the United States, according to the BPR inventory of 1914 was 2,478,552 miles.
- According to prevailing opinion, 10 percent of the roads in any State carry 75 percent of the total traffic. Therefore 250,000 miles of roads will carry 43 billion vehicle miles of traffic, or an average of 172,000 vehicles per mile per year. This is a little under 500 vehicles per day.
- From the Maryland traffic censuses of 1917, 1918, 1919, and 1920, Johnson knew that the seasonal daily peak traffic on heavily traveled highways, such as the Baltimore-Washington Road, was about 135 percent of the average annual daily traffic. From the BPR-California Traffic Study of 1922–23, he learned that the maximum hourly traffic was about 130 percent of the average hourly traffic for the day. "It is this high hourly traffic occurring during the months of high average daily traffic for which provision should be made," he said. Applying these factors to the average traffic of 500 vehicles per day, and assuming a 12-hour day, he came up with an average peak discharge of 73 vehicles per hour for the main rural highways in the United States, which was only a small fraction of his estimated capacity for a two-lane road (3).

Johnson conceded that traffic would not be distributed evenly over the 250,000 miles of main highways and that there would be tremendous variations in volume near large cities that would produce peaks many times higher than 73 vehicles per hour. (In fact, traffic between Washington and Baltimore was already more than 400 vehicles per hour at times.) But his principal assumptions were conservative: He used AAA's estimate of annual usage per vehicle instead of the lower BPR estimate; and although most vehicles, then as now, were owned and used in the cities, he distributed their entire annual usage to the *rural* road system. Later events showed that his other principal assumption—that 10 percent of all roads carry 75 percent of all traffic—was also on the high side. The Ohio Transportation Survey of 1925, for example, showed that the State system, with 13 percent of the total mileage, carried 58 percent of the total traffic while in Vermont the same year, 13.5 percent of the roads carried 66 percent of the total traffic.

It is interesting to note that by 1971 vehicle registration had increased 12 times over 1920, and rural highway travel 22 times, yet only 1.4 percent of all rural roads had three or more lanes.

First Aerial Traffic Survey

In 1927 at Johnson's instigation the Maryland State Roads Commission made an aerial photographic survey of the Baltimore-Washington Road, the main purpose of which was to determine the actual spacing of vehicles on a road during periods of heavy traffic flow. The time selected for the flight was the afternoon rush on the Fourth of July. While the photo flight was in progress, ground crews counted traffic at four places along the route at 5-minute intervals. In addition, six "spot cars" were phased into the traffic stream at various points, their drivers instructed to drive with the traffic. The tops of these cars were covered by white cloth so that they could be easily identifed on the photos and each carried an observer who noted the vehicle speed at intervals. These speeds were from 20 to 30 mph—the highest being 33 mph.

Traffic as shown by the hourly counts was remarkably uniform during the photo flight, ranging between 769 and 860 vehicles per hour for the rural sections of the road. But when analyzed by 5-minute intervals, the distribution was quite different. The hourly rate varied from a low of 504 vehicles per hour up to a maximum of 1,284 vehicles per hour. The photos showed that traffic was bunched in queues, some of which were composed of 23 or more cars. When the photos were analyzed by ¼-mile sections, the researchers found that some sections had as many as 20 cars while in others nearby there was only one vehicle or even none at all.

The scale of the photos and the time interval between exposures were known, therefore the investigators could determine the speed and spacing of the vehicles by measuring their positions in the overlap between successive photographs. This kind of analysis showed that the spacing between vehicles varied approximately as the 4/3 power of the velocity, rather than as the square, as Johnson had assumed from his previous studies (fig. 2), and that maximum discharge occurred when traffic was moving at an average speed of 34.5 mph rather than 15 mph (fig. 3) (*4*).

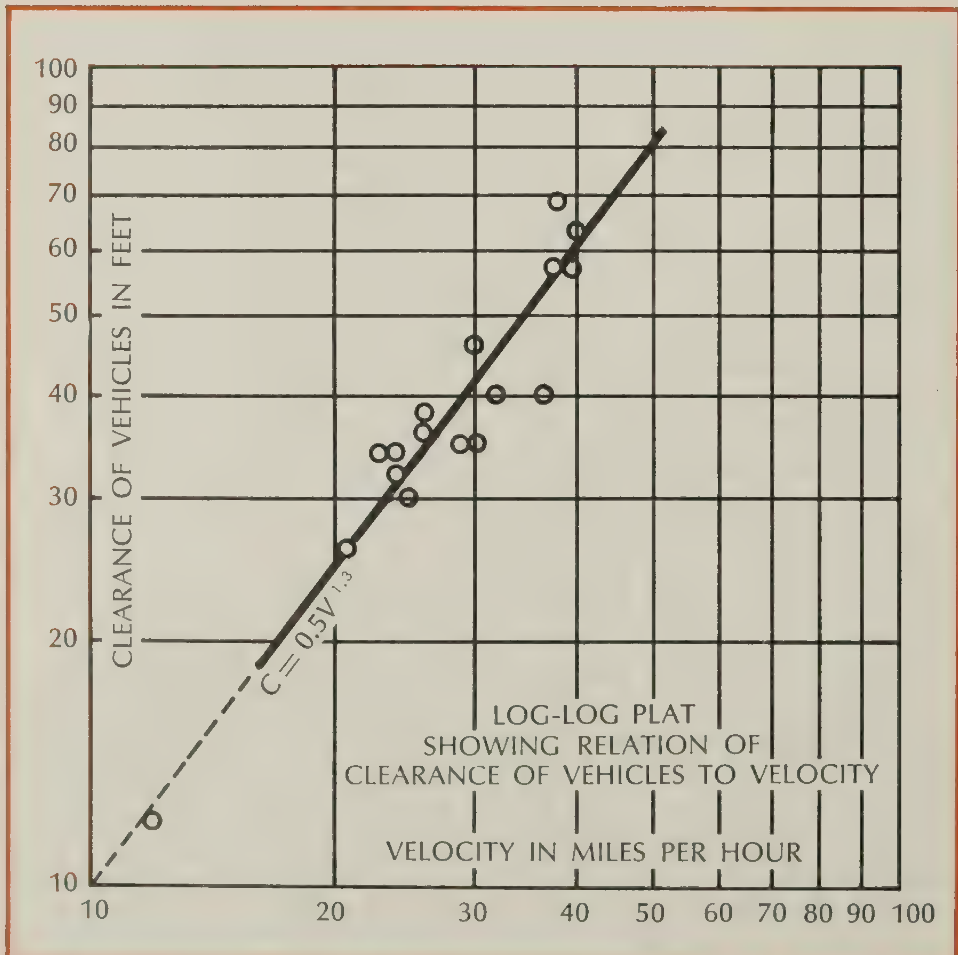


Figure 2.—Spacing of vehicles on Washington-Baltimore Road, July 4, 1927 (4).

The Cleveland Capacity Studies

While A. N. Johnson and the Maryland Roads Commission were engaged in this novel research, the BPR, with State and local cooperation, was making a comprehensive study of traffic in the Cleveland regional area of Ohio. An important part of this project was a traffic capacity analysis of roads of various surface widths from 18 to 40 feet. For this study the researchers devised a *traffic flow recorder*—essentially a box containing a speedometer, an odometer, a clock, and a motion picture camera. The odometer and speedometer were geared to the test vehicle which was operated to float with the traffic while the camera photographed the data on speed, distance, and elapsed time. The test crew consisted of a driver, an observer, and a recorder. The observer could see the instruments through a glass window and whenever the vehicle had to stop or reduce speed, he called out the mileage and time and the apparent cause of the delay and the recorder wrote this information on a form (*5*).

For the traffic analysis, representative sections of highway were selected ranging in width from 18 to 50 feet and in peak traffic from 2,000 to more than 30,000 vehicles per day. At these places traffic counts were made every 15 minutes throughout the day. Once in every 15-minute period the test car with the traffic flow recorder made a run through each section to measure the average speed of the traffic stream. Since traffic varies widely throughout the day on any road, the researchers were able to gather a wide range of 15-minute traffic volumes and their corresponding average speeds. Assuming that "congestion" was invariably reflected by abnormal retardation of the average speed of the traffic stream, they were able to determine for each width of road the traffic volume at which congestion first became apparent. They concluded that under open road conditions at a traffic speed of 25 mph a two-lane, 20-foot-wide highway would carry 10,000 vehicles per day. Under suburban conditions—with a larger volume of local traffic, some marginal parking, and more cross roads—capacity would drop to about 8,000 vehicles per day (*6*).

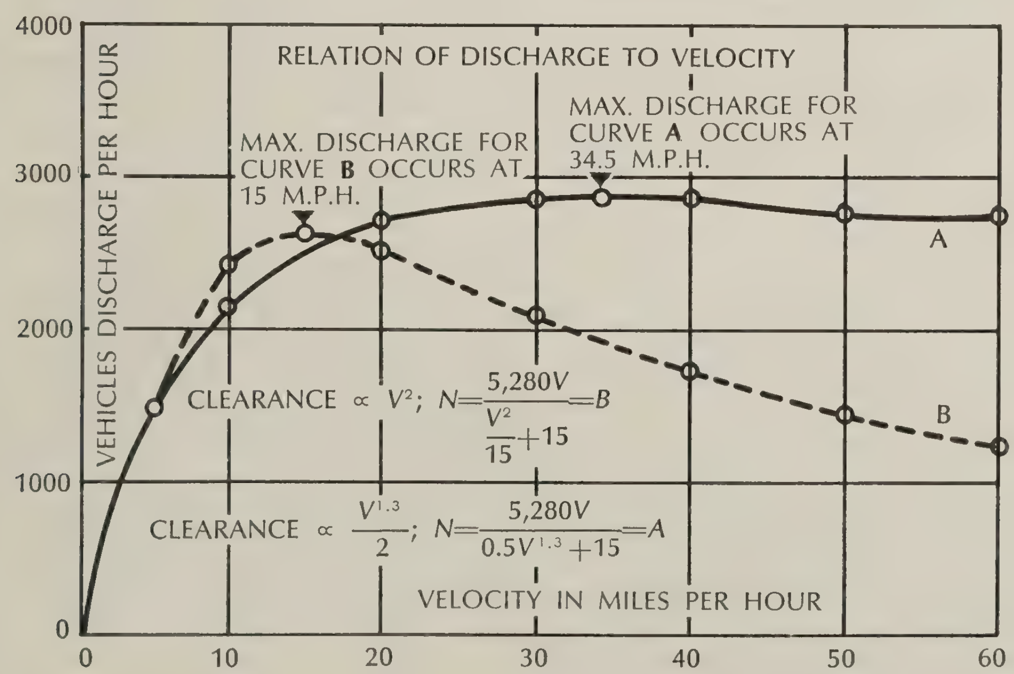


Figure 3.—Hourly vehicle discharge according to two formulas derived by A. N. Johnson (4).

Other Theoretical Studies

While Johnson was working out his discharge formula, others were attacking the capacity problem from slightly different angles. The Pennsylvania Department of Highways determined the spacing between vehicles traveling in a lane at uniform speed according to the time it would take for a following driver to perceive that the car ahead was stopping, then react, apply the brakes, and bring his own vehicle to a stop. This time of course would vary widely according to the driver, the vehicle, and the road, especially the road gradient. At this time, 1927, four-wheel brakes were being introduced and not all cars were equipped with them, so the Pennsylvania researchers assumed that only half of the vehicles in the traffic stream would have four-wheel brakes. They assumed a perception-reaction-braking time for the following driver varying from ½ second if his speed were 10 mph to 1½ seconds for 30 mph. Under these conditions, they calculated the *maximum carrying capacity* of one lane of a two-lane road on level grade to be 2,264 vehicles per hour at an average speed of 15 mph, decreasing to 1,970 vehicles at 25 mph and 1,456 vehicles at 40 mph (*7*).

However, such theoretical capacities are never encountered in practice because of the presence of slow-moving vehicles in the traffic stream and an insufficient number of gaps of suitable length in the opposing lane to permit free passing. The Pennsylvania investigators therefore concluded that the capacity of a two-lane road was "very approximately equivalent to the capacity of a single lane with traffic moving uniformly at the rate of speed of the majority of traffic units of the two-lane road being measured" (*7*). This rule indicated a capacity of 1,970 vehicles per hour in both directions for a two-lane highway at 25 mph average speed, which was almost double the BPR's figure based on the Cleveland research.

N. W. Dougherty of the University of Tennessee used practically the same approach as the Pennsylvania researchers. He assumed a perception-reaction time of ½ second for all speeds and a braking distance to bring the following vehicle to a stop of $S = 0.0556V^2$, where V is the velocity in feet per second (*8*).

Sigvald Johannesson's studies in New Jersey showed that following drivers tend to preserve a certain time interval between themselves and the vehicle ahead which he found to be 1½ seconds. The distance between vehicles on the road would approach a fixed distance of 5 feet plus the distance the vehicles would travel in 1½ seconds at the prevailing road speed (*8*).

Moving Picture Camera Analysis

In 1930 Bruce Greenshields of the University of Michigan studied vehicle spacing by photographing the traffic stream from the side with a motion picture camera. The camera was placed at right angles to the road and 300 feet away, which gave a field wide enough that the photographed vehicles would appear in two successive frames. Knowing the time interval between exposures and the scale of the image, Greenshields could calculate the speed and acceleration of the vehicles and the interval between them. He found that on heavily traveled roads where traffic tends to bunch up, the speed of the vehicles in the queue is controlled by the leading vehicle, a fairly obvious conclusion. When creeping along at crawl speed, the spacing center to center of vehicles was 15 to 30 feet. At higher speeds the spacing followed the straight-line equation:

$$S = 21 + 1.1V$$

where S was the spacing center to to center in feet, and V the average speed in miles per hour (*8*).

Table 1 shows the theoretical capacity of a single lane of traffic of a two-lane road as calculated from these various formulas. These formulas had the common fault of assuming uniform flow of traffic—something that does not occur in real life. Also, they did not take into account the constantly varying speeds of vehicles and the passing opportunities or lack of opportunities afforded by opposing traffic. In the end, the authors were thrown back on unverifiable assumptions to arrive at reasonable figures for the total discharge *in both directions* of a two-lane highway

Table 1.—Theoretical carrying capacity of a single lane of a two-way, two-lane road (vehicles per hour)

	Average speed of the traffic stream		
According to:	*15 mph*	*25 mph*	*40 mph*
Johnson (1921) (*3*)	2,640	2,330	1,740
Johnson (1927) (From aerial photo studies) (*4*)	2,490	2,780	2,800
Pennsylvania Division of Highways (1927) (*7*)	2,264	1,970	1,456
Dougherty (about 1929) (*8*)	2,040	1,950	1,585
Johannesson (about 1930) (*8*)	1,365	1,650	1,875
Greenshields (1932) (*8*)	2,110	2,720	3,250
Bureau of Public Roads (1934–37) (*12*)	1,500	2,000	1,990

(such as the Pennsylvania assumption that total two-way traffic would be about the same as that of one lane flowing freely).

Cooperative Study of 1930–31

In 1930 the BPR, the Maryland State Roads Commission, and the University of Maryland launched a cooperative study of the capacity of two-, three-, and four-lane highways, with A. N. Johnson in charge. At the very outset of the study the researchers realized that they would have to define traffic capacity before they could measure it. They finally agreed that the *working capacity* or *free-moving capacity* would mean the point at which congestion first becomes apparent:

> When a road carries only a few vehicles all will move freely and there can be no question of congestion. As the number of vehicles increases there will be reached a point at which some will be delayed because they can not immediately pass slower vehicles ahead of them. This delay indicates congestion.
>
> Beyond the free-moving capacity of a highway the number of vehicles passing in a given time may still increase, but traffic will move with more and more restrictions. The individual driver will have less and less freedom of action, being compelled to follow the vehicles directly ahead of him. The number of vehicles may increase until the rate of flow is at a maximum, when the ultimate capacity of the highway may be said to have been reached. Any attempt to put still more vehicles through will result in serious interference with the movement of traffic, and the number of vehicles passing a given point in a given time will actually decrease because of overcrowding (9).

The field work for the study was done by two teams of two observers each who roamed the highways from Washington to Boston looking for spots where traffic was heavy during rush hours. During the summers of 1930 and 1931 the observers counted traffic at 71 such spots in 7 eastern seaboard States. They were instructed to record the number of vehicles in each 5-minute interval in each direction for each lane. Automobiles, trucks, and buses were recorded separately. Congestion was considered to occur when the number of vehicles became great enough to fill the road and make turning out of line to pass impracticable: "When congestion occurs, reduction of speed will be noticed, along with the tendency for drivers to crowd one another" (9). Congestion was to be recorded only if it prevailed at least 1 minute in each 5-minute interval.

The observers had some difficulty finding four-lane highways that were congested by this definition, but no difficulty finding congested two-lane and three-lane roads. At all stations the heaviest traffic came between 3 p.m. and 7 p.m.

For purpose of analysis, the observations were first grouped according to whether they were on two-, three-, or four-lane highways. Within each of these groups the 5-minute counts were placed in four subgroups according to the directional distribution of traffic, ranging from 50 percent–50 percent (equal split) to 20 percent–80 percent. This gave 12 subgroups into which all the 5-minute counts for all the observation stations were divided. Within each of these four subgroups the individual 5-minute counts were plotted as vertical bars according to the number of vehicles counted, producing an array such as that shown in figure 4. The minutes of congestion observed in each 5-minute interval were then plotted cumulatively as in the lower graph of figure 4. The first sharp break in this cumulative congestion curve was interpreted to be the point at which working capacity was reached, and the corresponding 5-minute discharge rate was then taken as the working capacity of the road for that particular directional split. Since the maximum 5-minute discharge for any highway is seldom sustained for an entire hour, they reduced the former somewhat to arrive at the *practical hourly capacities* shown in table 2. Thus, without considering the relative safety of the three types of road the investigators concluded that the addition of one lane to a two-lane road doubles its capacity, while addition of two lanes triples the capacity.

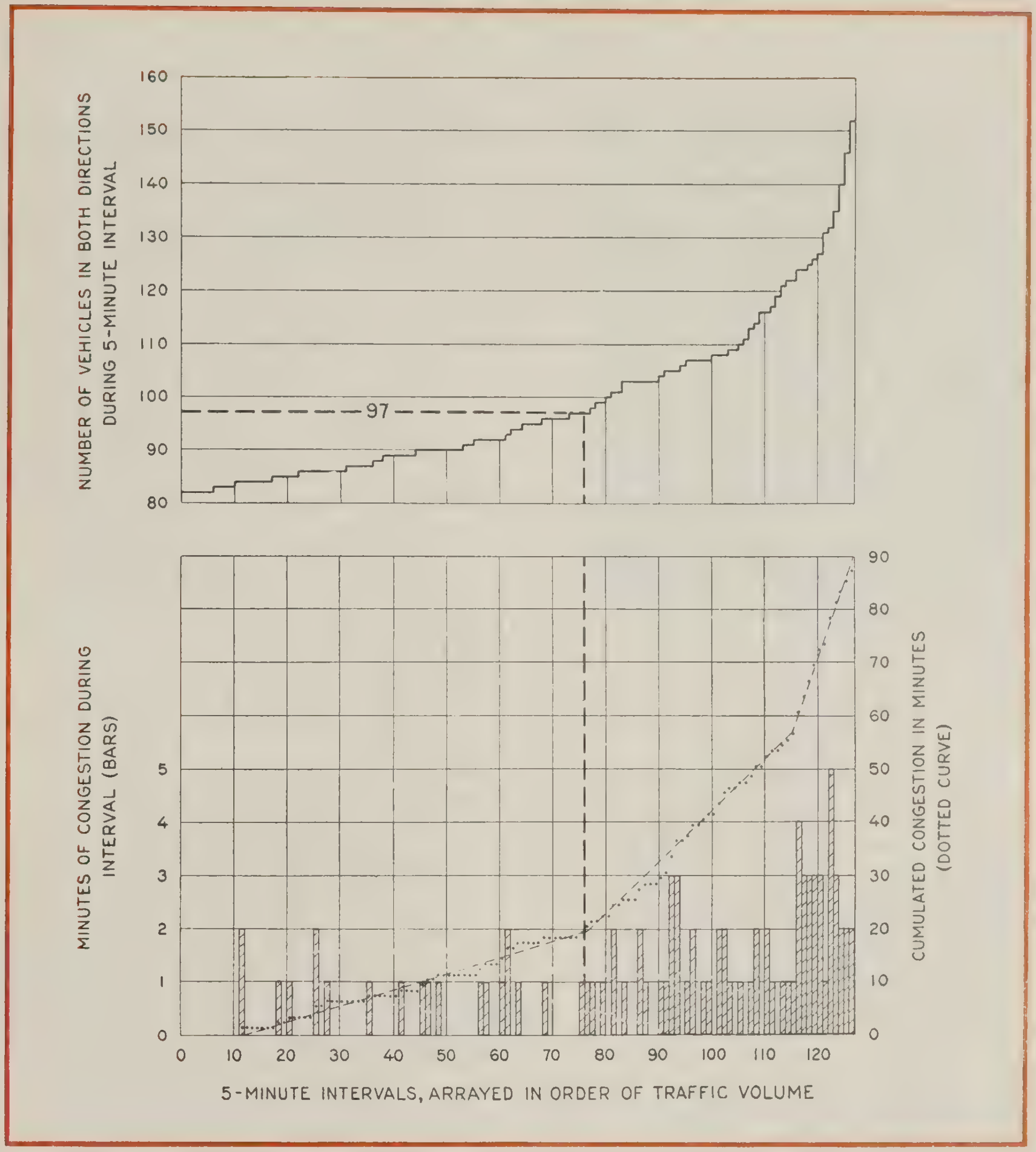


Figure 4.—Determination of traffic capacity of two-lane roads, 60 percent of traffic in one direction (9).

Table 2.—Working capacity of two-, three-, and four-lane highways

No. of lanes	Vehicles per 5-minute interval					Practical capacity in both directions
	Percentage of traffic in one direction					
	50	*60*	*70*	*80*	*Average*	*Vehicles per hour*
Two	90	97	90	105	97	1,000
Three	185	165	195	175	180	2,000
Four	[1] 300	[1] 300	290	270	290	3,000

[1] Estimated, because actual *congested* four-lane highways could not be found for these conditions.

The Ohio Study of 1934

In 1934 the Ohio State Highway Department undertook to measure the *working capacity* of a two-lane highway, using Greenshields' photographic method. In all, the investigators studied 1,180 groups of 100 vehicles each, on both "congested" and "uncongested" highways. "Congestion" was assumed to exist when the average speed of all vehicles was observed to decrease below the "free running speed," this latter being the speed of the traffic stream when conditions are such that drivers can overtake and pass slower drivers at will.

When they tabulated the results, the researchers found that the average free running speed of 434 groups on uncongested two-lane highways was 43.6 mph, and that the corresponding average hourly volume [3] of the traffic was 469 vehicles per hour, of which 5.3 percent were trucks.

For congested roads, the average speed declined as the density in vehicles per mile increased (fig. 5). The investigators found that the slope, *m,* of the speed/density curve was related to the number of slow-moving vehicles in the traffic stream, ranging from 0.232 for 1 to 5 percent trucks, to 0.272 for 2 to 12 percent trucks. When they expressed the traffic in vehicles per hour rather than vehicles per mile of pavement, the speed/volume curve assumed the shape of figure 6 which shows that for a given traffic volume there can be two speeds up to the point where maximum volume is reached (*10*).

By 1934, after wrestling with it for over a decade, highway engineers had lost all illusions that a simple solution could be found for the capacity problem. Enough information had been gathered by then to convince even the most skeptical that capacity was the result of a mix of climatological, dynamic, mechanical, and psychological factors so complex

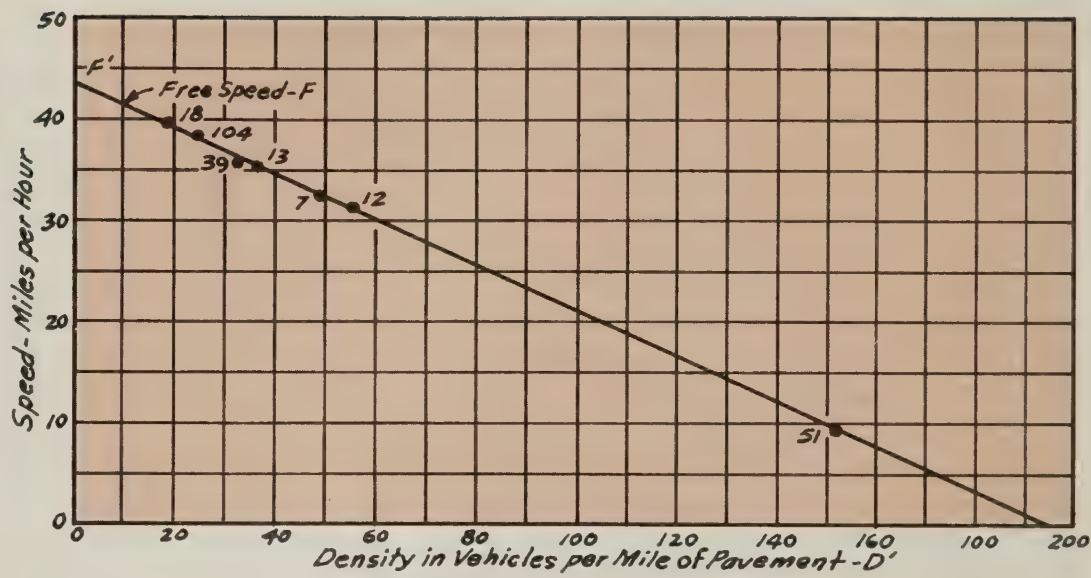


Figure 5.—Speed in miles per hour corresponding to a given average density in vehicles per mile of pavement (10).

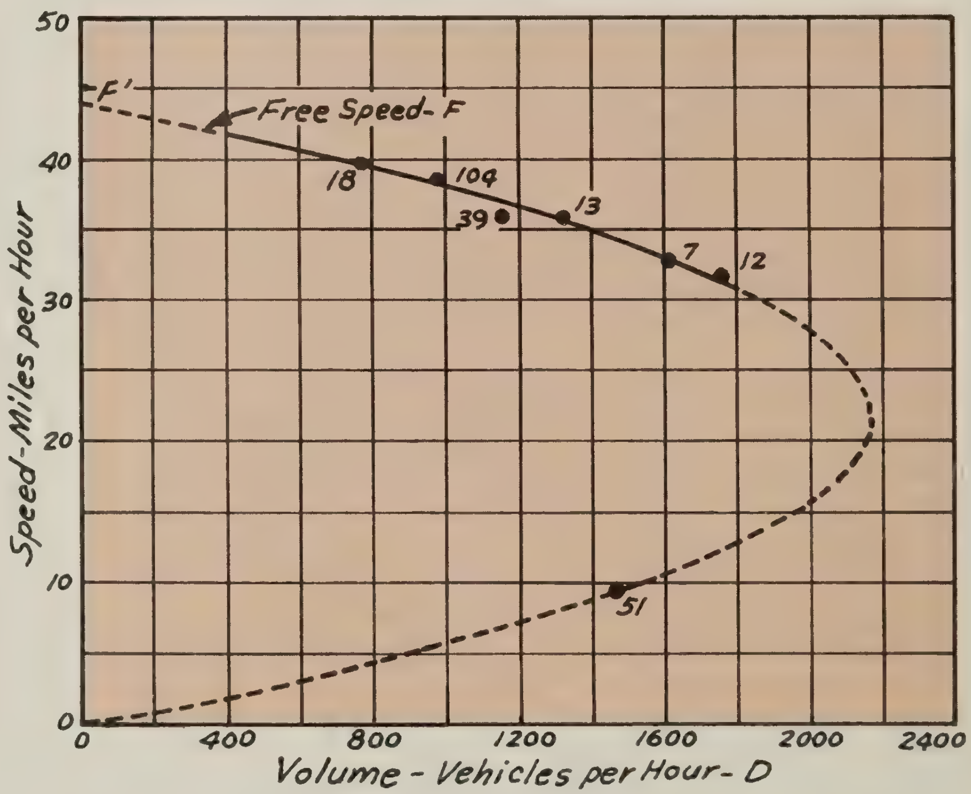


Figure 6.—Speed in miles per hour corresponding to a given volume in vehicles per hour on a two-lane highway (10).

[3] In the early days of traffic studies the terms *density* and *volume* were used interchangeably. *Volume* is now defined as the number of vehicles passing a given point on the highway in a given period of time; while *density* is the number of vehicles occupying the moving lanes of a highway at a given instant, usually expressed in vehicles per mile. In the discussions herein, appropriate changes have been made to convert to the modern usage.

as to defy exact measurement. Nevertheless, the constantly increasing number of motor vehicles made it imperative that some practical solution be found. What was needed, according to E. H. Holmes of the BPR, was a "concerted, intelligently directed effort to determine the effectiveness of the highway in performing one of its most important functions, that of permitting the safe and expeditious movement of traffic" (*11*). This, he stated, was "a problem of dynamics in which it is necessary not only to study the movement of the individual units of the traffic stream, but also to determine how the movement of these units is affected by the external forces within and without the stream itself." Furthermore, according to Holmes, there was an urgent need to coordinate geometric design with traffic requirements. "There is no justification for building, for example, a three-lane road, perfectly designed as to economy of construction, if its alinement is such that traffic must be restricted to two lanes on frequently recurring hillcrests or curves. In providing opportunity for passing only where the topography is especially suitable, the road does not fulfill the demands of the traffic which justified it" (*11*).

Coordinated Effort to Solve the Capacity Problem

The necessary coordinated effort got underway in 1934 under the leadership of the Bureau of Public Roads. This effort was pushed in several directions simultaneously:

- Development of improved methods for counting and forecasting traffic.
- Lateral placement studies to determine how traffic actually utilizes the roadbed and how it is affected by shoulders and nearby obstacles.
- Passing studies to determine the distances required for overtaking and passing.
- Speed studies of individual vehicles and groups of vehicles.
- Studies of the spacing of vehicles in a traffic stream and how they interact with each other.
- Studies of the hill-climbing abilities of motor vehicles, particularly trucks.
- Development of improved instruments for counting vehicles and measuring their speed and position on the highway.
- Development of methods for analyzing and interpreting huge volumes of factual data gathered in the field.

The first four of these fields of research have been reviewed in Parts 1, 2, and 3, and the preliminary work done by various investigators on the spacing of vehicles in traffic has been covered briefly in the preceding paragraphs. Now let us examine the studies of the spacing and interaction of vehicles in a traffic stream in greater detail.

In 1934 the BPR, after reviewing the various studies of volume versus speed and spacing, concluded that theoretical studies would never yield reliable results, and that the field studies previously made were "too limited or lacking in essential data, such as the speeds at which the individual vehicles were traveling, to yield accurate and conclusive results" (*12*). The Bureau engineers decided that a large quantity of detailed data on many roads in different parts of the country would have to be gathered before reliable indexes of capacity could be formulated. One of those assigned to this massive data collection program was a young highway economist, Olav K. Normann, who in the next 15 years was to play a major part in the solution of the capacity problem.

Data collection began the summer of 1934 with capacity studies on the most heavily traveled highways in New York and New England. The study stations were situated at substantially level tangent locations where there was adequate sight distance for passing. At each station the investigators laid out a course 1/5-mile long. Observers at each end of the section noted the license number of each vehicle as it entered and left the test section and recorded the time by closing a circuit with a telegraph key. This in turn caused a pen to mark a strip chart driven by clockwork at a fixed speed in an automatic graphic recorder. Two observers were required at each end of the test section for each direction of traffic, or a total of eight. One observer in each pair read the license number aloud and simultaneously recorded the time of passage with the telegraph key, while the other wrote the last three digits of the license number on a data sheet. To correlate the time recording on the strip chart with the license record on the data sheet every 10th, 50th, and 100th vehicle was checked on the data sheet and also distinguished by a special telegraph manipulation on the strip chart. With a little practice two observers could record as many as 800 vehicles per hour "with little difficulty" (*13*).

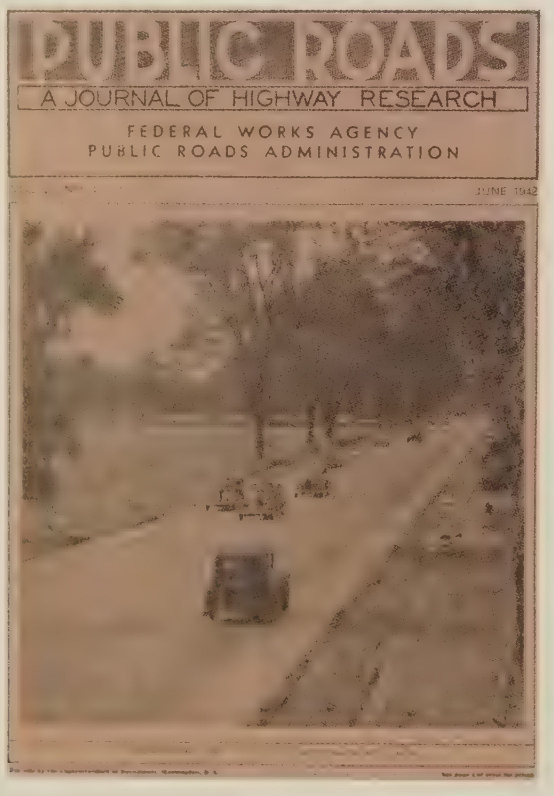
The studies were conducted for 8 daylight hours per day starting while traffic was light and continuing through the heaviest volumes, giving a range of volumes for each station. The BPR observations were carried through the summers of 1934 and 1935 in New York and New England, and in Illinois in cooperation with the Illinois Division of Highways during the summer of 1937. In all, data were assembled on over 300,000 vehicles traveling on two-, three-, and four-lane highways (*12*).

From the basic data recorded during these studies it was possible to obtain the speed of each vehicle, its time or distance spacing with respect to other vehicles in the traffic stream, and the exact volume of traffic in each direction during any desired time period. However, the reduction of this mass of data was a tedious process, even with the aid of card tabulating machines, so it was not until 1939 that preliminary conclusions became available. One of the first discoveries was that, contrary to some published discussions, the average vehicle speed of the traffic stream is not by itself a reliable measure of working capacity. Much more meaningful as an index of relative interference between vehicles was the average difference in speed between successive vehicles (*12*).

Measure of Capacity

On a rural highway, when traffic is light and the speed of each individual vehicle is not governed by the speed of the vehicle immediately ahead, fast drivers can pass slow ones almost at will, and there are large differences in speed between successive vehicles. As the volume increases, passing opportunities become scarcer and the speed of individual vehicles is governed more and more by the speed of preceding vehicles. Thus, their time spacing tends to become more and more uniform. This is shown graphically in figure 7. Curve B indicates that when the average time spacing between successive vehicles is 9 seconds or more, there is little interference between vehicles and the faster drivers tend to travel 6 to 7 mph faster than those they are overtaking. This is true at all speeds from 10 to 40 mph. At spacings below 9 seconds the faster drivers are more and more influenced by preceding vehicles until at a time difference of 1½ seconds there is an average speed difference of only 2 mph.

The researchers then analyzed the spacings between vehicles that were traveling at the same speed as preceding vehicles and not being passed by others behind them—in



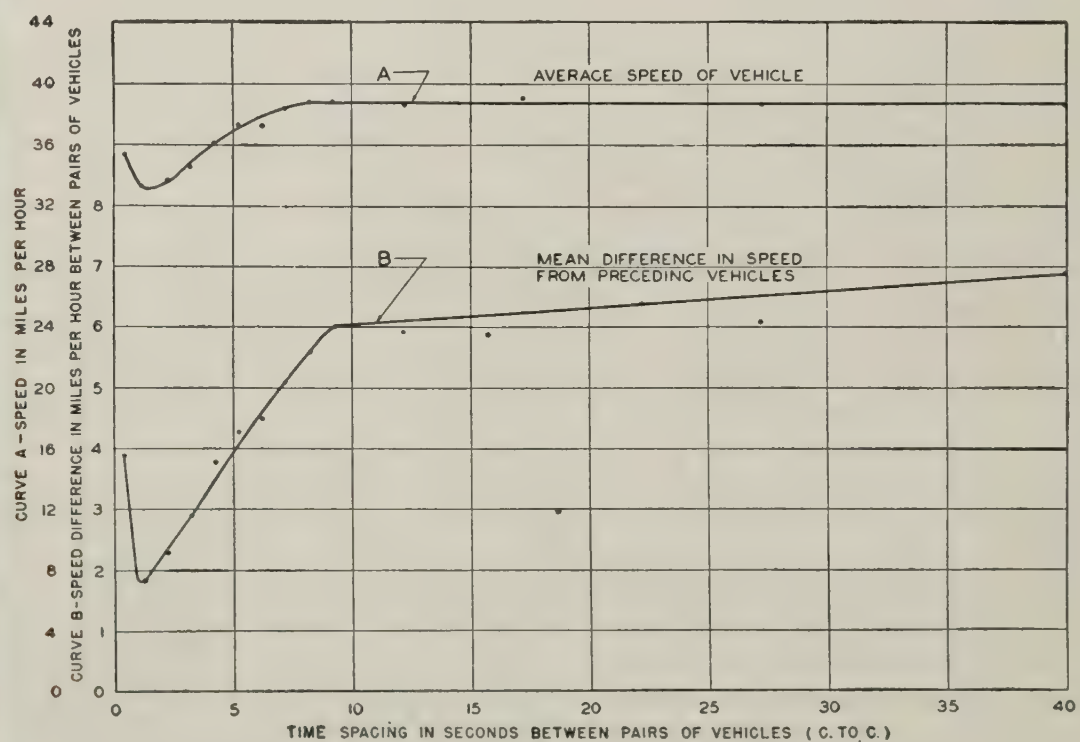


Figure 7.—Speed characteristics of vehicles traveling at given time spacings behind preceding vehicles (16).

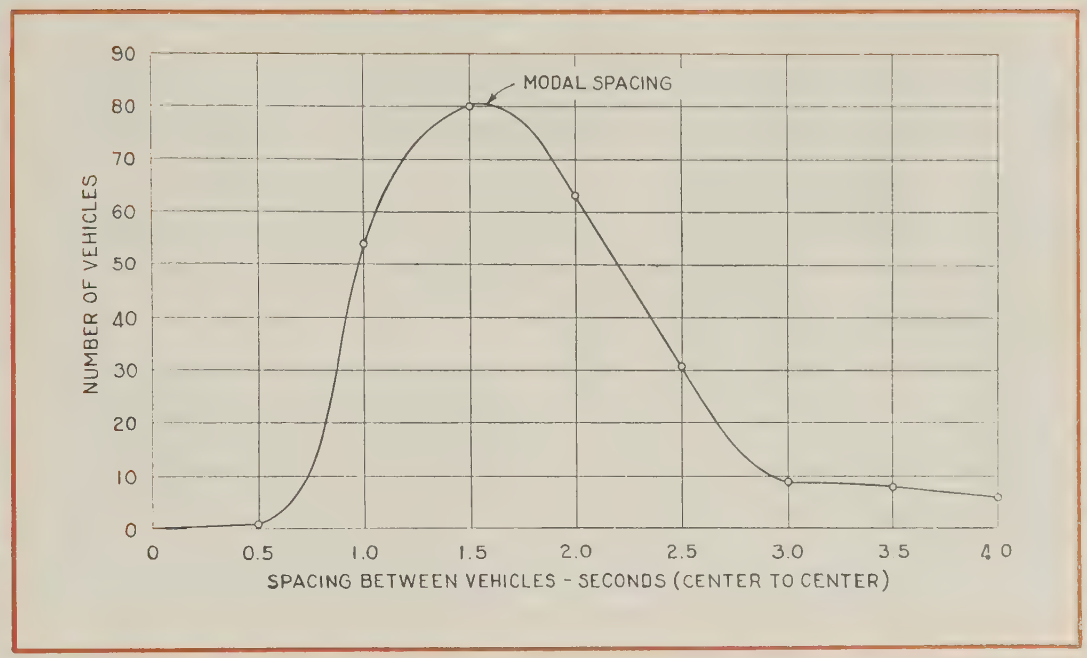


Figure 8.—Frequency distribution of spacings between vehicles traveling 31 mph preceded by vehicles traveling at the same speed on a two-lane tangent (12).

other words, vehicles whose drivers were content with their relative positions in the traffic stream. This analysis is shown graphically in figure 8. In all cases, the *modal spacing* preferred by the largest group was very close to 1½ seconds, and also less than the average spacing of all vehicles. Furthermore, the modal spacing of 1½ seconds was remarkably uniform at all speeds from 20 to 50 mph (fig. 9).

It is interesting to note that this interval of 1½ seconds between succeeding vehicles traveling at the same speed is exactly the interval proposed by Johannesson in the late 1920's.

Using their field-derived modal spacings in the classic capacity formula, the BPR engineers found the theoretical capacity of one lane of a two-lane highway to be about 2,400 vehicles per hour at 33 mph. However, they also realized that this figure had little practical value because it could be a true value only for the ideal condition where all vehicles were traveling freely at the same speed in one direction and there was no opposing traffic. Actually, of course, there would surely be opposing traffic in real life and its amount would have a direct effect on the capacity of the other lane by limiting passing opportunities.

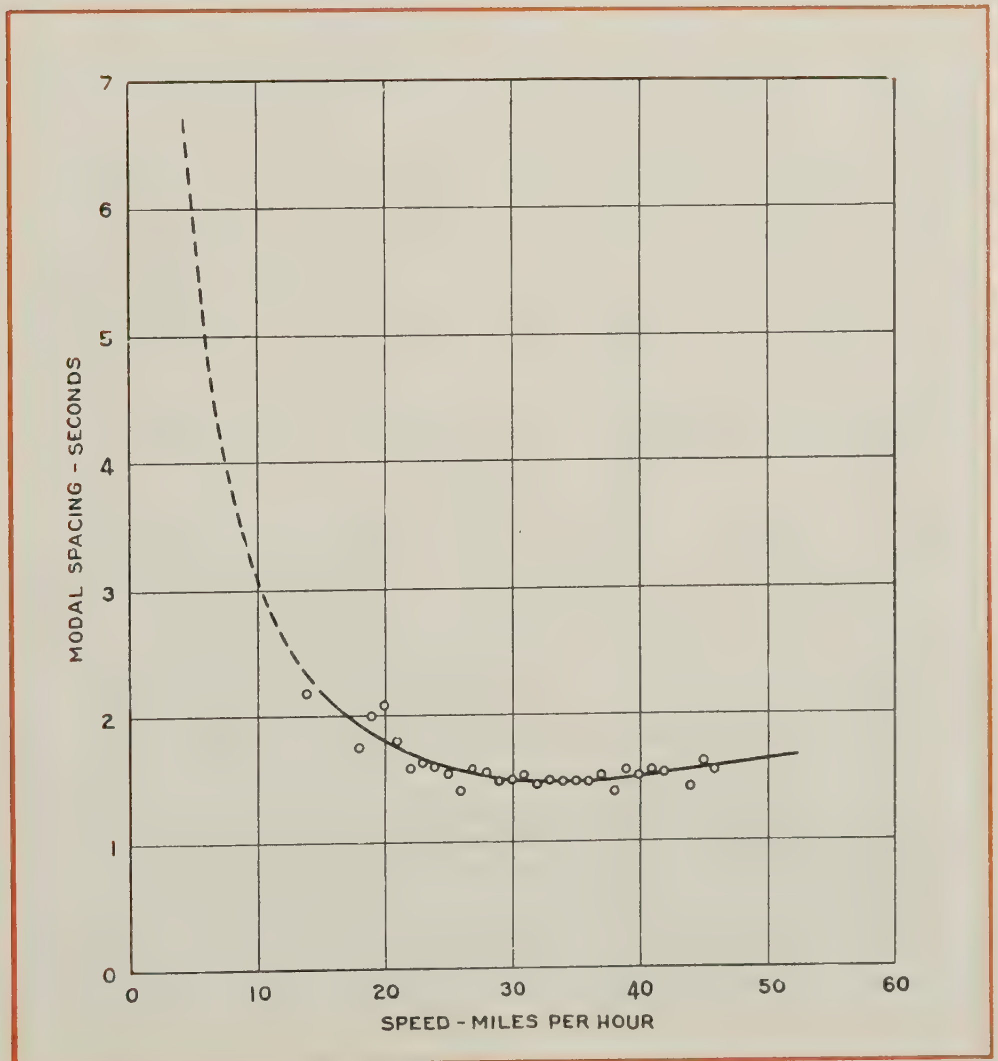


Figure 9.—Modal spacing in seconds between vehicles traveling at the same speed on a two-lane tangent (12).

Analysis of Data

The researchers then plotted mean differences in the speed of groups of vehicles against observed hourly volumes in one direction. This resulted in a seemingly hopeless scatter (fig. 10) but by applying multiple correlation to the data—using the mean difference in speed as the dependent variable and the volume of traffic in one direction together with the volume in the other direction as the two independent variables—they were able to resolve the scatter into a series of straight-line curves such as figure 11.

Figure 11 shows that when there is no opposing traffic and all vehicles are traveling at the same speed, a single lane of a two-lane road will carry 1,980 vehicles per hour. As opposing traffic builds up, this figure diminishes until with evenly balanced traffic it becomes 1,100 vehicles per hour in each lane.

By substituting speed in one direction for mean difference in speed, the analysts were able to construct figure 12. In this figure the dashed line indicates the volumes at which all vehicles will have to travel at the same speed; for values below this line one slow-moving vehicle can hold up all following vehicles, so working capacity values must always be above this line.

Curves such as those in figures 11 and 12 were constructed for three-lane and four-lane divided and undivided highways. The maximum hourly observed volumes *in both directions* when traffic was equally balanced are shown in figure 13 for seven typical locations. These curves show rather wide differences in capacity for apparently similar roads. For example one of the four-lane, undivided highways had a maximum

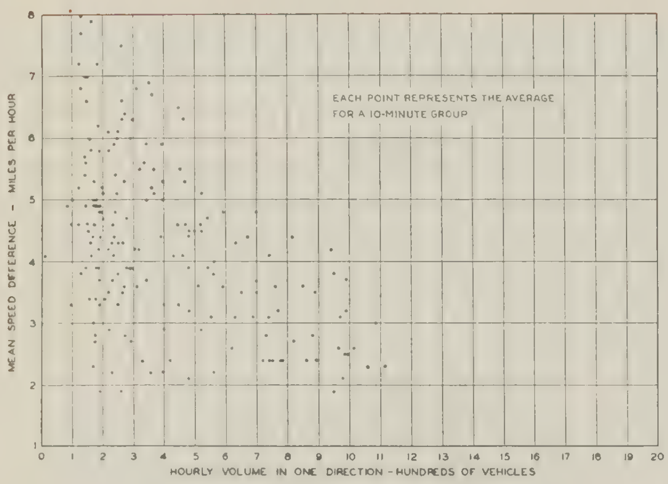


Figure 10.—Mean difference in speed on a two-lane tangent between successive vehicles for various volumes of traffic (12).

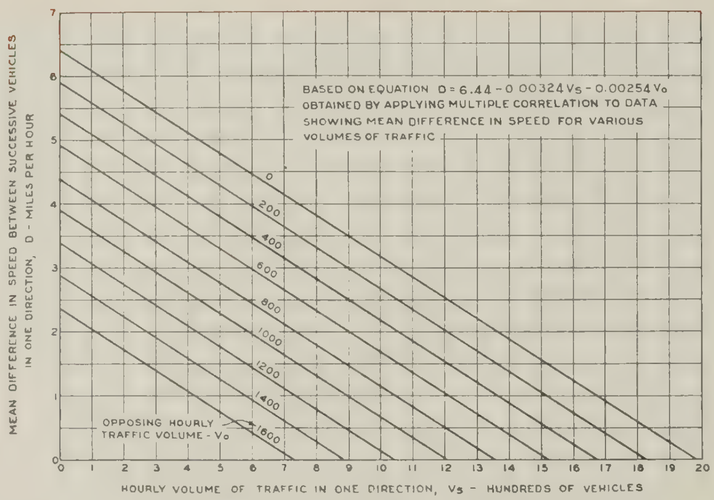


Figure 11.—Mean difference in speed on a two-lane tangent between successive vehicles with various volumes of traffic (12).

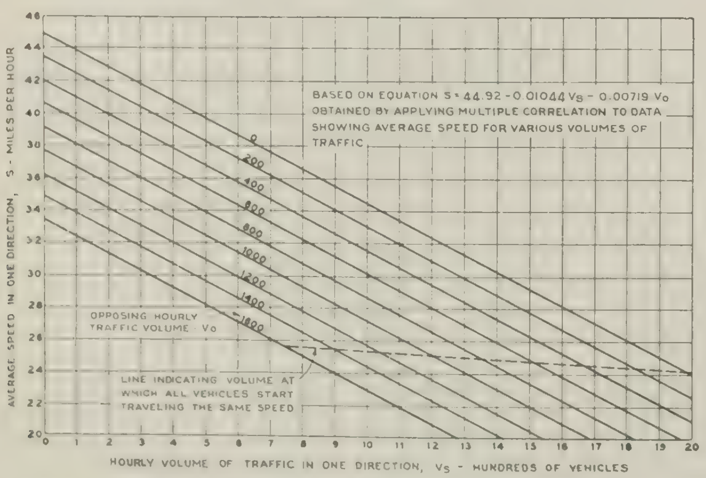


Figure 12.—Average speed with various volumes of traffic on a two-lane tangent (12).

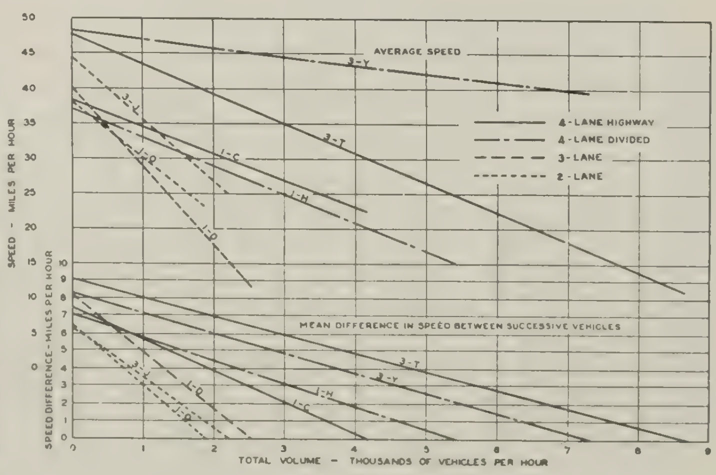


Figure 13.—Speed and mean difference in speed for level tangents with various total volumes equally distributed between the two directions (12).

capacity of 4,150 vehicles per hour at a speed of 22 mph, while the other peaked at 8,600 vehicles per hour at a speed of 11 mph.

The studies described above were intentionally limited to level tangent sections. In their conclusions the BPR engineers stressed the need for additional observations at other locations where the alinement was curved or on grades, and especially the need for greatly expanded knowledge of passing practices. As a final conclusion they stated:

> Although there is a wide variation in the driving characteristics of individual vehicle operators, certain fundamental principles of traffic behavior can be developed that will be generally applicable. The results may be entirely different from those derived by assuming average conditions (*12*).

Capacity Defined

One of the problems faced by the early traffic researchers was to define the term *capacity*. The earliest estimates of capacity, for example A. N. Johnson's, were theoretical capacities based on assumed vehicle spacings and uniform flow. Later *theoretical capacities,* such as those derived by O. K. Normann from the early BPR capacity studies of 1934–37, assumed uniform flow but used empirical *modal spacings* derived from a large number of field observations.

Normann coined the term *maximum hourly capacity* for the hourly discharge that occurs just before all vehicles lose their freedom to pass and have to start traveling at the same speed as the preceding vehicle. This later became known as the *possible capacity*.

Practical working capacity was defined by Normann in 1942 as the hourly discharge when the density of traffic is not so great as to unreasonably restrict passing opportunities. This, he added, was a relative rather than an absolute value, and might vary depending on the local conditions (*14*).

The development of the speedmeter and the pneumatic tube traffic counter by the BPR, as described in Parts 2 and 3, gave a tremendous boost to the investigations of highway capacity. The original studies of 1934–37 were extended to Massachusetts, Illinois, and California in 1938, and studies of capacity on grades and curves were included in the program. The data gathered in these studies of 1938–39 substantially confirmed the earlier preliminary findings. Among these were the following (*14*):

- The maximum theoretical capacity of a single traffic lane is about 2,000 vehicles per hour and occurs at speeds slightly above 30 mph. It can be attained only on four-lane roads, or for short periods, on short sections of two-lane roads.
- The possible capacity of a long section of two-lane highway with good alinement and carrying few trucks is about 2,000 vehicles total in both directions. Three-lane, two-directional highways under similar conditions will carry 2,600 vehicles per hour in both directions; and four-lane highways, 8,000 vehicles per hour in both directions.
- Under normal conditions, the maximum practical working capacities (totals in both directions) are 800 vehicles per hour for two-lane highways; 1,400 vehicles per hour for three-lane highways; and 2,800 vehicles per hour for four-lane highways.

HRB Organizes Committee on Highway Capacity

During World War II traffic research was largely suspended while the highway organizations and their engineers devoted themselves to other activities. However, the work already done on capacity studies was of such magnitude that, in 1944, the Highway Research Board (HRB) organized a Committee on Highway Capacity to coordinate the work in this field. For chairman of this committee the obvious choice was O. K. Normann of the BPR who, since 1934, had been in the forefront of the nationwide studies. "Over the years he organized and participated in a wide range of research studies of what he recognized as a dynamic system involving vehicle, road, and driver. Using the traffic stream as a laboratory, he imaginatively created apparatus and analytical methods to collect and reduce vast quantities of data to findings that greatly increased our scientific knowledge and understanding of traffic movement" (*15*).

With the conclusion of the war, traffic research was resumed, particularly research on the influence of lane width, grades, and curvature on rural highway capacities and on the capacities of freeways, ramps, weaving facilities, and urban streets and intersections. By 1949, an enormous volume of factual material had accumulated. The Committee on Highway Capacity and the Bureau of Public Roads undertook to reduce this mass of material to a form that would be usable by highway designers and traffic engineers. The result of this monumental labor originally appeared in *Public Roads* magazine, and was later reprinted by the BPR as the justly famous Highway

Wilshire Boulevard and Holmby Avenue, Los Angeles, Calif. —courtesy, California Division of Highways

Capacity Manual of 1950 (*16*). For 15 years, this manual was the faithful friend of highway engineers in the United States—a practical guide which had impressive influence on the planning of all subsequent highways, including the far-flung Interstate System.

Highway traffic research did not stop with the publication of the 1950 Highway Capacity Manual. Indeed, the pace quickened, and the need for updated information was soon evident. However, most of the underlying principles of traffic and driver behavior had been worked out by 1950, completing one of the longest-sustained research endeavors of history.

REFERENCES

(*1*) Andrew P. Anderson, "9,231,941 Motor Cars and Trucks Registered by the States in 1920," *Public Roads,* vol. 3, No. 36, April 1921, p. 21.

(*2*) A. N. Johnson, "The Traffic Census," *Public Roads,* vol. 3, No. 32, December 1920, p. 16.

(*3*) A. N. Johnson, "The Traffic Census and Its Use in Deciding Road Width," *Public Roads,* vol. 4, No. 3, July 1921, pp. 7, 23.

(*4*) A. N. Johnson, "Maryland Aerial Survey of Highway Traffic Between Baltimore and Washington," Proceedings of the 1928 Meeting, *Highway Research Board,* Washington, D.C., 1929, pp. 113, 114, 115.

(*5*) J. G. McKay, "New Traffic Flow Recorder in Use on Cleveland Traffic Survey," Proceedings of the Seventh Annual Meeting, *Highway Research Board,* Washington, D.C., 1928, p. 247.

(*6*) "A Study of Highway Traffic in the Cleveland Regional Area," *Public Roads,* vol. 9, No. 7, September 1928, p. 134.

(*7*) G. E. Hamlin, "Report of Committee on Highway Traffic Analysis," Proceedings of the Seventh Annual Meeting, *Highway Research Board,* Washington, D.C., 1928, pp. 233, 234.

(*8*) Bruce D. Greenshields, "The Photographic Method of Studying Traffic Behavior," Proceedings of the 13th Annual Meeting, *Highway Research Board,* Washington, D.C., 1934, pp. 388–390.

(*9*) A. N. Johnson, "Highway Traffic Capacity," *Public Roads,* vol. 13, No. 3, May 1932, pp. 41, 43.

(*10*) Bruce D. Greenshields, "A Study of Traffic Capacity," Proceedings of the 14th Annual Meeting, *Highway Research Board,* Washington, D.C., 1934, pp. 468, 470.

(*11*) E. H. Holmes, "Procedure Employed in Analyzing Passing Practices of Motor Vehicles," *Public Roads,* vol. 19, No. 11, January 1939, p. 209.

(*12*) O. K. Normann, "Preliminary Results of Highway Capacity Studies," *Public Roads,* vol. 19, No. 12, February 1939, pp. 225–240.

(*13*) E. H. Holmes and Lawrence S. Tuttle, "An Improved Method of Measuring Speed of Traffic," *Public Roads,* vol. 14, No. 12, February 1934, p. 243.

(*14*) O. K. Normann, "Results of Highway Capacity Studies," *Public Roads,* vol. 23, No. 4, June 1942, pp. 57–81.

(*15*) "O. K. Normann—A Tribute," Highway Capacity Manual—Special Report No. 87, *Highway Research Board,* Washington, D.C., 1965, p. vii.

(*16*) O. K. Normann and W. P. Walker, "Highway Capacity: Practical Applications of Research," *Public Roads,* vol. 25, No. 10, October 1949, and No. 11, December 1949. This report of the Highway Research Board Committee on Highway Capacity was later republished by the U.S. Department of Commerce under the title, "Highway Capacity Manual—Practical Applications of Research," *U.S. Government Printing Office,* Washington, D.C., 1950.

Third Annual FCP Conference Held in Minneapolis

by Susan E. Bergsman

The Federal Highway Administration's third annual Federally Coordinated Program of Research and Development in Highway Transportation (FCP) conference was held in Minneapolis, Minn., the week of September 15. The conference, hosted by FHWA's Region 5 and the Minnesota Division Office, brought together more than 400 participants from all over the country.

These meetings, first begun in 1973, have had a twofold purpose; to give reality to the concept of the FCP project team by providing open discussion on individual projects, and to encourage the participation of State highway department operating offices and FHWA field and headquarters offices in testing the research approach against the independent judgment of the intended customers for the output.

G. D. Love, Associate Administrator for Research and Development, welcomes conference participants.

This year, as a result of the growth of the FCP and successful implementation of project results, the objectives of the meeting were expanded in two directions: (1) to develop a better appreciation of current implementation efforts and obtain guidance for acceleration and expansion of these efforts, and (2) to receive valuable feedback from the research community and those responsible for design and operation of highways on the priorities and opportunities for new FCP projects. At this year's conference, in-depth reviews were given for 16 projects.

W. C. Merritt, Deputy Commissioner and Chief Engineer, Minnesota Department of Highways, at the opening session.

The 5-day conference attracted researchers from State highway departments and all the FHWA regional offices. Also attending were representatives from universities,

Don Trull speaks to conferees at the general review session.

other government agencies, and various private contractors.

Monday afternoon a general review of the FCP was conducted. After welcomes by G. D. Love, Associate Administrator for Research and Development; W. C. Merritt, Deputy Commissioner and Chief Engineer, Minnesota Department of Highways; and Don Trull, Regional Federal Highway Administrator, Region 5, Office of Research division chiefs presented summaries of the research in each FCP category.

An overview of development activities was held Tuesday morning, with an introduction by Rex C. Leathers, Director of the Office of Development. Emphasis was placed on the total FHWA implementation effort, with officials of the Office's Implementation Division speaking on their activities and welcoming questions and comments from the audience.

Tuesday afternoon, in a series of new projects and initiatives seminars, participants were given an opportunity to review and comment on proposed new research efforts and to suggest other problem areas to which resources should be applied at the national level. The sessions held Wednesday, Thursday, and Friday were devoted to in-depth, detailed reviews of progress, outputs, and future plans for individual projects.

An added benefit of the conference is the opportunity for participants to meet informally with their professional colleagues. An information center in which each R&D division had exhibits relating to its operation, with staff members in attendance to answer questions, operated Tuesday through Thursday. Tuesday evening the 3M Corporation presented a history of reflective highway materials and new developments in that field. A tour of their Transportation Safety Center was also available. The R&D banquet, this year featuring live musical entertainment, was Wednesday evening.

This third annual FCP review brought together members of the highway community in an atmosphere of open discussion and information exchange. Any reader wishing further information on FCP may write to the Associate Administrator for Research and Development (HRD–3), Federal Highway Administration, Washington, D.C. 20590.


Engineering Services Division exhibit featured demonstrations of the TRIS/MIS computer system.


Working group during one of Tuesday's new projects and initiatives seminars.


Informal discussion in the information center.


Conference coordinators John Ohrn, Minnesota Division, and Craig Ballinger, Offices of Research and Development.

A Snowplowable Highway Lane Delineator for Wet-Night Visibility

by [1] Michael M. Epstein, Daniel R. Grieser, Joseph R. Preston, and Charles E. Moeller

—courtesy, Connecticut Department of Transportation.

A snowplow resistant device has been developed to provide lane delineation for wet-night driving conditions. The device, known as the low-profile retroreflector, is a strip comprised of injection molded plastic elements specifically designed to capture and reflect the optimum amount of light at large angles of incidence. The strip is bonded to the highway surface in a recessed groove so that the top surface of the retroreflector is flush with the highway surface. Because the strip does not have to provide dry-night delineation, scratching of the top surface is not a concern. Water fills in the scratches during rainy periods and, in effect, repairs the marking strip; that is, wet-night reflectance is not impaired.

Limited road testing with experimental devices confirmed that the strip provides adequate lane delineation for wet-night driving conditions and is resistant to the abuse imparted by snowplows and the pounding of heavy traffic. The road test was conducted on two lengths of Interstate Highway in the Columbus, Ohio, area during the winter of 1972–73 and for a period of 10 months. Each test site experienced an average daily traffic density in excess of 10,000 vehicles per lane. Losses of recessed markers through the test period amounted to about 4 percent.

This concept was developed under a research contract with the Federal Highway Administration, U.S. Department of Transportation. Because of the unusual promise offered by this concept, the Federal Highway Administration currently is implementing field trials in a number of northern States.

Introduction

A major highway safety problem is the lack of adequate visibility under wet-night driving conditions. As every driver is aware, traffic paint disappears from view under most wet conditions at night. The driver is left with a highly insecure feeling resulting from this loss of guidance. The difficulty is compounded on multidirectional streets and highways by the glare from the headlights of oncoming traffic.

[1] This article is an abridgment of Final Report No. FHWA–RD–73–78, "Development of a New Low-Profile Highway Striping for Wet-Night Visibility," September 1973. The report is available as PB 234934/OAS from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161.

Stripe disappearance and glare are the results of a partial reflectance of light at a dielectric boundary. This boundary develops at the air-water boundary of the rain deposited on top of the road and paint stripe surfaces. When the headlights strike the wet pavement, the angle of incidence is very large, and under this circumstance most of the light is reflected forward. This is the bright glare that is so annoying to oncoming traffic.

To illustrate this point, figure 1 is a plot of light reflection from an air-water interface at low angles, that is, large angles of incidence. From a distance of about 100 ft (30 m) in front of a car, nearly 85 percent of the light from the headlights reflects forward at the opposing traffic, and a maximum of only about 15 percent is available to penetrate the air-water interface and provide some delineation. Unfortunately, when the reflected light encounters the air-water interface again, only 15 percent of the remainder is transmitted. Thus, only 3 percent or less of the original headlight illumination can be effectively seen by the driver from a distance of 100 ft (30 m). Since the road surface is a poor reflector, it appears to be black to the driver. Traffic paint is not much better as a reflector under wet conditions. It is difficult or impossible to see beyond 50 to 60 ft (15 to18 m) even with upper-beam illumination.

Many ways to solve this problem have been proposed, and several have been successfully demonstrated in warm-climate locations. Perhaps the most successful are the raised corner-cube retroreflector markers which are increasingly used in Florida, Georgia, and California. These markers stand above the rainwater, and can reflect brightly without experiencing the large reflection losses previously described. Unfortunately, their elevation which makes them so effective in these locations actually destroys their effectiveness in northern States because they are easily removed by snowplows.

Numerous ideas have been proposed and evaluated for solving the problem of providing adequate lane delineation for wet-night driving that would be unaffected by snowplows. There are several designs available from commercial sources using the raised markers which have been successful in southern climates. Instead of bonding the unit to the road surface, the molded plastic retroreflector is encased in a metal-armored device which is partially embedded in the road surface. The snowplow blade is diverted and it passes over the marker without causing damage. Another raised design approach relies on inherent flexibility to yield and then spring back into position after passage of the snowplow. Additional plans are of the low-profile type, and include a flush-mounted, electrically powered device and road grooving to minimize free-standing water.

None of the above-mentioned designs has been fully accepted by State highway departments, as they all exhibit one or more serious failings. Either they are damaged by snowplowing, and are costly to use because of need for frequent replacement, and represent a safety hazard to snowplows and snowplow operators; or they require auxiliary power; or they fail to provide adequate wet-night reflectance.

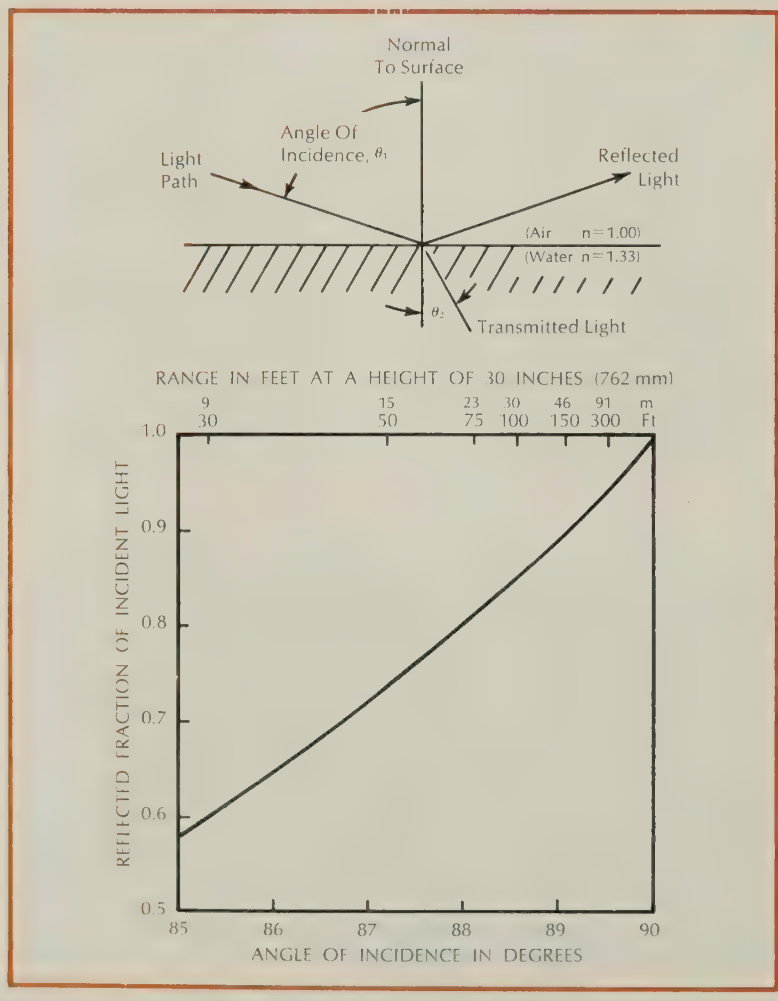


Figure 1.—Fresnel reflection for unpolarized light at an air/water interface.

Recognizing the complexity of this problem, Battelle-Columbus physicists and engineers devised a new approach. On the basis of limited field evaluation, the Battelle concept appears to satisfy all of the major requirements of **wet-night** driving in northern climates. Under the sponsorship of the Federal Highway Administration, U.S. Department of Transportation, a research study was undertaken by Battelle-Columbus to develop the concept, reduce to practice, and perform limited field evaluations.

Concept Description

The Battelle low-profile concept consists of a thin, transparent plastic stripe containing high efficiency, retroreflector arrays molded into the bottom surface. A typical injection molded retroreflector array is shown in figure 2. The plastic material used for these experiments was polymethyl methacrylate. After molding, the bottom or retroreflector surface is aluminized. The individual retroreflector units are assembled into stripes, which are embedded in the road in each skip zone so that the top surface of the stripe is flush with the road surface, as shown in figure 3.

The Battelle low-profile-marker design is to be used in conjunction with a high quality beaded traffic paint. The latter does an excellent job in delineating highways under dry-night conditions. The dual marking system delineates traffic lanes well under all possible driving conditions except, of course, where the highway is completely covered by snow or glare ice.

Traffic abrasion on the top surface of the plastic retroreflector results in a matte finish and eliminates all effective retroreflectance under dry conditions. This is desirable for ordinary driving conditions, as it does not interfere with the skip-pattern marking of the standard lane stripes. When wet, however, the plastic retroreflectors come "back-to-life." Water fills in or heals the top surface scratches because it has nearly the same index of refraction as the plastic. As a result, the wet retroreflectance of a traffic-worn plastic stripe and that of a new unit are the same. This has been demonstrated by laboratory photometer measurements with scratched and clean marker stripes.

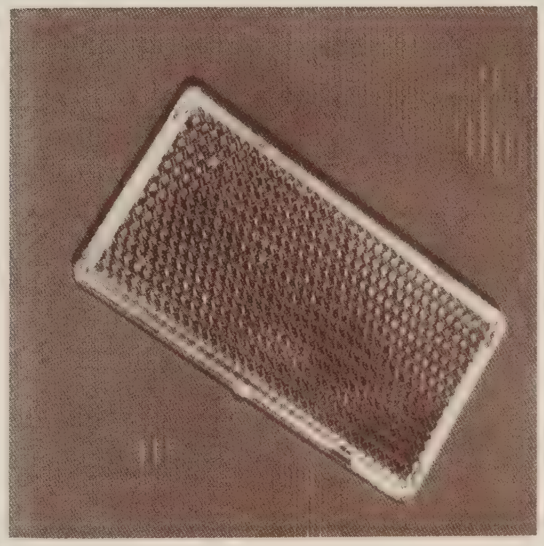


Figure 2.—Injection molded polymethyl methacrylate low-profile reflector.

Figure 3.—Complete stripe installed on the road surface.

Field Testing of Highway Stripes

Highway testing of the low-profile retroreflector stripe was initiated in September 1972. The test was designed to evaluate two important parameters: the availability of the stripes to provide adequate delineation, and their resistance to damage caused by high speed, high density traffic, and snowplows.

Site description

Two sites in the Columbus, Ohio, area were selected for the field evaluation. Both sites are subject to frequent snowplowing with steel-tipped blades. The first site was a stretch of Interstate 71, the north-south route from Columbus to Cincinnati, paved with a bituminous concrete surface. A State survey in the spring of 1973 showed this stretch of road had an average daily traffic (ADT) density of 10,057 vehicles per lane. The second site was an adjacent stretch of Interstate 270, the Columbus outerbelt, which has a portland cement concrete surface, and an ADT of 12,587 vehicles per lane. In both locations trucks comprise roughly 15 percent of the traffic. Both locations were close to exit ramps, which insured frequent lane changing. Hence, the markers at both locations would be subjected to maximum tire wear and impact.

Experimental plan

The experimental matrix called for the following evaluations:

- Recessed plastic stripes on bituminous concrete.
- Recessed plastic stripes on portland cement concrete.
- Nonrecessed plastic stripes on bituminous concrete.
- Nonrecessed plastic stripes on portland cement concrete.

Accordingly, the total installation consisted of four ¼-mi (400 m) lengths of highway, as described above. At each site (I–71 and I–270), the ¼-mi (400 m) length with unrecessed stripes was followed by the ¼-mi (400 m) length with the recessed stripes.

Assembly of stripes

For this evaluation, the individual aluminized retroreflector units shown in figure 2 were assembled into continuous stripes 3.5 in (89 mm) wide by 37.5 in (953 mm) long. The stripe was thus comprised of 20 individual units. This total length was selected on the basis of experiments in the laboratory and in the Battelle parking lot. The longer the stripe, the more depth it will appear to have when viewed from a distance on a dark, rainy night. From a great distance the stripe will appear as a thin slit and acquire depth as it is approached.

The actual selection of 37.5 in (953 mm) was therefore somewhat arbitrary, as the optimum stripe dimensions have not yet been determined on the basis of actual field experiments. Future demonstration programs planned by the Federal Highway Administration will attempt to more closely define this variable.

In the absence of any usable machinery for handling and/or installing the stripes, the markers were held together by mounting on strapping tapes as shown in figure 4.

Figure 4.—Taped stripe prior to installation.

Figure 5.—I–71 test site after installation.

Grooving of highway surface

Grooving of the skip zones for the recessed stripes was performed by a private contractor. A self-propelled concrete planer with a single diamond grinding wheel was used to make grooves ⅛ in (3 mm) deep, 4 in (102 mm) wide, and about 38 in (965 mm) long. Water was used in this operation as a lubricant and coolant for the grinding wheel. Before installing the stripes, the grooves were cleaned and dried.

Installation of stripes

The stripes were bonded to the road surfaces using a commercially available epoxy-polysulfide adhesive. The lanes were opened to traffic about 1 hour after installation (fig 5). This provided adequate time for the adhesive to set, or become rigid, although complete cure had probably not yet occurred.

Evaluation Procedures and Results

The following techniques or criteria were used to evaluate the installed retroreflector strips:

- Photometer measurements of wet retroreflectance as a function of time.
- Photographic, including the use of TV camera recording.
- Visual (direct observation).
- Physical inspection.

Optical performance measurements

Photometric measurements of the reflector strips were made approximately 1 month and 10 months after installation. A Gamma Scientific Instruments telephotometer was used for this purpose. The instrument, a portable power supply, and a single sealed-beam lamp were mounted in a van and configured to point out of the rear door of the vehicle. The measurements were made in this manner to protect the equipment from rain and to minimize problems associated with viewing through rain-streaked windshields. The van was parked backwards on the shoulder of the highway, and the lamp and telephotometer pointed toward the markers and paint stripes in the direction of traffic flow. Thus, the reflectance as seen by the instrument was similar to the view afforded the motorist.

The luminance values measured at the test sites are summarized in table 1. The values are corrected for the side angle-of-view factor resulting from being off the road. This amounts to a correction of about +25 percent of the total reflectance. In addition, all the measurements were corrected for the 6-minutes-of-arc field of view of the telephotometer setting, which more than covered the marker or paint stripes. These corrections ranged from —30 percent at 60 ft (18 m) to about —300 percent at 140 ft (43 m). A ratio was made of luminance values and the values measured for the road surface to indicate the apparent brightness of the markers or paint stripes compared with the adjacent road surface.

A direct comparison between the luminances determined after winter with those before the winter is somewhat obscured by the differences in the wetness and differing distances of measurement. It can be noted however, that even when not fully wet, the molded markers appear brighter than the paint stripe as shown by the data obtained before the winter. Even taking into account the slightly different distances, the molded marker is an order of magnitude more reflective than the road surface and twice as reflective as the paint stripe at a 120-ft (37 m) distance when damp. The measurements made after the winter show that the fully wet molded marker is still an order of magnitude more reflective than the pavement and the paint stripe is not even a factor of 2 more reflective than the pavement at the closer distance of 100 ft (30 m). The paint stripe does not become an order of magnitude more reflective than the pavement until only 60 ft (18 m) away. At this distance the marker strip would appear better than two orders of magnitude more reflective than the pavement, and even at 80 ft (24 m) away it is 40 times more reflective than the pavement. These measurements show that the molded markers have superior wet reflectivity compared with paint and indicate that the markers should be visible up to distances of roughly 120 ft (37 m).

Table 1.—Luminance [1] measured at test sites

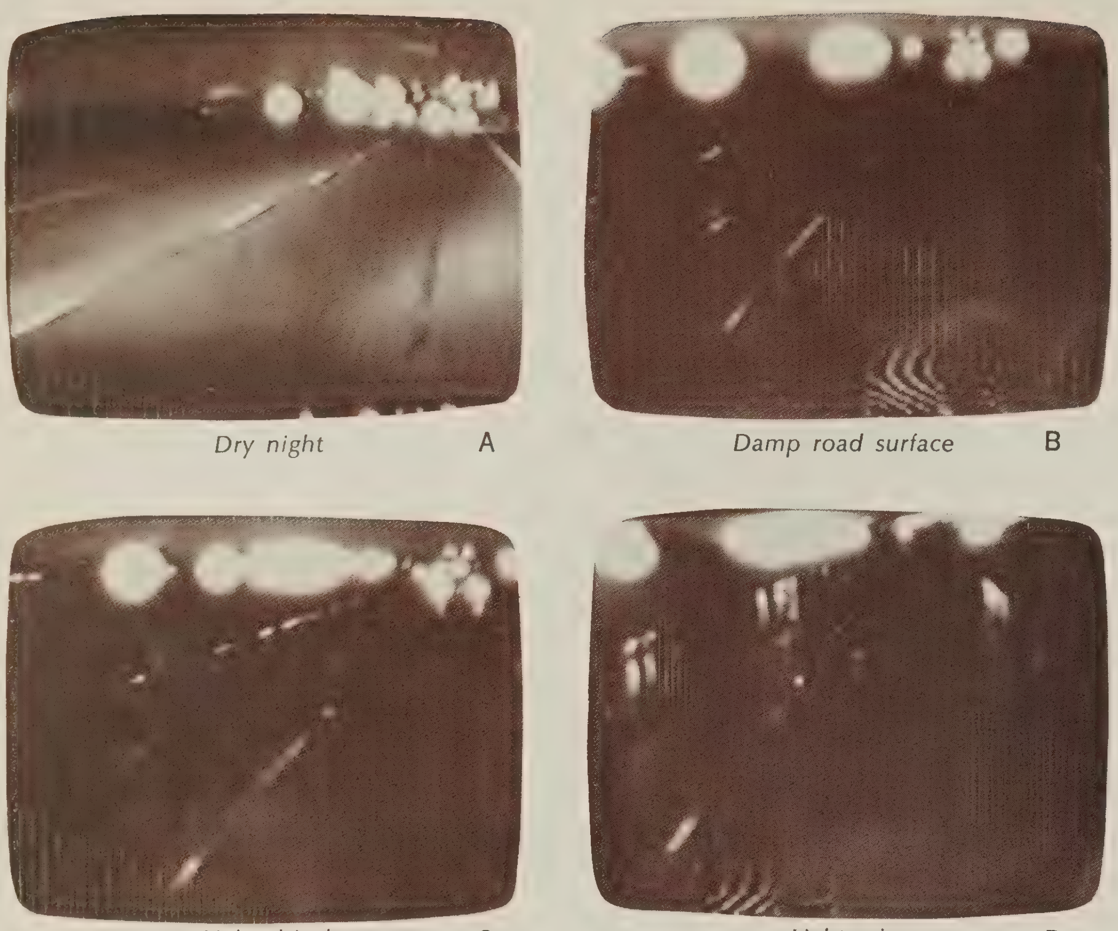
	Range		Heavy rain	Heavy drizzle	Light drizzle	Rain stopped
BEFORE WINTER						
	Feet	*Meters*				
Bituminous pavement	—	—	—	1	—	1
Paint stripe	140	43	—	5.3	3.6	6.6
Molded marker	120	37	—	12.1	9.3	9.4
AFTER WINTER						
Bituminous pavement	—	—	1	—	—	—
Paint stripe	60	18	10.4	—	—	—
Paint stripe	100	30	1.8	—	—	—
Molded marker	80	24	41.2	—	—	—
Molded marker	120	37	9.4	—	—	—

[1] Luminance values have been normalized relative to a value of 1 unit for the measured luminance of bituminous pavement.

Movie and closed-circuit television recording

Soon after installing the markers, an attempt was made to obtain motion pictures of their wet-night appearance as seen by an automobile driver. Two types of sensitive black-and-white recording film were used with very poor results. During the filming the traffic was so heavy at these sites that a safe minimum speed of 60 mph (96 km/h) was used. Although the light level was sufficient for human vision, it was inadequate for satisfactory filming at this road speed. Out of hundreds, only a few frames showed that at least three markers ahead of the car were reflecting light back to the driver.

A special high-sensitivity Sanyo Model VCS–3000 silicon-diode television camera was used with video tape recording and monitoring equipment to film the markers on a wet night after the markers had endured one entire winter. A tape recording was also made of the test site on a different night to show the appearance of the markers and paint stripes when dry. A frame from these dry-night pictures shows that four paint stripes ahead of the car can be



Dry night A

Damp road surface B

Light drizzle C

Light rain D

Figure 6.—Frames from television recording of I–71 test site.

seen under low-beam illumination (fig. 6a). This is equivalent to 160 ft (49 m). The molded marker strips located in the skip zones do not reflect from a distance since they are both abraded and dry. They appear as slightly dark patches compared with the road. When the road is slightly damp (fig. 6b), the paint stripes begin to darken, as does the road surface, and the molded markers begin to retroreflect the headlights. As the road gets wetter (fig. 6c), the paint stripes decrease and the molded markers increase in reflectance. Finally, when fully inundated (fig. 6d), the paint stripe becomes nearly invisible and the molded markers can be seen brightly at 80 ft (24 m) and less brightly at 120 ft (37 m). The television recordings compare very well with the visual observations and the photometric measurements, all of which show that the markers delineate the lanes under wet-night conditions at distances up to 120 ft (37 m) ahead of the vehicle under low-beam illumination.

Driver observation of wet-night markers

A survey of Battelle employees was made to obtain their subjective reaction to the effectiveness of the test-site markers. All responders who drove by the markers on wet nights were impressed by the presence of an indicator that located the lane dividers. Many remarked that they would prefer the markers to be visible farther ahead of the car and were surprised to find out that the strips were as long as 3 ft (0.91 m). All observers were in favor of some system of wet-night marking. The general observation by drivers has been that the marker strips can be readily seen and that they provide a sense of security that is pointedly missing immediately after passing the test sections.

Inspection of physical condition

Counts of missing marker units on both I–71 and I–270 were made during the daytime. Two runs were made over the sections on both highways to obtain a reasonably accurate figure. Because of traffic conditions, it was not possible to stop or even slow down sufficiently to perform an exact count of the missing units. The approximate counts of missing units from both runs are summarized:

I–71 (Bituminous) at approximately 35 mph (56 km/h)

Section	Run 1	Run 2	Average
Recessed	21	22	21½
Surface	78	79	78½

I–270 (Portland cement) at approximately 40 to 45 mph (64 to 72 km/h)

Section	Run 1	Run 2	Average
Recessed	32	16	24
Surface	147	172	158

Each quarter-mile section is comprised of about 600 marker units. The data show that on both portland cement (I–270) and bituminous roads (I–71) only 4 percent of the recessed marker units were missing. The markers on the surface of the roads did not fare as well: 25 percent of the units on the surface of I–270 (portland cement) and 12 percent of those on the surface of I–71 (bituminous) were missing.

It was surmised that heavy pounding from high-speed traffic was responsible for the larger numbers of unrecessed missing units on both I–71 and I–270. The quarter-mile sections of marker strips on the surface are located closer to the exit ramps than the recessed strips at both locations. At these locations there is much lane-changing to gain access to the ramp. The general rates of speed on I–270 are also higher than those on I–71, and the Ohio Department of Highways survey showed a 20-percent higher traffic density on I–270 than on I–71. During the exposure period, both test sites were subjected to about 10 to 15 passes with the snowplow.

No regular pattern of loss was shown by the marker units missing from the strips. It was anticipated that the leading edge of each strip (the edge nearest to oncoming traffic) would suffer the most and that snowplow damage would be heaviest at these points. This, however, did not seem to be the case. In some instances, alternate marker units midway in the strip were missing; others at or toward the end of the strip were missing; and some at the leading edge of the strip were missing, though not uniformly. In extreme cases most units in a strip might be missing, whereas the neighboring strip was intact.

If the damage had been caused by snowplowing, one would expect relatively uniform damage at the leading edge of the strips. Therefore, it was concluded that the damage was more attributable to heavy, high-speed traffic.

It was observed at the I–270 site that the aluminizing was missing from many units still on the road. This may have been caused by any or all of the following: regularly scheduled acid washing to roughen the portland cement concrete road surface to improve traction, frequent salting of the road surface for snow removal, and leaching of the aluminum by alkaline material dissolved from the portland cement itself. This accounts

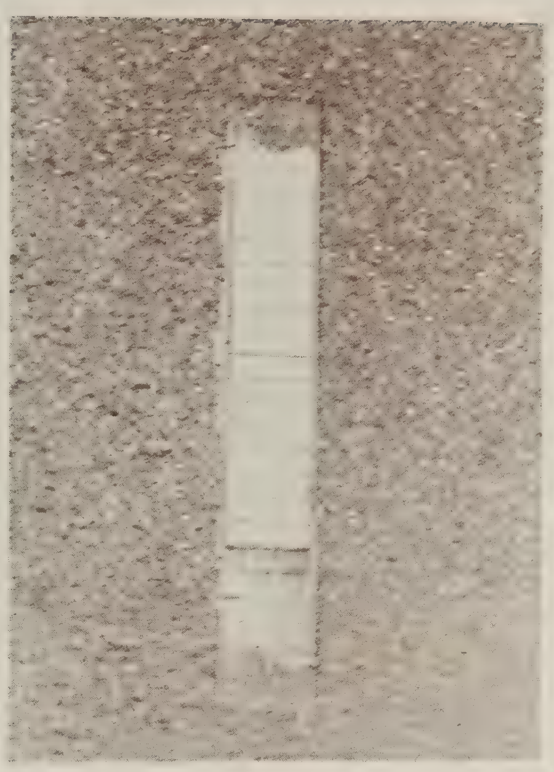


Figure 7.—Marking stripe after 10 months' service at I–71 test site showing typical failure pattern.

for loss of reflectance of markers in which the aluminizing has been lost. In these instances, water that flows under the dealuminized marker destroys the retroreflecting capability of the marker.

In most instances of failure it was noted both that the units broke away as a whole, and not in pieces, and that the adhesive remained bonded to the pavement (fig. 7). Thus, it is the adhesive-to-marker-unit bond that may be in question. It should be noted here that the highways were opened to traffic 1 hour after installation instead of the minimum required setting time of 2 hours, and this may be an additional factor in the observed failures.

Approximately 18 months after installation, the markers were inspected again. At this stage, two full winters had passed since installation of the strips. The frequency of snowplowing during the second winter (1973–1974) is not known. The statistical significance of this second inspection was reduced because one part of the test site had been resurfaced and all of the markers in that zone were gone. Despite this, it was possible to draw several conclusions from this second inspection:

- The percentage of lost markers in zones where the stripes were *not recessed* had risen dramatically. Although an exact count was not possible, the loss might have been as high as 75 percent.
- The percentage of lost markers in zones where the stripes were recessed had increased to about 20 percent. As in the previous year's inspection, it was noticed that the losses seemed to be predominantly caused by traffic rather than plow action, as individual units in the stripes were completely missing.
- The nature of the losses suggests that the problem is due to adhesive failure and could be corrected by redesign and development of more effective adhesive materials.

ACKNOWLEDGMENT

The authors wish to express their appreciation to Bernard Chaiken, Chief of the Chemistry and Coatings Group, Materials Division, Office of Research, Federal Highway Administration, for his support and guidance throughout the development and evaluation of this important concept.

Rapid Information Retrieval

for Federal Highway Administration Research and Development Management

by Antoinette D. Wilbur

Management Information System

The Management Information System (MIS) is a computerized system for providing up-to-date information on the current status of activities sponsored by the Offices of Research and Development of the Federal Highway Administration (FHWA). These activities consist of technical and/or scientific investigations including basic and applied research, development, engineering, evaluation, and demonstration projects in all fields of highway science. The investigations are conducted by personnel within the FHWA Offices of Research and Development (R&D), State highway departments, universities, private research firms, other government agencies, and individual consultants.

The MIS is designed to provide timely information regarding ongoing research and development activities. Computer software has been developed for entering new records into the MIS file, updating existing information, and retrieving this information in a variety of formats. Each data record, or work unit, contains information on the source and amount of funding for the project, the organization performing the research, the project duration, and a brief narrative describing its scope. These data are used for monitoring the progress of each individual effort, as well as providing FHWA personnel with consolidated information on the type and amount of research being conducted in a given field.

The R&D work units are classified by the method of funding into the following broad categories:

- **Staff R&D.** Work performed by FHWA employees on Federally owned or operated premises and supported by FHWA funds.
- **Contracts.** R&D activities supported by FHWA administrative contract funds and performed by qualified research organizations such as private research firms, universities, individual consultants, other Federal agencies, or State highway departments.
- **Highway Planning and Research (HP&R).** R&D activities supported jointly by the FHWA and the individual States and conducted by State highway departments, universities, or other research agencies. The Federal government funds are provided under Section 307c of the Federal Aid to Highways Act.
- **National Cooperative Highway Research Program (NCHRP).** FHWA R&D activities administered by the Transportation Research Board and sponsored jointly by the American Association of State Highway and Transportation Officials and the Federal Highway Administration.
- **Bureau of Motor Carrier Safety (BMCS).** Research activities conducted by the BMCS, a component of the Federal Highway Administration, to support existing or proposed regulations governing the safety and operation of interstate motor carriers. This research is performed by BMCS personnel, other government agencies, or private firms using administrative contract funds.

Figure 1.—A remote terminal used to enter batch programs to the central computer site.

The Development of the MIS Computerized File

The present MIS was conceived in the early 1960's when FHWA personnel found it increasingly difficult to monitor the growing HP&R program. Development of a computerized system began in 1962 to provide a consolidated data base of pertinent information on research and development activities. In 1964 the first complete summary of the HP&R program was published from information contained in the new computerized MIS. This publication contained a complete abstract of each work unit record, as well as tables showing the amount of funding supplied by each State. Administrative staff personnel updated the MIS file at the end of each fiscal year, and a new document was published to show the current status of all ongoing research and development projects.

The development of the Federally Coordinated Program of Research and Development in Highway Transportation (FCP) began in 1970. The FCP was designed to classify major problem areas in highway research and provide a unified approach for problem solution. Each major area was designated as a category. Each category was then subdivided into projects, and each project into tasks. After this structure was established, the MIS work units were assigned to their appropriate FCP category, project, and task. This classification provided a convenient means of grouping research and development activities aimed at similar problems and highlighting areas of possible additional effort.

Up-to-Date Maintenance of the MIS File

Personnel within the Offices of R&D provide technical assistance to the research organizations and monitor the progress of their work. In 1971 updating responsibility for the MIS was delegated to these technical advisors, and MIS file maintenance and updating began on a regular basis. Input to the computerized file was accomplished with punched cards and an R&D Order providing instructions for completing required data forms was published. When a new study was initiated or a change occurred in an existing activity, R&D monitors were required to code this information for input to the MIS computer file. This new updating system provides the MIS file with the latest available information on research and development efforts.

The Engineering Services Division (ESD), Office of Development, is responsible for updating and maintaining the MIS computer files. *Batch* updating from punched cards is usually performed once a week (fig. 1), depending on the number of update forms received. Following each update of the file, ESD provides the originating divisions with a copy of the updated work unit resume to verify that the computer file was correctly modified.

Engineering Services Division also provides listings of the contents of the MIS file to personnel within the Offices of R&D and the FHWA regional offices. The format of these computer printouts is tailored to the needs of the requesting individual or office. Certain types of records may be selectively chosen—for instance, only ongoing research activities sponsored by States in FHWA Region 1 or only contracts beginning in fiscal year 1976.

All or any portion of a work unit record may be printed, depending on the type and amount of data desired. A listing of the entire record, or standard list, is shown in figure 2. A more concise listing, generally one or two lines per study, is also available. This short format allows the requesting individual to specify the data fields of particular interest and to have the data grouped and printed in the desired format. A standard report package has been developed to produce the most commonly requested output formats. Brochures containing samples of each of these standard reports were distributed throughout the Offices of Research and Development in March 1975. A sample report is shown in figure 3.

On-Line Updating and Retrieval

A new method of updating the MIS computer file is presently being implemented. The earlier batch method of updating using punched cards for input is being replaced by *on-line* updating. On-line updating is accomplished using a cathode ray tube (CRT) terminal which accesses the U.S. Department of Transportation Computer Center facility via telephone lines. The system requests the required information via the CRT display and updating is accomplished using the terminal keyboard. Three types of updates may be performed—add an entire record, delete an entire record, or update selected fields in an existing record.

```
SYSTEM 28 4001-A04          MIS STANDARD LIST                    PAGE 0001

ID-NO: 093025354   FCP-CODE: 32C1022   CONTRACT(STATE STUDY): FH-11-8738

START-DATE: 03/31/75  COMPLETION-DATE: 03/31/77  SPONSOR: 54 AB: A FCE:

TITLE:

DEVELOPMENT OF TRAFFIC LOGIC FOR OPTIMIZING TRAFFIC FLOW IN AN
INTERCITY CORRIDOR

TOTAL COST: 00660      1972:  N.A.      1973:  N.A.      1974:  N.A.

                       1975: 00383      1976: 00277      BUDGET-TYPE: 1

FUNDING CODE:  3

PER-ORG: SPERRY SYSTEMS MGT DIV        PER-ORG-TYPE: 3    REGION:

CITY: GREAT NECK                 STATE: NY   ZIP: 11020

PRINCIPAL-INVESTIGATOR: REISS

FHWA-MONITOR: YOUNG                            GROUP: 4132

FTC/FPA: NONE                    ORGANIZATION:

WORK-UNIT-SUMMARY:

OBJECTIVE - DEVELOP A TRAFFIC CONTROL ALGORITHM WHICH WILL SELECT,
BOTH OFF-LINE AND IN REAL TIME, VALUES OF CONTROL VARIABLES WHICH
WILL OPTIMIZE TRAFFIC FLOW IN A GENERAL INTERCITY CORRIDOR.  TASKS -
FORMULATE CONTROL ALGORITHMS, VALIDATE TRAFFIC MODELS, PROGRAM
ALGORITHM, SPECIFY DATA REQUIREMENTS, SPECIFY COMPUTER REQUIREMENTS
AND APPLY OFF-LINE VERSION TO TYPICAL CORRIDOR.

LAST UPDATE:  08/05/75                                    STATUS: ACTIVE
```

Figure 2.—A standard list showing the data fields contained in an MIS work unit record.

ALL STUDIES IN SELECTED CATEGORY-PROJECT
BY STATUS

FCP	STATE	FIRST-55-CHARACTERS-OF-TITLE	P-YR	T-COST	C-COST	C-DATE
STATUS- ACTIVE						
TASK- 5A1						
25A1022	STAFF	AERODYNAMIC INVESTIGATION OF CABLE-STAYED BRIDGE MODELS	75	50	21	760630
35A1012	CONTR	LONG SPAN CABLE SUPPORTED BRIDGE WIND ANALYSIS	75	301	0	760930
35A1022	CONTR	DYNAMIC RESPONSE OF ANEMOMETERS UNDER FLUCTUATING AND T	75	89	0	751231
35A1032	CONTR	INVESTIGATION OF REPORTED NON-LINEAR CHARACTERISTICS OF	75	35	35	760630
35A1042	CONTR	RECENT METHODS IN THE APPLICATION OF SECTION MODEL TEST	75	6	0	751131
45A1042	AK	INVESTIGATION OF AERODYNAMIC BEHAVIOR	75	23	13	751231
45A1052	OH	TESTING OF SIGNS AND THEIR SUPPORT AGAINST WIND FORCES	75	50	25	760630
45A1064	NY	VEHICLE-INDUCED GUST LOADS ON OVERHEAD SIGN STRUCTURES	75	37	26	760331
45A1074	NY	FATIGUE FAILURE OF ALUMINUM LUMINAIRE SUPPORTS	75	53	34	760630
		** TOTAL RECORDS IN THE CATEGORY (TASK - 5A1) =		9		
TASK- 5A2						
35A2012	CONTR	INVESTIGATION OF HIGHWAY BRIDGE DESIGN METHODOLOGY	76	467	0	760930
35A2022	CONTR	FEDERAL COMPUTER FACILITY UTILIZATION	76	30	0	760930
35A2042	CONTR	SEISMIC ANALYSIS OF I-60 AND US 395 INTERCHANGE STRUCTU	76	20	0	751231
35A2052	CONTR	STRONG-MOTION RECORD INTERPRETATION AND STRONG-MOTION I	76	25	0	760701

Figure 3.—An MIS standard report. These reports may be requested by program name.

On-line updating offers many advantages over the traditional batch method and is much faster and easier to perform. Rather than keypunching input cards and submitting a series of computer runs to update the file, on-line updating allows records to be updated immediately. This can be done daily as the input forms are received, and the MIS file can be maintained on a more current basis. Errors are less likely to occur since the system requests each field and specifies the necessary format. Any incorrect entry is immediately rejected and must be reentered. After the data has been successfully entered or updated, the entire record may be displayed on the CRT screen to verify that all information was entered correctly.

In addition to updating, the new on-line system allows any R&D staff member to query the MIS file and display the selected work unit records on the CRT screen (fig. 4). Records may be selected in a variety of ways. Work units may be retrieved by the MIS identification number, a numeric code assigned to each work unit record to uniquely identify it in the computer system. Records may also be selected by FHWA contract number or by the study number assigned by the sponsoring State. Either of these methods allows the user to select and display a single work unit. A small printer is connected to the CRT terminal to provide *hard copy* of the displayed records.

Work unit groups may be selected and displayed by searching the contents of particular data fields in the record. The computer system allows the user to specify which fields he wishes to search and then asks him to enter the desired contents of the field. For instance, the user may request all HP&R studies dealing with vehicle protection systems that are performed by colleges or universities. The system responds with the number of work units which meet these criteria. At this point, the user has the option of displaying any or all of these records, or changing his search criteria and beginning again. Fields which may be searched include the type of funding, FCP category, project and task combinations, sponsoring State, FHWA region, the type of performing organization and its location, and the FHWA technical advisor and his R&D division. Any or all of these fields may be combined when selecting work unit records. Qualified records are displayed immediately on the CRT screen and may also be printed.

The final method of querying the MIS on-line system is the text search. The user enters a keyword which he believes will access the greatest number of pertinent records. The computer system then searches all MIS work units and displays those records which contain the requested keyword in either their title or summary. This type of search is particularly useful for retrieving all activities which fall within a specified subject area.

Figure 4.—A user searching the on-line MIS file from a cathode ray tube terminal.

Distribution of MIS Information

Information from the MIS data bases provides inputs to the Department of Transportation Work in Progress segment of the on-line Transportation Research Information System (TRIS).[1] TRIS is designed to provide information on the entire spectrum of transportation research and is accessed by users throughout the country.

Through on-line retrieval as well as cataloged computer programs, the R&D MIS can provide FHWA personnel with fast, easy access to timely information on R&D activities performed by a wide variety of research organizations. This consolidated data base is used to monitor these individual efforts, as well as provide a broad overview of the FHWA R&D program. To obtain information on the MIS data base, contact the Federal Highway Administration, Engineering Services Division, HDV–10, Washington, D.C. 20590.

[1] "Design Concepts for a National Network of Transportation Research Information Services (TRISNET). A report of the Committee on Transportation Research Information Systems," Final Report, DOT–OS–40022, *Transportation Research Board,* July 1975.

Papineau Bridge, Montreal, Canada.

A Review of the Aerodynamics of Bridge Road Decks and the Role of Wind Tunnel Investigations

by [1] Robert L. Wardlaw

In this article the aerodynamic phenomena that cause wind-induced vibrations of bridge road decks are examined and wind tunnel testing methods are reviewed. An example is given of a Canadian cable-stayed bridge. Deck section modifications were developed in the wind tunnel to suppress a serious vibration problem. With the new section, the motion amplitudes of the full-scale bridge have been reduced to insignificant levels.

[1] An abridgment of a report presented at the September 1973 Annual Research Progress Review of the Federal Highway Administration Federally Coordinated Project 5A, Improved Protection Against Natural Hazards of Earthquake and Wind.

Introduction

Through the introduction of high strength steels, orthotropic decks, cable-stays, increased use of welding, and other advances in engineering, bridges have become much lighter. Cable-stayed bridges may have deck weights of 70 lb/ft^2 (340 kg/m^2). At the same time structural damping has become much lower. The wind forces now take on greater significance and more attention must be given to the possibility of wind-excited vibration of the structure.

Today the designer of a modern suspension or cable-stayed bridge has several possibilities before him when selecting the type of road deck structure to be employed. Contemporary bridges are being built with truss-stiffened road decks, closed box sections, and box and plate girder systems. The final choice will be based on a variety of considerations, many of which will depend on local conditions. Whatever choice is made, the designer must ensure that the aerodynamic stability of the section is satisfactory.

Causes of Motion

It is important to distinguish between the static and dynamic effects of the wind; that is, between the wind forces which cause a bridge to deflect or deform and the aerodynamic phenomena that cause vibration. Often the dynamic effects are regarded as important only for long span bridges. This is not correct. Vibration has destroyed bridges with spans as short as 260 ft (79 m) and

Figure 1.—Vortex wake behind a circular cylinder.

as long as 2,800 ft (850 m). Bridges with spans outside this range have oscillated badly. There are many ways that interaction between the wind and a structure causes vibration, but only those that are important to the behavior of bridges will be described.

Vortex shedding

When the wind blows across a slender bluff object such as a circular or rectangular cylinder, a wake is formed that consists of a system of large vortexes that are spaced in a characteristic pattern (fig. 1). The vortexes form alternately on either side of the body with a marked degree of periodicity. The wind velocity, V, the frequency of vortex formation on one side of the wake, N, and the depth of the object, D, can be expressed as the dimensionless Strouhal Number.

$$S=\frac{ND}{V}$$

The value of the Strouhal Number depends on the section's geometry. For any given shape the Strouhal Number is reasonably constant over a large range of the aerodynamic similarity parameter, the Reynolds Number, Re. This parameter, Re, is $\frac{VD}{\nu}$ where ν is the kinematic viscosity of air.

The fluctuating character of such a wake can cause an oscillatory force on a bridge deck. If the velocity of the wind is such that the vortex shedding frequency N corresponds to a natural frequency of the structure, large vibration amplitudes may develop. The amplitudes will depend on the structural damping. Slender and streamlined deck sections narrow the wake, and reduce the intensity of the vortexes and the magnitude of the oscillatory forces.

The motion response of a bridge deck will only occur over a narrow range of wind velocity near the critical resonant value. Increased damping and streamlining can make the velocity range very narrow, and the natural wind will not stay within such limits for long periods. The buildup rate of motion is quite varied. In some cases peak amplitudes are reached in a small number of cycles of motion, but in other cases several hundred cycles of vibration may be required. For structures with low natural frequencies, many minutes of steady wind are needed for amplitudes to achieve maximum values.

Torsional motion as well as flexure may arise. Since torsional frequencies are generally higher than flexural frequencies, the motion occurs at higher wind velocities. These velocities are often beyond the design limit.

Vortex shedding excitation is amplitude limited. Structural problems arising from this mechanism are seldom catastrophic, although local damage and fatigue are possible after prolonged periods. Also, small motions that may be tolerated structurally can still be unpleasant to the bridge user. The natural frequencies of the bridge decks will decrease with increased span length. Consequently, the critical wind speeds for vortex excited motion will be higher for short spans than for long spans, and the probability of vortex excited motion will be correspondingly reduced.

While it may be possible to roughly estimate the critical wind speed for any section, there is no analytical procedure or empirical approach for predicting the amplitude of motion. Wind tunnel sectional model dynamic tests are a simple, quick and inexpensive alternative.

Flutter

Flutter is simultaneous torsion and vertical bending of the bridge deck, caused by aerodynamic coupling of the two types of motion. It occurs at a frequency between the natural frequencies of the independent degrees-of-freedom. It is characterized by a rapid buildup of amplitude, which may reach catastrophic magnitudes in a few cycles of motion. As wind velocity increases, a critical speed is reached where the flutter motion occurs. The bridge designer must ensure that the critical velocity at which flutter can occur is substantially higher than wind speeds expected at the bridge site.

There are no theoretical methods of predicting the critical flutter velocities of road decks; but this can be done for flat plates as described by Bleich et al. (*1*).[2] The critical velocities for bridge decks are lower than those for flat plates. Shape factors have been experimentally determined by Selberg (*2*) and others. These can be applied in some cases to predict the bridge critical velocity from the theoretical value for a flat plate, and reasonable agreement can be achieved between predicted critical flutter velocities and those measured in wind tunnels. These approaches must be used cautiously because the causative aerodynamic factors may differ from those assumed in the analysis. If there is any doubt, it is better to rely on wind tunnel testing. Often the motion is predominantly torsional. Apparently the dependence of the instability on coupling with the bending mode can become insignificant.

Typically, the flutter speed is lower if the wind is not blowing in the plane of the bridge deck. This may happen if the bridge deck or the wind is nonhorizontal. For example, a 5° change in vertical wind angle may reduce the critical speed from 100 mph (160 km/h) to 50 mph (80 km/h). For any given design the question of what maximum wind angle to assume arises. Site measurements of wind angle were made for the Severn Bridge (*3*). It was found that at low wind speeds it is necessary for the bridge to be stable for higher wind angles than at high wind speeds.

Flutter velocity depends on the elastic and dynamic properties of the bridge as well as the aerodynamic factors. The flutter velocity is increased by stiffening the bridge and increasing the natural frequencies. It is also increased as the ratio of the torsional natural frequency to the vertical bending natural frequency is increased (*1, 2*).

Turbulence

As a result of interacting with the earth's surface, the natural wind is not smooth and streamlined but is gusty and turbulent. The velocity fluctuations are vertical as well as horizontal, and they are random. Their energy is distributed over a wide range of frequencies. The relationship between frequency and energy content is usually described by a quantity called the spectrum.

A bridge responds to vertical and horizontal wind fluctuations at frequencies near its own natural frequencies. The turbulent wind energy is greatest at the lower frequencies. At the frequencies of intermediate and short span bridges, the wind energy is not sufficient to produce bridge motion that is significant even at very high wind speeds. The Long's Creek Bridge, a cable-stayed girder bridge in Canada (fig. 2), has a natural frequency of 0.6 Hz. This bridge has shown no sign of significant turbulence buffeting at wind speeds as high as 40 mph (64 km/h).

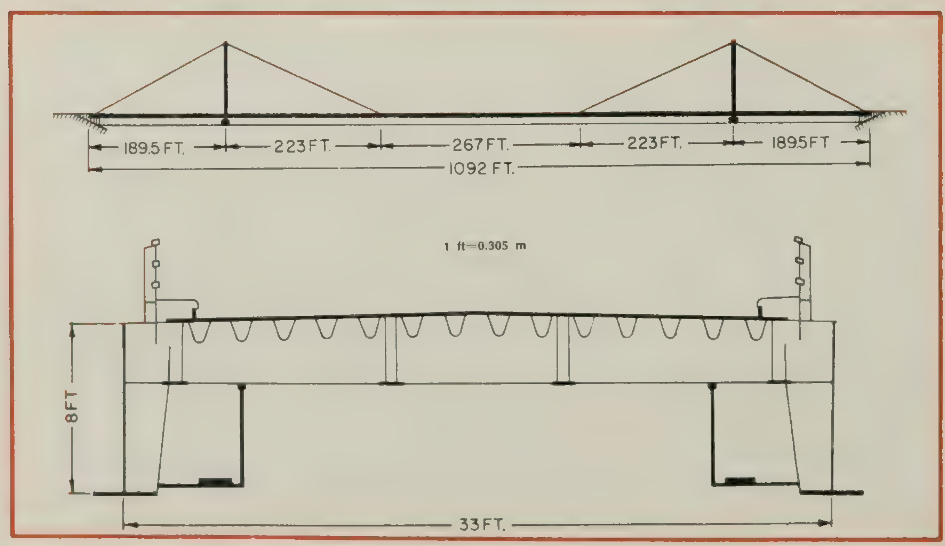


Figure 2.—Long's Creek Bridge.

[2] Italic numbers in parentheses identify the references on page 127.

There are also spatial variations in wind velocity; at any instant the wind velocity will not be constant in direction or magnitude along the entire length of the span. A consequence of the spatial and temporal variations is that vortex shedding excitation is less easily established than in smooth flow. Also the critical flutter speeds may be higher than in smooth flow. The larger the span of the bridge the greater these effects will become.

Wind Tunnel Testing

There are no adequate analytical or theoretical procedures for predicting the behavior of bridge decks. Because each bridge is unique, it is customary to conduct wind tunnel investigations during the design of intermediate and long span bridges. In such models the sometimes drastic effects of cross-section configuration on aerodynamic stability of the bridge deck can be studied.

A **full** model is a reproduction of the entire bridge with suitably scaled dimensions, mass moments of inertia, and elastic characteristics. A sectional model can also be used. The sectional model represents part of the bridge and is mounted on springs so that it has correctly scaled frequencies, mass, and moment of inertia (fig. 3). Advantages of the sectional model are a larger model scale and lower modeling costs. The scale ratio for sectional models may be about 1:30 or 1:50, but the scale ratio for full models in a conventional wind tunnel may be 1:200 or higher.

While the full model can be tested in a properly simulated turbulent flow, techniques for the simulation of the complete spectrum of the wind turbulence for the larger scale sectional models have not been developed. Sectional model tests are normally made in smooth flow. This can be conservative because turbulence usually reduces susceptibility to vortex excitation and raises critical flutter speeds.

Dynamic similarity

To achieve correspondence between model and prototype behavior, certain conditions of dynamic similarity must be satisfied. For a sectional model, these conditions are met if there is equality between model and prototype of these nondimensional parameters:

$$\text{(a)}\quad \frac{V}{N_Y D} \text{ and } \frac{V}{N_\theta D}$$

where N_Y and N_θ are the bridge natural frequencies in vertical flexure and torsion, D is a characteristic dimension, and V is the wind speed.

$$\text{(b)}\quad \frac{m}{\rho D^2} \text{ and } \frac{J}{\rho D^4}$$

where m and J are the mass per foot span and the mass moment of inertia per foot span and ρ is the air density.

$$\text{(c)}\quad \delta_Y \text{ and } \delta_\theta$$

the damping logarithmic decrements in vertical flexure and in torsion.

Also, the model center of gravity and the axis of torsional movement must correspond to those of the prototype bridge.

The velocity scale of the test is derived from (a) so that

$$\frac{V_p}{V_m}=\frac{D_p}{D_m}\bullet\frac{N_p}{N_m}$$

where subscripts m and p refer to model and prototype values.

Aerodynamic similarity

For equivalence of model and full scale, the aerodynamic similarity parameter is the Reynolds Number, $\mathrm{Re}=\frac{VD}{\nu}$. Although it is impractical for wind tunnel modeling to even approach full-scale values of the Reynolds Number, it has been established that for many sharp-edged bluff bodies, such as bridge decks, acceptable flow similarity between model and prototype can be practically achieved if the model scale is not too small.

In wind tunnel investigations of the Severn Bridge in Great Britain (4), it was shown that the wind forces on the model were Reynolds Number sensitive below $\mathrm{Re}=2 \times 10^6$ (Reynolds Number based on deck width) but that at higher values the forces were practically independent of

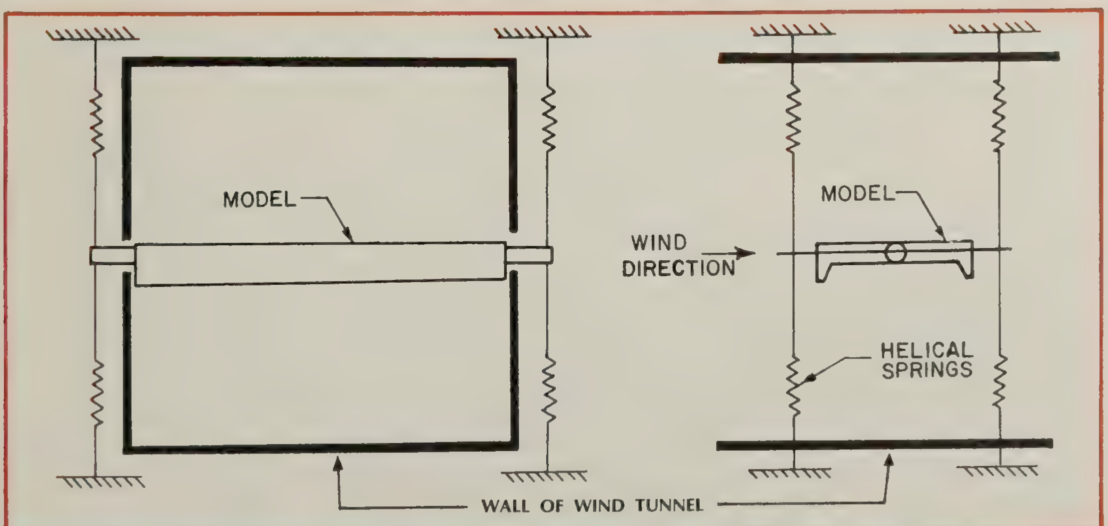


Figure 3.—Model suspension system.

Reynolds Number. The validity of aerodynamic model testing at a greatly reduced aerodynamic scale is questionable, and care must be taken because there is some limit beyond which the scaling effects can no longer be safely ignored.

Long's Creek Bridge

Wind tunnel model studies were conducted on Long's Creek Bridge. The bluff aspect of the original bridge deck caused intense vortex shedding. On one occasion when the handrails of the bridge had been blocked by snow, amplitudes of vibration, caused by vortex shedding, reached as much as 8 in (200 mm). The motion occurred only within a velocity range of 20 to 30 mph (32 to 48 km/h). This vortex shedding indicates a Strouhal Number range of 0.11 to 0.16. Model studies showed that a degree of streamlining would greatly reduce the excitation. Closing the section with soffit plating between the plate girders could reduce the amplitude of motion by 40 percent. This together with triangular edge modifications practically eliminated all motion of the model. Wind tunnel data with various edge configurations are shown in figure 4.

The use of girder perforations was also studied and it was concluded that 30 percent perforation of the girder would be required to reduce the motion to acceptable levels (fig. 5). The edge fairings and soffit plating suggested by the model studies were added to the bridge (fig. 6), and no further motion has occurred.

An almost identical bridge was constructed 10 miles (16 km) upstream from Long's Creek Bridge. The bridge was sheltered by a high embankment. As a result of different terrain conditions, no motion has ever been observed in the second bridge.

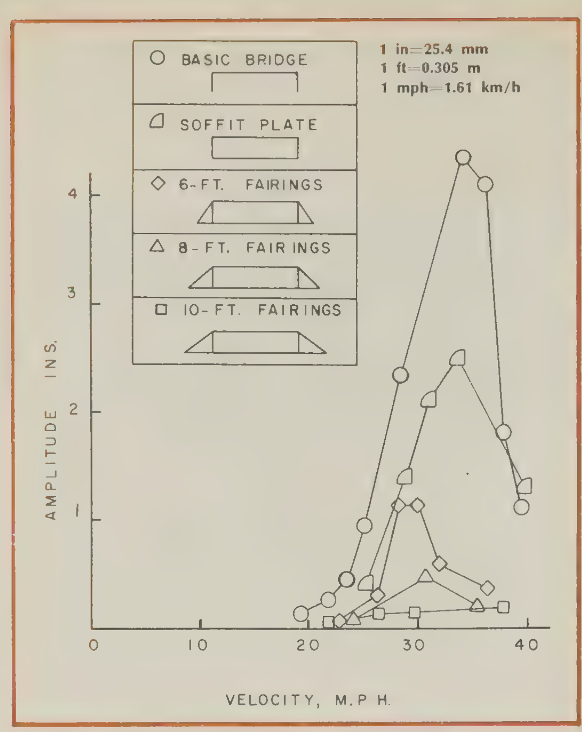


Figure 4.—Vertical amplitude with asymmetric fairings—effect of fairing width.

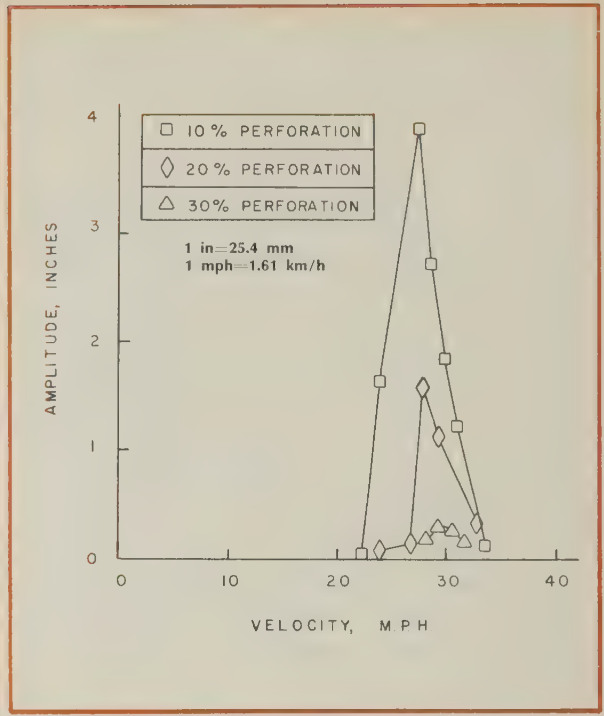


Figure 5.—Vertical amplitude with girder web perforations.

Tolerable Levels of Motion

Bridge deck motion that is destructive and motion that is structurally damaging over a period of time must be avoided, and suitable safety criteria must be established. Lesser motions that can be tolerated structurally may still be unpleasant to the bridge user. Appropriate acceptance levels for the motion need to be determined.

Because flutter is violent and destructive, it is necessary to establish a wind speed below which flutter must not occur. How is a safe value selected? There has been little written on this subject but Wardlaw and Buckland (5) suggested one approach.

For vibration levels at which user acceptance is critical, there is, again, little information for guidance. Wardlaw and Buckland provided a tentative criteria:

- For wind speeds of 0 to 30 mph (48 km/h) 2 percent of g.
- For wind speeds of 30 to 70 mph (48 to 113 km/h) 5 percent of g.
- Over 70 mph (113 km/h) the effect on the observer could be disregarded.

On Long's Creek Bridge acceleration values of 30 percent of g had been observed—8 in (200 mm) amplitude at 0.6 Hz. An amplitude of 1 in (25 mm) corresponding to an acceleration of 3.7 percent g was established as an acceptable target for correcting the problem.

Damping

As the bridge deck vibrates, the wind imparts energy to the bridge, and the energy is dissipated within the structure by its movements. For vortex shedding the energy input per cycle of motion is small, and a small amount of energy absorption by the structure helps reduce the amplitude. Flutter, conversely, is relatively insensitive to damping.

The level of structural damping is commonly expressed in terms of the **logarithmic decrement,** δ. It can be determined experimentally by observing the free decay of a vibration resulting from an initial disturbance, and for practical purposes:

$$\delta = ln\left(\frac{X_{n+1}}{X_n}\right)$$

where X_n and X_{n+1} are the amplitudes of successive cycles of vibration. The logarithmic decrement can be related to the critical damping ratio c/c_c by $\delta = 2\pi\ c/c_c$.

Measuring damping in large, completed bridges is difficult because exciting motion is a problem. Qualitatively, any slipping motion that can take place between bridge members, however small, increases the damping. Thus, stringers sliding on crossbeams produce a higher δ than is possible in an orthotropic deck. Riveted or bolted sections damp better than welded ones. The logarithmic decrement observed in Long's Creek Bridge was $\delta \doteq 0.065$.

Permanent dampers are not currently being built into bridges. As an emergency measure, dampers were put on the Long's Creek Bridge. Open boxes containing rocks were suspended from the bridge and immersed in the water. This device successfully suppressed vertical motion. Under certain circumstances, especially designed, light-weight damping devices as design components would allow the structural optimization of the deck section and provide freedom from oscillatory motion. Different types of dampers might be considered. One type is the **damped vibration absorber** discussed in "Some Approaches for Improving the Aerodynamic Stability of Bridge Road Decks" (6). Analytical considerations and wind tunnel studies show that a damper weight of ½ to 1 percent of the deck weight can eliminate vortex excitation.

Figure 6.—Modified Long's Creek Bridge.

Erection phase

A bridge that would be stable when completed may be subject to undesirable vibrations during construction. Welded tower components, for example, increase the susceptibility of towers to vibration during construction.

While under construction, a suspension bridge has frequencies far different from those when it is completed and problems may occur as a consequence. Results from the sectional model tests of the complete structure may be scaled to any frequency; therefore, if the frequencies of the partially complete structure are known, the same test results can be used.

Summary

The wind tunnel investigation is still an important part of the design process for intermediate and long span cable-stayed or suspension bridges. The design state of the art has not reached a point where the dynamic behavior as a result of wind action can be satisfactorily predicted analytically.

There are gaps in present knowledge. The effects of turbulence and terrain are not completely understood. More information is needed on damping in completed structures and on means of predicting damping. Sectional model tests give reasonable results, but further studies of the aerodynamic motion of completed structures, including careful measurements of concurrent wind conditions, are needed.

REFERENCES

(1) F. Bleich, C. B. McCullough, R. Rosecrans, and G. S. Vincent, "The Mathematical Theory of Vibration in Suspension Bridges," U.S. Department of Commerce, Bureau of Public Roads, *U.S. Government Printing Office,* 1950.

(2) A. Selberg, "Aerodynamic Effects on Suspension Bridges," Proc. Symposium No. 16, Wind Effects on Buildings and Structures, *Nat. Physical Lab.,* England, 1963.

(3) G. Roberts, "Severn Bridge—Design and Contract Arrangements," *Proceedings, Institute of Civil Engineers,* vol. 41, September 1958, pp. 1–48.

(4) D. E. J. Walshe and D. V. Rayner, "A Further Aerodynamic Investigation for the Proposed River Severn Bridge," *National Physical Laboratory,* England, NPL Aero Report 1010, March 1962.

(5) R. L. Wardlaw and P. G. Buckland, "Some Aerodynamic Considerations in Bridge Design," *The Journal of the Engineering Institute of Canada,* April 1972.

(6) R. L. Wardlaw, "Some Approaches for Improving the Aerodynamic Stability of Bridge Road Decks," Proceedings, Third International Conference on Wind Effects on Buildings and Structures, *Saikon Shuppan Co., Ltd.,* Tokyo, September 1971.

Our Authors

Charles Philip Brinkman is a physicist in the Environmental Design and Control Division, Office of Research, Federal Highway Administration. He is involved in the research of ice and snow control and skid reduction. Mr. Brinkman is also working with the Federal Highway Administration Coordinating Task Force on Metrication.

Susan E. Bergsman is a technical publications writer-editor with the Federal Highway Administration's Office of Development, Engineering Services Division. She has been with FHWA for 2 years, where she was an assistant editor of this journal and now is responsible for the Offices of Research and Development newsletter. Before coming to FHWA she worked at the National Bureau of Standards where she was involved in innovative housing research and surveys dealing with standardization of law enforcement equipment.

Michael M. Epstein is the Associate Manager of the Polymer and Paper Chemistry Section at Battelle's Columbus Laboratories. He has considerable experience in plastic fabrication technology. During the development of the low-profile retroreflector, Mr. Epstein was responsible for the development of specialized tooling for molding the retroreflectors and studies on all materials of construction, including adhesives and plastic molding materials.

Daniel R. Grieser is an optical engineer in the Plasma Physics and Electromagnetics Section at Battelle's Columbus Laboratories. He was the principal investigator on the FHWA-sponsored program on wet-night highway delineation. Mr. Grieser has also been engaged in extensive research to commercialize holography and has conducted numerous research programs for the development of conventional and laser-oriented optical metrology systems. He is currently engaged in the design of optical accessories for a fusion laser system.

Joseph R. Preston is a research chemist in the Polymer and Paper Chemistry Section at Battelle's Columbus Laboratories. He has extensive experience in polymer processing technology. He played a major role in the development of the low-profile road marker concept by helping to develop the process technology for its fabrication and to implement the road test program. Mr. Preston is currently engaged in several research programs concerned with the development of new uses for biodegradable plastic materials.

Charles E. Moeller is a research physicist in the Solid State and Optical Sciences Section at Battelle's Columbus Laboratories. He worked on the optical design and optical evaluation of the wet-night lane delineator. He has also developed innovative optical solutions to a variety of other problems and is currently working on optical and electro-optical methods for data storage and display.

Antoinette D. Wilbur is a mathematician in the Engineering Services Division, Office of Development, Federal Highway Administration. She has experience in all phases of computer systems analysis, including scientific programing, statistical analysis, teleprocessing, and computer time sharing techniques. Ms. Wilbur's special interest has been in data base management and information retrieval, particularly involving the R&D Management Information System.

Robert L. Wardlaw is a Senior Research Officer at the Low Speed Aerodynamics Laboratory of the National Research Council of Canada in Ottawa and has been with the Research Council since 1949. His research activities have included wind tunnel aerodynamic investigations of aircraft, tall buildings, towers, chimneys, and power cables, in addition to his extensive work on cable-supported bridges.

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

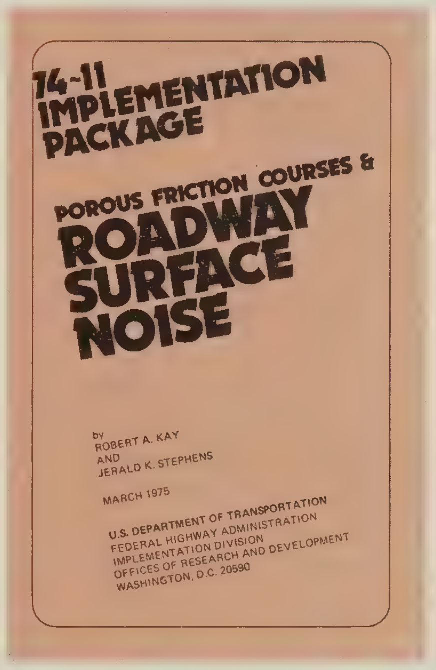
The following are brief descriptions of selected items which have been recently completed by State and Federal highway units in cooperation with the Implementation Division, Offices of Research and Development, Federal Highway Administration (FHWA). Some items by others are included when they have a special interest to highway agencies. These items will be available from the Implementation Division unless otherwise indicated. Those placed in the National Technical Information Service (NTIS) will be announced in this department after an NTIS accession number is assigned.

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

Porous Friction Courses and Roadway Surface Noise

by FHWA Region 9 and Implementation Division

The use of open-graded asphaltic friction courses is increasing because they provide a smooth ride and an anti-skid surface at a reasonable cost. In this study, the noise properties of these porous friction courses are compared with three other surfaces: portland cement concrete, chip seals, and dense-graded asphaltic concrete. Three types of tires were tested on each surface: mud and snow, standard rib, and radial rib recaps. For all three types of tires and at various vehicle speeds, the open-graded asphaltic friction courses generally produced lower noise levels than the other surfaces tested. Also the radial rib recaps were found to be slightly quieter than the standard rib tires, and much quieter than the mud and snow tires. The report contains a description of procedure and equipment, testing and data analysis procedures, test results, and conclusions.



This report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock No. PB 237483).

Development of a New Collapsing Ring Bridge Rail System

by Southwest Research Institute and FHWA Offices of Research and Development

The Collapsing Ring Bridge Rail System was developed to fulfill the need for a bridge rail design which is not only capable of withstanding impacts by large vehicles such as trucks and buses, but also does not impart high accelerations to impacting smaller vehicles. The system uses the plastic deformation of steel rings as primary impact energy absorbers. Full-scale crash tests were performed, and redirection of high-speed, 40,000-lb (18,100 kg) vehicles impacting at a 19 degree angle was demonstrated. There was no significant elastic rebound of the rails and energy absorbing rings during the tests, and vehicle damage was limited to mostly sheet metal damage and limited suspension damage of the impacting front quadrant and side panels. The bridge rail damage ranged from slight to extreme for subcompact to heavy vehicle impacts respectively. The report includes summations and illustrations of the tests performed. This bridge rail system is now ready for nationwide display and implementation, and FHWA, Region 15, will provide assistance to States that are interested in constructing pilot installations.

This report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock No. PB 241222).

Use of Rubber Snowplow Blades in Washington (Phase II)

by Washington State Highway Commission and FHWA Implementation Division

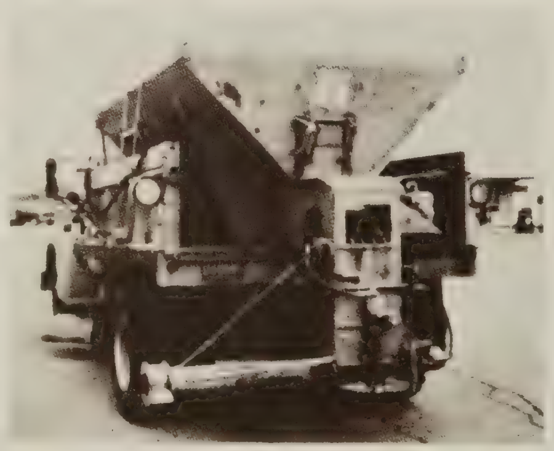
Maintenance engineers and traffic operations engineers who are concerned with snow removal will be interested in this report on the positive and negative aspects of using rubber snowplow blades rather than steel blades. Rubber blades are especially useful in areas using raised traffic lane markers as in western Washington State where a portion of this study was conducted. The damage to raised traffic lane markers is considerably less when rubber blades are used to clear freshly fallen or slushy snow. When the study was extended to the eastern portion of Washington where a colder climate exists, it was found that the effectiveness of rubber blades decreases when the temperature averages below 28° to 30° F (—2° to —1° C) and the snow and ice on the roadway become hard. This problem can be alleviated somewhat by using chemicals to create a slushy or thawing condition. Another favorable quality of the rubber blades is that they do not wear out as quickly as steel blades when they are properly adjusted to bear evenly on the road surface with a downward pressure of approximately 70 pounds per linear foot (107 kg/m) of blade. The report also discusses optimum blade exposure and effective plowing speed, and presents a cost analysis of the use of the two blades.

This report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock No. PB 241914).

Manuals for Deicing Chemicals: Application Practices Storage and Handling

by U.S. Environmental Protection Agency reprinted by FHWA Implementation Division

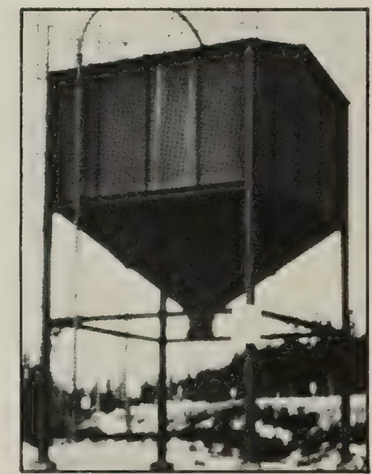
These manuals are the products of a U.S. Environmental Protection Agency funded study to identify the best current practices being used in snow and ice control. Since organizations ranging from State highway departments to shopping centers annually spend about $140 million for approximately 9 million tons of salt and other deicing chemicals, concern in this area has increased for both environmental and economic reasons.



Practical guidelines in the **Application Practices** manual include technical and managerial techniques for reducing the amount of chemicals used. Several recommendations are made: determination of amounts of material being used by spreaders, establishment of levels of service, material application rates for varying weather conditions and various road classes, emphasis on plowing rather than salting, and accurate accounting of the amount of salt used on each section of roadway.

The **Storage and Handling** manual contains guidelines for supervisional requirements, selection and design of storage sites, and proper handling of deicing chemicals. All aspects of storage and handling related to both operational and environmental issues are discussed.

Together these manuals offer workable solutions to the problems faced by maintenance managers when trying to provide clear roads in an efficient and environmentally safe manner. Officials concerned with the initial capital cost, environmental and land-use aspects of storage and handling, protection of water supplies, and public sentiment in the area of deicing chemical usage will also find the manuals useful.



These manuals are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Vol. 1: Stock No. PB 239694; Vol. 2: Stock No. PB 236152).

Debris Removal from Concrete Bridge Deck Joints

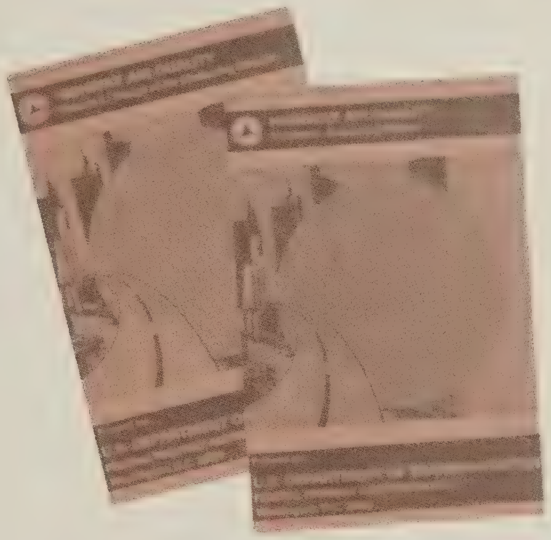
by Texas Transportation Institute and Texas Highway Department

In the past, the technique for removing debris from joints of bridge decks involved loosening the debris by hand with picks and chisels, then blowing out the loosened material with an air hose. Besides being difficult and time consuming, this technique only worked effectively on joints wide and shallow enough to accommodate hand tools. For this study a technique was developed using commercially available high-pressure water-jet equipment and a small, simply constructed cart which facilitates operator control of the water jet. When tested by Texas Highway Department maintenance personnel, this technique was found to be very effective on even the deep and narrow joints of pan-formed bridges. Since almost all pier-cap distress found in pan-formed bridges is apparently caused by debris in fixed joints, this technique combined with the sealing of joints should help prevent additional pier-cap fractures.

This report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock No. PB 240626).

Highway Air Quality
Volume 1: Design of Air Monitoring Surveys
Volume 2: Monitoring Manual

by University of Tennessee and FHWA Offices of Research and Development and FHWA Office of Environmental Policy



In areas with serious air quality problems it is frequently necessary to measure background air pollution levels in order to forecast the impact of a proposed highway improvement. Volumes 1 and 2 of **Highway Air Quality** provide generalized guidelines and information to those agencies involved with air quality monitoring.

Volume 1, **Design of Air Monitoring Surveys,** provides instructional material for individuals engaged in planning, designing, and managing air quality monitoring studies. It enumerates all of the factors that should be considered when determining the need for air monitoring, setting objectives for the study, designing the survey, selecting monitoring equipment, and evaluating results.

Volume 2, **Monitoring Manual,** describes how monitoring equipment works, various sampling methods, how and why calibration is important, and how to obtain the equipment needed to conduct the study.

The manuals are available from the Implementation Division.

Artist **Carl Rakeman's** series of paintings, Historic American Highways, is to be on display by the Federal Highway Administration during the Bicentennial celebration. The series is comprised of 109 paintings, one of which appears on the back cover of this magazine, and traces the history of American highway transportation from the days of colonial America to 1945. The narratives which accompany each of the 109 paintings were written by a historian for the Bureau of Public Roads.

A native of Washington, D.C., Rakeman was an accomplished artist having received his education at the Corcoran Art School and the Royal Academies in Dusseldorf, Munich, and Paris. In 1922, he was employed by the Bureau of Public Roads and remained with the Bureau for 30 years. It was during this period that he painted the Historic American Highways series.

New Research in Progress

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

FCP Category 1—Improved Highway Design and Operation for Safety

FCP Project 1C: Analysis and Remedies of Freeway Traffic Disturbances

Title: Testing and Evaluation of Improved Incident Detection Algorithms. (FCP No. 41C3534)
Objective: Determine the efficiency of incident detection models on the Chicago freeways for various traffic, geometric, and environmental conditions; develop model parameters and thresholds; compare the efficiency of new models with previously used algorithms.
Performing Organization: Illinois Department of Transportation, Springfield, Ill. 62706
Expected Completion Date: July 1977
Estimated Cost: $110,000 (HP&R)

Title: Development and Evaluation of On-Freeway Traffic Control Systems and Surveillance Techniques. (FCP No. 41C3563)
Objective: Evaluate on-freeway metering control; freeway-to-freeway merging control; and incident detection systems for elevated freeways, causeways, and tunnels. Develop and evaluate the use of CCTV to survey traffic operations over large freeway networks.
Performing Organization: Texas Transportation Institute, College Station, Tex. 77840
Funding Agency: Texas Highway Department
Expected Completion Date: August 1976
Estimated Cost: $117,000 (HP&R)

FCP Project 1E: Safety of Pedestrians and Abutting Property Occupants

Title: Feasibility Analysis and Design Concepts and Criteria for Community-Wide, Separate Pedestrian Networks. (FCP No. 31E1042)
Objective: Determine the feasibility, design concepts, and design criteria for separate pedestrian networks in both existing and planned areas. The compatibility of pedestrians and bicyclists on the same facility will be examined.
Performing Organization: RTKL Associates, Inc., Baltimore, Md. 21210
Expected Completion Date: June 1977
Estimated Cost: $296,000 (FHWA Administrative Contract)

FCP Project 1H: Skid Accident Reduction

Title: Design Prediction of Pavement Skid Resistance from Laboratory Tests. (FCP No. 41H1354)
Objective: Develop method for pre-evaluating aggregates and asphalt paving mixtures to predict skid resistance properties of proposed and in service pavement types.
Performing Organization: Kansas State Highway Commission, Topeka, Kans. 66611
Expected Completion Date: June 1978
Estimated Cost: $176,000 (HP&R)

Title: Evaluation of Methods to Restore the Surface Texture of Worn Grooved Highways and Polished PCC and AC Pavements. (FCP No. 41H1364)
Objective: Determine by comparative laboratory testing and field evaluation the best methods to improve skid-resistant characteristics of worn grooved PCC pavements and polished PCC and AC pavements.
Performing Organization: California Department of Transportation, Sacramento, Calif. 95814
Expected Completion Date: June 1978
Estimated Cost: $93,000 (HP&R)

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

Title: Open-Graded Asphalt Friction Course Lane Marking System. (FCP No. 31I1133)
Objective: Develop a snowplow-resistant lane delineation system that has porosity and texture characteristics similar to open-graded asphalt friction courses and that provides adequate lane stripe visibility at night under rainy conditions.
Performing Organization: Georgia Technical Research Institute, Atlanta, Ga. 30322
Expected Completion Date: December 1977
Estimated Cost: $144,000 (FHWA Administrative Contract)

FCP Project 1K: Accident Research and Factors for Economic Analysis

Title: The Development of a Cost-Effectiveness Model for Guardrail Selection. (FCP No. 31K6042)
Objective: Develop a cost-effectiveness model for guardrail selection to include cost parameters for various guardrail configurations as well as criteria for analysis of system effectiveness under various dynamic impact conditions.
Performing Organization: Southwest Research Institute, San Antonio, Tex. 78284
Expected Completion Date: December 1976
Estimated Cost: $213,000 (FHWA Administrative Contract)

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

FCP Project 2G: Coordination of the Traffic Operation of an Urban (Dallas) Freeway with Parallel and Cross Arterial Streets

Title: Development of a Frontage Road Level of Service Evaluation Program—PASSER III. (FCP No. 42G1023)
Objective: Evaluate techniques for making signal pattern transitions for frontage roads; modify PASSER II time-plots for progression; develop travel-time predictions for arterial streets, frontage roads, and freeways during freeway incidents; study the effect of entrance and exit ramp location on the interchange and frontage roads; analyze frontage road geometric design procedures.
Performing Organization: Texas Transportation Institute, College Station, Tex. 77840
Funding Agency: Texas Highway Department
Expected Completion Date: August 1976
Estimated Cost: $60,000 (HP&R)

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

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

Title: The Effects of Construction on Water Quality in Louisiana. (FCP No. 43E2172)
Objective: Determine (by physical, chemical, and biological testing) the effects of construction on the water quality of nearby waters or water systems including bridge structure and hydraulic fill embankment construction.
Performing Organization: Louisiana Department of Highways, Materials Section, Baton Rouge, La. 70804
Expected Completion Date: June 1978
Estimated Cost: $130,000 (HP&R)

Title: Study of Long Range Effect on Aquatic Ecosystems from Adjacent Construction. (FCP No. 43E2182)
Objective: Investigate the effects on the aquatic environment from channel alterations resulting from highway construction on perennial streams and evaluate selected mitigation techniques employed to minimize these impacts.
Performing Organization: California Transportation Laboratory, Environmental Change Branch, Sacramento, Calif. 95819
Expected Completion Date: July 1980
Estimated Cost: $82,000 (HP&R)

Title: Predicting Sediment Flow from Proposed Highway Construction Projects. (FCP No. 43E2192)
Objective: Develop and evaluate procedure to predict sediment erosion from highway construction sites through parameter analysis.
Performing Organization: Pennsylvania State University, University Park, Pa. 16802
Funding Agency: Pennsylvania Department of Transportation
Expected Completion Date: August 1978
Estimated Cost: $162,000 (HP&R)

FCP Project 3F: Pollution Reduction and Visual Enhancement

Title: Planting Techniques and Materials for Revegetation of California Roadsides. (FCP No. 43F1872)
Objective: (1) Select and evaluate plant species for use in the Mojave Desert area; (2) study the methods of increasing the rate of invasion of native vegetation along roads; (3) study the establishment of ground covers from seed; and (4) evaluate and monitor plantings from previous study.
Performing Organization: U.S. Department of Agriculture Soil Conservation Service, Davis, Calif. 95616
Expected Completion Date: June 1980
Estimated Cost: $244,000 (HP&R)

Title: Statistical Analysis of Aerometric Data from Highway Line Sources. (FCP No. 43F3172)
Objective: Identify and develop, as required, parameters of micrometeorological processes which influence atmospheric diffusion near roadways. Evaluate, modify, and validate microscale air quality models to incorporate the findings of the aerometric data analysis.

Performing Organization: California Department of Transportation, Sacramento, Calif. 95819
Expected Completion Date: June 1977
Estimated Cost: $63,000 (HP&R)

FCP Category 4—Improved Materials Utilization and Durability

FCP Project 4G: Substitute and Improved Materials to Reduce Effects of Energy Problems in Highway Costs

Title: Alternatives for Optimization of Aggregate and Pavement Properties Related to Friction and Wear Resistance. (FCP No. 34G2011)
Objective: Determine optimal aggregate properties and pavement surface characteristics needed to provide and retain desirable functional performance requirements; establish warrants for use of optimal pavement surfacing systems; explore the range of candidate aggregates and pavement surfacing strategies to meet requirements; conduct economic analyses.
Performing Organization: Pennsylvania State University, University Park, Pa. 16802
Expected Completion Date: March 1977
Estimated Cost: $99,000 (FHWA Administrative Contract)

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

FCP Project 5A: Improved Protection Against Natural Hazards of Earthquake and Wind

Title: Highway Bridge Response to Seismically Induced Soil Liquefaction. (FCP No. 35A2082)
Objective: Provide guidelines for assisting in the siting and design of highway structures in areas which are subject to potential liquefaction from earthquakes.
Performing Organization: Naval Civil Engineering Laboratory, Port Hueneme, Calif. 93043
Expected Completion Date: June 1977
Estimated Cost: $125,000 (FHWA Administrative Contract)

FCP Project 5B: Tunneling Technology for Future Highways

Title: Monitoring Soil-Structure Interaction in a Colorado Tunnel—Second Bore. (FCP No. 35B3011)
Objective: Generate movement and stress data in soil, rock, and tunnel lining before, during, and after construction. Integrate this new data with engineering information from first and pilot bores to show how site investigation and measurement of soil and rock properties can be used to predict best tunneling methods and lining loads.
Performing Organization: U.S. Bureau of Reclamation, Denver, Colo. 80225
Expected Completion Date: June 1978
Estimated Cost: $490,000 (FHWA Administrative Contract)

FCP Project 5D: Structural Rehabilitation of Pavement Systems

Title: Maintenance Methods for Continuously Reinforced Concrete Pavements (I–65, 5 Miles, Experimental Repair). (FCP No. 45D2354)
Objective: A CRCP built about 1970 is experiencing premature distress. Various rehabilitation techniques—subdrains, subsealing, patching, overlays, and concrete shoulders—will be used in different combinations and the performance of these sections will be statistically compared to controls.
Performing Organization: Purdue University, West Lafayette, Ind. 47907
Funding Agency: Indiana State Highway Commission
Expected Completion Date: June 1978
Estimated Cost: $78,000 (HP&R)

Title: Implementation of a Rating Procedure for Pavement Surface Roughness. (FCP No. 45D4012)
Objective: Design and construct a simple survey profilometer, with continuous recording of rear axle relative vertical motion and vehicle acceleration. Develop a data acquisition and processing method. Write standard procedures for measuring, evaluating, and reporting road roughness.
Performing Organization: Pennsylvania Transportation Institute, University Park, Pa. 16802
Funding Agency: Pennsylvania Department of Transportation
Expected Completion Date: August 1976
Estimated Cost: $77,000 (HP&R)

Non-FCP Category 0—Other New Studies

Title: Evaluation of Epoxy Coated Reinforcing Steel in Bridge Decks. (FCP No. 40M2654)
Objective: Bridge decks constructed using epoxy coated reinforcing steel will be evaluated. Items to be studied include: problems encountered during application, fabrication, shipping, and construction; AC electrical resistance of in-place rebars; cost; and long-term performance.
Performing Organization: Maryland State Highway Administration, Baltimore, Md. 21203
Expected Completion Date: June 1980
Estimated Cost: $81,000 (HP&R)

Title: Evaluation of Latex Modified Concrete Bridge Deck Overlays. (FCP No. 40M2664)
Objective: Evaluate the handling and placing characteristics of latex modified concrete, and the construction and performance of the bridge deck overlay system.
Performing Organization: Maryland State Highway Administration, Baltimore, Md. 21201
Expected Completion Date: June 1980
Estimated Cost: $68,000 (HP&R)

Highway Research and Development Reports Available from the National Technical Information Service

The following highway research and development reports are for sale by the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161.

Other highway research and development reports available from the National Technical Information Service will be announced in future issues.

STRUCTURES

Stock No.

PB 241854 Fatigue Damage in the Lehigh Canal Bridge.
PB 241861 Evaluation of Full Depth Asphaltic Concrete Pavements.
PB 241915 Behavior of Three Instrumented Drilled Shafts Under Short Term Axial Loading.
PB 241917 The Behavior of Statistically Heterogeneous Excavated Earth Slopes—Supplemental Final Report.
PB 242169 Vehicle-Pavement Interaction Study.
PB 242171 Sawing Joints to Control Cracking in Flexible Pavements.
PB 242363 Final Report for Project 3–5–63–56.
PB 242394 Improved Subsurface Investigation for Highway Tunnel Design and Construction. (Vols. 1 and 2.)
PB 242395 Vol. 1—Subsurface Investigation System Planning.
PB 242396 Vol. 2—New Acoustic Techniques Suitable for Use in Soil.
PB 242420 Numerical Analysis of Embankment Over Soft Soils.
PB 242425 Stress Histories for Highway Bridges Subjected to Traffic Loading.
PB 242470 Computer Program for Curved Bridges on Flexible Bents.
PB 242522 Structural Behavior of a Curved Two Span Reinforced Concrete Box Girder Bridge Model (complete set).
PB 242523 Vol. I—Design, Construction, Instrumentation, and Loading.
PB 242524 Vol. II—Reduction, Analysis, and Interpretation of Results.
PB 242525 Vol. III—Detailed Tables of Experimental and Analytical Results.
PB 242555 Molded Fiberglass Narrow Median Barrier.
PB 242557 Highway Bridge Vibration Studies.
PB 242710 Determination of the In-Situ State Stress in Soil Masses.
PB 242736 Environmental Factor Determination from In-Place Temperature and Moisture Measurements Under Arizona Pavements.
PB 242938 Rebound of a Deep Shale Cut.
PB 242968 Field Evaluation of Joint Seal Materials.
PB 243013 Compaction Control of Cement Treated Base.
PB 243108 The Significance of Pavement Texture.
PB 243213 Interim Report Vol. 1: Flexible Highway Pavement Design—The State of the Art.
PB 244089 Effects of Selected Pavements Surface Textures on Tire Noise.

MATERIALS

Stock No.

PB 242260 Feasibility of Using Sewage Sludge in Highway Embankment Construction—Interim Report.
PB 242286 Use of Latex in Concrete Bridge Decks.
PB 242288 Evaluation of Full-Scale Experimental Concrete Highway Finishes.
PB 242546 Continuing Measurements of a Swelling Clay in a Ponded Cut.
PB 242556 Development and Evaluation of Chemical Soil Stabilizers.
PB 242566 Effect of Temperature, Wind, and Humidity on Selected Curing Media.
PB 242731 Correlation of the Texas Highway Department Cone Penetrometer Test with Unconsolidated-Undrained Shear Strength of Cohesive Soils.
PB 242741 A Laboratory Evaluation of Lignite Flyash as a Stabilization Additive for Soils and Aggregates.
PB 242812 Concept of Internally Sealed Concrete.
PB 242992 Depth of Concrete Cover over Bridge Deck Reinforcement.
PB 243011 Internally Sealed Concrete.
PB 243033 Predictability of Physical Changes of Clay Forming Materials in Oklahoma.
PB 243039 Evaluation of Thermoplastic Materials.
PB 243106 Development of Laboratory Methods for Determining D-Cracking Susceptibility of Ohio Gravel and Limestone Coarse Aggregate in Concrete Pavements.
PB 243107 Pavement Surface Polishing Characteristics: A Circular Track Test.
PB 243377 Selecting Pavement Marking Materials Based on Service Life—Final Report.

PB 243390 Traffic Markings—A Procedure for Putting to Use Findings of Research.
PB 243622 A New Rapid Method for Cement Analysis: Atomic Absorption Spectrophotometry—Interim Report.
PB 244071 Laboratory Evaluation of Pavement Surface Texture Characteristics in Relation to Skid Resistance.

TRAFFIC

Stock No.
PB 241857 A Psychophysiological Evaluation of Devices for Preventing Lane Drift and Run-Off-the-Road Accidents.
PB 241862 The Prediction of Driver Record Following Driver Improvement Contacts.
PB 241864 Data Processing Computer Programs: Freeway Operations Study—Phase IV.
PB 241865 Evaluation of Selected Surface Street Network Models.
PB 241870 Urban Traffic Control System and Bus Priority System: Traffic Adaptive Network Signal Timing Program (TANSTP).
PB 241883 Evaluation of Existing Incident Detection Algorithms.
PB 242276 Cost-Effectiveness Evaluation of Freeway Courtesy Patrols in Houston.
PB 242324 Warrants for Highway-Highway Grade Separations.
PB 243040 A Study of Detector Reliability for a Safety Warning System on the Gulf Freeway.

ENVIRONMENT

Stock No.
PB 241983 Effects of Current State Licensing, Permit, and Fee Requirements on Motor Trucks Involved in Interstate Commerce.
PB 242842 Soil Stabilization for Erosion Control.
PB 242991 Capacity and Quality of Service of Arterial Street Intersections.
PB 243007 Dynamic Behavior on an Automobile Traversing Selected Curbs and Medians.
PB 243008 Evaluation of Roadway Safety Features by Computer Simulation—Final Report.
PB 243042 Roadside Vegetation Studies, 1969–1973.
PB 244079 Speed Advisory Information for Reduced Visibility Conditions.

IMPLEMENTATION

Stock No.
PB 236152 Manual for Deicing Chemicals: Storage and Handling. Final Report.
PB 239694 Manual for Deicing Chemicals: Application Practices. Final Report.
PB 241914 Use of Rubber Snowplow Blades in Washington. Phase II—Final Report.
PB 242730 Culvert Outlet Protection Design: Computer Program Documentation.
PB 242969 Implication of Statistical Quality Control of Portland Cement Concrete—Final Report.
PB 243010 Roadway Maintenance Evaluation User's Manual—Interim Report.

PLANNING

Stock No.
PB 240409 Review, Analysis, and Conclusions Concerning Planning Data Systems and Organization.
PB 242737 Feasibility of an Exclusive Bus/Carpool Lane on New Jersey Route 3—Vol. I.

GENERAL

Stock No.
PB 242057 Federally Coordinated Program of Research and Development in Highway Transportation (complete set).
PB 242058 Introduction and Summary.
PB 242059 Vol. 1—Improved Highway Design and Operation for Safety.
PB 242060 Vol. 2—Reduction of Traffic Congestion and Improved Operational Efficiency.
PB 242061 Vol. 3—Environmental Considerations in Highway Design, Location, Construction, and Operation.
PB 242062 Vol. 4—Improved Materials Utilization and Durability.
PB 242063 Vol. 5—Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety.
PB 242064 Vol. 6—Construction, Maintenance, Implementation, and Management.

☆ U.S. Government Printing Office: 1975—621–805/6

Publications of the Federal Highway Administration

The following publications are sold by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. Orders should be sent direct to the Superintendent of Documents. Prepayment is required.

The Audible Landscape: Manual for Highway Noise (1974), $1.55.

Bicycles and Pedestrian Facilities in the Federal-Aid Highway Program (1974), 45 cents.

Bridge Inspector's Training Manual (1970), $2.50; (1971), $2.50.

Car and Bus Pool Matching Guide—4th edition, $1.10.

Construction Manual FP–74 (1974), $5.75.

Coordination of Urban Development and the Planning and Development of Transportation Facilities (March 1974), $2.50.

Corrugated Metal Pipe (1970), 65 cents.

Economics and Social Effects of Highways (1972), $1.45.

Evaluation of Potential Effects of U.S. Freight Transportation Advances on Highway Requirements (Research Phases 1 and 2), $2.75.

Fatal and Injury Accident Rates on Federal-Aid and Other Highway Systems (1973), $1.25.

Federal Assistance Available (1975), 25 cents.

Federal Laws, Regulations, and Other Material Relating to Highways (1974), $2.95.

A Guide to Parking Systems Analysis, $2.85.

Handbook of Highway Safety Design and Operating Practices (1973), $2.

Highway and Urban Mass Transportation (Spring 1972), 90 cents; (Fall 1972), 90 cents; (Winter 1972), 90 cents.

Highway Joint Development and Multiple Use (1970), $1.50.

Highway Statistics (published annually since 1945): (1968), $3.15; (1970), $3.30; (1971), $3.30; (1972), $3.20; (1973), $4.90. (Other years out of print.)

Highways in the River Environment. Hydraulic and Environmental Design Considerations—Training and Design Manual (1970), $5.25.

Hydraulic Design Series:

No. 1—Hydraulics of Bridge Waterways, $1.60.

No. 3—Design Charts for Open-Channel Flow (1961), $2.10.

No. 4—Design of Roadside Drainage Channels, $1.

Hydraulic Engineering Circulars:

No. 5—Hydraulic Charts for the Selection of Highway Culverts (1965), 95 cents.

No. 11—Use of Riprap for Bank Protection (1967), 85 cents.

No. 12—Drainage of Highway Pavements (1969), $1.55.

No. 13—Hydraulic Design of Improved Inlets for Culverts (1974), $2.20.

Improving Urban Mobility—Through Better Transportation Management (1975), $1.05.

Interstate System Accident Research Study (1970), $1.90.

Interstate System Route and Log Finder List (1971), 35 cents.

Manual on Uniform Traffic Control Devices for Streets and Highways (1971), $4.90.

Part VI, Traffic Controls for Street and Highway Construction and Maintenance Operations (1973), $1.25.

Part VII, Traffic Controls for School Areas (1971), 75 cents.

Maximum Safe Speed for Motor Vehicles (1969), $1.50.

Motor Carrier Safety Regulations (1974), $1.55.

National Highway Needs Report, H. Comm. Print 91st Cong., $1.35.

The National System of Interstate and Defense Highways (1972), 25 cents.

The New Look in Traffic Signs and Markings (1972), 50 cents.

Park & Recreational Facilities (1971), 90 cents.

Positive Guidance in Traffic Control (1975), 85 cents.

Quality Assurance in Highway Construction (1970), $1.05.

R&D Highway and Safety Transportation System Studies (1971), $3.70; (1973), $4.50.

Reinforced Concrete Bridge Members—Ultimate Design (1969), $1.10.

Reinforced Concrete Pipe Culverts—Criteria for Structural Design and Installation (1963), 95 cents.

Road User and Personal Property Taxes on Selected Motor Vehicles (1973), $1.50.

Socio and Economic Effects of Highways (1974), $2.15.

Specifications for Aerial Surveys and Mapping by Photogrammetrical Methods for Highways (1968), $2.

Standard Plans for Highway Bridges:

Vol. II—Structural Steel Superstructures (1968), $2.60.

Vol. III—Timber Bridges (1969), $2.

Vol. IVA—Typical Continuous Bridges Load Factor Design (1973), $2.90.

Vol. V—Typical Pedestrian Bridges (1962), $3.40.

Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (1974), $4.55.

Status of the Urban Corridor Demonstration Program (1974), $1.80.

Traffic Assignment—Methods, Applications, Products (1973), $2.90.

Traffic Control Devices Handbook—An Operating Guide (1975), $2.80.

Transportation Planning Data for Urbanized Areas Based on 1960 Census (1970), $13.

Urban Mass Transportation Travel Surveys (1972), $2.10.

Urban Origin-Destination Surveys/Sampling Urban Travel Behavior, $3.20.

Urban Planning General Information (March 1972), $3.65.

Ultrasonic Testing Inspection for Butt Welds in Highway and Railway Bridges (1973), 80 cents.

United States
Government Printing Office
Public Documents Department
WASHINGTON, D.C. 20402

Official Business

PENALTY FOR PRIVATE USE, $300
POSTAGE AND FEES PAID
FEDERAL HIGHWAY ADMINISTRATION
DOT 512

U.S.MAIL

Foreign Projects
Inf. | Act.
DIVIS
LA
EAA
ETC
ADM.

RECEIVED
JAN 13 1976
FOREIGN PROJECTS DIVISION

public roads

A JOURNAL OF HIGHWAY RESEARCH AND DEVELOPMENT